SUPPRESSION OF DIFFUSION FLAMES WITH WATER MIST

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CERTIFICATE

Certified that the thesis entitled “**SUPPRESSION OF DIFFUSION FLAMES WITH WATER MIST”** being submitted by Shri Suresh Lal, to the University of Delhi, Delhi, Faculty of Technology, in the Department of Mechanical Engineering at Delhi College of Engineering, in fulfillment of the requirements for the award of the degree of **DOCTOR OF PHILOSOPHY**, is a record of bonafide research work carried out by him. He has worked under our guidance and supervision and has fulfilled the requirements for the submission of thesis which has attained the standard required for a Ph.D degree of the University of Delhi. The results presented in this thesis have not been submitted elsewhere for the award of any degree or diploma.

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ABSTRACT

The relation between man and fire is very old. From the early stages of life on the surface of earth, fire has been of great assistance to the mankind. Life would not have remained life, had the element of fire been taken away, but at the same time, if the fire becomes uncontrolled, every thing is brought to naught. Thus, in one way, if fire is the best friend of mankind, at the same it is also the worst enemy of man.

For all diffusion flames hydrogen (H) and hydroxyl group (OH) are responsible for flaming. A fire will continue unless radicals are diverted into other reactions by anti-catalytic agents. Flame propagation results from the fast reactions of key species (H and O atoms, OH radicals) with vaporized fuel molecules. These species exist at concentrations far above those expected from thermal equilibrium at flame temperatures. Chemically active agents decompose in the flame to generate the entities that catalytically reduce the radical concentrations toward equilibrium levels. While this catalytic process slows the flame, it does not necessarily extinguish it. Both chemically active and physically active suppressants increase the heat capacity of the fuel/air mixture, reducing the flame temperature and thus, along with the decreased concentrations of radical reactants, decrease the flame reaction rates below the level needed to sustain combustion. These two effects are synergistic. Thus, if weight limitations allow, the effectiveness of a chemical agent can be enhanced by combination with a high heat capacity flame suppressing agent.

When the mass of hot gases is surrounded by the cold gases, the hotter and less dense mass will rise upwards due to density difference, or rather, due to buoyancy. This is what happens above burning fuel source, and the buoyant flow, including any flames, is referred as a fire plume. As the hot gases rise, cold air will be entrained into the plume, causing a layer of hot gases to be formed.

Flammable liquids tend to burn as pools with uniform horizontal surface. However accidental spills of liquid fuels in industrial process and power plant systems can pose a serious fire hazard. Some liquids are highly volatile at ambient

temperatures; they can evaporate and form a flammable mixture with air, leading to a possible explosion in a confined space. Other liquids have high flashpoint and require localized heating to achieve ignition. Once ignited, however, very rapid flame spread will occur over the liquid spill surface. In free burn conditions, the burning rate will quickly reach a constant value, depending on the diameter of the spill. This is a typical case of pool fire. A pool fire is a type of turbulent diffusion flame, which burns above a pool of vaporizing fuel where the fuel vapour has negligible initial momentum.

For suppression of such diffusion flames various chemicals such as Halon 1211 ($CBrClF_2$), Halon 1301 ($CBrF_3$) and Halon 2402 ($CBrF_2CBrF_2$) are used but they contribute in ozone depletion (ODP) and global warming (GWP). The two protocols on environment Montreal Protocol and Kyoto Protocol restricted the use of such chemicals for fire suppression applications.

Water mist is most suitable alternative technology for suppression of diffusion flames, which has favorable physical properties for very effective fire suppressing agent with zero ODP and GWP. Its high heat capacity (4.2 $J/g^{o}K$) and high latent heat of vaporization (2442 J/g) can absorb a significant quantity of heat from diffusion flames. Water also expands 1700 times when it evaporates to steam, which results in the dilution of the surrounding oxygen and fuel vapors. With the formation of small droplets, the effectiveness of water in fire suppression is further increased due to the significant increase in the surface area of water that is available for heat absorption and evaporation.

An internally mixed twin –fluid mist generator (atomizer) can be potentially used in the suppression of diffusion flames inside the enclosed spaces, which provided droplets with sauter mean diagram (SMD) in the 15-85 μm range at a low pressure of water and air (2-4 bar). The measured data suggest that such injectors can be employed to control the atomization process by simultaneously varying the liquid and air supply pressures.

The minimum extinguishing concentration (MEC) of water mist was experimentally measured in modified cup burner apparatus for suppression of n-heptane diffusion flame. The mist with droplet size of 40 µm was injected into flame chimney and it was observed that MEC increases with increase in the air flow rate and 34% increase in value of MEC was observed. The MEC of water mist was 102 gm /m^3 for suppression of n-heptane diffusion flame. It is also observed that on mass to mass basis water mist is 1.7 times more effective then Halon 1301 and 4.4 times more effective then HFC227ea in suppressing a n-heptane diffusion flame as measured in standard cup burner apparatus.

The pool fire suppression tests were conducted in large enclosed space (40 m^3 chamber) using water mist and results indicate that the water mist suppress the diffusion flame in the enclosed space mainly through the evaporating cooling and oxygen displacement by water vapors resulting in inefficient combustion. The fire suppression time decreases with a decrease in droplet diameter. It is much easier to suppress a larger fire due to faster rates of evaporation of water droplets and therefore, the critical mist concentration decreases with an increase in the fire size.

The presence of water vapor in the reaction zone works as a deterrent to the fire by diluting the air and hence reducing the overall concentration of oxygen in the enclosed room. The sharp reduction in the temperature was observed after injection of mist.

The evaporation of water droplets into vapor, causing dilution of air and the subsequent slow down of the combustion process, leading to inefficient combustion manifested by an increase in the concentration of CO, is the primary mechanism for fire suppression using water mists in enclosed spaces. Larger the fire size less is the time required to extinguish the fire. This can be attributed to the larger heat available for evaporation of the water mist droplets leading to attaining the inert environment faster by formation of water vapor and causing dilution of oxygen concentration below that required for sustained combustion reaction. Therefore, the critical mist concentration reduces with an increase in heat release rate (HRR) of the fire. The rate of vaporization is enhanced with an increase in heat release rate, thus, reducing the combustion efficiency and impeding the burning of fire. Therefore, the amount of mist required to suppress a pool fire in an enclosure reduces with an increase in the heat release rate.

Smaller droplets are more effective in the suppression of fire because of their ease of convection to the flame zone and faster and easier evaporation. Water mist with Sauter mean diameter of 40 µm is observed to be most effective in suppressing the fire. The extinction time increases with an increase in droplet diameter. The critical concentration (MEC) of was measured for suppression of diffusion flames of different HRR and it was observed that critical concentration of mist required to suppress the diffusion flame decreases with increase in HRR of pool fires. For suppression of pool fires of n-heptane having HRR of 800 kW, critical mist concentration (MEC) of 150 gm/m3 was required with droplets having 40 µm SMD.

The use of nitrogen as atomizing gas and its effect on diffusion flame suppression performance was evaluated. The critical mist concentration required for suppression of unobstructed & obstructed diffusion flame reduced by 30-50% by use of nitrogen as atomizing gas.

The experimentally measured data on critical concentration of mist required for suppression of diffusion flames in large enclosed spaces forms the basis for design of water mist system. The design concentration of mist will be MEC X Factor of Safety (FOS). The FOS will be in the range of 1.5 to 2

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ABBREVIATIONS

ALR	Air liquid mass ratio
C_D	Discharge Coefficient
D^*	Non-dimensional droplet diameter
D_{32}	Sauter Mean Diameter - SMD (μm)
A_0	Orifice Area (m^2)
D_l	Effective diameter of liquid ligament (m)
D_o	Droplet Diameter (µm)
Dv_{10}	10% Volume mean diameter (μm)
Dv_{50}	50% Volume mean diameter (μm)
Dv_{90}	90% Volume mean diameter (μm)
m_a	Mass flow rate of air (kg/s)
m_w	Mass flow rate of water (kg/s)
m^{II}	Mass burning rate (kg/m^2-s)
$\Delta H_{c\ eff}$	Effective heat of combustion (kJ/kg)
A_{pool}	Surface area of pol fire (m^2)
D	Diameter of pool (m)
t_b	Burning duration of pool fire (s)
H_f	Flame height of pool fire (m)
P_a	Air supply pressure (Pa)
P_w	Liquid supply pressure (Pa)
Re_l	Reynolds number of liquid ligament
V_a	Velocity of air (m/s)
V_w	Velocity of liquid (m/s)
We_l	Weber number of liquid ligament
Q	Flow rate (lpm)
Q_{air}	Air flow rate (lpm)
C_C	Coefficient of contraction,
A_2	Area between float and tube (m^2)
V_f	Volume of float (m^3)

A_f	Effective area of float (m^2)
Sc	Schmidt number
Sh	Sherwood Number
M_w	Momentum of the spray,
m_{wl}	mass of liquid-phase water entrained by mist
m_{wv}	mass of vapour-phase water entrained by mist
m_{wa}	mass of liquid- air entrained by mist
V_w	Velocity vector of water mist
L	Latent heat of vaporization (KJ/Kg)
ΔT	Temperature difference between the droplet and surroundings (^oC)
Q_c	Convective heat transfer rate (kW)
MEC	Minimum Extinguishing Concentration (%v/v)
Halon 1301	CF_3Br
HFC227ea	CF_3CHFCF_3
HRR	Heat release rate (kW)

Subscripts

D(32)	Volume to area ratio (SMD)
O	Orifice
a	Air
w	Water
l	Liquid ligament
f	Fluid
fl	Float

Greek Letters

ρ	Density (kg/m^3)
σ	Surface tension (kg/s^2)
μ	Viscosity of water (kg/ms)
ν	Regression rate (m/sec)

Chapter 1
INTRODUCTION

1.0 THE EVOLUTION OF FIRE SUPPRESSION

The ability to control fire is universally and exclusively human. The history of that controlled use is also the history of civilization [1]*. While individuals likely recognized the first principles of fire control, it was the rise of organized societies that led to structured activities and, later, products to mitigate the unwanted outcomes of fires. Now, the application of chemicals, manually and by mechanical devices, to control fires has become a mainstay of modern society. In particular, the development of the use of fire suppressant chemicals has a rich history [2].

In the earliest years, small nomadic groups of these pre-humans observed the nature of fire. While they could see its destructive power, they soon recognized its benefits as well. They saw that animals ran from it, and thus it became a tool for trapping food. They found that animals and nuts that had been exposed to the flames were easier to eat. They enjoyed the radiant warmth from the fire on cold nights. They no doubt observed that rain made the fires stop, and some might have even noticed that there were few fires following a rainstorm.

An enabling breakthrough in fire suppression came in the late 17th century, with the invention by Jan van der Heyden of Holland of the rollable fire hose. In 1725, Richard Newsham of London patented an improved pump design that could take advantage of van der Heyden's hoses. Soon a variety of hand pumps were devised to move water (still the suppressant of choice) efficiently from a city reservoir to the fire. During the Industrial Revolution in the mid-nineteenth century, these pumps became combustion-powered.

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* Numbers in the parentheses indicate references at the end of the thesis

The scientific and technologic revelations of the 18th and 19th centuries led to new capabilities for the control of fires. In particular, James Watt's invention of the steam engine in 1769 led to two major innovations. In 1812, William Congreve received a patent for a steam-driven, perforated pipe water distribution system. In the middle of the century, the fusible link and self-opening valve were added, making the system fully automatic. In 1852, Moses Latta produced the first steam-powered, self-propelled fire engine, and the first commercially successful ones followed in 1867. Now there were ways to bring water, still the predominant suppressant, to the fire. It thus became possible to react in time to save a complex commercial or residential structure and many of the people within. The installation of the first automatic sprinklers in the U.S. and England in the late 19th century began bringing the water directly into the building [3]. This provided faster response and further containment of the fire damage. What remained was the development of technology to assure the safety of the contents.

The relation between man and fire is very old. From the early stages of life on the surface of earth, fire has been of great assistance to the mankind. Life would not have remained life, had the element of fire been taken away, but at the same time, if the fire becomes uncontrolled, every thing is brought to naught. Thus, in one way, if fire is the best friend of mankind, at the same it is also the worst enemy of man. To stop, that fire may not become our enemy it is very essential to control and fight the fire most effectively and timely. The type of extinguishing medium should be used to control or extinguishing media as per the classification of fire.

The most common fuels in fire and explosion incidents are petroleum products, cellulosic materials (wood, paper), and polymers. Fires of cellulosic materials are termed "Class A" and liquid fuel fires are termed "Class B". Polymeric material fires can exhibit characteristics of either "Class A" or "Class B" depending on the extent of melting (if any) during combustion. "Class C" fires involve energized electrical equipment and "Class D" fires, flammable metals. Rapid gas phase combustion can result in an explosion or, in the limit as the combustion becomes very rapid, detonation.

There are two general types of fire and explosion suppression techniques (1) total-flood fire suppression (2) streaming fire extinguishment,

In total-flood applications, an extinguishing agent is discharged into an enclosed space to achieve a concentration sufficient to extinguish or suppress an existing fire. The agent concentration that a system/agent combination is designed to produce is termed the .design concentration.. Total-flood extinguishment usually uses fixed systems (e.g., non portable systems attached to a protected structure) with either manual or automatic activation. Automatic systems detect a fire and automatically discharge the extinguishing agent. Total-flood applications include protection of enclosed spaces.

In streaming applications, an agent is applied directly onto a fire or into the region of a fire. This is usually accomplished using manually operated wheeled or portable extinguishers. Hand-held portable extinguishers provide fire protection in aircraft passenger compartments.

Halons are bromine-containing gaseous or volatile liquid chemicals used in fire and explosion protection. Most widely employed are Halon 1301, bromotrifluoromethane ($CBrF_3$), used primarily as a total-flood agent, and Halon 1211, bromochlorodifluoromethane ($CBrClF_2$), used primarily in streaming applications. These clean (residue-free) chemicals are applicable to Class A, B, and C fires. They cannot be used for Class D fires.

1.1 ANATOMY OF FIRE

Practically in all fires (except metals), the hydrogen (H) and hydroxyl group (OH) are responsible for flaming. A fire will continue unless radicals are diverted into other reactions by anti-catalytic agents. This has been explained below in Fig. 1.1

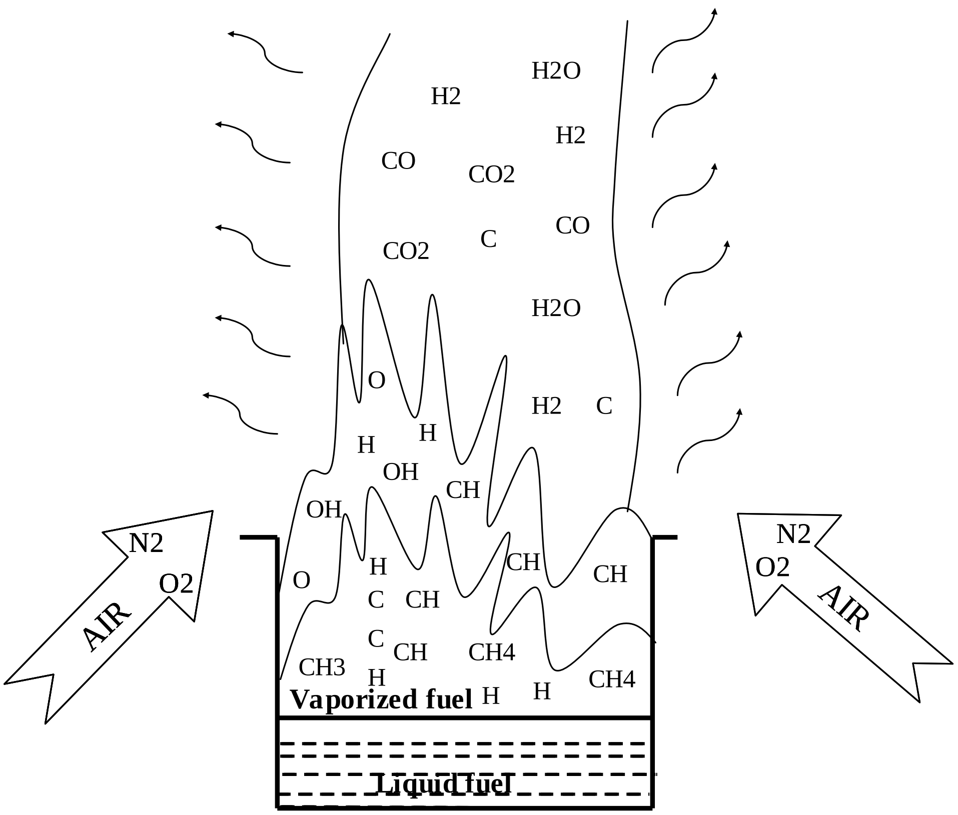


Fig. 1.1 Anatomy of fire

Flame propagation results from the fast reactions of key species (H and O atoms, OH radicals) with vaporized fuel molecules. These species exist at concentrations far above those expected from thermal equilibrium at flame temperatures. Chemically active agents decompose in the flame to generate the entities that catalytically reduce the radical concentrations toward equilibrium levels. While this catalytic process slows the flame, it does not necessarily extinguish it. Both chemically active and physically active suppressants increase the heat capacity of the fuel/air mixture, reducing the flame temperature and thus, along with the decreased concentrations of radical reactants, decrease the flame reaction rates below the level needed to sustain combustion. These two effects are synergistic. Thus, if weight limitations allow, the effectiveness of a chemical agent can be enhanced by combination with a high heat capacity flame suppressing agent.

1.2 DIFFUSION FLAMES AND FIRE PLUMES

The principal characteristic of the diffusion flame is that the fuel and oxidizer (air) are initially separate and combustion occurs in the zone where the gases mix. The classical diffusion flame can be demonstrated using a simple Bunsen burner as indicated in Fig. 1.2(b) with air inlet port closed.

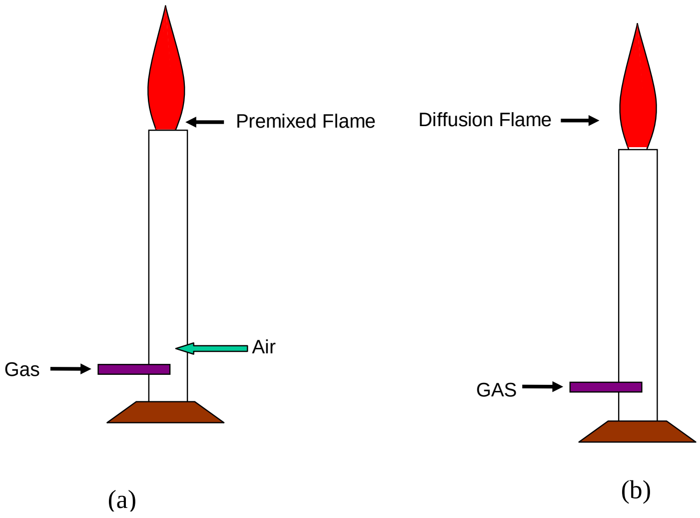


Fig. 1.2 Bunsen Burner Flames (a) Premixed flame (b) Diffusion flame

The stream of fuel issuing from the burner chimney mixes with air by entrainment and diffusion and, if ignited, will burn wherever the concentrations of fuel and oxygen are within the appropriate (high temperature) flammability limits. The appearance of the flame will depend on the nature of the fuel and the velocity of the fuel jet with respect to the surrounding air. Thus, hydrogen burns with a flame which is almost invisible, while all hydrocarbon gases yield flames which have the characteristic yellow luminosity arising from incandescent carbonaceous particles formed within the flame. Laminar flames are obtained at low flowrates. Careful inspection reveals that just above the burner rim, the flame is blue, similar in appearance to a premixed flame. This zone exists because some premixing can occur close to the rim where flame is quenched eventually 'lifting off' when flame stability near the burner rim is lost due to excess air entrainment at the base of flame.

The momentum of the fuel vapour largely determines the behavior of these types of flame which are often referred to as ‘momentum jet flames’.

In contrast, flames associated with the burning of condensed fuels (i.e. solids and liquids) are dominated by buoyancy, the momentum of the volatiles rising from the surface being relatively unimportant. If the fuel bed is less than 0.05 m in diameter, the flame will be laminar, the degree of turbulence increasing as the diameter of the fuel bed is increased, until for diameters greater than 0.3 m buoyant diffusion flames with fully developed turbulence are observed

1.2.1 Laminar jet flames

When a jet of gas issues into a still atmosphere, air is entrained as a result of sheer forces between the jet and the surrounding air. However, the shear forces cause instability in the gas flow which gives rise to flame flicker [4]. For hydrocarbon diffusing flames on a Bunsen burner the flickering has a frequency of 10-15 Hz. This can be virtually eliminated if the surrounding air is made to move concurrently with and at the same linear velocity as the gas jet. Bruke & Suchumann [5] chose to work with this arrangement in their classic study of laminar diffusion flames. They enclosed the burner tube inside a concentric cylinder carrying the flow of air: by varying the relative diameters of the tubes they were able to establish ‘over-ventilated’ and ‘under-ventilated’ flames as shown in Fig. 1.3 These studies established that combustion flame structure could be analyzed on the assumption that the burning rate was controlled by the rate of mixing rather than by the chemical kinetic.

The rate of diffusion of one gas into another can be described by Flick’s law which for one dimension is:

$$\dot{m}_i'' = -D_i \frac{dC_i}{d_x}$$

Where $\dot{m}_i''$ and C_i are the mass flux and concentration of species $_i$ respectively and D_i is the diffusion coefficient for species $_i$ in the particular gas mixture.

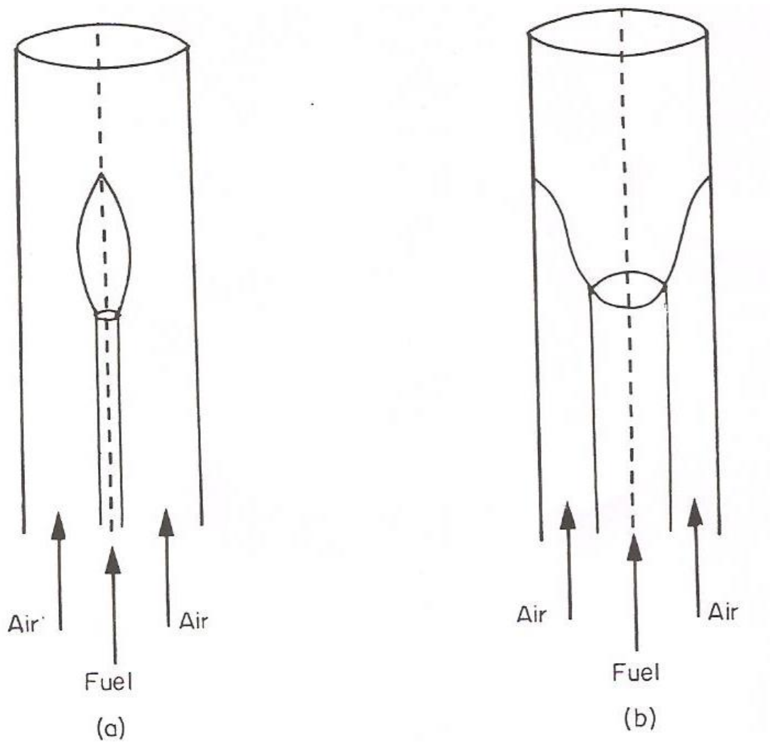


Fig. 1.3 Bruke & Schumann study of the structure of diffusion flame (a) Over-ventilated and (b) Under – ventilated flames.

Laminar jet flames are unsuitable for studying the detailed structure of the diffusion flames. The flat diffusion flames was developed using a burner consisting of two contiguous slots, one carrying the fuel gas and other oxidant as indicated in Fig. 1.4(a).

This type of burner had concurrent flow of nitrogen surrounding the burner, this arrangement yields a stable, vertical flame sheet on which various types of measurements can be made on both sides of combustion zone. Using this device, valuable information has been obtained on the spatial concentrations of combustion intermediates (including free radicals) which has better understanding of the chemical process with in the flame. This type of work has given insight into the mechanism of smoke formation in diffusion flames [6]

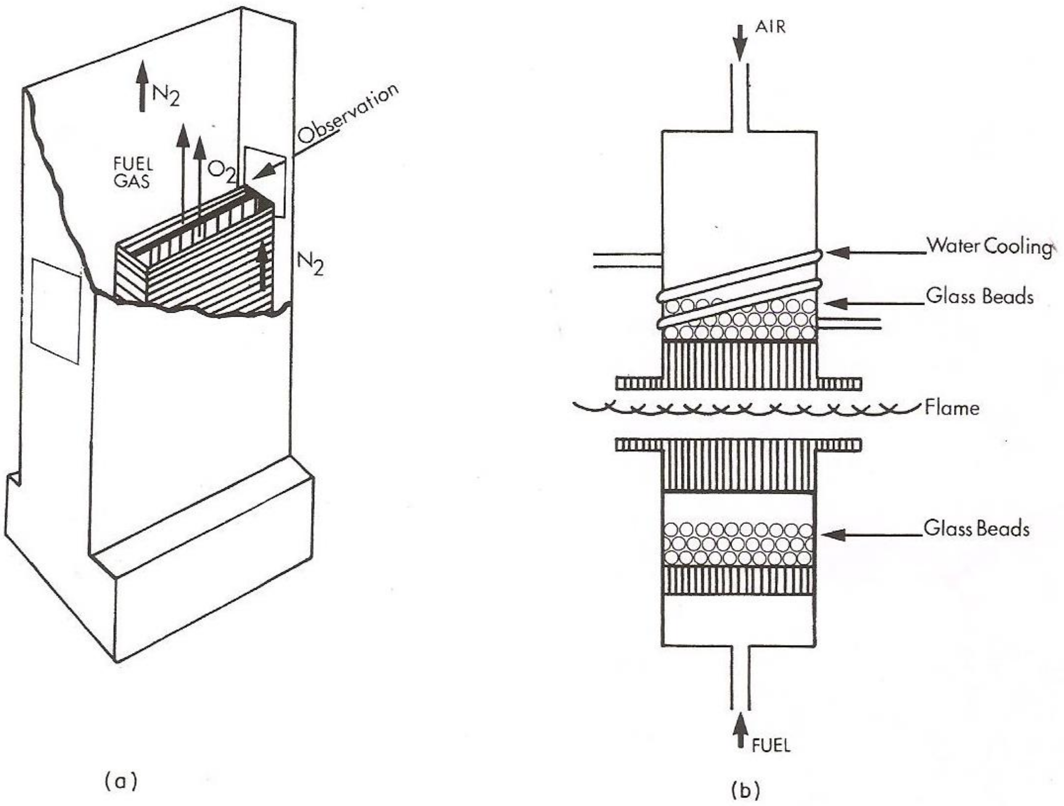


Fig. 1.4 (a) The flat diffusion flame, (b) The counter flow diffusion flame

However like jet flames, this type of flat flame is affected by the presence of the burner rim. This can be avoided by using counter - flow diffusion flame burner in which a flat flame is established in the stagnant layer where diametrically opposed flows of fuel and oxidant meet as indicated in Fig. 1.4 (b)

All above mentioned systems has been widely used to examine the stability and extinction of diffusion flames of gaseous, liquid and solid fuels. [7]

1.2.2 Turbulent jet flames

The height of a jet flame will increase approximately as the square root of the volumetric flow rate of the fuel, by this is true only in the laminar regime. Above a certain jet velocity, turbulence begins initially at the flame tip, and the flame height decreases with footrace to a roughly constant value for the fully turbulent flame. The transition from a laminar to a turbulent flame is observed to occur at a nixie Reynolds number significantly greater than 2000 as it is the local Reynolds number ($Re = ux / v$)

within the flame which determines the onset of turbulence. Re decreases significantly with rise in temperature as a result of the variation in kinematic viscosity (ν). Turbulence first appears at the tip of the flame, extending further down towards the burner nozzle as the jet velocity is increased, although never reaching it as indicated in Fig. 1.5. The decrease in flame height from the maximum inside the laminar region to a constant value in the fully-turbulent regime can be understood qualitatively in terms of increased entrainment of air by eddy mixing which results in more efficient combustion.

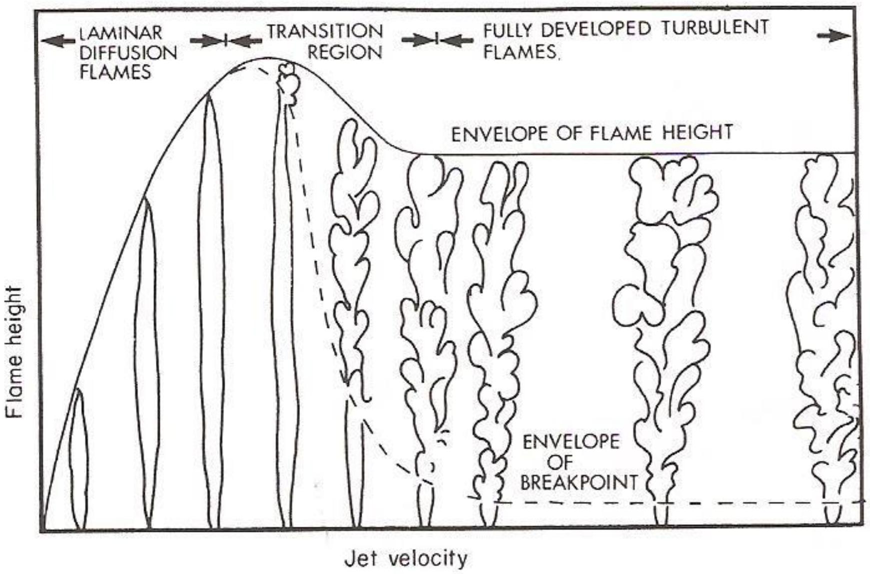


Fig. 1.5 Height of momentum jet flames as a function of nozzle velocity

1.2.3 Flames from natural fires

Unlike the momentum jet, the upward movement of the flame gases in natural fires is created entirely by buoyancy. The flow rate of the fuel vapour into the flame above a condensed fuel is generally too low for the associated momentum to have any measurable effect on flame behavior. Consequently the structure of the flame is not as highly ordered as a laminar jet flame as indicated in Fig. 1.6, although Corlett [8] has pointed out that a significant fuel-rich core exists above the surface for fuel beds of diameter between 0.03 and 0.3 m: ‘structured flames’. Several studies of these flames have been made using porous bed burners with gaseous fuels fires involving combustible solids and liquids in that the fuel.

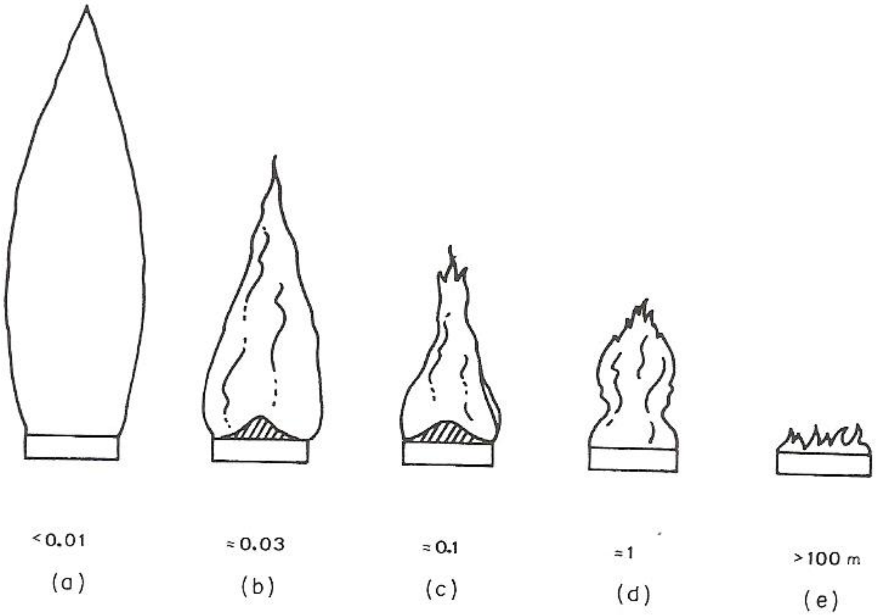


Fig. 1.6 Classification of natural diffusion flames a 'structured' (b and c) and 'unstructured' (a,d, and e)

Flow rate is an independent variable and the flame can be maintained indefinitely for experimental purposes. McCafrey [9] showed that the 'fire plume' above a 30 cm square burner consisted of three distinct regimes as indicated in Fig. 1.7 namely:

(i) The near field, above the burner surface, where there is persistent flame and an accelerating flow of burning gases (the flame zone);

(ii) A region in which there is intermittent flaming and a near constant flow velocity (the intermittent zone); and

(iii) The buoyant plume which is characterized by decreasing velocity and temperature with height.

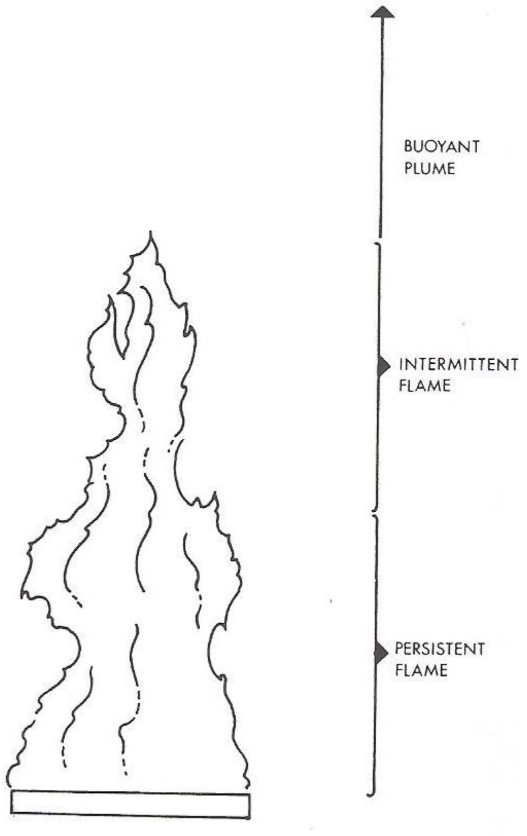


Fig. 1.7 Schematic diagram of the fire plume showing three regimes

While these are inseparable in the fire plume, it is appropriate first to consider the buoyant plume since its properties are relevant to other aspects of fire engineering, including fire detection and smoke movement and control.

1.3 FIRE PLUMES

When the mass of hot gases is surrounded by the cold gases, the hotter and less dense mass will rise upwards due to density difference, or rather, due to buoyancy. This is what happens above burning fuel source, and the buoyant flow, including any flames, is referred as a fire plume. As the hot gases rise, cold air will be entrained into the plume, causing a layer of hot gases to be formed. The concept of buoyancy was introduced in relation to natural convection. If a density difference exists between adjacent masses of fluid as result of a temperature gradient, then the force of buoyancy will cause the less dense fluid to rise with respect to its surroundings. The buoyancy force (per unit volume) which is given by g(p –p), where g is the gravitational acceleration constant, is resisted by viscous drag within the fluid, the relative magnitude of these opposing forces being expressed as the Grashof number

1.4 FLAME CHARACTERISTICS

In most fire safety engineering applications we are concerned with the so-called buoyant, turbulent diffusion flame, The some of the processes that characterize such flames, show results from flame height measurements, and give correlation equations that can be used for estimating flame heights[10].

1.4.1 Diffusion

Diffusion flames refer to the case where fuel and oxygen are initially separated, and mix through the process of diffusion. Burning and flaming occur where the concentration of the mixture is favorable to combustion. Although the fuel and the oxidant my come together through turbulent mixing, the underlying mechanism is molecular diffusion. This is the process in which molecules are transported from a high to low concentration. Opposite to this is the premixed flame, as is the case with a welder’s torch, where the fuel and the oxidant are mixed before ignited. Flames in accidental fires are nearly always characterized as diffusion flames.

1.4.2 Buoyancy

When a mass of hot gases is surrounded by colder gases, the hotter and less dense mass will rise upward due to the density difference, or rather, due to buoyancy. The upward velocity of the flow within a flame will be dominated by the buoyancy force if the velocity at which the fuel in injected is not exceptionally high. Opposite to the buoyancy – dominated flames are the flows formed above a high pressure gaseous fuel source (for example, a ruptured pipeline under high pressure) where the flow is not buoyancy dominated, but momentum dominated; these are termed jet flames.

1.4.3 Turbulence

Very small diffusion flames can be laminar, such as the flame on a candle. Larger diffusion flames are turbulent and will fluctuate with periodic oscillations with large eddies shedding. The eddies, which are visible in turbulent plume) more so in momentum-driven plumes than in buoyancy – driven ones), roll up along the outside of the plume and are a result of the instability between the hot flame and the cold air.

These random fluctuations, which are characteristic of turbulent, will give rise to periodic flame height (and shape) fluctuations. The fluctuations normally have a frequency of the order of 1-3 Hz, i.e. will occur between one and three times per second; in general, this shedding depends on fire diameter.

1.4.4 Mean flame height

In order to provide engineering equations allowing calculation of the flame height, we must first define the mean flame height. This is most conveniently done by averaging the visible flame height over time. The luminosity of the lower part of the flaming region appears fairly steady. The upper part fluctuates or, in other words, is intermittent.

1.5 POOL FIRES

Liquids tend to burn as pools with uniform horizontal surface. However accidental spills of liquid fuels in industrial process and power plant systems can pose a serious fire hazard. Some liquids are highly volatile at ambient temperatures; they can evaporate and form a flammable mixture with air, leading to a possible explosion in a confined space. Other liquids have high flashpoint and require localized heating to achieve ignition. Once ignited, however, very rapid flame spread will occur over the liquid spill surface. In free burn conditions, the burning rate will quickly reach a constant value, depending on the diameter of the spill. This is a typical case of pool fire. A pool fire is a type of turbulent diffusion flame, which burns above a pool of vaporizing fuel where the fuel vapour has negligible initial momentum.

The early work [11-13] on liquid pool fires remains the most extensive single study. The rates of burning of pools of hydrocarbon liquids have been studied with diameters ranging from 3.7×10^{-3} to 22.9 m. A constant head device was used with all the smaller ‘pools’ to maintain the liquid surface level with the rim of the container. They found that the rate of burning expressed as a ‘regression rate’ R (mm/min) (equivalent to the volumetric loss of liquid per unit surface area of the pool in unit time) was high for small-scale laboratory ‘pools’ (1 cm diameter and less), and exhibited a minimum at around 0.1 m as indicated in Fig. 1.8

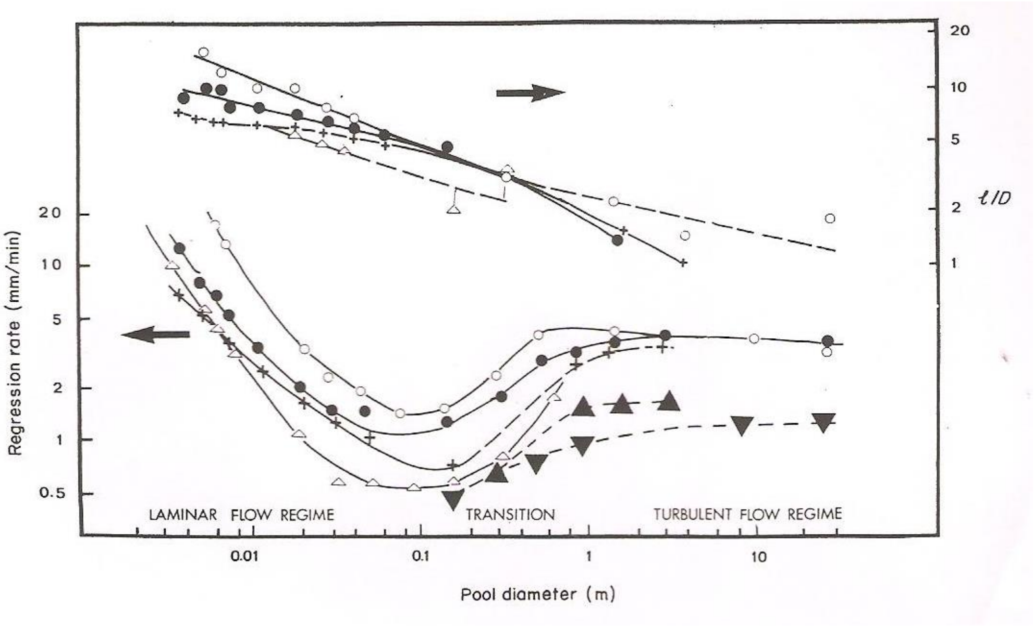


Fig. 1.8 Regression rates and flame height for liquid pool fires with diameters in the range 3.7 X 10 -3 _22.9 m, o, Gasoline;• ,tractor kerosene; Δ, solar oil;+, diesel oil; ▲, petroleum oil; ▼, mazt oil. [11]

Three regimes can be distinguished. If the diameter is less than 0.03 m, the flames are laminar, and the rate of burning, R, falls with increase in diameter, while for large diameters (D 1.0 m, ‘transitional ‘ behavior, between laminar and turbulent, is observed. The dependence on pool diameter can be explained in terms of changes in the relative importance of the mechanisms by which heat is transferred to the fuel surface from the flame.

1.5.1 Estimating pool fire heat release rate

When an object burns it releases a certain amount of energy per unit time and denoted Q. This energy released per unit time is known as Heat release rate (HRR). HRR is also known as energy release rate and measured in watts or Kilowatts (kW). The HRR in compartment fire controls to a extent the environmental consequences of the fire, such as the plume flows, the hot gas temperature and the rate of descent of hot gas layer. There are number of calculations procedures to enable an estimation of environmental consequences of a fire. Fire development is generally characterized in terms of HRR Vs time. There are basically two approaches available when determining the design fire for a given scenario. One is based on knowledge of the amount and type of combustible materials in the compartment of fire origin. The other is based on knowledge of the occupancy where very little is known about the details of fire load. We have followed the first approach as we know the amount and type of fuel to be used for the pool fires. HRR in a fire depends mainly on type of fuel, pool diameter [14].

$$Q = m''\Delta H_{c,\,eff}\,(1 - e^{-k\beta\,D})\,A_{pool} \qquad \text{(i)}$$

Where Q = HRR, heat release rate (kW)

m'' = mass burning rate of fuel per unit surface area (kg/m^2-sec)

$\Delta H_{c,eff}$ = effective heat of combustion of fuel (kJ/kg)

A_{pool} = surface area of pool fire (area involved in vaporization) (m^2)

$k\beta$ = empirical constant (m^{-1})

D = diameter of pool fire (m)

Fairly extensive pool fire experiments have been carried out for vide range of liquids and it is found that, for a diameter larger than 0.2 m, the burning rate increase with diameter up to certain value, which is called as asymptotic diameter mass loss rate, denoted by m'', usually given in kilograms per square meter per second. The values of burning rate for larger pool diameters is given in the table 1.1 but for the smaller pool diameters the burning rate reduces.

The mass loss rate from free burning pools depends not only on diameter of pool but also on two empirical constants that characterize the particular fuel used and are a function of the radiative heat flux from the flame towards the fuel surface. One of these is the extinction - absorption coefficient of the flame denoted by k, and the other is the mean beam length corrector, denoted by β. For pool fire calculation purposes it is not necessary to determine these two constants separately, only their product is used as empirical constant. Table 1.2 indicates value of empirical constant and heat of combustion of various fuels.

Table 1.1: Burning Rate per Unit Area and Complete Heat of Combustion for Various Materials [15]

Material (pool diameter m)	m'' (kg/m^2-sec)	ΔH_c (MJ/kg)
Polyethylene	0.026	43.6
Polypropylene	0.024	43.4
Heavy fuel oil (2.6-23)	0.036	----
Kerosene (30 -80)	0.065	44.1
Crude oil (6.5 – 31)	0.056	----
n-Dodecane (0.94)	0.036	42.2
Gasoline (1.5 – 223)	0.062	----
JP – 4 (1-5.3)	0.067	----
JP – 5 (0.6 – 1.7)	0.055	----
n – Heptane (1.2 – 10)	0.075	44.6
n – Hexane (0.75 – 10)	0.077	44.8
Transformer fluids (2.37)	0.025 – 0.030	----

Table 1.2. Empirical constant (kβ) and Heat of Combustion (KJ/Kg) for various fuels

Fuel	Empirical constant (kβ)	Heat of Combustion (KJ/Kg)
n Heptane	1.1	44600
Gasoline	2.1	43700
Diesel	2.1	44400

1.5.2 Pool Fire Diameter Calculation

Pool fire area is calculated using equation (i) and then pool Diameter is calculated putting values in equation (ii)

$A_{pool} = \pi D^2/4$ (ii)

Where A_{pool} = surface area of pool fire (m^2)

D = pool fire diameter (m)

$D = \sqrt{(4A_{pool}/\pi)}$

The pool diameter, denoted by D, is assumed to be circular. Square and similar configurations can be treated as pool of equivalent circular area. For alcohols, the diameter dependence for burning rate is negligible. The flames contain little soot and are nearly invisible to the human eye, so radiation to the surface is much less than that for sootier flames. The mass loss rate is therefore a relatively constant value for almost all diameters larger than 0.2 m. Also, the combustion efficiency for alcohols is close to unit for the same reason.

For sootier flames, such as those that appear when transformer oil burns, the diameter dependency is considerable and combustion efficiency is lower, perhaps around 60 to 70 % for free burning experiments.

Table 1.3. Pool diameter for different HRR for various pool fires.

HRR(KW)	Pool Dia (m) for n - Heptane	Pool Dia (m) for Gasoline	Pool Dia (m) for Diesel
300	0.462	0.496	0.534
500	0.556	0.606	0.653
800	0.662	0.735	0.794

1.5.3 Regression Rate

Regression rate is rate of burning of fuels expressed in m/sec. It is calculated using following equation

$\nu = m''/\rho$---------------------------- (iv)

Where ν= regression rate (m/sec)

m'' = mass burning rate of fuel (kg/m^2-sec)

ρ = liquid fuel density (kg/m^3)

Table 1.4: The mass burning rate, density and regression rate for various fuels

Fuel	m''(kg/m^2-sec)	Density(Kg/m^3)	Regression Rate(R) m/sec
n Heptane	0.101	675	$15\text{x}10^{-5}$
Gasoline	0.055	740	$7.4\text{x}10^{-5}$
Diesel	0.045	918	$4.9\text{x}10^{-5}$

1.5.4 Estimating pool fire burning duration

During the fire suppression test using water mist, some pre burn time before the water mist system can be operated will have to be given to the fire so that the temperature in the chamber reaches above 60^{o}C. The fuel quantity should be enough for free burning for sufficient time.

$t_b = 4V / \pi D^2 \nu$ (iii)

Where t_b = burning duration of pool fire (sec)

V = volume of liquid (m^3)

D = pool diameter (m)

ν= regression rate (m/sec)

The amount of fuel required for five minutes free burning of various fuels is calculated using above equation. The quantity required for five minutes burning is more for n Haptane fuel as compared to Gasoline and Diesel. Diesel required least quantity for same period burning. The reason for these is that the n Haptane has very high regression rate(R) as compared to Diesel fuel.

Table 1.5. Fuel quantity required for five minute free burning of various fuels of different HRR

HRR(KW)	n - HEPTANE (ltrs)	GASOLOINE (ltrs)	DIESEL(ltrs)
300	7.50	4.30	3.30
500	10.90	6.40	4.90
800	15.50	9.50	7.20

1.5.5 Estimating pool fire flame height

The pool fire flame height is obtained by using Heskestad equation [16] . The main advantage of this method is he relaxed the assumption of point source by introducing a “virtual origin” at height Z_o.

$H_f = 0.235\ Q_c^{2/5} - 1.02\ D$ (v)

Where H_f = pool fire flame height (m)

Q_c = pool fire heat release rate (Convective heat transfer =0.7 x HRR) (kW)

D = pool fire diameter (m)

Table1.6: Flame height of various fuels for different HRR

HRR (KW)	n – Heptane (m)	Gasoline(m)	Diesel (m)
300	1.67	1.64	1.60
500	2.06	2.01	1.96
800	2.50	2.43	2.36

1.6 ENCLOSURE FIRE CHARACTERISTICS

Fire is a physical and chemical phenomenon that is strongly interactive by nature. The interactions between the flame, its fuel, and the surroundings can be strongly nonlinear, and quantitative estimation of the processes involved is often complex. The processes of interest in an enclosure fire mainly involve mass fluxes and heat fluxes to and from the fuel and the surroundings. Fig. 1.9 shows a schematic of these reactions, indicating the complexity of the mass and heat transfer process occurring in the enclosure fire [17].

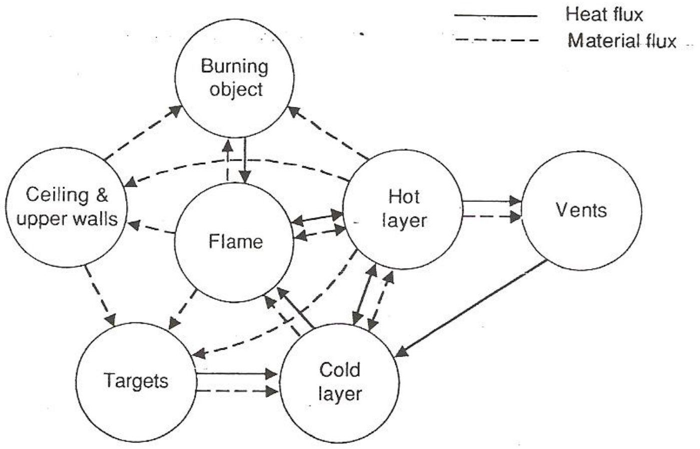


Fig. 1.9 Schematic of interactions indicating complexity of the mass and heat transfer process

1.6.1 FIRE GROWTH IN AN ENCLOSURE

A fire in an enclosure can develop in a multitude of different ways, mostly depending on the enclosure geometry and ventilation and the fuel type, amount and surface area. The following is a general description of the various phenomena that may arise during the development of a typical fire in a enclosure.

1.6.1.1 Ignition

After ignition, the fire grows and produces increasing amounts of energy, mostly due to flame spread. In the early stages the enclosure has no effect on the fire, which then in fuel controlled. Besides releasing energy, a variety of toxic and nontoxic gases and solids are reduced. The generation of energy and combustion products is a very complex issue and one must rely on measurements and approximate methods in order to estimate energy release rates and the yield of combustion products.

1.6.1.2 Plume

The hot gases in the flame are surrounded by cold gases, and the hotter, less dense mass will rise upward due to the density difference, or rather due to buoyancy. The buoyant flow, including any flames, is referred to as a fire plume. As the hot gases rise, cold air will be entrained into the plume. This mixture of combustion products and air will impinge on the ceiling of the fire compartment and cause a layer of hot gases. Only a small portion of the mass impinging on the ceiling originates from the fuel; the greatest portion of this mass originates from the cool air entrained laterally into the plume as it continues to move the gases onward the ceiling. As a result of this entrainment, the total mass flow in the plume increases, and the average temperature and concentration of combustion products decreases with height.

1.6.1.3 Ceiling jet

When the plume flow impinges on the ceiling, the gases spread across it as a momentum-driven circular jet. The velocity and temperature of this jet is of importance, since quantitative knowledge of these variables will allow estimates to be made on the response of any smoke and heat detectors and sprinkler links in the vicinity of the ceiling. The ceiling jet eventually reaches the walls of the enclosure and is forced to move downward along the wall, as shown in Fig. 1.10 [18]. However, the gases in the jet are still warmer than the surrounding ambient air, and the flow will turn upward due to buoyancy. A layer of hot gases will thus be formed under the ceiling.

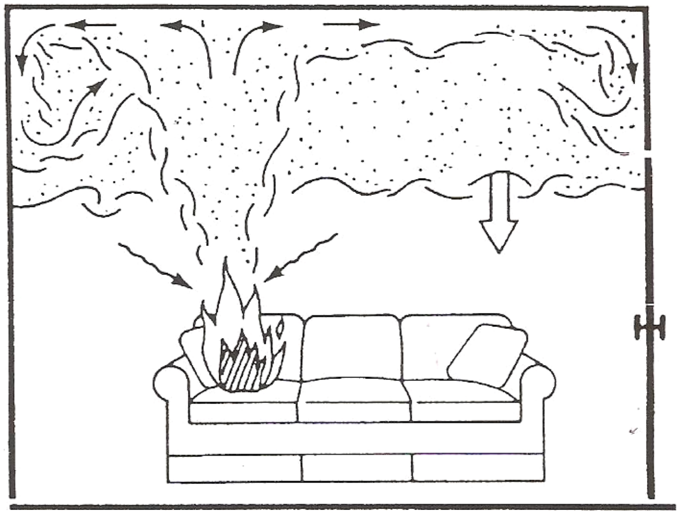


Fig. 1.10 Schematic of the development and descent of a hot smoke layer

1.6.1.4 Gas Temperatures

Literature indicate, for a wide range of compartment fires, that it is reasonable to assume that the room becomes divided into two distinct layers: a hot upper layer consisting of a mixture of combustion products and entrained air, and a cold lower layer consisting of air. Further, the properties of the gases in each layer change with time but are assumed to be uniform throughout each layer. For example, it is commonly assumed when using engineering methods that the temperature is the same throughout the hot layer at any given time.

1.6.1.4 The hot layer

The plume continues to entrain air from the lower layer and transport it toward the ceiling. The hot upper layer therefore grows in volume, and the layer interface descends towards the floor.

1.6.1.6 Heat transfer

As the hot layer descends and increases in temperature, the heat transfer recesses are augmented. Heat is transferred by radiation and convection from the hot gas layer to the ceiling and wall that are in contact with the hot gases. Heat from the hot layer is also radiated layer. Additionally, heat is transferred to the fuel bed, not only by the flame, but to an increasing extent by radiation from the hot layer and the hot enclosure boundaries. This leads ton increase in the burning ate of the fuel and the heating up of other fuel packages in the enclosure.

1.6.1.7 Vent flows

If there is an opening to the adjacent room or out to the atmosphere, the smoke will flow out through it as soon as the hot layer reaches the top of the opening . Often, the increasing heat in the enclosure will cause the breakage of windows and thereby create an opening.

1.6.1.8 Flashover

The fire may continue to grow, either by increased burning rate, by flame spread over the first ignited item, or by ignition of secondary fuel packages. The upper layer increases in temperature and may become very hot. As a result of radiation from the hot layer toward other combustible material in the enclosure, there may be a stage where all the combustible material in the enclosure is ignited, with a very rapid increase in energy release rates. This very rapid and sudden transition from a relatively benign state to a state of awesome power and destruction.

The solid line in Fig. 1.11 [19] shows the initiation of the transition period at Point A, resulting in a fully developed fire at Point B has been reached (the fully developed fire), flashover is said to have taken place.

1.6.1.9 The fully developed fire

At the fully developed stage, flames extend out throught the opening and all the combustible material in the enclosure is involved in the fire. The fully developed fire can burn for a number of hours, as long as there is sufficient fuel and oxygen available for combustion.

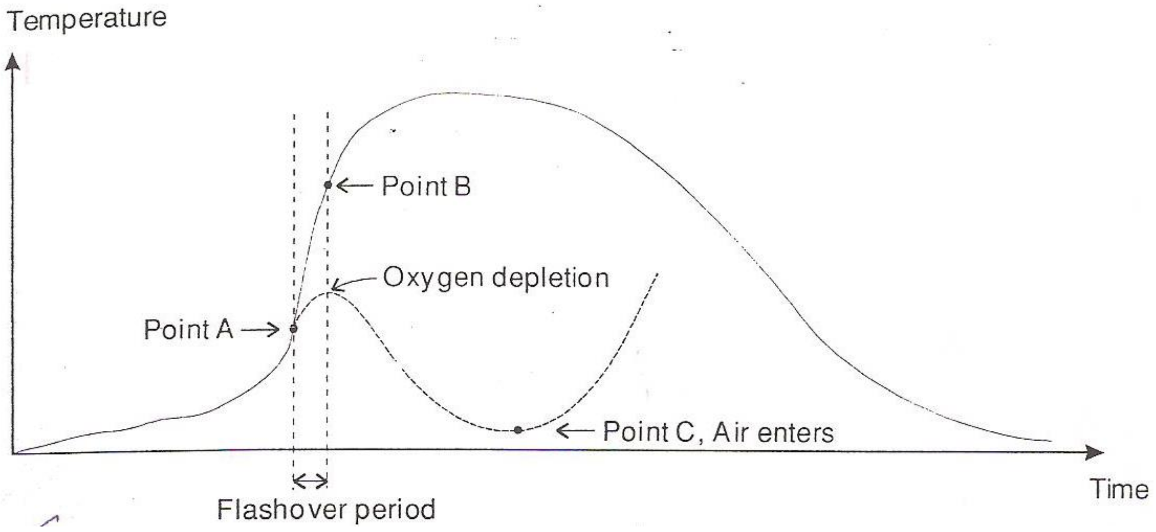


Fig. 1.11 Enclosure fire development in terms of gas temperature

1.6.1.10 Oxygen Starvation

For the case where there are no openings in the enclosure or only small leakage areas, the hot layer will soon descend toward the flame region and eventually cover the flame. The air entrained into the combustion zone now contains little oxygen and the fire may die out due to oxygen starvation. The dotted line in Fig. 1.11 shows that a fire may reach Point A and start the transition period toward flashover, but due to oxygen depletion the energy release rate decreases, as well as the gas temperature.

Even though the energy release rate decreases, the pyrolysis may continue at a relatively high or if the fire service create an opening, the hot gases will flow out through the top of the opening and cold and fresh air will flow in throught its lower part. This may diminish the thermal load in the enclosure, but the fresh air may cause an increase in the energy release rate. The fire may then grow toward flashover, as shown by the dotted line in Fig. 1.11.

1.6.1.11 Backdraft

As a worst case, the inflowing air may mix up with the unburnt pyrolysis products from the oxygen starver fire. Any ignition sources, such as a glowing ember, can ignite the resulting flammable mixture. This leads to an explosive or very rapid burning of the gases. Expansion due to the heat created by the combustion will expel the burning gases out through the opening. This phenomenon, termed back draft, can be extremely hazardous, and many fire fighters have lost their lives due to this very rapidly occurring event. In Fig. 1.11 this is illustrated by a straight, vertical line, rising directly from point C and reaching high temperatures. Usually, a backdraft will only last for a very short time, in the order of seconds (backdrafts lasting for minutes have, however, been observed). A backdraft will usually be followed by flashover, since the thermal insult will ignite all combustible fuel in the enclosure, leading to fully developed enclosure fire.

1.6.1.12 Smoke gas explosion

When unburnt gases from an under ventilated fire flow through leakages into an closed space connected to the fire room, the gases there can mix very well with air to form a combustible gas mixture. A small spark is then enough to cause a smoke gas explosion, which can have very serious consequences. This phenomenon is, however very seldom observed in enclosure fires.

1.7 STAGES IN ENCLOUSER FIRE DEVELOPMENT

Enclosure fire are often discussed in terms of the temperature development in the compartment and divided into different stages accordingly. Fig. 1.12 shows an idealized variation of temperature with time, along with the growth stages, for the case where there is no attempt to control the fire. Following are stages of fire [20]

1.7.1 Ignition

Ignition can be considered as a process that produces an exothermic reaction characterized by increase in temperature greatly above the ambient. It can occur either by piloted ignition (by flaming match , spark, or either pilot source) or by spontaneous ignition (through accumulation of heat in the fuel). The accompanying combustion process can be either flaming combustion or smoldering combustion.

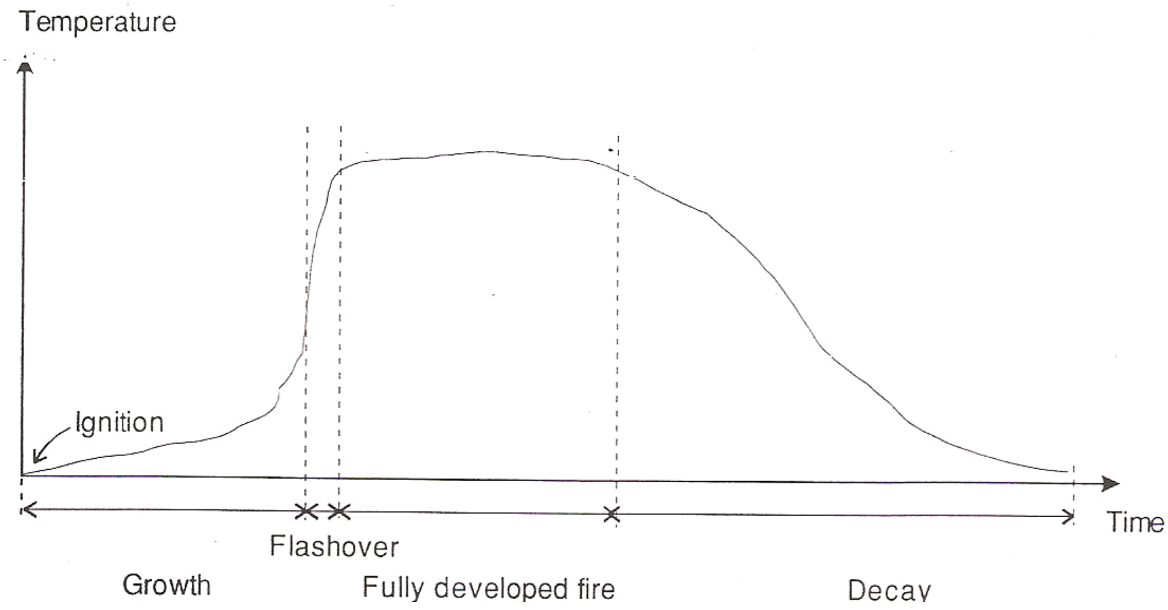


Fig. 1.12 Idealized description of the temperature variation with time in an enclosure fire.

1.7.2 Growth

Following the ignition, fire may grow at a slow or a fast rate, depending on the type of combustion, the type of fuel, interaction with surroundings, and access to oxygen. The fire can be described in terms of rate of energy released and the production of combustion gases. A smoldering fire can produce hazardous amounts of toxic gases while the energy release rate may be relatively low. The growth period of such a fire may be very long, and it may die out before subsequent stages are reached.

The growth rate can also occur very rapidly, specially with flaming combustion, where the fuel is flammable enough to allow to rapid flame spread over its surface, where heat flux from the first burning fuel package is sufficient to ignite adjacent fuel packages, and where sufficient oxygen and fuel are available for rapid fire growth. Fires with sufficient oxygen available for combustion are said to be fuel – controlled.

1.7.3 Flashover

Flashover is transition from the growth period to fully developed stage in fire development. The formal definition from international Standard Organization [21] is given as “the rapid transition to a state of total surface involvement in a fire of combustible material within an enclosure”.

Flashover is not a precise term: several variations in definition can be found in the literature. The criteria given usually demand that the temperature in the compartment has reached 500 - 600^{o}C or that the radiation to the floor of the compartment is 15 to 20 kW/m^{2}, or that flames appear from the enclosure openings. These occurrences may all be due to different mechanisms resulting from the fuel properties, fuel orientation, fuel position, enclosure geometry, and conditions in the upper layer. Flashover cannot be said to be mechanism, but rather a phenomenon associated with a thermal instability.

1.7.4 Fully Developed Fire

At this stage the energy released in the enclosure is at its greatest and is very often limited by the availability of oxygen. This is called ventilation – controlled burning (as opposed to fuel – controlled burning) since the oxygen needed for the combustion is assumed to enter through the openings. In ventilation - controlled fires, unburnt gases can collect at the ceiling level, and as these gases leave through the openings they burn, causing flames to stick out through the openings. The average gas temperature in the enclosure during this stage is often very high, in the range from 700 to 1200^{o}C.

1.7.5 Decay

As the fuel becomes consumed, the energy release rate diminishes and thus the average gas temperature in the compartment declines. The fire may go from ventilation – controlled to fuel controlled in this period.

1.8 FACTORS INFLUENCING FIRE DEVELOPMENT IN AN ENCLOSURE

The factors that influence the development of a fire in an enclosure can be divided into two main categories: those that have to do with the enclosure itself, and those that have to do with the fuel. These factors are:

- the size and location of the ignition source

- the type, amount, position, spacing, orientation and surface area of the fuel packages.
- the geometry of the enclosure
- the size and location of the compartment openings
- the material properties of the enclosure boundaries

1.8.1 Size and Location of Ignition Source

An ignition source can consist of spark with very low energy content, a heated surface or large pilot flame. The source of energy is chemical, electrical or mechanical. The greater the energy of the source, the quicker the subsequent fire growth on the fuel source. A spark or a glowing cigarette may initiate smoldering combustion, which may continue for a long time before flaming occurs, often producing low heat but considerable amount of toxic gases. A pilot flame usually produces flaming combustion directly, resulting in flame spread and fire growth.

The location of ignition source is also of great importance. A pilot flame positioned at the lower end of, say, a window curtain may cause rapid upward flame spread and fire growth. The same pilot flame would cause much slower fire growth, if it placed at he top of the curtain, resulting in slow, creeping, downward flame spread.

1.8.2 Fuel

The type and amount of combustible material is, of course, one of the main factors determining the fire development in an enclosure. In building fires usually consist of solid materials, such as furniture and fittings normally seen in the enclosure interior; in some industrial applications the fuel source may also be in liquid state.

Heavy, wood based furniture usually causes slow fire growth but can burn for a long time. Some modern interior materials include porous lightweight plastics, which cause more rapid fire growth but burn for a shorter time. A high fire load therefore does not necessarily constitute a greater hazard; a rapid fire growth is ore hazardous in terms of human lives.

The position of fuel packages can have a marked effect on the fire development. If the fuel package is burning away from the walls, the cool air is entrained into the plume from all directions. When placed close to a wall, the entrainment of cold air is limited. This not only cause higher temperature but also higher flames since combustion must take place over a greater distance.

The spacing and orientation of the fuel packages are also of importance. The spacing in the compartment determines to a considerable extent how quickly the fire spreads between the fuel packages. Upward flame spread on a vertically oriented fuel surface will occur much more rapidly than lateral spread along a horizontal oriented fuel surface.

Combustible lining materials mounted on the compartment walls and / or ceiling can cause very rapid fire growth. Fig. 1.13 shows results from a small – scale room test where the lining material is mounted on the walls only (with noncombustible ceiling) and where the material is mounted on both walls and ceiling [22].

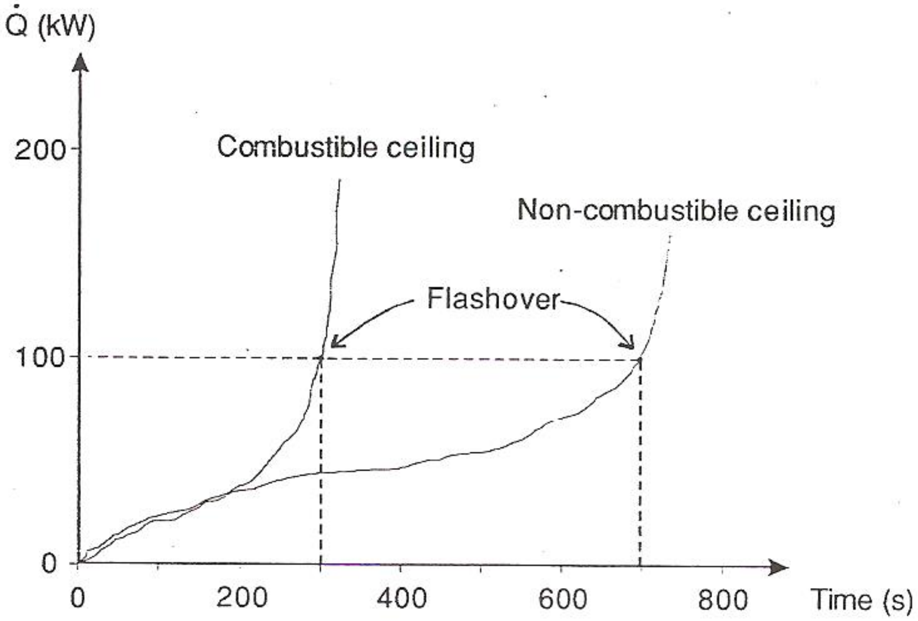


Fig. 1.13 Energy release rate v/s time

In both cases an initial flame was established on lining material along one corner of the room. With material mounted on the ceiling, the flame spreads with the flow gases (concurrent – flow flame spread), causing rapid fire growth. With the noncombustible ceiling the flame spreads horizontally (opposed – flow flame spread) across the material, a process that is much slower and requires the lining material to be heated considerably before the flame can spread rapidly over it. As a result, the time to flashover is 4 minutes in the former case and 12 minutes in the latter case.

A fuel package of a large surface area will burn more rapidly than an otherwise equivalent fuel package with a small surface area. A pile wooden sticks, for example, will burn more rapidly than a single log of wood of the same mass.

1.8.3 Enclosure Geometry

The hot smoke layer and the upper bounding surfaces of the enclosure will radiate towards the burning fuel and increase its burning rate. Other combustible item in the room will also be heated up. The temperature and thickness of the hot layer and the temperature of the upper surfaces thus have a considerable impact on the fire growth.

A fuel package burning in small room will cause relatively higher temperatures and rapid fire growth. In a large compartment, the same burning fuel will cause lower gas temperatures, longer smoke filling times, less feed back to fuel, and loser fire growth.

The fire plume entrains cold air as mixture of combustion products and air move upward toward the ceiling. The amount of cold air entrained depends on the distance between fuel source and hot layer interface. In an enclosure with a high ceiling this causes relatively low gas temperatures, but due to large amount of air entrained, the smoke filling process occurs relatively rapidly. The smaller the floor area, faster the smoke filling process.

With a low ceiling the heat transfer to the fuel will be greater. Additionally, the flames may reach the ceiling and spread horizontally under it. This results in a considerable increase in the feedback to the fuel and to other combustibles and a very rapid fire growth is imminent.

For enclosure with high ceiling and large floor area, the flames may not reach the ceiling and the feedback to the fuel in modest. The fire growth rather occurs through direct radiation from the flame to nearby objects, where the spacing of the combustibles becomes important.

In a building with large floor area, but a low ceiling height, the feedback from the hot layer and ceiling flames can be very intensive near the fire source. Further away, the hot layer has entrained cold air and has lost heat to the extensive ceiling surfaces, and the heat flux to the combustible material. In the early stages of fire, is therefore lower than the heat flux closer to the fire source.

We can conclude that the proximity of ceiling and walls can greatly enhance the fire growth. Even in large spaces, the hot gases trapped under the ceiling can heat up the combustibles beneath and result in extremely rapid fire spread over a large areas.

1.8.4 Compartment Openings

Once flaming combustion is established the fire must have access to oxygen for continued development. In compartments of moderate volume that are closed or have very small leakages areas, the fire soon becomes oxygen staved and may self extinguish or continues to burn at a very slow rate depending on the availability of oxygen.

For compartments with ventilation opening, the size, shape, and position of each openings becomes important for the fire development under certain circumstances. During the fire growth phase of the fire, before it becomes ventilation – controlled, the opening may act as an exhaust for the hot gases, if its height or position is such that the hot gases are effectively removed from the enclosure. This will diminish the thermal feed back to the fuel and cause slower fire growth. For other circumstances the geometry of the opening does not have any significant effect on the fire growth during the fuel – controlled regime.

It is when fire becomes controlled by the availability of oxygen that the opening size and shape first becomes all important. The rate of burning depends very strongly on the ventilation factor, defined as $A_o \sqrt{H_o}$, where A_o is the area of the opening and H_o is its height [23]. The rate of burning is controlled by the rate at which air can flow into the compartment. An increase in the factor $A_o \sqrt{H_o}$ will lead to an equal increase in the burning rate. This is valid up to a certain limit when the burning rate becomes independent of the ventilation factor and the burning becomes fuel – controlled.

1.8.5 Material properties of the enclosure boundaries

The material in the bounding surfaces of the enclosure can affect the hot gases temperature considerably and thereby the heat flux to the burning fuel and other combustible objects. Certain bounding material designed to conserve energy, such as mineral wool, will limit the amount of heat flow to the surfaces so that the hot gases will retain most of their energy.

The material properties controlling the heat flow through the construction are the conductivity (k), density (ρ), and heat capacity (c). They are commonly collected in a property, called thermal inertia and given as the product kρc. Insulating material have a low thermal inertia; materials with relatively high thermal inertia such as brick and concrete, allow more heat to be conducted into the construction, thereby lowering the hot gas temperatures.

1.9 CHEMISTRY OF FIRE SUPPRESSION

For the last 50 years of flame inhibition research, intensive research efforts have generated more detailed understanding of the interaction of inhibiting chemicals with flames and culminated in a unified model of fire suppression. This included effectiveness by both physical and chemical processes. In different ways, each of these affects the rates of the chemical reactions that must proceed at rates sufficient to sustain fuel combustion.

Flame extinguishment without any direct chemical or catalytic activity entails making it harder for the flame-generated enthalpy to maintain the fuel/air “bath” at a temperature high enough for these reactions to continue.

- The sink for this enthalpy is the heat needed to raise the suppressant from the ambient temperature to flame temperature. For a gaseous agent, this enthalpy is determined by its heat capacity. A high heat capacity typically results from a molecule having a large number of atoms, with the associated large number of excitable vibronic modes. It is also possible that one or more weak chemical bonds can be thermally dissociated. For compounds that reach the flame zone as an aerosol, additional endothermic contributions come from the liquid phase heat capacity and the heat of vaporization.
- Fire suppressants also dilute the fuel/air mixture, slowing the reaction rates. This is small effect in any case, since the magnitude is linear in additive concentration, while the thermal cooling has an exponential effect on reaction rate. For compounds near Halon 1301 in flame suppression effectiveness, the effect is negligible.
- For a constant mass of an aerosol, there is a monotonic increase in the flame extinction efficiency with decreasing droplet size. Water aerosols below about 50 µm in diameter were found to be more effective on a mass basis than Halon 1301 at extinguishing diffusion flames. These droplets are small enough to evaporate fully in the flame zone. Modeling studies confirm that this effectiveness is largely due to the high heat of vaporization and the complete evaporation of such small droplets.
- Aerosols delivered to the hot surfaces in the vicinity of a fire can assist in quenching the flames and preventing relight by cooling surfaces. Effectiveness is enhanced by high values of the mass delivered, the droplet diameter, and the droplet velocity.

In the simplest chemical process, radical trapping, a suppressant’s breakdown products react with the radicals to form stable product species which are relatively inert in the flame. The most prevalent example is that of fluorine atoms. These are generated by pyrolysis or reaction of fluorine-containing suppressants and combine with hydrogen atoms to form HF. The H-F chemical bond is sufficiently strong (570 kJ/mol) that the H atom no longer participates in the flame propagation chemistry.

By contrast, catalytic radical recombination is a chain reaction process. Species formed from the thermal or chemical breakdown of the suppressant molecule initiate a cyclical process. (The typical bond energy between a catalytic scavenger and a flame radical is in the range of 300 kJ/mol to 400 kJ/mol, notably weaker than the H-F bond energy.) The net result is that pairs of reactive radicals combine to form more stable molecules, while the catalytic species is regenerated. In flames, the H, OH, and O radical concentrations in the reaction zone are well above those that correspond to thermal equilibrium. The rapid catalytic process drives the system toward thermal equilibrium.

In summary, a unified view of the suppression of diffusion flames by chemically active agents is as follows:

Flame propagation results from the fast reactions of key species (H and O atoms, OH radicals) with vaporized fuel molecules. These species exist at concentrations far above those expected from thermal equilibrium at flame temperatures. Chemically active agents decompose in the flame to generate the entities that catalytically reduce the radical concentrations toward equilibrium levels. While this catalytic process slows the flame, it does not necessarily extinguish it. Both chemically active and physically active suppressants increase the heat capacity of the fuel/air mixture, reducing the flame temperature and thus, along with the decreased concentrations of radical reactants, decrease the flame reaction rates below the level needed to sustain combustion. These two effects are synergistic. Thus, if weight limitations allow, the effectiveness of a chemical agent can be enhanced by combination with a high heat capacity chemical.

1.9.1 Required Agent critical concentration and Residence Time

For an open flame, the criterion for flame extinguishment is that the concentration of suppressant exceeds some minimal value long enough for the chemical kinetics to quench the flame chemistry. For occluded flames, there are two distinct flame stabilization conditions: rim-attached and wake-stabilized. In the former, the flame detaches and goes out as soon as the agent arrives. In the latter, the shear layer first becomes unstable, followed by flame extinguishment in the recirculation zone. Time is required for an extinguishing concentration of agent to exist in this recirculation zone. This time depends on the concentration of the agent in the free stream and the time interval over which the agent has been injected into the free stream, i.e., the duration of the suppressant wave.

To the extent that a significant fraction of the suppressant mass is in the form of a volatile aerosol, there are additional dwell time and droplet size considerations that determine whether that fraction will take part in the flame extinguishment process. For a given mass of suppressant, small droplet diameters are to be preferred. Droplets that are too large will not be entrained into the recirculation zone. Smaller droplets may be entrained, but may require extended time within the recirculation zone to evaporate fully. Droplets with diameters below about 50 µm were entrained into laboratory flames and evaporated fully.

Combined with the boiling point requirement for non-loss at cold services, this small droplet requirement for effective evaporation has significant implications for the dispensing of an agent. To make use of the full mass of suppressant stored and released in the bottle, a chemical must be:

- Released as a gas, a condition virtually impossible for a volume-efficient fluid;
- Prone to flashing upon release, requiring a boiling point below the ambient temperature, a condition satisfied for very few fluids; or
- Dispensed as fine droplets, a condition requiring fine nozzles on the distribution piping and a high backing pressure. This will be difficult to achieve a sufficiently high discharge rate.

1.9.2 Fire Suppression Techniques

Fire suppression, in principle consists in the limitation of one or more of the three essentials of fire i.e Fuel, Oxygen & heat, generally referred as triangle of fire. The fourth quadrant which is chemical chain reaction also plays important role in suppression of diffusion flames .

1.9.2.1 Starvation is essentially the limitation or removal of fuel. Starvation is applied in three ways:

(i) By removing combustible material from the neighborhood of the fire.

(ii) By removing the fire from the neighborhood of the combustible material.

(iii) By sub-dividing the burning material when the smaller fires produced may be left to burn out or to be extinguished more early by other means.

1.9.2.2 Smothering is essentially the limitation of oxygen. If the oxygen content of the atmosphere in the immediate neighborhood of burning material can be sufficiently reduced combustion will cease. However, this principle is ineffective where as in the case of celluloid the burning material contains within itself, in a chemically combined from, the oxygen it requires for combustion.

1.9.2.3 Cooling is the limitation of temperature. If the rate at which heat is generated by combustion is less than the rate of which it is dissipated through various agencies, the combustion cannot persist. The application of a jet or spray of water to a fire is invariably based on this simple but fundamental principle.

1.9.2.4 Chemical Chain Reaction is the interruption of chain reaction of combustion process by capturing the H, OH and O radicals that drive flame propagation. The process can be simple removal or catalysis of radical combination to less reactive compounds. In either case, the vibronic modes of the suppressant also absorb enthalpy and function, in part, as a thermal suppressant. Typically, for agents that are comparable in flame suppression efficiency (mass basis) to Halon 1301, this thermal component is smaller than the chemical component.

1.10 DIFFUSION FLAME SUPPRESSION WITH HALONS

In previous studies, Halons {CF_3Br (and related compounds)} have been the subject of much fundamental research, for example in flow reactors [24] premixed flames [25-33] co-flow diffusion flames[34-36] and counter flow diffusion flames.[37-41] Much recent research has been aimed at finding both short [42-43] and long-term [44] replacements for CF_3Br. As a result, CF_3Br itself has been the continuing subject of many studies [45-48] since an improved understanding of its mechanism of inhibition will help in the search for alternatives, and nearly all assessments of new agents use CF_3Br as a baseline for comparison of the new agents.

As outlined above, the flame configurations used to study flame inhibition mechanisms have tended to be premixed and counterflow diffusion flames. Premixed flames have been selected mainly because the overall reaction rate, heat release, and heat and mass transport in these flames can be described with a single fundamental parameter - the laminar burning velocity, and because over certain regions, the flow field can be considered one-dimensional (greatly simplifying data collection and numerical simulation). Similarly, counterflow diffusion flames can be considered one-dimensional along the centerline, and the extinction strain rate has been commonly used as the characteristic suppression parameter. In principle, such fundamental parameters can ultimately be used to relate the behavior of the agent in the laboratory flame to its behavior in suppressing a large-scale fire [49], although this scaling is difficult in practice.

1.10.1 ENVIRONMENTAL ISSUES OF HALONS

Incoming ultraviolet radiation from sun is very damaging to living organisms causing sunburn, skin cancer, damage to eyes including cataracts, and premature aging and wrinkling of the skin. Fortunately the damaging forms of UV radiation are absorbed by the ozone in the atmosphere and do not reach the earth. Thus, the ozone layer acts as a giant sunscreen or umbrella enveloping the earth and protecting life from the more dangerous UV radiation. Depletion of ozone will allow more UV radiation to strike the earth and living organisms.

1.10.1.1 Ozone Depletion Potential

Halons have very high ozone Depletion Potential (ODP) as indicated in table 1.9. Those that are fully substituted with halogens (i.e. fluorine, chlorine or bromine) and contain chlorine or bromine, are the most destructive because their inherent stability gives them a long life allowing them to make their way up into the stratosphere where they react with and destroy ozone. The relative ozone depleting potentials of fully and partially halogenated hydrocarbons are summarized below

Table 1.9 : Substance Ozone Depleting Potential and Usage

AGENT	ODP	USAGE
CFC-11	1.0	Aerosols, Foam
CFC-12	1.0	Refrigerant
CFC-113	0.8	Solvent
Halon 1211	3.0	Fire Extinguishing
Halon 1301	10.0	Fire Extinguishing
Halon 2402	6.0	Fire Extinguishing

These ozone depletion potentials (ODP) are estimates based on existing knowledge and are to be reviewed. The ODP is based on giving CFC-11 a value of one and comparing CFCs with it (on a mass basis). As can be seen from this table, ozone depletion resulting from halon (i.e., bromofluorocarbons or BFCs) emissions may be greater per kilogram than that associated with CFCs.

1.10.1.2 The Montreal Protocol

In September 1987, at the Montreal Conference, a Protocol was developed to globally reduce emissions by placing a control on the consumption of CFCs and halons, which were referred to as controlled substances. A staged reduction in CFC consumption of 50 percent is required by 1998, beginning in 1989. A freeze on halon consumption to 1986 levels is required in 1992.

The nations of the world moved toward an international agreement to protect the environment, the Montreal Protocol on Substances that Deplete the Ozone Layer [58]. As the agreement was being forged, it was realized that some brominated compounds were potentially even more dangerous than their chlorinated cousins [59] and the halons were named explicitly. Their production was curtailed sharply in amendments to the U.S. Clean Air Act of 1990. As of January 1, 1994, under the 1992 Copenhagen Amendments to the Montreal Protocol, halon 1301 was banned from production, except in certain developing countries and countries whose economies were in transition and cession of the production in the developed nations effective from January 1, 1994.

1.10.1.3 GLOBAL WARMING

Global warming is the increase in the average temperature of the Earth's near-surface air and oceans since the mid-20th century and its projected continuation. Climate model projections summarized in the latest International Panel on Climate Change (IPCC) report indicate that the global surface temperature will probably rise a further 1.1 to 6.4 °C (2.0 to 11.5 °F) during the 21st century [60]. An increase in global temperature will cause sea levels to rise and will change the amount and pattern of precipitation, probably including expansion of subtropical deserts. It will likely cause the continuing retreat of glaciers, permafrost and sea ice, and warming will be strongest in the Arctic. Other likely effects include increases in the intensity of extreme weather events, species extinctions, and changes in agricultural yields.

1.10.1.4 Kyoto Protocol

The Kyoto Protocol on global warming was initially adopted on 11 December 1997 in Kyoto, Japan and entered into force on 16 February 2005. As of November 2009, 187 states have signed and ratified the protocol. The most notable non-member of the Protocol is the United States, which is a signatory of UNFCCC and was responsible for 36.1% of the 1990 emission levels.

Under the Protocol, 37 industrialized countries commit themselves to a reduction of four greenhouse gases (GHG) (carbon dioxide, methane, nitrous oxide, sulphur hexafluoride) and two groups of gases (hydrofluorocarbons and perfluorocarbons) produced by them, and all member countries give general commitments. Annex I countries agreed to reduce their collective greenhouse gas emissions by 5.2% from the 1990 level. Emission limits do not include emissions by international aviation and shipping, but are in addition to the industrial gases, chlorofluorocarbons, or CFCs, which are dealt with under the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer.

1.10.1.5 Copenhagen Summit

The 2009 United Nations Climate Change Conference, commonly known as the Copenhagen Summit, was held at the Bella Center in Copenhagen, Denmark, between 7 -18 December 2009.

The Copenhagen Accord was drafted by the US, China, India, Brazil and South Africa and judged a "meaningful agreement" by the United States government. It was "taken note of", but not "adopted", in a debate of all the participating countries the next day, and it was not passed unanimously. The document recognised that climate change is one of the greatest challenges of the present day and that actions should be taken to keep any temperature increases to below 2°C. The document is not legally binding and does not contain any legally binding commitments for reducing CO_2 emissions. Many countries and non-governmental organisations were opposed to this agreement. One part of the agreement pledges US$ 30 billion to the developing world over the next three years, rising to US$ 100 billion per year by 2020, to help poor countries adapt to climate change. Earlier proposals, that would have aimed to limit temperature rises to 1.5°C and cut CO_2 emissions by 80% by 2050 were dropped. The Accord also favors developed countries' paying developing countries to reduce emissions from deforestation and degradation. During the conference some countries stated what actions they were proposing to take if a binding agreement was achieved. In the end, no such agreement was reached and the actions will instead be debated in 2010.

The commitment was made by all countries to cut down the emmisions as per their own set targets. India to cut carbon emissions intensity by 20–25% below 2005 levels by 2020.

1.10.2 India’s Halon Phase-out Strategy

Ever since India became a signatory to the 1992 Montreal Protocol for phasing out ozone depleting substances (ODS), internationally researchers are looking for environment friendly (No ODP & GWP) fire suppression agents. India has to achieve total phase-out by 2010, although production of Halons - an ozone depleting substance used for fire suppression agent has already stopped in 1998.

Halons were once one of the most widely used fire-fighting and explosion suppression agents in the world. Their use is now restricted under the internationally binding Montreal Protocol on Substances that Deplete the Ozone Layer. As halons are one of the most ozone-damaging substances they were amongst the first group of chemicals to be targeted for phase out under the Protocol. Production and consumption were banned in developed countries from 1994, except for critical / essential uses, and are due to be phased-out of developing countries by 2010. The halon banking system in India is used to collect and store halon made available from non-essential uses, for example when facilities are phased-out or have reached the extent of their service life. This halon can then be retained for use in remaining critical use applications. Recovery, recycling, reclaiming and storing non-essential halon for other critical uses progressively reduces dependence on long-term halon imports for key sectors.

Addressing halon is an integral component of a India’s Halon Phase-out Strategy prepared by India's Defence Institute of Fire Research (Now Centre for Fire, Explosive & Environment Safety) Defence Research & Development Organization Ministry of Defence Government of India, in recognition of halon’s status as the most aggressive ozone depleting substance to be controlled under the Montreal Protocol. Second only to China in the production and consumption of ODS by developing countries, India had recently closed its two halon production facilities. Regulations that penalize the continued production or servicing of equipment containing halon except for approved critical uses have recently been enacted in India, as will regulations prohibiting the production and import or new halon. The provision of skills and equipment to India was intended to enable India to responsibly manage approximately 4000 MT of its existing halon stock which would otherwise present an ongoing threat to the ozone layer.

As an interim measure, the MoD had created "bank" of Halons 1301 and 1211 as a means of continuing protection during the search for alternatives at Center for Fire, Explosive and Environment Safety an organization of Defence Research & Development Organization, Ministry of Defence, Government of India. It is these banks from which supplies are still drawn as the halons are deployed critical applications. The scientists at Center for Fire, Explosive and Environment Safety are progressing the research work to finding out environment friendly halon alternative technologies.

The thesis work reported by the author is one of the outcome of this ongoing research work to develop environment friendly water mist technology for defence applications.

1.10.3 Need for Halon Alternative Fire Suppressing Agent

Halon 1301's exceptional performance and success over the years had resulted in minimal research into alternatives for fire suppression. After a period of bewilderment, denial, and indecision following the 1987 Montreal Protocol, manufacturers and users of the halons began searching for safe replacements and alternatives. The early solutions were identified during the quest for replacement refrigerants, a far larger commercial market. Some of these, such as the hydrochlorofluorocarbons (HCFCs) were ozone depleters themselves and were soon generally disregarded as fire suppressants. An early brominated compound, CHF_2Br (halon 1201), was found to have a fire suppression efficiency comparable to halon 1301, but even though its ODP value was far lower than that of halon 1301, it was above that permitted by the U.S. Clean Air Act. For a variety of applications, chemical manufacturers began increased production of hydrofluorocarbons, or HFCs, which had no bromine or chlorine atoms and thus zero ozone depletion potential (ODP) values. These were far less effective fire suppressants, but appeared to have no harmful atmospheric effects. Other commercial products included mixtures of inert gases, also less efficient suppressants, and blends of halocarbons.

However, despite the examination of a wide range of chemicals in the laboratory and at real scale, none of the available alternatives offered all the needed properties of halon 1301. The best available replacement chemicals were two HFCs: C_2F_5H (HFC-125) onboard aircraft and C_3F_7H (HFC-227ea) for shipboard use. These were substantially less efficient fire suppressants and thus required two to three times the mass and storage volume relative to halon 1301. This would severely compromise their implementation, given the tight weight and space limitations. In addition, their use would result in a post-deployment atmosphere containing appreciable concentrations of acid gases, that was not suitable for human occupancy, and that could chemically attack metals, synthetic materials, and electronics. Nonetheless, some engineering was conducted to adapt the use of these chemicals for some platforms. One alternative approach that showed some promise was the use of solid propellant fire extinguishers. Similar to the units developed for automobile airbags, these systems rapidly generated large quantities of inert gases. They were considered for use in aircraft dry bays, where people would not be exposed to the resulting sub-habitable oxygen levels.

Since the middle of the 20th century, there had been concern that anthropogenic carbon dioxide was increasing in the lower atmosphere. Its increasing absorption of infrared radiation from the planet surface and re-radiation back to that surface would lead to warming of the earth. The term “greenhouse gas” was created, and it was soon realized that most of the replacements for clean fire suppressants fell into this category. This added yet another constraint to the search for the successors to the halons.

The challenge for the fire protection engineer is to select or develop a risk based and cost effective fire protection strategy for the protection of life, the environment and assets that also conforms to community expectations.

Confronted by often confusing claims, selective reporting of fire test results, rapidly changing technology and environmental regulations as well as limited "real" fire fighting experience with some of the new technologies this is a complex process.

It is made even more difficult because appropriate standards have only recently become available and then not universally so. It is also crucial to recognize that all halon replacements and alternatives currently available represent a compromise. As such, an appropriate balance must be struck between extinguisher efficiency, agent (or thermal decomposition product) toxicity to exposed personnel, damage to protected assets, the cost of installation or change-out and environmental impact.

1.10.4 Options to Halons

Manual response - using incipient fire condition monitoring if appropriately trained fire response team or local fire brigade is able to respond quickly enough. Portable first hand fire fighting equipments are used as manual response for suppression of diffusion flames.

- Modern fire and gas detection with automatic or manual response.
- Traditional application of water sprinklers, foam, dry powder & carbon dioxide. etc.
- Halocarbon fire fighting agents that do not contain ozone depleting chlorine or bromine.
- Emerging technology such as fine solid particulates (powdered aerosols).
- Environment friendly agents such as water mist and inert gases.

The alternative fire suppressing agents used for suppression of diffusion flames is explained in detail in chapter 2

Chapter 2

DIFFUSION FLAME SUPPRESSING AGENTS - LITERATURE SURVEY

2.0 INTRODUCTION

The halon alternatives can be divided into two types: classical alternatives and new alternatives as indicated in table 2.1. The classical alternatives are conventional fire suppressing agents and are in use for last many decades.

Table 2.1 Halon alternative agents for suppression of diffusion flame

Classical Alternatives	New Alternatives
Foams	Inert Gases
Water Sprinklers	Halocarbons
Dry Chemical Powders	Particulate Aerosols
Carbon Dioxide	Water Mist

The use of classical alternatives i.e traditional fire suppressing agents such as dry chemical, CO_2, water sprinklers and foams are used to protect fire hazards has been promoted as a means of replacing halon. The effectiveness of these traditional fire protection alternatives is dependent on the occupancy they are selected and designed to protect. The uses of these traditional agents are given serious consideration as appropriate halon replacements in occupancies where they are agreeable with the hazard. They are installed in accordance with applicable standards.

The new alternatives not necessarily imply that a technology was developed recently, but that there is a new or renewed interest in the use of a technology as a replacement for halons. Misting and particulate aerosols require decreased amounts of agent. This may decrease the probability of secondary fire damage. Thus, these technologies may allow protection while minimizing the problems normally associated with water and solids. Recent advances allow the use of inert gases and inert-gas blends in new applications, particularly in occupied areas.

2.1 CLASSICAL HALON ALTERNATIVES

2.1.1 FIRE FIGHTING FOAMS.

Fire fighting foam is a mass of gas-filled bubbles formed by various methods from aqueous solution of specially formulated foaming agents. Since foam is lighter than the aqueous solution from which it is formed and is lighter than flammable liquids, it floats on all flammable or combustible liquids producing an air – excluding cooling continuous vapour – sealing water bearing material for purposes of halting or preventing combustion.

Fire fighting foams are formulated in several ways for fire extinguishing action, some foams are thick and viscous, forming tough heat resistant blankets over burning liquid surfaces. Other foams are thinner and spread more rapidly. Some are capable of producing a vapour sealing film of surface active water solution on a liquid surface and some are meant to be used as large volumes of wet gas cells for immediating surfaces and for filling cavities.

Foams are an alternative to halon systems for a number of hazards, particularly those involving flammable liquids [62]. Foams extinguish fires by establishing a barrier between the fuel and air. Drainage of water from the foam also provides a cooling effect, which is particularly important for flammable liquids with relatively low flash points and for Class A fuels where glowing embers are a problem. The disadvantages of foams are similar to those of water. They can cause secondary damage and cannot be used on fires involving electrical equipment without careful design considerations.

2.1.1.1 Mechanical Foam

Mechanical foam is generated by a turbulent mechanical action by mixing air into the foaming water solution, hence the name mechanical foam. Following are the categories / type of foam concentrates (air foam) which are commonly in use at present:

i) Protein foam
ii) Fluoro protein foam
iii) Aqueous film forming foams (AFFF)
iv) Synthetic medium and high expansion foam
v) Alcohol Foam

2.1.1.2 Chemical Foam

Sodium Bicarbonate and Aluminum sulfate are added with saponion to form a foam froth i.e. sodium sulfate and Aluminium hydroxide as expellant. The chemical reaction is shown as below :

$$6NaHCO_3 + Al_2 (SO_4) \longrightarrow \underset{\text{Foam / Froth}}{3Na_2 SO_4} + \underset{\text{Expellant}}{2A1 (OH)_3} + 6CO_2$$

2.1.2 DRY CHEMICAL POWDER

Fire extinguishing dry chemical powder is important because it is the most powerful three dimensional medium available. Foam is a two-dimensional medium acting by seating the static surface of fuel and preventing evolution of flammable vapour. Powder on the other hand is effective as an airborne cloud of small particles and in this condition it interrupts the chain reaction of combustion. This essentially a chemical effect, not dependent on smothering or Oxygen deprivation. A great draw back to powder is the fact that it has no sealing effect, so that unless the fire is extinguished completely, it will very quickly return to its full intensity (flash back). The most important dry powders in current use are described below.

2.1.2.1 **Sodium Bicarbonate BC Powder**: Until fairly recently this was by far the most common powder in use. Base on Sodium Bicarbonate together with some water repellency and flow promoting additives, it gives rapid fire extinguishment of B &C type fires.

2.1.2.2 **Potassium Bicarbonate BC Powder**: This is more expensive but it is roughly twice as powerful as Sodium bicarbonate powder. More skilled operator must be put to use this powder to get full advantage. This is because of the need to distribute the powder relatively timely over the whole fire area in a short time.

2.1.2.3 **Potassium Sulphate foam compatible BC powder**: This is roughly equal to Sodium bicarbonate powder in performance, but it has the merit that it does not break-down protein foam as other powders do, and this is valuable when foam and powder are used together. The need for this powder disappeared because fluoro chemical ad fluoroprotein foam is not affected by powders to any thing like the same degree as protein foam.

2.1.2.4 **Potassium Chloride BC Powder**: This is rather powerful than potassium bicarbonate, though it has the draw-back of being more corrosive.

2.1.2.5 **Monnex BC Powder**: This is most powerful three – dimensional fire fighting medium available. It is an addition of urea and potassium bicarbonate and is unique in chemical fire extinguishment reactions. Urea or Carbamide $CO(NO_2)$ is capable of forming adducts or inclusion complexes under the correct provisioning conditions. Such complexes are not true compounds, but are crystalline mixtures in which the molecules of one of the components are contained within the crystal lattice frame work of the other compound, when certain physical pressures (such as heat) are exerted on the complex, it may separate into its original components. Apparently a “Monnex” dry Chemical powder is such an inclusion complex with urea bound up with potassium bicarbonate. It can be used very effectively in first aid extinguishers ad small quantity powder can extinguish, some times, a big fire depending upon the operational skill of the operator.

2.1.2.6 **General Purpose ABC Powder**: All fire fighting powders will deal with the flame in the air borne condition but when used on class a material (wood, paper, fabric, plastic etc) smoldering of the material will often continue after the powder cloud has settled. ABC power overcome this drawback by forming a fire proof coating on the burning material and this has the effect of arresting of smoldering combustion. Such powders are based on mono-ammonium phosphate. It is usual to specify ABC powders for general use where a considerable Class A risk is present as well as B or C risks.

2.1.2.7 **COMBUSTIBLE METAL EXTINGUISHING AGENTS :** Another class of fire, Class D, is an important consideration in any discussion of combustible material and suitable extinguishments for fires in them. Mg. Al, etc. are metals that burn in air. When a big quantity of these metals is involvement in fire, the need for halting the vigorous and high temperature oxidation become major. The flame zone in the combustion of metal is a high temperature and highly reactive area. To halt the oxidation readiness of burning metals, reliance must be placed upon; (i) withdrawal of oxygen (Smothering or inerting) and (ii) Cooling in some way, be it through radiation or heat removal with a cooling agent, in order to lower the temperature of the burning mass below its ignition point. The following extinguishing agent and methods operate in either both of these modes.

2.1.2.7.1 **G – 1 Powder**: G-1 powder is a proprietary mixture composed of graphite and foundry coke, carefully sized to facilitate easy handling and packing with carefully applied to the burning surface with a new scoop or shovel. An organic phosphate is also added to the mixture. This is suitable for all types of metal fires.

2.1.2.7.2 Mel – X Powder: This powder is also a proprietary item consisting largely of carefully sized sodium Chloride with added tricalcium phosphate powder, Zinc Stearate to facilitated discharge from a pressurized dry Chemical type extinguisher and delivery atomizer. A small amount of powdered Thermo Plastic material is added to the mixture so that when the powder is carefully discharged on the burning metal surface in some bulk, the thermoplastic melts and holds the sodium Chloride particles together for efficient cooling and smothering of the burning area. Suitable for all types of metal fires.

2.1.2.7.3 Na – X Powder: It is similar in action to Met-L-X powder. Its main ingredient is Sodium Bicarbonate for a greater resistance to higher temperatures. Na- X is suitable for Sodium fires.

2.1.1.7.4 TEC Powder : Ternary Eutectic Chloride powder is very effective on all metal fires. It contains proportions of Sodium Chloride, Potassium Chloride and Barium Chloride. This mixture melts at low temperature. When applied on metal fires, it melts very soon after falling at the burning surface of the metal and forms a crust over the burning surface thereby excludes oxygen. Water should not be applied on metal fires.

$$Mg + H_2O \rightarrow MgO + H_2 + Heat$$

$$2\,Al + 3\,H_2O \rightarrow Al_2O_3 + 3H_2 + Heat$$

The powder should be applied very gently over the fire. Dry chemicals generally provide very rapid knockdown of flames and are more effective than Halons in most applications [63]. The main disadvantages of dry chemical fire extinguishants include:

(i) Poor penetration behind obstacles,
(ii) No inhibiting atmosphere after discharge,
(iii) No direct cooling of surfaces or fuel,
(iv) Secondary damage to electronic, electromechanical, and mechanical equipment,

(v) Cleanup problems, and

(vi) Temporary loss of visibility if discharged in a confined space.

Fixed dry chemical systems are very uncommon; uses are normally limited to localized applications, such as with textile machines or deep-fat fryers, for which halons would not normally be used. However, these systems should be considered for fire suppression in some marine engine spaces and land-based transportation engine compartments.

Dry chemical extinguishers are suitable for Class A, B, and in some cases, C fires depending on the type of powder used. Powder extinguishers are often suitable substitutes for halon with fires of flammable liquids. They are also suitable for situations where a range of different fires can be experienced, e.g., electrical fires, flammable liquid fires, and fires in solids. In this respect, powder extinguishers resemble halon extinguishers.

2.1.2 CARBON DIOXIDE.

Carbon Dioxide can be considered a classical alternative and is the most common inert gas used as a fire extinguishant today. The physiological effects of carbon dioxide, however, differ significantly from those of the other inert gases. Inerting gases are gases that do not react with combustible materials and that are capable of simple dilution of oxygen or air / atmospheres to the point where oxidation or combustion either cannot start or cannot continue. Since these gases are non-reactive, they are classified as inert gases Helium, Argon, Krypton, Nitrogen and Carbon dioxide are used to produce inert atmospheric but amongst all these gases carbon dioxide and nitrogen are principle inert gases in modern use. Several of the halogenated hydrocarbon gases are also employed as inert gases; however, these compounds also exert a free radical quenching action in the presence of flames.

CO_2 is a well-tried and tested fire extinguishing agent and was the agent most widely used before the development of Halon. CO_2 has been used for decades and this has generated a considerable knowledge on its benefits and drawbacks as a fire fighting agent. CO_2 has a zero ODP and zero atmospheric life time but is a greenhouse gas and does contribute to global warming.

Like Halons 1301 and 1211, CO_2 is a gas at normal ambient temperature and pressure. It is also a clean, electrically nonconductive agent with good penetrating capability. Carbon dioxide is discharged as a gas, though some frozen particulate (dry ice) often forms. The presence of frozen particulate increases the heat absorption capacity. Only through the use of refrigerated systems (see below) can any liquid discharge occur.

At one time, CO_2 systems were used for many of the applications that now use halon. Indeed, fixed CO_2 systems still remain in popular use for a number of applications, particularly in unmanned areas. Carbon dioxide is also a common agent in portable fire extinguishers and in localized fixed systems. Research is under way for using carbon dioxide as a component in twin-fluid water misting systems and mixed with particulate aerosols. Carbon dioxide is used as a pressurizing agent in some dry chemical extinguishers.

Design concentrations for carbon dioxide total-flood systems for protection against Class B fires involving typical liquid hydrocarbons range from 34 to 43 percent depending on the fuel [64] compared with approximately 5 to 8 percent for Halon 1301 systems [65]. Cup burner data show that a concentration of approximately seven times that of halon is required for n-heptane [66]. (Note, however, that this does not imply that seven times as much CO_2 is needed in a streaming or localized application.) Carbon dioxide is less efficient than halon. The time to extinguishment is longer and, in general, storage requirements are greater. Carbon dioxide is, however, more efficient than other inert gases, a characteristic that may be due to endothermic decomposition processes. For most total-flood applications, an agent storage volume of approximately eight times that required for halon is required for most CO_2 systems (however, see the next paragraph for a discussion on liquid CO_2 systems where the ratio can be as low as four times). Weight and space considerations are more relevant in retrofitting than in new installations, but they are unlikely to be major obstacles for retrofit into existing industrial and commercial facilities. On the other hand, weight and space requirements are likely to be a barrier for CO_2 retrofit of onboard aircraft applications. Traditionally, CO_2 fixed systems cost two to three times (excluding agent cost) that of halon systems.

Concerns exist about the safety hazard to personnel in areas protected with fixed, total-flood CO_2 systems. Unlike the other inert gases, CO_2 is toxic in large amounts (it is a respiratory regulator), and the design concentrations are well above dangerous levels (above 9 percent, loss of consciousness occurs within a short time, with death occurring around 25 to 30 percent [67]). With most fixed localized systems, on the other hand, the hazard is much less and with portable extinguishers, any hazard is minimal. It is possible to manage the safety hazard with fixed, total-flood CO_2 installations by designing the system to ensure that automatic discharge does not occur while people are present in the protected area or by using manual activation. There are many well developed internationally recognized standards that provide the guidelines for the safe use of CO_2 total-flood systems. However, owing to the toxicity and the reduced efficiency, CO_2 is generally less attractive to fire insurers.

Concerns have been expressed about erasing of magnetic tape and damage from thermal shock due to CO_2. Testing has failed to substantiate the first concern, and thermal shock does not normally occur unless the discharge is directed at objects close to the atomizer. Some specialized installations are designed to pass the CO_2 through a vaporizing unit (converting all of the CO_2 to a gas) to reduce cooling by vaporization and sublimation. Continued use by telecommunications and modern power supply industries support compatibility of CO_2 with risks of this type.

Carbon dioxide portable fire extinguishers have been available for many years and are in common use. They have certain disadvantages compared with Halon 1211: larger size, greater weight, lower efficiency, shorter throw range, and no Class A rating. In many applications, however, these disadvantages do not rule out the use of CO_2 fire extinguishers. Note, however, that complete protection of any facility with CO_2 may leave the facility devoid of sufficient Class A protection, and other types of agents like water, foam, dry chemical may be needed.

2.1.2.1 Characteristics of CO_2 as a Fire Extinguishing Agent

- (i) Carbon dioxide is the only one gas where large volume of gas may be liquefied and maintained in that state in a small container volume at ordinary temperatures and at not extremely high pressures (Critical Temp = 31.1 C)
- (ii) It has a very high expansion ratio 1: 450
- (iii) It produce a cooling effect
- (iv) It is mildly toxic, no lasting toxic effect at 5% concentration
- (v) It is heavier than air and dilutes the concentration of oxygen thereby kills the fire by smothering.
- (vi) It is bad conductor of electricity, hence can be applied directly on live wires.

CO_2 gases used by local application (Sweeping action) and also by the total flooding systems (fixed systems). CO_2 systems have long discharge times of up to 3 minutes or longer, much longer than the 10 second discharges associated with Halon. It is a clean, non-conductive agent and achieves extinguishment primarily by reducing the oxygen level in the vicinity of the fire below the level necessary to support combustion (12 -15% down from the normal 21%). In addition discharge of CO_2 does provide a significant cooling effect.

Finally, because of the high extinguishing concentration required for CO_2, far more cylinders will be required to protect a risk than with Halon. Storage of these cylinders can pose problems, especially if space is at a premium. CO_2 systems are used extensively in the marine industry for the protection of machinery spaces and also in countries such as Germany and Scandinavia for protection of electrical switch rooms and control rooms. Elsewhere in the world they are widely used in the protection of electrical control rooms and the like, which are not normally occupied.

2.1.3 WATER AS FIRE SUPPRESSING AGENT

Water is a very effective extinguishing agent because of its unusually high specific heat and heat of vaporization. Water can be delivered in three ways from fixed systems, from head lines, and from portable extinguishers. It is primarily a Class A fire extinguishant, cooling the fuel to a temperature below the fire point; however, fine water sprays can be very effective against Class B fires and have the additional benefit of cooling to prevent reignition. The quantity of water required is, in some installations, less than the amount of halon needed for the same degree of protection.

Water is very old and most common fire suppressing agent, which is environment friendly with zero ODP and GWP. Water is available cheaply and abundantly every where and is always considered a very effective source / means for fire fighting. Simultaneously water, our most useful and heat removing agent for fire protection purposes, possesses some physical qualities that restrict its use under certain conditions. Some of the merits / demerits of water have been discussed below:-

2.1.3.1 Merits of water as an fire suppressing agent

- **Solvent Ability**: It dissolves and washes many products of combustion (ash) so that the heart of the combustion or seat of the fire can be reached.
- **Small change in Viscosity with temperature**: It may be easily pumped and conducted in hose and pipes from 1 ^{0} C to as high as 99 ^{0} C.
- **High Latent Heat**: The latent heat of vaporization of water is 2,260 KJ / KG, which means water, can absorb a tremendous amount of heat when transformed from boiling state to steam. Thus water is the most efficient heat removing and cooling liquid.
- **High Expansion**: It possesses a property of flashing into large volumes –

an expansion of about 1700 times the liquid volume of inerting steam upon exposure to temperature above its boiling point, thus displacing air and oxygen in the combustion atmosphere (perhaps temporarily).

- **High Surface Tension**: The high surface tension of water at ordinary temperatures (72 dynes per centimeter) enables it to issue in a consolidated stream or in discrete water droplets from the so called ‘fog’ atomizers or spraying devices.
- **High Density**: The reasonably high density of water confers physical mass to a projected atomizer stream for penetration purposes.
- **High Molecular Stability**: Its high molecular stability enables it to avoid breakdown or dissociation to any appreciable amount in temperatures approaching 1650 ^{0} C which are higher than ordinary flame matrix temperature.

2.1.3.2 DEMERITS OF WATER AS AN EXTINGUISHANT

- **Freezing:** Water freezes at temperatures frequently found in temperature climates and as a result it is impossible to use it at places of sub-zero temperature conditions as it cannot be transported to a fire.
- **High Surface Tension:** High Surface tension restricts water from penetrating and wetting various tightly packed combustibles where this action is vitally needed for deep seated fire extinguishment.
- **Low Viscosity:** Due to low viscosity Water runs-off readily from a non-horizontal surface. Leaving a very thin coating of heat-removing or fire protecting liquid.
- **High Friction:** Water demonstrates a problem of high friction loss in transportation thorough pipes and hoses i.e. fall of pressure through hoses.
- **High Density:** High density and immiscibility of water with hydro-carbon fuels results in loss of material for heat removal function by sinking into the fuel.

- **Good Conductor of Electricity:** Water is a good conductor or electricity; hence its use is restricted on live electrical wires and other similar conditions.
- **Metal Reactive:** Reacts with many materials, which causes the evolution of heat, creation of toxic or flammable gases and even explosives.

$$Mg + H_2O \rightarrow MgO + H_2 + Heat$$

$$2A1 + 3\ H_2O \rightarrow Al_2O3 + 6H_2 + Heat$$

It may be seen from the above that there are many situation where the use of water is restricted and accordingly some modification have been suggested to make water suitable for most of the applications.

2.1.3.3 MODIFICATIONS IN PROTERTIES OF WATER :

(i) By adding inorganic freezing point depressants: 94% pelleted grade $CaCl_2$ along with chromate radicals may be added to water as shown in the table given below for the prevention of freezing of water at the stated temperatures.

Table 2.2 Effect of $CaCl_2$ on freezing point of water

Freezing Point ^{0} C	$CaCl_2$ Gms / litre
-1.1	25.1
-3.9	87.4
-6.7	132.9
-9.4	174.9
-12.2	208.4
-15.0	236.0
-17.8	260.0
-20.5	285.1
-28.1	328.2
-29.0	347.4
-34.4	384.5
-40.0	412.1

Sodium chromate is needed for corrosion protection to the extent of 0.5% of the $CaCl_2$ used.

(ii) By Adding modern Wetting agents:

Suitable wetting agents can be added to water to lower its surface tension from its normal level of 73 dynes / cm to about 25 dynes / cm. This means that the strength of the surface "Skin" (that part of the body or particle of water that is exposed to air) of water as dramatically lowered. When a liquid with low surface tension comes in contact with a solid surface such as cotton cloth with tiny open spaces, the liquid 'soaks in' quickly. A liquid with high surface tension might remain on the surface of a cloth in the foam of tight droplet and may refuse to allow its skin to part so that it could enter the tiny spaces in the cloth.

The effect of wetting agents dissolved in water is to increase the wetting and spreading power of ordinary water, hence the term 'wet water' has been given to these solutions. When wetting agent solutions contact materials such as cottons bales, mattresses, stacked hay or straw, or other tightly consolidated class 'A' fire hazard materials, the liquid soaks into the material instead of being lost as 'run off'.

(iii) By adding viscosity enhancing materials:

Viscosity enhancing materials can be added to increase the viscosity and thickness' of water so that it may be applied to surface that are almost vertical in layers upto several times that of plain water. Here again the function of 'run-off' of heat removing water is diminished and the economy of water application to a fire hazards is extended. There are a mainly two type of water 'thickness':

(i) Organic gel – producing substances to give higher viscosity water solutions to coat burning material or to prevent its ignition.

(ii) Bentonite – a powered mineral that yields a water slurry of mixture of ammonium phosphates and sulfates also give a thick slurry, for application to fire hazards, particularly in forest fire incidents. The later slurry type mixtures have an added property of retarding flames due to their 'solids' content and the capability of ammonium salts to halt flaming and glowing ignition.

(iv) By adding flow property modifier:

By adding recently developed flow property modifiers, the friction losses of water can be lowered during transmission at high velocity through hoses. The pressure loss is due to two main factors.

(i) The loss due to frictions between the water and the walls of the hose which amounts about 10% of the loss, and

(ii) The loss due to turbulent flow within the hose at high velocity of transit of the water which amounts to about 90% of the pressure loss.

Polyethylene oxide(POLYOX) is a white powder, soluble in water, each molecule of which is made up of thousands of small molecular units strung together in a long chain to form a giant molecule, causes water to flow in a non turbulent flow in a tube such as a fire hose. By dissolving 3.81 Litres of POLYOX in 22,500 Litres of water, 55% to 70% increase in flow can be achieved.

Another polymeric additive in this regard is ‘rapid water’, when this in the form of concentrated slurry into water in the ratio 1:6000, larger amounts of water are delivered on fire using smaller and more manageable hose sizes without sacrificing atomizer pressures or flow volumes.

(v) By modifying the density of Water:

This involves the addition of air to water to form a semi-stable air foam that is lighter than almost all flammable and combustible liquids (see the fire fighting foams also). The other way is to add an emulsifier to water. Adding to water an emulsifying agent that’s capable of mixing with the top layer of the burning liquid to give an on-flammable floating emulsion of water and fuel.

Synthetic detergent emulsifying agents are used in percentage from 0.5 to 2.0 and yield a fuel – solution – air emulsion of lesser density than water and fuel. This emulsion may be temporary; however, in fire involving high flash point fuels, only a short period of cessation of combustion is sufficient to halt re-ignition.

2.1.3.4 Water sprinklers

As an extinguishing agent, water has a number of disadvantages compared with halons:

(i) Secondary damage (damage to facilities and contents due to the agent) may result from discharge.

(ii) A cleanup requirement may exist after discharge: runoff water may have to be removed and contents of protected areas may require drying.

(iii) Water is unsuitable for discharge onto live electrical equipment.

(iv) Water does not penetrate enclosures as well as halons and other gaseous agents.

(v) Discharge normally takes longer than that of a gaseous agent.

(vi) Most water fire protection applications are unsuitable for Class B fires although this may be overcome by misting systems.

(vii) Water causes problems with storage, discharge, and cleanup at very low temperatures.

(viii) Of particular importance in aviation is that water may carry a relatively large weight penalty, though this may not be true for zoned systems.

There are several types of fixed water systems for fire protection [68]. Wet pipe sprinkler systems are widely used. These systems have pipes that are constantly pressurized with water and that are connected to sprinkler heads which are opened by heat activation. They require no electrically activated fire detectors. Dry pipe systems are filled with air or nitrogen under pressure. When the sprinkler heads are opened by fire, the gas is released allowing water to flow to the heads. These systems are a little more costly than wet pipe systems and have a slower response time. Preaction sprinkler systems require a detection system to actuate a valve allowing water to fill pipes to sprinkler heads which are closed until fire activation opens them. These systems are used primarily where inadvertent discharge must be avoided. A detector is required. Water deluge systems have heads that are normally open unlike the wet pipe, dry pipe, and preaction systems which require fire activation of the sprinkler heads. A detector activates a valve allowing water to discharge from all of the heads. This type of system results in widespread water discharge and, therefore, has a higher possibility of water damage. Deluge systems are unlikely to be used for replacement of Halon 1301 total-flood systems. Other, combination and special, systems have been used, including some that shut off the water when a fire has been extinguished.

Automatic sprinkler systems were first developed in the last century and are well proven, highly reliable form of fire protection. This is particularly true in general industrial and commercial premises in which none of the disadvantages listed above are of major practical significance. Automatic sprinklers may be used for protection of many facilities (e.g., computer rooms) for which halon is traditionally used. To avoid damage to the equipment, however, the electrical power must be deactivated before water is discharged. Although most of the new generation of computer equipment is not permanently damaged by water, if it is first powered down, it must be dried out before use. This means that either redundant equipment is needed or the facility must be able to withstand any losses due to down time.

A fixed water sprinkler system may be very cost-effective for protection of an area that already has halon systems if existing piping, valves, and miscellaneous equipment do not require major modifications. However, if protection of a limited area involves installation of a water supply and if a storage tank, pumps, and increased pipe sizing are required, sprinkler protection could be much more expensive than a halon system. Predesign inspections should be a mandatory consideration for all existing halon-protected areas

2.2 NEW ALTERNATIVES

2.2.1 Inert Gases

Combustion cannot occur when the oxygen content of air at normal pressures is sufficiently reduced (below approximately 15 percent fires cannot be initiated; at lower concentrations, fires are extinguished). Thus, inert gases, such as nitrogen and argon, etc., can extinguish fires by diluting the air and decreasing oxygen content. Extinguishment is also facilitated by heat absorption.

Health problems can occur at low concentrations of oxygen. Although asphyxiation is not probable at concentrations required to extinguish a fire, sufficient impairment could occur to prevent safe evacuation or emergency response. Occupational Safety & Health Adminstration (OSHA) requires that no one enter a space with less than 19.5 percent oxygen without a self-contained breathing apparatus (SCBA). National Institute of Occupational Safety & Health (NIOSH) gives the following effects at varying oxygen concentrations [69]. Note, however, that health problems that can occur would not happen immediately and would be a problem only for extended stays in an environment with a low oxygen level. Thus, there is some feeling that these predictions are meaningless without specifying a time period [70].

- 16 percent -impaired judgment and breathing
- 14 percent -faulty judgment and rapid fatigue
- 6 percent - difficult breathing, death in minutes

The minimum oxygen concentration where astronauts can still perform the minimum physical and mental activities required to safely pilot a spacecraft, although with great difficulty, has been established by the National Aeronautics and Space Administration (NASA) as 12.3 volume percent [71]. Between 16 and 12.3 volume percent oxygen, performance is increasingly impaired. An expert panel has reported, however, that a 3-minute exposure to an atmosphere containing 10 volume percent oxygen provides an adequate margin of safety considering the variability of a working population, but that lethality occurs quickly at oxygen concentrations below 8 volume percent [72].

One method that can be used is to increase the atmospheric pressure so that the partial pressure of oxygen does not decrease below that required for human respiration while reducing the percent oxygen to the point that extinguishment occurs [73]. The higher heat capacity due to increased atmospheric pressure also helps suppress fires. For example, submarines could use nitrogen flooding to dilute the oxygen while keeping its partial pressure constant to maintain life support [74]. This method can only be applied to completely enclosed areas with high structural strengths and is, therefore, limited to very few applications. Pure and blended inert gases marketed as alternatives to halons are shown in table 2.3.

Table 2.3: Pure and blended inert gases

Designation	Composition	Extinguishment Concentration (vol %v/v)
IG-541	Nitrogen 52 ±4% Argon 40 ±4% CO_2 8 ±1%	33
IG-55	Nitrogen 50 ±5% Argon 50 ±5%	35
IG-01	100% Argon	42
IG-100	100% Nitrogen	33

The two most commonly used inert gases (other than CO_2) for Fire Protection since the phase out of Halon have been IG 541 & IG 55. Both have zero ODP, GWP and ALT. No environmental restrictions on their use exist. IG 541 & IG 55 are classified as suitable for use in occupied spaces. They require an extinguishing concentration of approximately 34% minimum (typically 40% is used) and work in a similar manner to CO_2 by reducing oxygen concentration within the protected space below that level necessary to support combustion. Although the resulting oxygen concentration is far lower than that necessary for human occupants in normal conditions, concentration of oxygen down to 10% are allowable for short periods.

Typically, the residual oxygen concentration for either IG 541 & IG 55 is designed to be about 12%. The CO_2 used in the IG 541 blend stimulates the breathing and heart rates of individuals exposed to a discharge with a view of compensating for the oxygen depletion resulting from the discharge.

2.2.1.1 Limitations

Inert Gases are stored at very high pressure in excess of 150 bar (some systems have storage pressures of 200 or 300 bar). Because of the extreme pressure associated with these gases, special high-pressure pipe work is required for system installations. As a result, installations costs for such systems are likely to be higher than for other agents.

The concentrations needed for extinguishment are approximately 34 to 52 percent, depending on the fuel and the fire scenario. This leads to large concentration of gas requirement for fire suppression. As similarly to CO_2, IG 541 & IG 55, are stored in high-pressure storage cylinders. However, unlike CO_2, IG 541 & IG 55 are not liquefied and requires even more cylinders and associated storage area than CO_2. These large numbers of cylinders has ongoing implications in terms of the additional regular maintenance costs associated with each cylinder.

Inert Gas Systems have long discharge times of up to 90 seconds. Inert gases by their very nature are chemically inert providing a clean non-conductive fire extinguishant with no products of decomposition. The extinguishing properties of argon are similar to those of nitrogen for Class A, B, and C fires; however, unlike nitrogen, argon is suitable for Class D fires involving metals that react with nitrogen (e.g., magnesium and lithium). Effective extinguishment of a series of n-heptane, wood crib, and polyvinyl chloride (PVC) cable crib fires has been reported by the UK Loss Prevention Council for IG-541, IG-55, and IG-01 using the recommended design concentration and systems provided by commercial equipment manufacturers [75]. In general, extinguishment times were longer with the inert gases than found for halocarbon extinguishing agents.

Inert Gases are particularly useful for suppressing fires in hazards where an electrically non- conductive medium is desirable. However, owing to the long discharge time and agent volume, inert gases generally are not suitable for rapidly escalating hydrocarbon fires or explosion inertion in normally occupied areas.

2.2.2 Dry Particulate Aerosols.

Dry particulate aerosols are air-suspended dry chemicals with micron-size particles that give some total-flood capabilities. Dry chemical agents are at least as effective as halons in suppressing fires and explosions in many applications; however, such agents can damage electronic and mechanical equipment. Moreover, dry chemical agents, as now used, do not provide explosion inertion or fire suppression for time periods similar to those provided by halon systems due to settling of the particles. The discharge of dry chemicals also obscures vision. In Geneva, Switzerland, at the 2nd Conference on the Fire Protecting Halons and the Environment, 1-3 October 1990, representatives of the Soviet Union provided information on a solid agent that they claimed provided relatively long-term (20 minutes or more) inertion of an enclosed volume and excellent fire extinguishment [76]. The first detailed technical information on this technology, however, was provided in the 1993 Halon Alternatives Technical Working Conference in Albuquerque, New Mexico [77-79].

Most, but not all, of the commercialized technologies for production of particulate aerosols employ an oxidizing agent and a solid fuel which, when ignited, produces a fine solid particulate aerosol providing extinguishment similar to that provided by dry chemical agents. An alternative process manufactures aerosol-size dry chemical agents by spray drying. spraying aqueous solutions into a heated space [80]. The small particle size appears to increase efficiency, decrease deposits, and increases the space-filling capability (multidimensionality) relative to normal dry chemical agents. Some have termed this type of technology as pyrotechnically generated aerosol (PGA).. Others have suggested that the term pyrogenic aerosol. is more appropriate [81].

As particle size decreases, the particulate surface on which heterogeneous recombination of combustion chain propagators can occur increases (e.g., Reactions 1, 2). Moreover, as particulate size decreases, the sublimation rate increases, enhancing homogenous gas phase inhibition mechanisms, examples of which are shown in Reactions 3 through 5 for potassium-containing aerosols (the most common type) [82]. Thus, in addition to improving dispersion, the small particle sizes inherent in particulate aerosols give these materials a greater weight effectiveness than standard dry chemical agents, decreasing problems due to residue. Both heterogeneous (particulate surface) and homogenous (gas-phase) inhibition appear to contribute to flame inhibition by particulate aerosols. Heat absorption by decomposition reactions and phase changes may also contribute.

$$O^{\bullet} + H^{\bullet} \longrightarrow OH^{\bullet} \tag{1}$$

$$H^{\bullet} + OH^{\bullet} \longrightarrow H_2O \tag{2}$$

$$K^{\bullet} + OH^{\bullet} + M \longrightarrow KOH + M \tag{3}$$

$$KOH + H^{\bullet} \longrightarrow K^{\bullet} + H_2O \tag{4}$$

$$KOH + OH^{\bullet} \longrightarrow H_2O + KO^{\bullet} \tag{5}$$

The design factor is the mass of unignited material per unit volume of a protected area as specified by the manufacturer or distributor. At present, the NFPA has no standard on fine aerosol technology.

2.2.2.1 Limitations

Fine particulate aerosols are suitable only for limited enclosed unoccupied spaces. The powders are corrosive in nature, and damage the equipments in the area of application.

2.2.3 Halogenated Fire Suppressing Agents

At present, Halon replacements (e.g., halocarbons) fall into four major categories as indicated in table 2.5.

Table 2.5 Classes of Halon Replacement

HCFCs	Hydrochlorofluorocarbons
FCs (PFCs)	Perfluorocarbons
HFCs	Hydrofluorocarbons
FICs	Fluoroiodocarbons

There are a number of desirable characteristics for replacement agents. They must have acceptable global environmental characteristics (low ODP, low GWP, and low atmospheric lifetime) and an acceptable toxicity. A continuing debate on acceptable levels for these characteristics is expected. The primary reason for using halocarbons, rather than such alternatives as foams and dry chemicals, is that halocarbons are clean, volatile, and electrically nonconductive. Finally, the agent must be effective. Note, however, that effectiveness does not necessarily mean as effective as the present Halons, though this is desirable.

Most halocarbons now proposed as Halon replacements require significantly higher concentrations than required for Halons 1301 and 1211 and produce larger amounts of toxic or corrosive byproducts (e.g., hydrogen fluoride and, for chlorine-containing agents, hydrogen chloride) [83]. One halocarbon, CF_3I, produces relatively large amounts of iodine. Byproduct formation is strongly influenced by the mass flux of inhibitor into the flame sheet and the extinguishment time. Slow extinguishment due to the use of lower concentrations of agent produces more byproducts.

HCFCs have a nonzero ODP and currently face an eventual regulated production phase out. HFCs are attractive as replacements for ozone depleting substances for three reasons: (1) they are usually volatile and many have low toxicities, (2) they are not ozone depleting as are the HCFCs and because they have lower atmospheric lifetimes than PFCs, they are likely to receive less regulatory action than HCFCs or PFCs, and (3) they have properties similar to those of halocarbons that have been used in the past. This does not, however, mean that HFCs are not receiving scrutiny from environmental organizations. A recent study by the National Institute of Public Health and Environmental Protection, The Netherlands, has projected a significant increase in greenhouse gas emissions due to use of HFCs to replace CFCs and HCFCs [84]. Moreover, Denmark has announced they plan to phase out all hydrofluorocarbons (HFCs) within the next 10 years (written in 1996) due to global warming [85]. Other European countries such as Austria and Norway are considering regulation of

HFC use [86].

A large number of candidate replacement agents have been announced for commercialization, and even more chemicals are under serious consideration. A number of halocarbon replacements have been announced for total-flood applications as indicated in table 2.6. All of these agents are contained in the NFPA 2001 Standard [87].

Table 2.6 Commercialized Total Flooding Agents

Agent	Chemical	Formula	Trade Name
Halon 1301	Bromotrifluoromethane	$CBrF_3$	
HCFC-124	Chlorotetrafluoroethane	$CHClFCF_3$	DuPont FE-241
HCFC Blend A HCFC-123 HCFC-22 HCFC-124	Additive plus Dichlorotrifluoroethane Chlorodifluoromethane Chlorotetrafluoroethane	$CHCl_2CF_3$ $CHClF_2$ $CHClFCF_3$	North American Fire Guardian NAF S-III
HFC-23	Trifluoromethane	CHF_3	DuPont FE-13
HFC-125	Pentafluoroethane	CHF_2CF_3	DuPont FE-25
HFC-227ea	Heptafluoropropane	CF_3CHFCF_3	Great Lakes FM-200 DuPont FE-227
HFC-236fa	1,1,1,3,3,3-Hexafluoropropane	$CF_3CH_2CF_3$	DuPont FE-36
FC-218	Perfluoropropane	$CF_3CF_2CF_3$	3M CEA-308
FC-3-1-10	Perfluorobutane	$CF_3CF_2CF_2CF_3$	3M Company CEA 410
FIC-13I1	Trifluoroiodomethane	CF_3I	West Florida Ordnance Iodoguard; Ajay North America

The weight and storage volume equivalents are directly calculated from the laboratory-determined properties. This method does not use the specified design concentration or the fill densities; however, it does more closely compare the actual agent performance to that of Halon 1301. The results are shown in table 2.7. The extinguishment concentrations are cup burner values taken from a single source [87]. Note that the number of significant figures for the equivalents is larger than justified by the extinguishment concentration precision.

TABLE 2.7 Comparative performance of total flooding agents for n-heptane fuel

Agent	Cup Burner Extinguishment Concentration, vol%	Liquid Density, g/mL, 25°C	Weight Equivalent	Storage Volume Equivalent
Halon 1301	3.4	1.551	1.00	1.00
HCFC-124	6.6	1.357	1.81	2.06
HCFC Blend A	9.9	1.20	1.82	2.25
HFC-23	12.9	0.685	1.80	4.07
HFC-125	8.7	1.190	2.11	2.75
HFC-227ea	6.5	1.395	2.22	2.46
HFC-236fa	6.3	1.356	1.89	2.16
FC-218	6.5	1.321	2.26	2.66
FC-3-1-10	5.5	1.497	2.49	2.58
FIC-13I1	3.2	2.106	1.24	0.91

The environmental and toxicity properties of commercialized total-flood agents are shown in table 2.8. All agents other than Halon 1301 listed in table are acceptable under Significant New Alternatives Policy (SNAP), however, there are limitations on its use for certain agents.

Table 2.8 Environmental and toxicity properties of commercialized total flooding agents

Agent	ODP	GWP (100 years)	Atmospheric Lifetime, (yrs)	NOAEL (%)	LOAEL (%)
Halon 1301	12	6,900	65	5	7.5
HCFC-124	0.026	620	6.1	1.0	2.5
HCFC Blend A	0.044	1,450	12	10.0	>10.0
HCFC-123	0.012	120	1.4	1.0	2.0
HCFC-22	0.034	1,900	11.8	2.5	5.0
HCFC-124	0.086	620	6.1	1.0	2.5
HFC-23	0.0	14,800	243	50	>50
HFC-125	0.0	3,800	32.6	7.5	10.0
HFC-227ea	0.0	3,800	36.5	9.0	10.5
HFC-236fa	0.0	9,400	226	10.0	15.0
FC-218	0.0	8,600	2,600	30	>30
FC-3-1-10	0.0	8,600	2,600	40	>40
FIC-13I	<0.008	<1	0.005	0.2	0.4

2.2.3.1 Limitations

All of the halocarbon agents have tradeoffs for total-flood and/or streaming applications. As noted earlier, Halon replacements should have four characteristics: a low global environmental impact (low ODP & GWP), acceptable toxicity, cleanliness/volatility, and effectiveness. Though it is very easy to find candidate replacements that meet any three of these criteria, it has been difficult to find agents that meet all four. For most (but not all) applications, significantly more replacement agent is needed to provide the same degree of protection as provided by the present Halons. All the halocarbons have very high GWP, exception is FIC-13I1, which has total-flood use limitations owing to toxicity.

One potential problem that occurs with many (but not all) of the new halocarbon agents is that they generate four to ten times more hydrogen fluoride (HF) than Halon 1301 does during comparable extinguishment [88 and 89]. Although a large amount of information is available on hydrogen fluoride toxicity [87 and 90], it is difficult to determine what risk is acceptable. A good review of the toxicity of HF as it relates to short exposures of high concentration of HF can be found in the NFPA 2001 Appendix [87]. Some data exists to determine what hydrogen fluoride levels are likely in real fire scenarios. In general, agent decomposition products and combustion products increase with fire size and extinguishment time [87 and 91]. To minimize decomposition and combustion products, early detection and rapid discharge are recommended. The effects of HF will occur at the site of contact and will be observed as inflammation (irritation) that can progress to severe, deep-penetrating irritation. At high concentrations of HF (>200 ppm) for an extended duration of time, e.g., 1 hour, fatalities may occur, particularly in the absence of any medical treatment.

At concentrations of <50 ppm for up to 10 minutes, definite irritation of upper respiratory tract, skin, and eyes would be expected to occur. At these low concentrations, escape-impairing effects would not be expected in the healthy individual. As HF concentrations increase to 50 to 100 ppm, an increase in irritation is expected. At 100 ppm for 5 minutes, moderate irritation of all tissue surfaces would be expected, and as the duration of exposure increases to 10 minutes, escape-impairing effects would begin to occur. As the concentration of HF increases, the severity of irritation, including escape-impairing irritation of the eyes and respiratory tract, increases and the potential for delayed systemic effects also increases. At these higher concentrations, humans would be expected to shift to mouth breathing, and deeper lung irritation is expected. At greater concentrations (>200 ppm), respiratory discomfort, pulmonary (deep lung) irritation, and systemic effects are possible. Continued exposure at these concentrations may be lethal in the absence of medical treatment.

2.2.4 WATER MIST

The term "water mist" refers to fine water sprays in which 99% of the volume of the spray is in drops with diameters less than 1000 microns [92]. The use of water mist in fire suppression, compared to the use of gaseous agents and conventional sprinkler systems, has demonstrated advantages including the following:

(1) No toxic and asphyxiation problems;
(2) No environmental problems;
(3) Low system cost;
(4) Limited or no water damage; and
(5) High efficiency in suppressing certain fires.

The study and description of the fundamental principles of extinguishment of liquid and solid fuel fires by water mist can be traced back to the mid-1950s [93]. Research continued to be carried out during the 1960s and 1970s at university, industry and government research facilities [94-102]. These early studies focused on the extinguishing mechanisms of water mist and the optimum droplet parameters for efficient fire suppression. It was shown that water mist with fine sprays was very efficient in controlling liquid and solid fuel fires, and suppressing hydrocarbon mist explosions [103]. At the same time, however, Halon 1301 and 1211, the most effective chemical fire suppressants ever developed, were introduced. The application of water mist to fire suppression was, therefore, not considered practical until the recent requirement to phase out halon agents due to their negative environmental effects.

Over the last decade, studies on water mist technology have significantly increased. A survey carried out by Mawhinney and Richardson [104] in 1996 indicated that nearly 50 agencies around the world are involved in the research and development of water mist fire suppression systems, ranging from theoretical investigations into extinguishing mechanisms and computer modelling to the development, patenting and manufacturing of mist-generating equipment. These recent studies have shown that water mist technologies have the potential either to replace current fire protection techniques that are no longer environmentally acceptable, or to provide new answers to problems where traditional technologies have not been as effective as desired [104-114].

Water misting systems allow the use of fine water sprays to provide fire protection with reduced water requirements and reduced secondary damage. Calculations indicate that on a weight basis, water could provide fire extinguishment capabilities better than those of halons provided that complete or near-complete evaporation of water is achieved. Since small droplets evaporate significantly faster than large droplets, the small droplets achievable through misting systems could approach this capability.

More recent reviews are presented in references [115] and [116]. Water misting is being evaluated both as a possible replacement for total-flooding Halon 1301 systems [117] and for use in hand-held extinguishers [118].

At the request of the Environment Protection Agency (EPA), manufacturers of water misting systems and other industry partners convened a medical panel to address questions concerning the potential physiological effects of inhaling very small water droplets in fire and non fire scenarios. Disciplines represented on the medical panel included inhalation toxicology, pulmonary medicine, physiology, aerosol physics, fire toxicity, smoke dynamics, and chemistry with members coming from the commercial, university, and military sectors. The executive summary of the final report [119] states the following:

The overall conclusion of the Health Panel’s review is that water mist systems using pure water do not present a toxicological or physiological hazard and are safe for use in occupied areas. The Panel does not believe that additional studies are necessary to reach this conclusion. The Health Panel recommends that additives be evaluated on a case-by-case basis depending on the toxic properties of the additive and the concentration at which it is used.

The detailed theoretical investigations regarding the diffusion flame suppression mechanism of water mist, factors affecting flame suppression effectivessness, & atomization process its mathematical modeling is given in chapter 5.

Chapter 3

CONCLUSIONS FROM LITERATURE SURVEY AND STATEMENT OF THE PROBLEM

3.0 INTRODUCTION

In this chapter the significant conclusions that have been derived from the literature survey carried out pertaining to the area of utilization of alternative fire suppressing agents are briefly described for their fire suppression effectiveness, application area and environmental concerns. Based on these conclusions, the objective and need for present work are highlighted. Subsequently the statement of the problem is defined.

3.1 CONCLUSIONS FROM LITERATURE SURVEY

Based on the comprehensive literature survey carried out, the following conclusions have been derived.

1) The flames associated with the burning of most of the condensed fuels (i.e. combustible solids and flammable liquids) are diffusion flames, because fuel and oxidizer (air) are initially separate and combustion occurs in the zone where the gases mix. Suppression of diffusion flames inside the enclosed spaces with fire suppressing agents depends upon the enclosure fire characteristics, various factors influencing fire development in side the enclosure and physical & chemical properties of fire suppressing agent and fire suppression mechanism.

2) Halons are considered to be most effective diffusion flame suppressing agents as they break down under the temperature of flame and their products of decomposition have an affinity for uniting with the highly active free radicals O, H, OH produced by burning fuels, subsequently removing them from combustion zone. Halons are required in small concentration 4–6 % vol / vol and are applicable for all types of fire. They have low

boiling point, therefore they can be stored in small cylinders leading to low space / weight requirement for the halon fire protection system. Halons are used as total flooding agents (Halon 1301) as well as streaming agent for localized applications (Halon 1211).

3) Halons are not environment friendly fire suppressing agents. They have high ozone depleting potential (ODP) and global warming potential (GWP). India being as signatory to Montreal Protocol, has obligation to phase-out halons. The production of halons in India has been already stopped and will completely be phased-out in 2010. India's halon phase out strategy allows use of halons only for critical application's till the shelf life of existing halon system and gas for these system will be drawn from National Halon Bank.

4) The classical / traditional halon alternatives such as dry chemical, CO_2, water sprinklers & foams and are useful only for limited/selected applications. Water sprinkler system discharges very large amount of water and only 5-10% of total water discharged does the fire fighting, therefore this excess water contributes to secondary damage to the equipment and machinery. Foams are used only for suppression of fires involving flammable liquids (class 'B') as they cut off the supply of air required for combustion. Dry chemical powders and CO_2 are useful for suppression of fires involving solid combustible materials (class 'A') like wood, paper, cloth, plastic etc. where as for electric fires (class 'C') only Dry Chemical Powders are used. The choice of traditional fire suppressing agents is based on type / class of the fire and proper selection of fire suppressing agent is very important.

5) The new halon alternative technologies are available for suppression of diffusion flames, but they have some limitations. The inert gases require very high concentration (35 - 50% V/V), resulting very high space / weight ratio. Some of halocarbons (HFC227ea) are very close substitute to halons, but they require higher concentration as compared to halons and

have high GWP. All such agents come under Kyoto Protocol, therefore will be phased out for their global warming potential. Other halocarbons having low GWP, have very high toxicity (e.g CF_3I) making them unsuitable for occupied spaces. Dry chemical particulate aerosols are suitable only for limited applications as they are corrosive in nature and unsuitable for occupied spaces.

6) Water is very old, cheapest and one of the most commonly used fire suppressing agent, unlike Halo-Carbon fire extinguishing agents, it is environment friendly with zero ODP & GWP. The physical properties of water makes it very efficient fire suppressing agent, like its high latent heat of vaporization (2440 kJ/kg) helps it in absorbing a large amount of heat when converted into vapour making it as one of the most efficient heat removal and cooling agent, its high specific heat capacity (4.183 kJ/kg) helps it in carrying large amount of heat, its solvent ability washes away many products of combustion, its high expansion ratio (1:1700) helps it in displacing air surrounding the fire, thereby removing the air required for combustion, its high surface tension helps it to issue in a consolidated stream or in discrete water droplet, its high molecular stability enable it to avoid dissociation and its higher density helps it for penetration through flame and radiation's.

7) There has been renewed interest in use of water for suppression of diffusion and premixed flames because of the environmental issues of Halons and Halocarbons. Over the last decade, studies on water mist technology have significantly increased. The literature survey indicated large number of agencies around the world are involved in the research and development of water mist fire suppression systems, ranging from theoretical investigations into extinguishing mechanisms and computer modelling to the development, patenting and manufacturing of mist-generating equipment. These recent studies have shown that water mist technologies have the potential either to replace current fire protection techniques that are no longer environmentally acceptable, or to provide

new answers to problems where traditional technologies have not been as effective as desired.

8) Water mist is fine water sprays used to provide fire protection with reduced water requirements and secondary damage. Calculations indicate that on a weight basis, water could provide fire extinguishment capabilities better than those of halons provided that complete or near-complete evaporation of water is achieved. Since small droplets evaporate significantly faster than large droplets, the small droplets achievable through misting systems could approach this capability.

9) The diffusion flame suppression with water mist involves two mechanisms: primary mechanism is heat extraction (cooling of fire plume & Wetting/ Cooling of the fuel surface) and displacement (Displacement of oxygen & Dilution of fuel vapour); secondary mechanism is radiation attenuation and kinetic effects of water mist on the flame. The fire suppression performance of water mist is function of mist characteristics such as droplet size, mist momentum, mist concentration per unit volume and direction of mist etc.

10) The water mist is generated by various atomization techniques, the basic three atomization techniques used for diffusion flame suppression are impingement, pressure jet and twin fluid atomization. In some cases ultrasonic atomization is also used. The mist generation rate of atomizers should be high in order to achieve critical concentration of mist in minimum time for complete suppression of diffusion flames.

Internally mixed atomizers are mot suitable for fire suppression in large enclosed spaces as they have high mist generation rate & control on atomization process. Controlled atomization helps in generation of mist of desired droplet size during the experiments.

11) Cup Burner Apparatus is internationally accepted method to experimentally measure the Minimum Extinguishing Concentration (MEC) of gaseous agents for suppression of diffusion flame, which forms the

basis for a design of fire protection systems. The critical concentration of water mist (MEC) can not be measured in standard cup burner apparatus, however with some modifications cup burner apparatus can be used to experimentally measure critical concentration of water mist (Minimum Extinguishing Concentration – MEC) for suppression of diffusion flame.

12) The cup burner results for water mist must be validated in large fire test enclosure, as mist concentration required for suppression of diffusion flames is function of droplet size, heat release rate, location of diffusion flame, compartment geometry, direction of spray, ventilation conditions etc.

13) The design of water mist is application specific, there can not be one universal design. The optimization of mist parameters like droplet size, mist generation rate, mist direction, type of atomizing gas etc are important for optimizing critical concentration of water mist for diffusion flame suppression.

14) The water mist can also be used for suppression of diffusion flames in open areas if water mist throws of 10-15 m is achieved by using atomizing gun. Portable water mist systems are in use for such applications, which serve the purpose of first hand fire fighting equipment.

3.2 AREAS WHERE FURTHER WORK IS REQUIRED

There has been renewed interest in use of water mist for suppression of diffusion flame because of its physical properties which make it one of the most efficient fire suppressing agent. The diffusion flame suppression performance of water mist depends on mist parameters like droplet size, mist injection rate, mist direction, type of atomizing gas and flux density etc. Following are the areas where further work is required:

1) Design and develop atomizers having high mist generation rate (1-2 lpm) with controlled atomization in the droplet size range 10-100 µm (SMD) with respect to its operating parameters.
2) Establish the critical concentration of water mist (MEC) for suppression of n-heptane diffusion flame in cup burner apparatus and its mass to mass basis comparative effectiveness with respect to Halon 1301 and HFC227ea.
3) Validation of cup burner apparatus results in large enclosed space for establishing critical concentration of water mist for suppression of diffusion as a function of droplet size, flux density, type of atomizing gas, mist direction, heat release rate (HRR), location of diffusion flame (obstructed/unobstructed) etc.
4) Understand the diffusion flame suppression mechanisms of water mist in the enclosed spaces.

3.3 OBJECTIVES

To summarize in the proposed work, attempts are made to quantify, on a comparable basis to experimentally measure critical concentration of water mist with optimized droplet size required for suppression of diffusion flames. In order to achieve this objective the following were decided:

1) To investigate the diffusion flame suppression performance of water mist in cup burner apparatus and large enclosed space.

2) To experimentally measure critical concentration of Halon 1301 & HFC 227ea and water mist for suppression of n-heptane diffusion flame in cup burner apparatus.

3) To design and develop externally & internally mixed twin fluid atomizer for mist generation for suppression of diffusion flame in cup burner apparatus and large enclosed space respectively.

4) Set – up a atomizer characterization facility for measuring droplet size distribution in the size range from 3-850 µm coupled with atomizer traversing system for traversing the atomizer in horizontal and vertical direction for characterization of complete spray.

5) To carry out experiments in large enclosed space (40m^3 chamber) establishing critical concentration of water mist for suppression of diffusion as a function of droplet size, flux density, type of atomizing gas, mist direction, heat release rate (HRR), location of diffusion flame (obstructed/unobstructed) etc and study environmental conditions in the test chamber.

6) To optimize the critical concentration of water mist required for suppression of diffusion flame as a function of droplet size, flux density, type of atomizing gas, mist direction, heat release rate (HRR), location of diffusion flame (obstructed/unobstructed) etc.

3.4 STATEMENT OF PROBLEM

An attempt was made to attain the above envisaged objectives by defining the problems through the following phases:

1) Assessment of various alternative agents used for diffusion flame suppressing and their limitations.

2) Assessment of suitability of water mist as diffusion flame suppressing agent and investigate the diffusion flame suppression performance of water mist in cup burner apparatus and large enclosed space.

3) To design and develop standard cup burner apparatus for experimental measurement of critical concentration of Halon 1301 & HFC227ea for suppression of diffusion flame.

4) To design & develop modified cup burner apparatus for experimental measurement of critical concentration of water mist for suppression of diffusion flame to establish the critical concentration of water mist (MEC) for suppression of n-heptane diffusion flame in cup burner apparatus and study its mass to mass basis comparative effectiveness with respect to Halon 1301 and HFC227ea.

5) To design and develop externally & internally mixed twin fluid atomizer for mist generation for suppression of diffusion flame in cup burner apparatus and large enclosed space respectively.

6) To set – up atomizer characterization facility for measuring droplet size distribution in the size range from 3-850 µm coupled with atomizer traversing system for traversing the atomizer in horizontal and vertical direction for characterization of complete spray.

7) To carry out experiments in large enclosed space (40m^3 chamber) establishing critical concentration of water mist for suppression of diffusion as a function of droplet size, flux density, type of atomizing gas, mist direction, heat release rate (HRR), location of diffusion flame (obstructed/unobstructed) etc and study the effect of water mist on compartment temperature and O_2, CO_2 & CO during and after fire.

8) Optimization of critical mist concentration required for suppression of diffusion flame as a function of droplet size, flux density, type of atomizing gas, mist direction, heat release rate (HRR), location of diffusion flame (obstructed/unobstructed) etc.

9) To understand the diffusion flame suppression mechanisms of water mist in the enclosed spaces.

Chapter 4

EXPERIMENTAL SETUP AND TEST PROCEDURE

4.0 INTRODUCTION

To appreciate the potential of water mist as diffusion flame suppressing agent adequate experimental data is required to quantify the critical concentration of fire suppressing agents on lab scale. The cup burner apparatus is used as experimental test set-up for measuring critical concentration of gaseous fire suppressing agents (Standard Cup Burner Apparatus). In case of flammable liquid fuels the Cup Burner method has assumed a prominent position, as the definitive method for measuring MEC. The international standards requires that “the flame extinguishing concentration for class B fuel shall be determined by Cup Burner method" [87,120]. The critical concentration of water mist for suppression of diffusion flames can also be measured in cup burner apparatus with some modifications (Modified cup burner Apparatus). The chosen experimental set-ups should facilitate the diffusion flame in an enclosed glass chimney for interaction of agent and flame under independently controlled air and agent flow rates. The critical concentration measured in cup burner apparatus is basis for calculating design concentration (cup burner value x factor of safety) of any fire suppressing agent. The critical concentration of water mist measured in modified cup burner apparatus are validated in scaled –up experimental facilities for obtaining third party approval of a fixed fire suppressing system, it is usually necessary to perform large-scale test e.g. in case of class B fuels, pan fire test in relation to accepted cup burner value of the test fuel which is usually commercial n- Heptane. The scaled–up experiments for experimentally measuring critical concentration of water mist were carried out in large enclosed space (40 m^3 test chamber) instrumented for measuring: spatial and temporal temperature, species of gases (O_2, CO, CO_2), fuel burning rate, Heat release rate, flame imaging and processing etc during diffusion flame and mist interaction.

4.1 ATOMISER CHRACTERISATION

Two types of atomizers were designed, developed and characterized for carrying out experiments in modified cup burner apparatus and large enclosed space (40 m^3 chamber). Externally mixed atomizer was developed with low generation rate (0.2-70 ml/min) and internally air assisted atomizer was developed with high generation rate (0.2 – 2 lpm) with droplet size range of 10 – 100 µm.

4.1.1 Internally Mixed Atomizer

The availability of a controllable mist generator producing fine sprays over a range of operating conditions can improve the efficiency of a fire fighting system, which can be modulated to provide desired mist characteristics for different classes of fires and during a particular fire fighting operation depending on the most important fire suppression mechanism. The results of an investigation of an internally mixed twin fluid mist generator that may potentially overcome some of the limitations of state of the art atomizers. In contrast to single fluid atomizers requiring quite high pressures to produce fine sprays, twin fluid atomizers can provide a fine spray at relative lower supply pressures [121].

Internally mixed atomizers are gaining popularity because of the controllability over the atomization process and the improved quality of atomization provided by them. In such atomizers, low flow rate of marginally pressurized air is impinged upon the liquid inside the atomizer, a short distance from the injector's exit. It is believed that two effects induce atomization in such an injector which could be effectively employed for diffusion flame suppression applications. [122]. First, as both the liquid and the air share the same flow passage in the injector, the liquid is restricted to a smaller available flow area. The reduction in flow area accelerates the liquid, thus, increasing its kinetic energy, which induces fine atomization. Second, the relative motion between the air and the liquid phases produces shear forces at their interface leading to the onset of flow instability at the interface resulting in ligament formation. Furthermore, the shear force strips liquid droplets from the liquid filaments inducing atomization. The positive aspect of the internally mixed air assisted atomizer is that its atomization characteristics can be controlled [123-129].

Furthermore, internally mixed atomizers need a significantly lower flow rate of atomizing air compared to air blast atomizers [127-131]. The disadvantage of the internally mixed atomizer is that it requires additional compression of the atomizing air, but that can be provided easily from a compressed air bottle during fire fighting operation. Conceptually, these atomizers are similar to effervescent atomizers, which require a small amount of air to produce a very fine spray [126, 130-132]. Good operation of an effervescent injector requires the formation of a mixture of air and liquid in a mixing chamber whose characteristics correspond to a bubbly two-phase flow [132]. However, when operating in bubbly flow regime, operation of an effervescent atomizer is restricted to a maximum ALR (air liquid mass ratio) of 0.05 [126], restricting the controllability of the atomization process.

The internally mixed atomizers discussed in the literature [124- 129] provide quite low flow rates and are therefore unattractive for diffusion flame suppression applications. The challenge is to produce fine mist at a high throughput rate (greater than 1 LPM), which was achieved in the present atomizer by modifying the internal geometry and providing a mixing chamber. The spray was characterized for mist generation rate and droplet size for a range of operating parameters. The results show that if the supply pressures of both the water and air are controlled independently, the atomization of the spray can be controlled over a wide range of liquid flow rates. Consequently, employing such an atomizers for diffusion flame suppression will enable fire fighters to independently control the characteristics of the generated mists. The cross-sectional view of the developed internally mixed atomizer is shown in Fig. 4.1

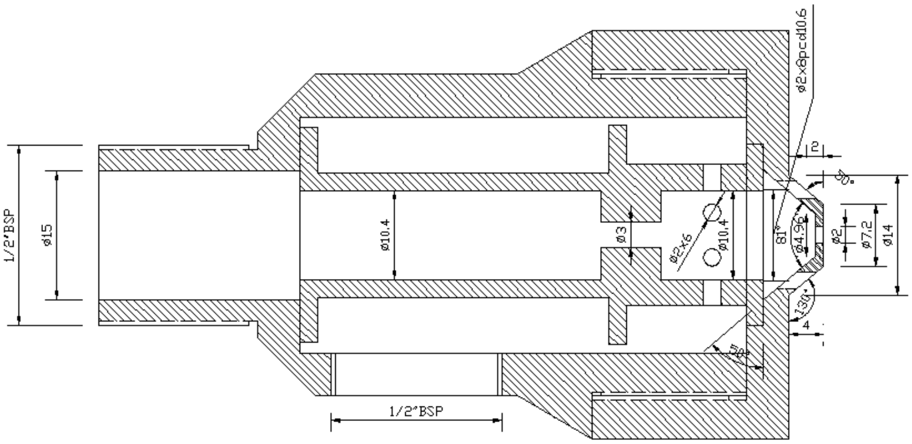


Fig. 4.1: Sectional view of internally mixed atomizer assembly.

Fig. 4.2 shows the schematic of the experimental setup used for mist generation and atomizer characterization. The water was stored in a mild steel vessel. Pressurized air was introduced into this vessel to drive the water at desired pressure using a pressure regulating valve, a metering valve and a flow meter. The flow rate of the atomizing air was controlled and measured using the air pressure regulating valve and the calibrated rotameter respectively. For the sake of corrections in density variation, the supply pressure of the atomizing air was closely monitored using a pressure gauge. The required variation in the air supply pressure to achieve the desired operating condition was also monitored.

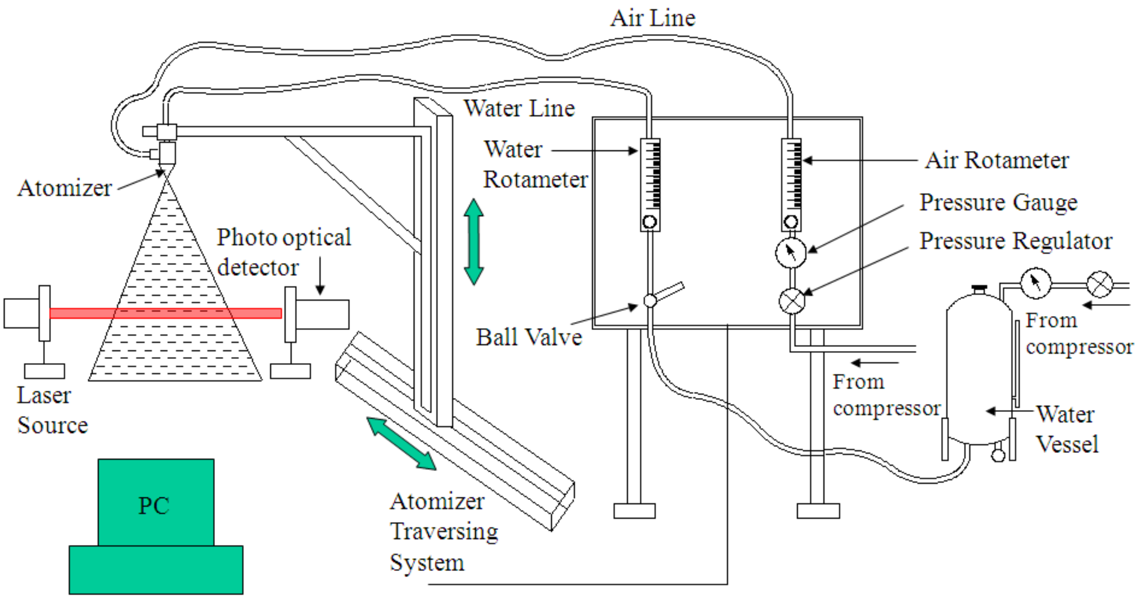


Fig. 4.2: Schematic of the experimental setup

4.1.1.1 Experimental Procedure

The liquid used in the study was water at room temperature, which is supplied to the atomizer from the liquid inlet port of 15 mm in diameter. The air is supplied to the air settling chamber of the atomizer from the air inlet port of 15 mm in diameter. This chamber ascertains the uniform distribution of air through the holes in the circular tube. The air is then introduced into the liquid stream through six radial holes, 2 mm in diameter, on the circular wall of the inner chamber in which the liquid flows. The air coming out of the air inlet holes interacts with the liquid in mixing chamber and creates a two-phase air liquid mixture. This two- phase flow finally comes out of the 9 injection orifices (2 mm diameter each) of the atomizer at high velocity and the spray characteristics are obtained depending upon the ALR and the other flow conditions.

In the study, the liquid supply pressure was kept constant and the air flow rate through the mist generator was varied over a range by changing the air supply pressure to obtain the variation in Air to Liquid Mass Ratio (ALR). The liquid supply pressure was then varied and the entire procedure was repeated for different values of air supply pressure. The spray characteristics corresponding to a range of liquid supply pressures (i.e., 34.3 kPa to 171.2 kPa), air supply pressure (206 kPa to 756 kPa) and ALR (0.16 to 2.9) were studied and the results are presented in the next chapter.

4.1.2 Externally Mixed Atomizer

A schematic of developed externally mixed atomizer assembly is shown in Fig. 4.3. Liquid enters the water chamber (2) through water inlet port (1). The liquid is sucked through three hypodermic needles (3) because of the pressure difference created at the needle tip by air pressure. The air is supplied through air inlet port (4) and injected through three holes (5) at the upstream of water entry point. Two streams, air and water, interact at the exit of the atomizer and droplets are discharged through outer chamber (6).

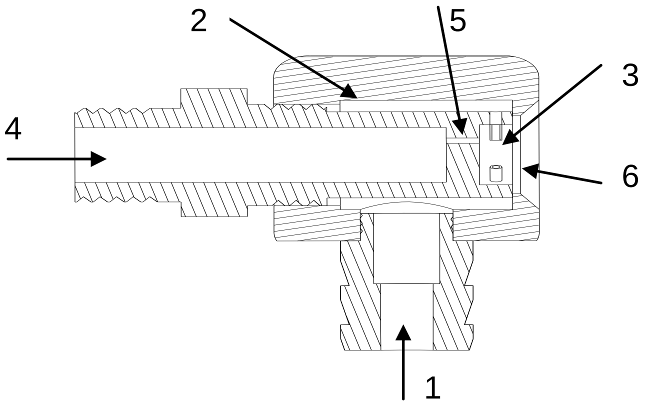


Fig. 4.3: Schematic of the Atomizer [(1) Liquid inlet port, (2) Water chamber, (3) Hypodermic needle for water injection, (4) Air inlet port, (5) Air discharge port, (6) Outer chamber for discharge of droplets]

4.1.2.1 Experimental Procedure

Fig. 4.4 shows the schematic of the experimental setup used for mist generation during study. The water was siphon fed to the atomizer through water bottle. The water feed to the atomizer is a function of air flow rate which was controlled using a control valve. The flow rate of the atomizing air was controlled and measured using the air pressure regulating valve and the calibrated rotameter respectively.

For the sake of corrections in density variation, the supply pressure of the atomizing air was closely monitored using a pressure gauge.

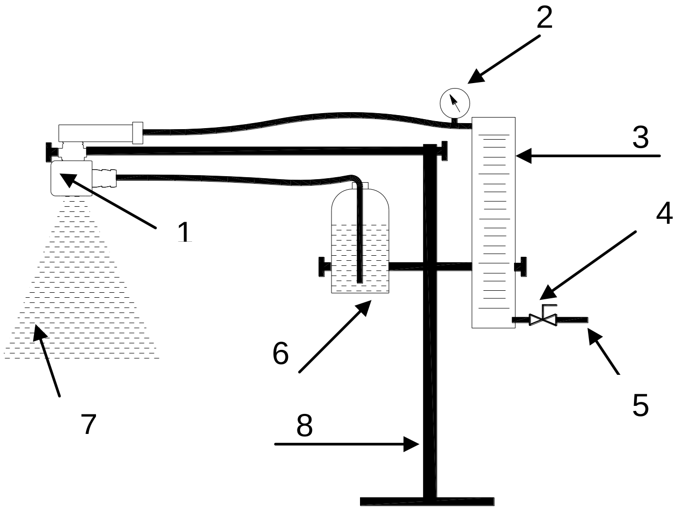


Fig. 4.4 : Schematic of the mist generation setup [(1) Externally mixing air atomizer, (2) Pressure gauge, (3) Air rotameter, (4) Control Valve, (5) Compressed air line (6) Water Bottle, (7) Solid cone water spray, (8) Stand for holding atomizer, water bottle & air rotameter]

Fig. 4.5 indicate atomizer characterization facility for droplet size measurement. As indicated in this the atomizer was fixed on atomizer traversing system for two axis (1 meter horizontal and 1 meter vertical) traverses of the atomizer. The atomizer was connected with water and air feed system using flexible tubing for ease of the traverse. The traversing system was computer controlled using microcontrollers. The droplet size analyzer was fixed on the stand which was fixed on floor to avoid any vibration during the measurements. The droplet size distribution measurements were taken at a fixed location i.e. at a distance of 1 meter from the atomizer.

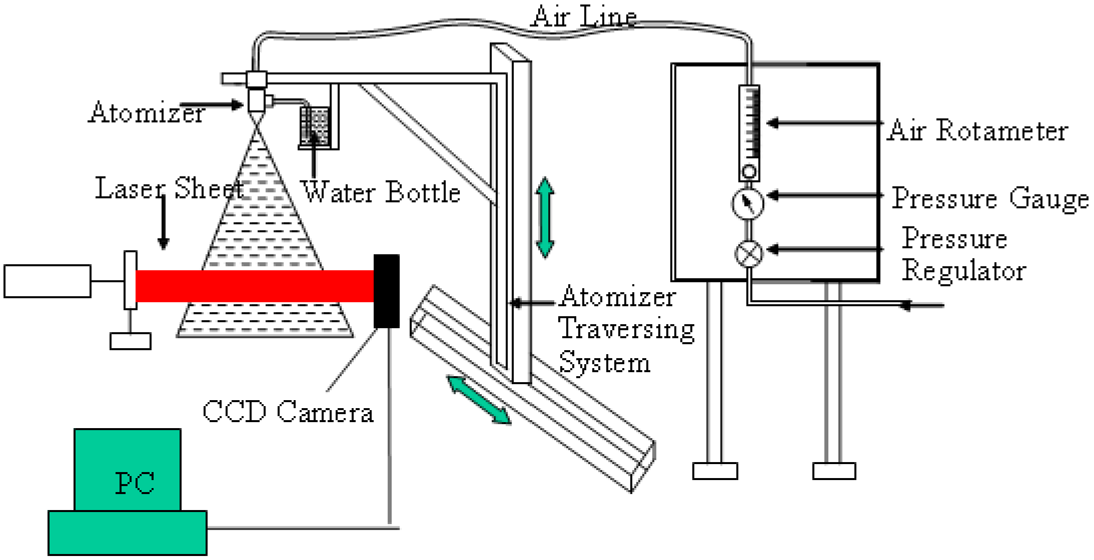


Fig. 4.5 Schematic of the experimental setup

4.1.3 Atomizer Characterization - Droplet Size Measurement

An Ensemble Particle Concentration and Sizing apparatus (EPCS, Insitec/Malvern®, Worcestershire, U.K.) was used to measure the droplet diameter of the mist. The operating principle of this apparatus is based on low angle laser light scattering. The dynamic measurement range for this system was between 2 microns to 850 microns. To determine droplet diameter from the input signals, EPCS uses a computer program (RTSizer, Insitec/Malvern®, Worcestershire, U.K.), which is based on the Mie theory of light-particle interactions. The instrument uses 670 nanometer He-Ne laser with a beam diameter of 10 mm. The accuracy of the instrument was ± 3% of full scale (specified by the manufacturer) and it could measure the size distribution of sprays with obscurations up to 95%. The measurement rate of equipment was one measurement every 400 microseconds. Measurements were taken along the centerline of the spray cone at a distance of 1 meters below the exit of the atomizer. Sauter mean diameter (SMD) was used as a meaningful quantity to represent the average of droplet diameter. SMD represents an average droplet diameter with the same volume to surface area ratio as that of the entire mist. It should be noted that for fuel combustion applications, emphasizes is given to the use of this average diameter criteria, since it is least susceptible to a large spread in the droplet diameter distribution.

Fig. 4.6 Characterization of Atomizer for Droplet Size Measurement

Fig. 4.6 indicate the photograph of the atomizer characterization facility, which has droplet size analyzer, atomizer traversing system and water / air feed system all coupled to gather.

The mist was required to be separated from the electronic noise and the background. In order to filter out the electronic noise, a sample snap (keeping the lens of the camera covered) was captured. This image was then subtracted from the mist images in order to deduct the effect of the electronic components. To filter the background optical noise, an image, containing only the background (keeping the spray off), was taken and the pixel wise intensity distribution was estimated. Once the mist was turned on, the zone containing the mist got brighter than the background resulting in an increase in the corresponding pixel intensities in the image matrix. Thus, a pixel, in an image containing the spray, with an intensity value higher than the corresponding values in the image containing solely the background was considered to be the one representing the mist.

4.2 STANDARD CUP BURNER APPARATUS

Gaseous diffusion flame suppressing agents are used as total flooding agents in fire protection systems. Fundamentals to the use of gaseous diffusion flame suppressing agents is the notion that there exists a concentration of the agent which when present in air renders the inhabited air incapable of supporting diffusion flame combustion. This limiting concentration is known as critical concentration or minimum extinguishing concentration (MEC). This experimental measurement of critical concentration of gaseous agents was carried out in standard cup burner apparatus [133-137]. The Fig. 4.7 indicates photograph of standard cup burner apparatus used in the experiments.

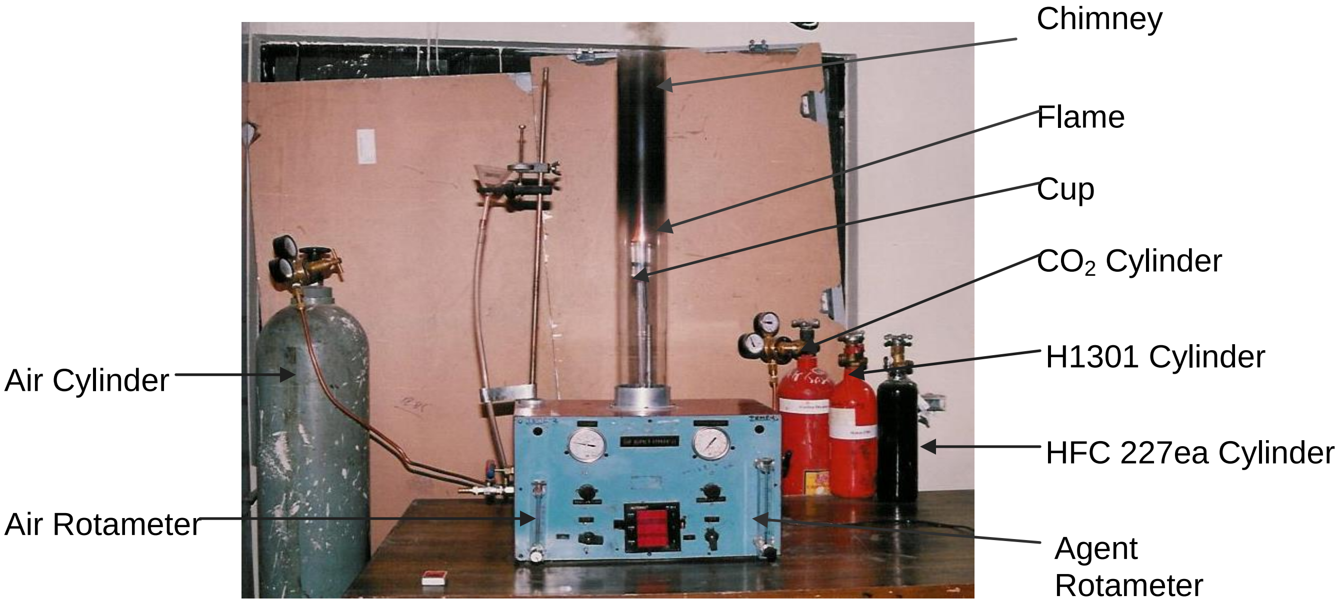
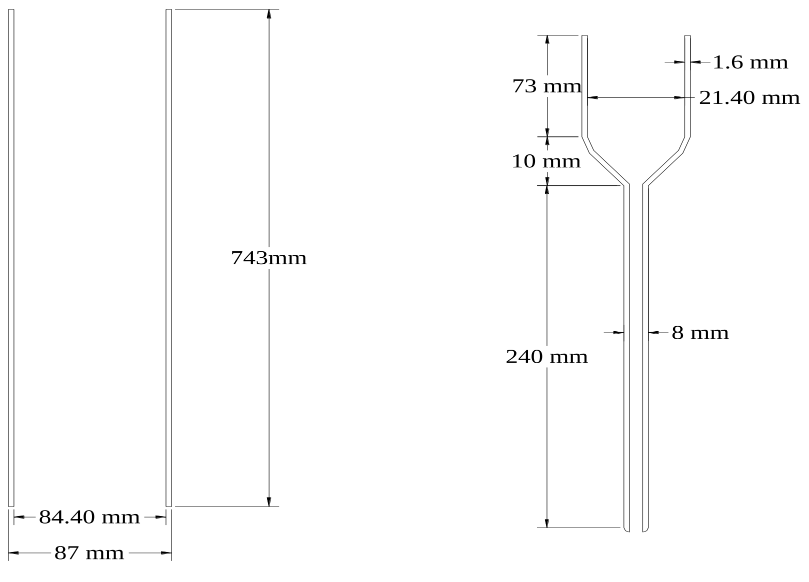


Fig. 4.7: Standard Cup Burner Apparatus

The flame is established above the cup of fuel surrounded by a cylindrical chimney. Air & agent are mixed in diffuser & flow up the chimney surrounding the flame. The minimum concentration of agent (in air) at which the flame is extinguished is the critical concentration / minimum extinguishing concentration (MEC). The chimney diameter, different mixing and measuring methods, agent / air mixture velocity past the flame, chimney height, cup diameter and height etc. are designed as per applicable international standard [87& 120]

4.2.1 Fuel Cup

Fuel cup is made of high temperature glass or quartz, having outside diameter of 30mm with wall thickness of 2mm. Cup is chamfered at 45^{o} at the top edge. The body of cup with overall length of 83 mm and taper to base diameter of 12mm, where it is fused to the fuel supply stem. The top of the cup is approximately 386 mm above the diffuser bed and 357 mm below the top of the chimney. The stem is connected to the fuel supply connection located in the diffuser bed. The fuel cup is indicated in Fig. 4.8 (b)



(a) (b)

Fig. 4.8 Chimney and fuel Cup of Standard Cup Burner Apparatus

4.2.2 Chimney

The chimney is made of high temperature glass or quartz tube having an outside diameter of 87mm & inside diameter of 85 mm & height of 743 mm. The chimney is seated on the diffuser assembly body, which is fitted with ports for entry of air, agent & fuel. The chimney is indicated in Fig. 4.8(a)

4.2.3 Diffuser

Diffuser assembly is made of aluminum & it supports the chimney about 100 mm above a bed having glass beads of 2 mm diameter and has entry port for fuel, air & agent. The depth of glass beads is approximately 45 mm & extends above the position of air & agent entry. The schematic of diffuser is indicated in Fig. 4.9

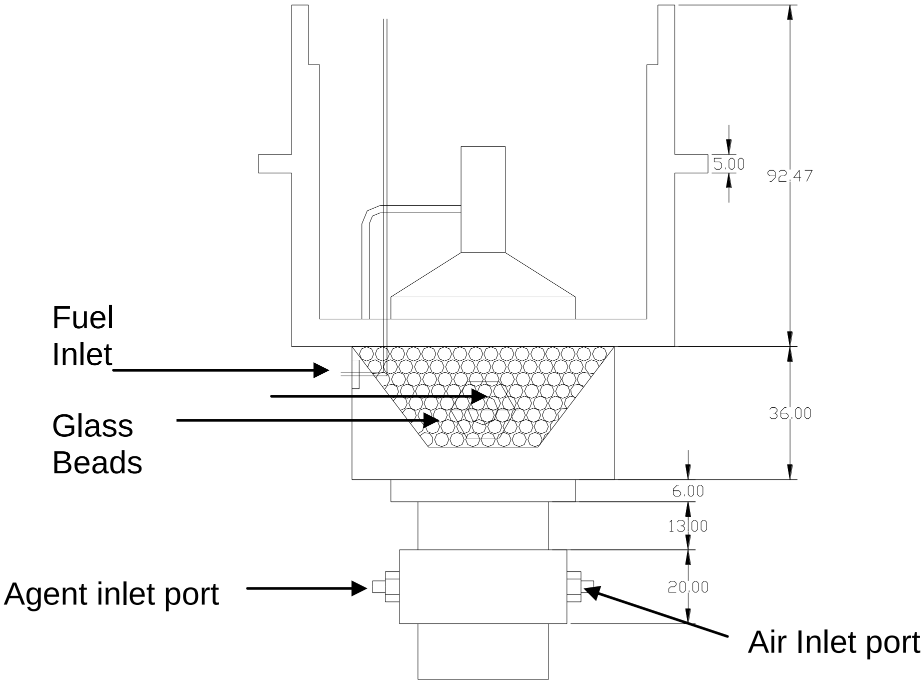


Fig. 4.9: Diffuser of Standard Cup Burner Apparatus

4.2.4 Fuel Reservoir

Liquid fuel is placed in a funnel with flexible tubing connecting fuel funnel with fuel inlet connection in diffuser. The fuel reservoir is supported on an adjustable stand adjacent to the cup burner assembly. The fuel reservoir has a means to precisely adjust & maintain liquid fuel level in the cup by moving fuel reservoir up and down.

4.2.5 Experimental Procedure

The experiments were conducted using standard cup burner apparatus to experimentally measure critical concentration (minimum extinguishing concentration (MEC) of various extinguishing agents like Halon 1301, HFC227ea and CO_2 for suppression of diffusion flame of various fuels like n-Heptane, Ethyl Alcohol. Fuel is filled in funnel and fuel level is adjusted in the cup in such a way that fuel is filled up to the lip of the cup by adjusting the position of fuel funnel and in no case fuel is allowed to be less than 2 mm from the lip of the cup. Once the fuel level is maintained, air flow rate (F_1) is supplied as air is required to sustain the combustion inside the chimney. This air is supplied from air cylinder which is pressurized at high pressure and fixed with pressure regulator for reducing pressure from 150 bar to 0-10 bar. The air than passes through air control valve (needle valve) to control the flow of air before entering into the air rotameter.

Flame is established using the flame torch and then chimney is placed at its position. A pre-burn of 60 seconds is given. Now, diffusion flame suppressing agent is added in small increments till the flame is suppressed. This agent flow rate (F_2) is noted down. Using measured flow rate values of the air and agent, critical concentration of the diffusion flame suppressing agent is calculated.

4.2.5.1 Air Flow Measurement

The air flow rate (F_1) is measured using air rotameter having flow range of 0-25 lpm and least count of 1 lpm with accuracy of ± 3% of full scale. The generalized equation for flow rate measurement through this rotameter is given as:

$$Q = C_c \ A_2 \ \sqrt{2g \frac{V_f}{A_f}\left(\frac{\rho_{fl}}{\rho_f} - 1\right)} \qquad (1)$$

For air this equation will be

$$Q_{air} = C_c \ A_2 \ \sqrt{2g \frac{V_f}{A_f}\left(\frac{\rho_{fl}}{\rho_{air}} - 1\right)} \qquad (2)$$

Where

Q : Flow rate in lpm
Q_{air} : Air flow rate in lpm
C_C : Coefficient of contraction,
A_2 : Area between float and tube ; m^2
V_f : Volume of float ; m^3
A_f : Effective area of float ; m^2
ρ_{fl} : Density of float ; kg/m^3
ρ_f : Density of fluid ; Kg/m^3

Air after passing through rotameter enters the diffuser where it is mixed with agent.

4.3.5.2 Agent flow measurement

The diffusion flame in standard cup burner apparatus is suppressed using three types of gaseous agents, these are Halon 1301, HFC227ea and CO_2 . These gaseous agents stored in the cylinders under pressure. The cylinders are fixed with pressure regulator for reducing pressure having two dial gauges for indicating cylinder pressure and agent delivery pressure. The agent than passes passes through agent control valve (needle valve) to control the flow of agent before entering into the agent rotameter.

The agent flow rate(F_2) is measured using two air rotameters having flow range of 0-2 lpm having least count of 0.02 lpm & 0-10 lpm having least count of 0.5 lpm with a accuracy of ±3% of full scale. The selection of rotameter for agent flow rate measurement is made with reference to their concentration required for suppression of diffusion flame e.g for Halon 1301 & HFC 227ea rotameter with range of 0-2 lpm is used.

For equation (1) for agent flow measurement becomes:

$$Q_{air} = C_c \; A_2 \; \sqrt{2g \frac{V_f}{A_f}\left(\frac{\rho_{fl}}{\rho_{agent}} - 1\right)} \qquad (3)$$

As all gaseous diffusion flame suppressing agents have different densities than that of air, therefore, agent flow rate is measured by using following equations:

$$Q_{agent} \;=\; \sqrt{\left(\frac{\rho_{fl}}{\rho_{agent}}\right)} \times Q_{air} \qquad (4)$$

4.2.5.3 Multiplication factor

The flow rate of agent is measured using rotameters calibrated for air. As all the gaseous agents have different densities than that of air, therefore multiplying factor is calculated for all the agents. Following is the multiplication factor calculated for three agents used for suppressing diffusion flame in standard cup burner apparatus.

i) Multiplying factor for H 1301:

At 27 °C

ρ_{Air} = 1.1774 kg/m^3

ρ_{Halon} = 6.131 kg/m^3

Q_{Halon} = (0.438) Q_{Air} (5)

ii) Multiplying factor for HFC 227ea:

At 27 °C

ρ_{Air} = 1.1774 kg/m^3

$\rho_{HFC\ 227ea}$ = 7.059 kg/m^3

$Q_{HFC\ 227ea}$ = (0.408) Q_{Air} (6)

iii) Multiplying factor for CO_2:

At 27 °C

ρ_{Air} = 1.1774 kg/m^3

ρ_{CO2} = 1.7973 kg/m^3

$Q_{CO2} = (0.81)\ Q_{Air}$ (7)

4.2.5.4 Critical concentration of gaseous agents

The critical concentration (MEC) of gaseous diffusion flame suppressing agents is calculated using two experimentally measured flow rates. Following equation is used to calculate critical concentration

$$CriticalConcentation = \frac{F_2}{F_1 + F_2} \times 100 \quad \% V/V \qquad (8)$$

Where F_1 is air flow rate (lpm)

F_2 is fire suppressing agent flow rate (lpm)

4.3 MODIFIED CUP BURNER APPARATUS

The critical concentration of water mist required for suppression of diffusion flame is measured in modified cup burner apparatus. The mist is produced using an atomizer placed under the flame cup and injected into the chimney for interaction with diffusion flame. Fig. 4.10 indicates the photograph of modified cup burner apparatus used for experiments.

Fig. 4.10 : Modified Cup Burner Apparatus

The fuel cup and chimney used in modified cup burner apparatus is of same dimensions as that used in standard cup burner apparatus.

The Fig. 4.11 indicates schematic of the atomizer used in experimental studies. The diffusion flame is created in the fuel cup (7) and chimney (8) is placed to allow mist interact with flame. The atomizer (6) used for generating mist is siphon fed externally mixed atomizer and water is siphoned from water bottle (9). The atomizing gas is measured through rotameter (1) and combustion gas through the rotameter (2) and controlled by control valves (4&5) The combustion and atomizing air is supplied through air cylinder (3).

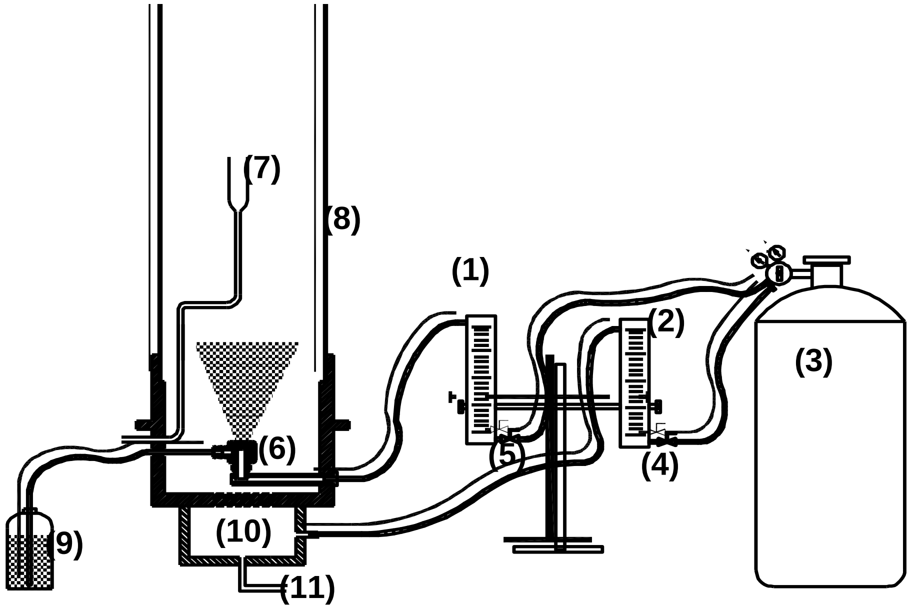


Fig. 4.11: Schematic of Modified Cup Burner Apparatus

The diffuser assembly is not the part of this apparatus and atomizer is fixed in place of diffuser assembly. Diffusion flame is created by feeding fuel in the cup and flame tube is placed for creating upward flow conditions around the flame to allow interaction of water- droplets with diffusion flame. The cup and flame tube are made of high temperature quartz glass.

4.3.1 Experimental Procedure

Fuel (n-heptane) is filled in funnel and fuel level is adjusted in the cup in such a way that fuel is filled up to the lip of the cup by adjusting the position of fuel funnel and in no case fuel is allowed to be less than 2 mm from the lip of the cup. Once the fuel level is maintained, air flow rate (F_1) is supplied as air is required to sustain the combustion inside the chimney. Flame is established using the flame torch and then chimney is placed at its position. A pre-burn of 60 seconds is given. Now, mist is injected in small increments till the flame is suppressed. This mist injection rate (F_2) is noted down. Using measured flow rate values of the air and mist , critical concentration of the mist is calculated.

4.3.2 Air flow measurement

Air is supplied from high pressure air cylinder fixed with pressure regulator having two dial gauges for indicating cylinder pressure and air delivery pressure. The air is made to pass through air control valve (needle valve) to control the flow of air before entering into the air rotameter. The air flow rate (F_1) is measured using air rotameter having flow range of 0-30 lpm and least count of 1 lpm with accuracy of ±3% of full scale.

4.3.3 Mist concentration measurement

The water mist was introduced into the flame tube in co-flow direction by feeding water mist from bottom. Loss of water droplets deposited on the inner side of flame tube surface is measured by taking weight of dry and wet flame tube to obtain the net droplet concentration in the air flow. Atomizer used for creating water mist is siphon-fed which takes the water from water bottle. The air used for atomization is also measured using air rotameter.

The atomizer generates water mist of droplet size of 40 µm. Water is supplied axially to the atomizer at its upstream at atmospheric pressure through siphon by creating a venture effect and made to pass through hypodermic needles of 4 mm diameter. Air is supplied through series of three holes symmetrically distributed around the atomizers periphery downstream of the liquid entry point. The interaction of the air and water at the needle tip result in the atomization of the water. As water is sucked because of the venture effect, there is acceleration of the liquid and, thus an increase in its kinetic energy, which results in the atomization of the water. Also the relative motion between the two phases produces shear forces at their interfaces that strip liquid droplets from the ligaments, resulting in further atomization of the water.

The atomizer is characterized for mist generation rate at different operating conditions (air flow rates). The mist generation rate of 0.45 gm/sec is achieved at atomizing air flow rate of 26 lpm. The mist generation rate of atomizer is increased to 0.5gm/sec at air flow rate of 28 lpm and 0.58 gm/sec at air flow rate of 30 lpm.

4.4 DIFFUSION FLAME SUPPRESSION IN LARGE ENCLOSED SPACE

The experiments for suppression of diffusion flames with water mist in large enclosed space having dimensions of 3.6x3.5x3.1m. the total volume of this enclosed space is 40 m^3. The schematic of this experimental set-up is indicated in Fig. 4.12.

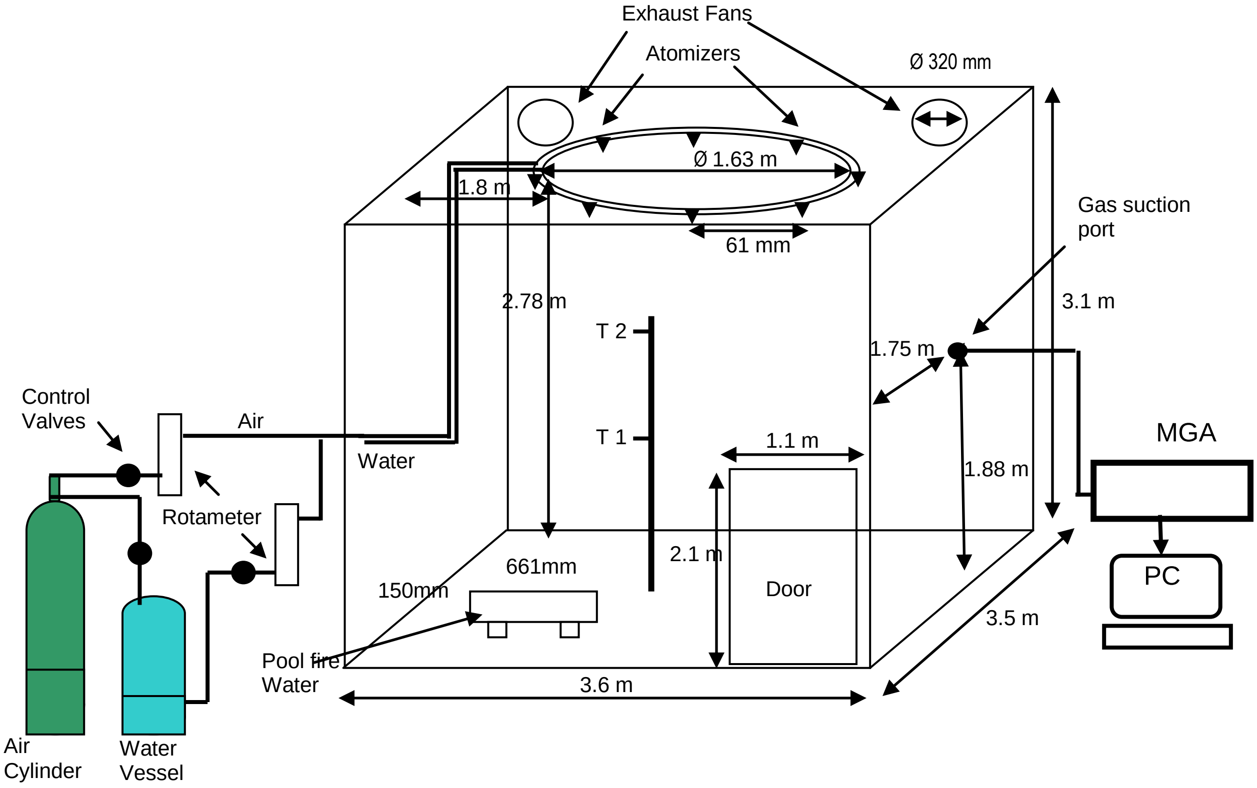


Fig. 4.12: Schematic of Fire- Mist Interaction Test Chamber

4.4.1 Water supply station

The two phase atomizers require water at different pressure and flow rate, which was supplied to the atomizers from water supply unit as indicated in Fig. 4.13. Water vessel of 50 lt capacity is used to supply water, this vessel will pressurized with air being supplied from 2x1 air cylinder manifold. Air cylinders have 65 lt water capacity. The air pressure will be regulated with the help of double stage high pressure regulator. The water flow is controlled with the help of needle valve. Water flow is measured using rotameters & pressure is measured using pressure gauges. All flow measuring and control devices are installed on display panel.

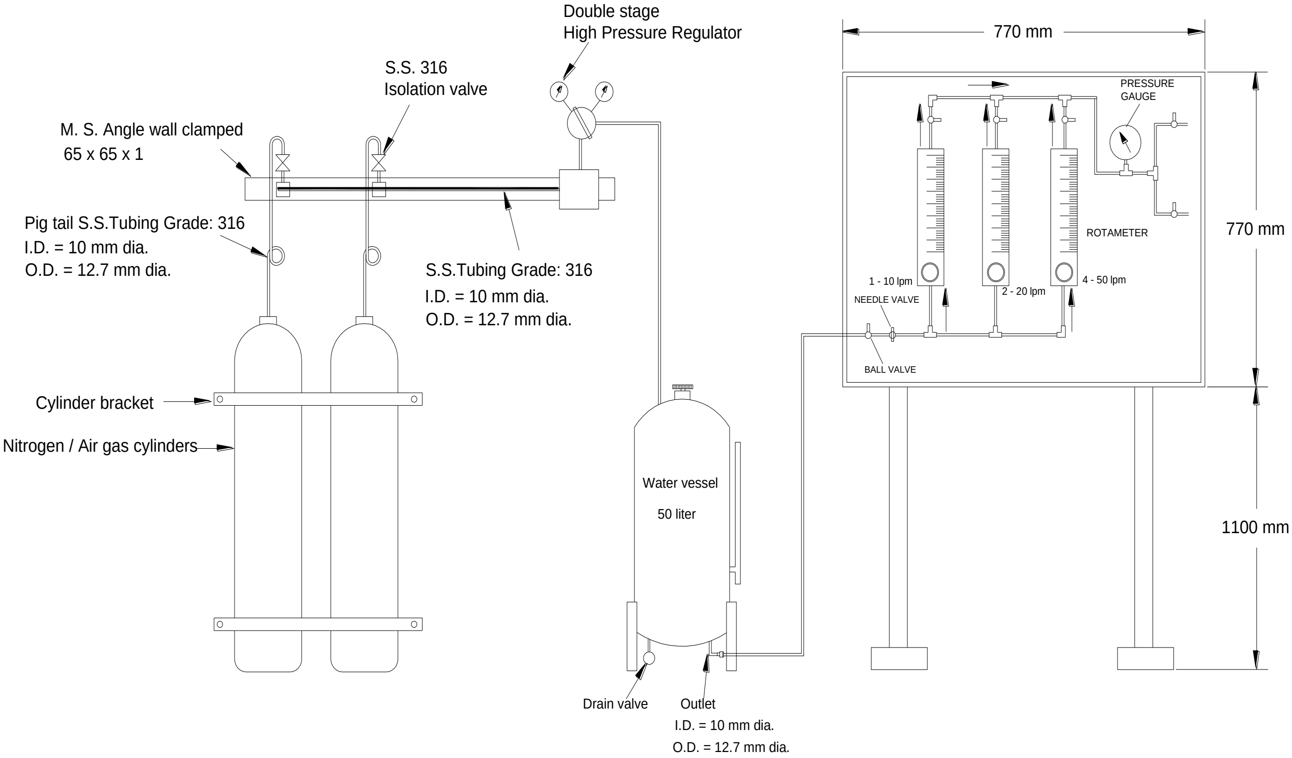


Fig. 4.13: Water Supply Unit

Water is pressurized with air in the pressure range of 2- 4 bar using pressure regulator. The air pressure in side the manifold is measured with pressure gauge having range of 0-200 bar and least count of 5 bar and regulated air pressure is measured with pressure gauge having range of 0-30 bar and least count of 1 bar. The water feed rate to the atomizers is measured using rotameters having range of 0-10 lpm and least count of 0.2 lpm. The water feed line to the atomizers was carried out using SS 304 pipe of 10 mm ID size.

4.4.2 Air supply station

Two phase atomizers require air as atomizing media and atomizers of different design require air at different flow rates. The air is supplied from air cylinders connected to the manifold of 4x1 cylinders having 65 lt water capacity as indicated in Fig. 4.14. This manifold has isolation valve for isolating the cylinder as per requirement and high pressure regulator to reduce the air pressure from 150 bar to 10-25 bar. The air pressure in side the manifold is measured with pressure gauge having range of 0-200 bar and least count of 5 bar and regulated air pressure is measured with pressure gauge having range of 0-30 bar and least count of 1 bar. The air feed rate is measured using rotameters having range of 0 – 5000 lpm and least count of 50 lpm. The air feed line to the atomizers was carried out using SS 304 pipe of 10 mm ID size. All measuring and control devices are installed on display panel.

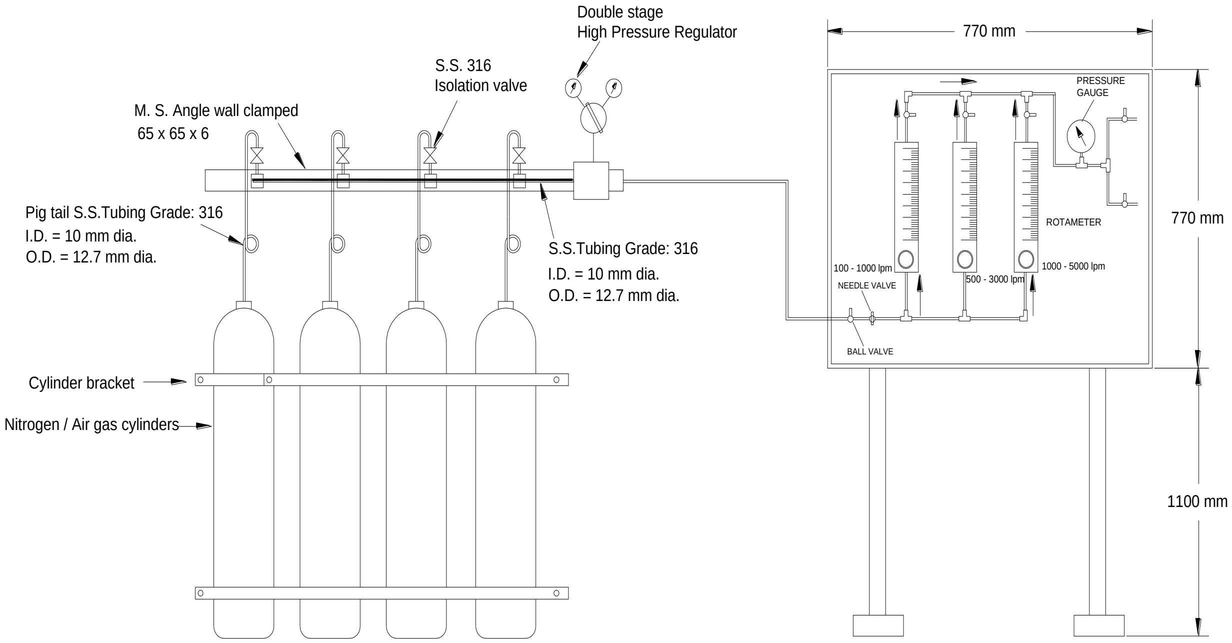


Fig. 4.14: Atomizing Gas Supply Unit

4.4.3 Experimental procedure

A pool fire is a type of turbulent diffusion flame, which burns above a pool of vaporizing fuel where the fuel vapor has negligible initial momentum. Fire development is generally characterized in terms of Heat Release Rate (HRR) versus time. There are basically two approaches available when determining the design fire for a given scenario. One is based on the knowledge of the amount and type of combustible materials in the compartment of the fire origin. The other is based on the knowledge of the occupancy where very little is known about the details of fire load. We have followed the first approach as we know the amount and type of fuel to be used for the pool fires. HRR for a fire depends mainly on type of fuel, pool diameter and is calculated using the following equations.

$$Q = m''\Delta H_{c,eff} (1 - e^{-k\beta D}) A_{pool} \qquad (1)$$

$$A_{pool} = \pi D^2/4 \qquad (2)$$

Experiments were performed with n-heptane pool fires to investigate the critical concentration of water mist for suppressing pool fire of different HRR. The fire was created in fire pans made of stainless steel having diameters of 460, 560 and 660 mm, which generated HRR of 300, 500 and 800kW respectively. The pans were filled with water up to ¾ of the total depth of the pans, which was equal to 130 mm. 750 ml of n-heptane was poured in the pan. The fire pan was placed on a 313 mm high stand, which was placed at a corner of the room at a distance of 150 mm from the adjacent walls. For all the fire tests, a pre burn time of 20 seconds was provided that ensured that the fire had reached the maximum heat release rate as described by Eq. (1).

The experiments were performed in a large scale fire test enclosure having dimensions of 3.5 m × 3.6 m × 3.1 m, shown schematically in Fig. 5.12, having a door of 1.1 m x 1.94 m and two exhaust fans of diameter 0.40 m and 0.30 m were installed at a height of 2.5 m from the floor for the removal of combustion / hot gases after the experiments. This enclosure was constructed using reinforced concrete with fire brick walls on inner side of the enclosure to restrict the heat transfer from the enclosure during fire tests. This test room was fitted with two toughened glass windows to view the experiments from outside.

Temperature in the enclosed compartment was measured using two K type thermocouples mounted on a stainless steel stand at 1.5 m and 2.5 m height from the floor. The stand was located at a distance of one meter from the pool fire. The locations of the thermocouples are indicated in Fig. 5.12. A Multi Gas Analyzer (MGA) model MRU Vario plus® was used for in-situ measurement of CO, CO_2 and O_2 in the test room. The sampling tube of multi gas analyzer was installed at 1.88 m from the floor level. A Fluke® model 2686 data acquisition system having 40 analog input and 8 digital input/output channels was used for the recording of temperature and gas concentrations.

Internally mixed, air-assisted, atomizers were used to generate water mist for the suppression of fire. These atomizers were selected in order to have a control over the atomization process by changing the water and compressed air feed conditions. Eight internally mixed atomizers, at equal distances of 61 mm were installed on the circular ring having diameter of 1.63 meter, which was located at the centre of the room at a height of 2.8 m from the floor. The circular ring was connected to air and water supply stations as indicated in Fig. 4.12.

A 50 lt. water vessel was used for the supply of water, which was pressurized by compressed air, stored in a cylinder at a pressure of 2 bar, to drive the water mist into the test chamber. The atomizing air was supplied from high pressure cylinders connected with the manifold. The air pressure was regulated using pressure regulators for supplying air at desired pressures. Three cylinders of 80 lt (water capacity) pressurized at 150 bars were used for the experiments. The flow and pressure control and measuring devices were installed on the pneumatic line. The maximum water pressure at the inlet of the atomizers was 2 bar. The maximum air pressure at the inlet of the atomizers was 6 bar.

The characteristics of the sprays produced by the atomizers at different operating conditions (water supply pressure and air supply pressure) were measured using a laser diffraction technique before installing the atomizers in the fire room. A 10 mm diameter laser beam from 670 nm laser diode was used to illuminate the spray. The laser light was passed through the centre of the spray. The equipment used for the characterization of the presented atomizer was “Spray- Tech” from Malvern® Instruments having an accuracy of ± 3 percent of the full scale and could measure the size distribution of sprays with obscurations up to 95 percent. The measurement rate of equipment was one measurement every 400 microseconds. The water mists generated by the atomizers were characterized under atmospheric conditions, in the absence of fire. The mist of different size were generated by varying compressed gas feed in to the atomizer while keeping same water feed to the atomizer, which was 1 lpm/ atomizer.

The fire suppression tests were conducted by injecting water mist of different droplet sizes (40 μm, 80 μm and 120 μm SMD at cold flow test conditions) from the atomizers into the fire room when the fires had attained their estimated heating value, i.e., after the pre burn period. The time of ignition of pool fire was recorded and after a pre-burn of 20 seconds, water mist, at a rate of 1 lpm/atomizer was injected into the chamber. The time of extinction of fire was recorded, the pre-burn time was subtracted and the resultant time was recorded as extinction time.

Chapter 5

THEORETICAL INVESTIGATIONS & COMPUTATIONAL TECHNIQUE OF ATOMISATION PROCESS

5.0 INTRODUCTION

Water has favorable physical properties for fire suppression. Its high heat capacity (4.2 J/g°K) and high latent heat of vaporization (2442 J/g) can absorb a significant quantity of heat from flames and fuels. Water also expands 1700 times when it evaporates to steam, which results in the dilution of the surrounding oxygen and fuel vapors. With the formation of fine droplets, the effectiveness of water in fire suppression is further increased due to the significant increase in the surface area of water that is available for heat absorption and evaporation. Such an increase in the surface area of water is shown in table 5.1 for a given volume of water (0.001 m^3).

Table 5.1 Variation of Surface Area of Water with Droplet Size

Droplet Size (mm)	6	1	0.1
Total Number of Droplets	8.8×10^3	1.9×10^6	1.9×10^9
Total Surface Area (m^2)	1	6	60

5.1 DIFFUSION FLAME SUPPRESSION MECHANISMS

Water mist in fire suppression, however, does not behave like a “true” gaseous agent. When water is injected into a compartment, not all the sprays that are formed are directly involved in fire suppression. They are partitioned into a number of fractions as follows [24]:

(1) Droplets that are blown away before reaching the fire;

(2) Droplets that penetrate the fire plume, or otherwise reach the burning surfaces under the fire plume, to inhibit pyrolysis by cooling, and the resultant steam that dilutes the available oxygen;

(3) Droplets that impact on the walls, floor and ceiling of the compartment and cool them, if they are hot, or otherwise run-off to waste;

(4) Droplets that vaporize to steam while traversing the compartment and contribute to the cooling of the fire plume, hot gases, compartment and other surfaces;

(5) Droplets that pre-wet adjacent combustibles to prevent fire spread.

Braidech and Rasbash in their early studies [93,94] identified two mechanisms by which water mist extinguishes fires: displacement of oxygen and heat extraction, resulting from the evaporation of water mist in the area surrounding the fire. Research conducted to date has not altered the accuracy of such extinguishing mechanisms. Recent studies, however, suggest that there are additional mechanisms in fire suppression using water mist. For example, Wighus [138, 139] suggested that a reduction of fuel evaporation is another extinguishing mechanism, together with cooling and diluting of the fire. Mawhinney et al [140, 141] further suggested that radiant heat attenuation, the kinetic effect of water mist on the flame, and fuel vapour/air dilution by entrained air are additional extinguishing mechanisms. They classified the extinguishing mechanisms of water mist in fire suppression as primary and secondary mechanisms [28], which can be summarized as follows:

5.1.2 Primary Mechanisms

There are two primary mechanism of diffusion flame suppression with water mist:

(1) Heat extraction

- Cooling of fire plume
- Wetting/ Cooling of the fuel surface

(2) Displacement

- Displacement of oxygen
- Dilution of fuel vapour

5.1.2.1 Heat Extraction (Cooling)

The cooling mechanisms of water mist for fire suppression can be divided broadly into cooling of the fire plume and wetting/cooling of the fuel surface. Flame cooling by water mist is attributed primarily to the conversion of water to steam that occurs when a high percentage of small water droplets enter a fire plume and rapidly evaporate. A fire will be extinguished when the adiabatic flame temperature is reduced to the lower temperature limit, resulting in the termination of the combustion reaction of the fuel-air mixture. For most hydrocarbons and organic vapours, this lower temperature limit is approximately 1600 K (1327°C) [142].

Rasbash has calculated the efficiency of water for flame cooling [143]. It was found that when all the water is vaporized to steam, the heat absorption required for fire extinction can be halved, in comparison to condensed steam or partly vaporized water. With the formation of fine droplets, the surface area of the water mass and the speed at which the spray extracts heat from the hot gas and flame are significantly increased. As indicated by Kanury [144] and Herterich [145], the rate of vaporization of a droplet depends on: 1) surrounding temperatures; 2) the surface area of the droplet; 3) the heat transfer coefficient; and 4) the relative velocity of the droplet in relation to the surrounding gas. For droplets of 100 μm < d < 1000 μm, the heat transfer coefficient, H, is directly related to the size of the droplet and can be expressed as [145]:

$$H = \frac{0.6}{d} k \,\mathrm{Pr}^{1.5} \,\mathrm{Re}^{0.5} \qquad (1)$$

where d is the diameter of the droplet, K is the thermal conductivity of air, Pr is the Prandtl number and Re is the Reynolds number.

Various attempts have been made to establish a design relationship between the fire size and the amount of water needed to cool the fire enough for extinguishment. Wighus [146] introduced the concept of the Spray Heat Absorption Ratio (SHAR) in a study of the extinguishment of propane fires by water mist. SHAR was defined as the ratio of the heat absorbed by the spray (Q_{water}) to the heat released by the fire (Q_{fire}):

$$SHAR = \frac{Q_{water}}{Q_{fire}} \qquad (2)$$

It was found that the value of SHAR or the heat absorption rate of water needed for fire extinguishment varied substantially with the fire scenarios encountered, because the efficiency of delivery of water mist into flame was almost unpredictable. For an unconfined propane flame, the value of SHAR was as low as 0.3 under optimum conditions while the value was in the range of 0.6 for more ‘realistic’ machinery space conditions due to small fires in shielded areas.

A fire will also be extinguished when the fuel is cooled below its fire point by removing heat from the fuel surface, or when the concentration of the vapour/air mixture above the surface of the fuel falls below the lean flammability limit due to the cooling. In order to cool the fuel surface, a spray must penetrate the flame zone to reach the fuel surface and then remove a certain amount of heat from the fuel surface at a higher rate than the flame can supply it. It is recognized that heat is mainly transferred from the flame to the fuel by convection and radiation, while fuel cooling by water mist is primarily due to the conversion of water to steam. Thus, the heat rate per unit area that must be removed by water for fire suppression is given by [143]:

$$S_h = (H_f - \lambda_f)\,\dot{m}_b + R_a - R_s \qquad (3)$$

where S_h is heat removed per unit area by water spray, H_f is convective heat transfer from flames per unit mass of fuel entering flames, λ_f is heat required to produce a unit mass of vapour, m_b is burning rate per unit area, $R._a$ is other forms of heat transfer to the fuel surface and R_s is heat lost from the surface not included in λ_f (e.g., radiant heat loss).

Fuel wetting/cooling by water mist also reduces the pyrolysis rate of the fuel and prevents re-ignition when the fuel is cooled down. For fuels whose low flash points are above normal ambient temperature, more water sprays are needed to cool the fuel surface, because less heat is required to produce fuel vapour. Also, more water sprays are needed to prevent re-ignition of a hot, deep-seated fire. The wood crib and slab tests carried out by Tamanini [147] showed that the risk of re-ignition is greater for higher water application rates, if spraying is stopped as soon as the flames go out. This is because higher water flow rates extinguish the fire faster, but the fuel remains hot and continues to pyrolize if the water is switched off immediately after extinction.

Fuel wetting/cooling by water mist may be the predominant extinguishment mechanism for fuels that do not produce combustible mixtures of vapour above the fuel surface [148]. The primary combustion reaction with this type of fuels, such as solid fuels, occurs within the carbon-rich zone that forms on the fuel surface. Hence, cooling of the diffusion flame above an established char zone of solid fuel may not be enough to achieve suppression [141]. Water mist must be applied to cool the fuel surface either before a deep char zone has developed, or water droplets must penetrate the char zone to reach the actual interface between the burned and unburned fuel.

5.1.2.2 Oxygen Displacement

Oxygen displacement can occur on either a compartmental or localized scale [148]. On a compartmental scale, the oxygen concentration in the compartment can be substantially reduced by the rapid evaporation and expansion of fine water droplets to steam, when water mist is injected into a hot compartment and absorbs heat from the fire, hot gases and surfaces. Calculation results showed that oxygen concentration in a room with a volume of 100 m^3 could decrease approximately 10%, when 5.5 liters of water is completely converted into steam [149].

The reduction of the oxygen concentration in a compartment by water mist is a function of the fire size, the length of pre-burn period, the volume of the compartment and the ventilation conditions in the compartment. As the fire size or the length of the pre-burn period of the fire increases, both the oxygen depletion due to the fire and the oxygen displacement due to the formation of more water vapour caused by high compartment temperatures are increased. This combined effect significantly reduces the oxygen concentration in the compartment and enhances the effectiveness of water mist for fire suppression.

On a localized scale, when the water sprays penetrate into the fire plume and are converted to vapour, the vaporizing water expands to 1700 times its liquid volume. The volumetric expansion of the vaporizing water disrupts the entrainment of air (oxygen) into the flame and dilutes the fuel vapour available for combustion of the fuel. As a result, when the fuel vapour is diluted below the lower flammable limit of the fuel-air mixture, or when the concentration of oxygen necessary to sustain combustion is reduced below a critical level, the fire will be extinguished.

Water vapour as an inert agent in fire suppression has been widely studied. Rosander and Giselsson [149] described the process of extinguishing a fire by the formation of steam as "indirect extinguishment." They recommend a 35% mixture of water in the surrounding gas to extinguish the fire by steam formation. From an analysis of computer modelling, Dlugogorski et al [150] indicated that, for effective suppression, the required concentrations of water vapour in the mixture of flammable gases vary with the surrounding temperatures and reach 36% and 44% for surrounding temperatures of 100°C and 300°C, respectively.

The impact of oxygen dilution by water mist on fire suppression is strongly dependent on the properties of the fuel [141]. This is because the minimum amount of free oxygen required to support combustion varies with the type of fuel. For most hydrocarbon fuels, the critical oxygen concentration for maintaining combustion is approximately 13% [142]. For solid fuels, the critical oxygen concentration required for combustion is even lower.

5.1.3 Secondary Mechanisms:

There are two secondary mechanism of diffusion flame suppression with water mist :

(1) Radiation attenuation

(2) Kinetic effects

5.1.3.1 Radiant Heat Attenuation

When water mist envelops or reaches the surface of the fuel, water can act as a thermal barrier to prevent further heating by radiation of the burning fuel surface as well as non-burning surfaces [150-153]. Also, water vapour in the air above the fuel surface acts as a gray body radiator that absorbs radiant energy, and re-radiates it to the fuel surface at a reduced intensity. Blocking radiant heat by water mist stops the fire from spreading to unignited fuel surfaces and reduces the vaporization or pyrolysis rate at the fuel surface.

Experimental tests conducted at the National Research Council of Canada [153] showed that the radiant flux to the walls of a test compartment was reduced by more than 70% by the activation of the water mist system. The calculation conducted by Log [153] also showed that given a spray load of 100 g/m^3 and a 1 m path length, a spray on the borderline between Class 1 and Class 2 ($D_{v0.1}$= 100 µm and $D_{v0.9}$ =200 µm) is capable of blocking about 60% of the radiant heat from a black body at the temperature of 800 ^{o}C.

It has been shown that the attenuation of radiation depends very much on drop diameter and mass density of the droplets. A given volume of water will provide a more efficient barrier against radiation if it is made up of very small droplets in a dense spray, than a dilute spray with larger droplets. The calculation carried out by Ravigururajan and Beltran [151] showed that, to achieve the same radiation attenuation at the object temperature of 650 K, the mass density of the 100 micron droplets had to be 10 times larger than that of the 10 micron droplets. The wavelength of the radiation, however, is also important in determining the radiation attenuation of water mist. The spray will absorb more radiation if the droplet diameters are close to the wavelength of the radiation. For non-burning fuel, water droplets wet the fuel surface, preventing further heating by radiation and reducing the risk of ignition.

5.1.3.2 Kinetic Effects of Water Mist on Flames

Experimental tests carried out by Mawhinney [154], and Jones and Thomas [155] showed that when "under-designed" water mist systems failed to extinguish a liquid fuel pool fire, the heat release rate of the fire was higher than that of a fire without the suppression by water mist. Mawhinney [156] indicated that the increase in the heat release rate of the fire may result from kinetic effects of water mist on flames.

A momentary increase in the liquid pool fire size was also observed at the beginning of the water mist discharge in the case of successful fire extinguishment [157, 158]. This increase in fire size, however, is attributed to the enlarged flame surface caused by the impingement of water sprays, as water mist impinged the pool flame and increased the mixing area between the oxidizer and the fuel.

Suh and Atreya [159] conducted both experimental and theoretical studies on the effect of water vapour on the combustion of the fuel-air mixture. Their studies showed that, although the fire extinguishment by water is mainly due to the physical effects, the addition of water vapour to the fuel-air mixture could result in an increase in the flame temperature, CO_2 production rate and O_2 depletion rate as well as a decrease in CO and soot production rate. These effects are due to the water vapour enhancing chemical reactions inside the flames. As the water vapour concentration is increased in the flame, the OH radical concentration increases, resulting in an increase in flame temperature and CO_2 production rate. After the addition of approximately 30% of the water vapour in the fuel-air mixture, however, the chemical enhancement of the flame by water vapour was not observed and the flame temperature began to decrease.

5.2 FACTORS THAT AFFECT WATER MIST PERFORMANCE

It has been recognized that although all the extinguishing mechanisms of water mist are involved to some degree in fire extinguishment, only one or two mechanisms play a predominant role [157]. Which suppression mechanism is dominant, depends on the characteristics of the water mist, fire scenarios, compartment geometry and ventilation conditions. Many other factors, such as the enclosure effect, dynamic mixing created by water mist discharge, types of water mist systems applied (total or local application) and the use of additives and discharge modes, have important impacts on the effectiveness of water mist in fire suppression [148, 160, 161].

5.2.1 Water Mist Characteristics

The effectiveness of a water mist system in suppressing a fire is directly related to the mist characteristics produced by the atomizers. Rasbash [143], in his early study, gave a detailed list of the important parameters of water mist for fire suppression. These are:

(1) Mean flow rate per unit area in the fire region;
(2) Distribution of flow rate in and about the fire area;
(3) Direction of application;
(4) Droplet size and distribution;
(5) Entrained air velocity; and
(6) Droplet velocity relative to entrained air, flame velocity, and fuel types.

Although these important mist parameters can be used to describe the characteristics of water mist in fire suppression, they can be further broadly classified as three main parameters: droplet size distribution, flux density and spray momentum [156]. These three main parameters of water mist not only directly determine the effectiveness of the water mist for fire suppression but also potentially determine the atomizer spacing as well as the ceiling height limitation for a given installation.

5.2.2 Droplet Size Distribution

Droplet size distribution refers to the range of droplet sizes contained in representative samples of a spray or mist cloud measured at specified locations. NFPA 750 [162] has divided the droplets produced by a water mist system into three classes to distinguish between "coarser" and "finer" droplet sizes within the 1000 micron window. The classifications are: Class 1 mist has 90% of the volume of the spray ($D_{v0.9}$) within drop sizes of 200 microns or less; Class 2 mist has a $D_{v0.9}$ of 400 microns or less; and Class 3 mist has a $D_{v0.9}$ value larger than 400 microns.

In theory, small droplets are more efficient in fire suppression than large droplets, because of their larger total surface area available for evaporation and heat extraction. They are more effective in radiation attenuation [151]. Also, small droplets have longer residence times, allowing them to be carried by air currents to remote or obstructed parts of an enclosure. They can exhibit more gaseous-like behaviour and superior mixing characteristics. However, it is very difficult for small droplets to penetrate into the fire plume and to reach the fuel surface due to the drag and the hydrodynamic effect of the fire plume. Fine droplets with low momentum are easily carried away from the fire by air currents. In addition, more energy is required to produce fine droplets and transfer them to the fire.

Large droplets can penetrate the fire plume easily to provide direct impingement, and to wet and cool the combustibles. However, large droplets have smaller total surface areas available for heat extraction and evaporation. The capability of water mist in suppressing obstructed/shielded fires is reduced as the size of the droplets is increased. As well, large droplets with high velocities can cause liquid fuels to be splashed, resulting in an increase in fire size.

A wide range of experimental tests under different fire conditions [163,164] was carried out to identify the optimum droplet size for fire suppression. Andrews [164] summarized the optimum droplet sizes suggested by various authors, It is observed that the optimum size of droplets for fire suppression is strongly dependent on many factors, such as the properties of the combustibles, the degree of obstruction in the compartment, and the size of the fire. The droplet size distribution that is most effective in extinguishing one fire scenario will not necessarily be the best for other scenarios. There is no one-size distribution to fit all fire scenarios. Actually, the performance of water mist with a well-mixed distribution of fine and coarse droplets is better than that with a uniform droplet size [154,156]. Furthermore, any changes in fire size, spray velocity (momentum) and enclosure effects will change the optimum droplet size for fire suppression.

5.2.3 Flux Density

Spray flux density refers to the amount of water mist in a unit volume (Lpm/m^3) or applied to a unit area (Lpm/m^2) [156]. On a compartmental scale, the increase in the flux density will reduce the compartment temperature but will have little effect on the oxygen concentrations in the compartment [160]. On a localized scale, however, the fire is extinguished only when water mist achieve a minimum flux density. Without sufficient flux density of water mists to remove a certain amount of heat from a fire or to cool the fuel below its fire point, the fire can sustain itself by maintaining high flame temperature and high fuel temperature.

Since water mist behave like a gaseous agent, therefore it is possible to establish the "critical concentration" of water droplets required to extinguish a fire (i.e., the minimum total mass of water in droplets per unit volume or per unit area for fire suppression) [157, 112, 165]. However, the amount of mist reaching the fire is determined by many factors. These include the mist momentum and angle, shielding of the fuel, fire size, ventilation conditions and compartment geometry.

In addition, current mist technology and corresponding atomizer allocation in the compartment cannot provide a uniform flux density of the mist. The flux density distribution of water mist within a single atomizer mist cone is non-homogeneous. Some types of atomizers for the production of water mist concentrate a high percentage of the water mist into the centre of the cone area while other types of atomizers may have less water mist concentration at the centre area [154, 160]. When spray cones from a group of atomizers overlap, the flux densities at any point are also different from those observed with a single atomizer due to the dynamics of mist interaction.

Andrews [165] has compared the minimum flow rates required for extinguishing solid fuel fires suggested by 19 authors. It was found that these minimum flow rates varied widely with application conditions and no “critical concentration” of water mists could fit all applications.

5.2.3 Spray Momentum

Spray momentum refers to the mist mass, mist velocity and its direction relative to the fire plume. The spray momentum determines not only whether the water droplets can penetrate into the flame or reach the fuel surface, it also determines the entrainment rate of surrounding air into the fire plume. The turbulence produced by the spray momentum mixes fine water droplets and water vapour into the combustion zone, which dilutes the oxygen and fuel vapour and increases the extinguishing efficiency of water mist in fire suppression. The spray mass defined in the momentum of the spray, therefore, not only includes the mass of liquid-phase water but also includes the mass of vapour-phase water and air entrained by water mist [148]. The momentum of the spray, M_w, can be expressed as follow:

$$M_w = (m_{wl} + m_{wv} + m_{wa}) \times V_w \qquad (4)$$

Where m_{wl}, m_{wv}, and m_{wa} are mass of liquid-phase water, vapour-phase water and air entrained by mist, respectively, and V_w is associated to the velocity vector of water mist.

Water spray momentum is determined by many factors. These include droplet size and velocity, discharge pressure and cone angle, the spacing of atomizers, ventilation conditions and the compartment geometry [148]. In addition, the spray momentum will gradually decrease, as fine water droplets travel through hot gas and the droplet velocity and size are reduced due to gravitational and drag forces on the droplets with the evaporation [167]. The distance (X_o) from the atomizer which water droplets must travel before falling in the air, is determined by spray momentum and discharge cone angle [167].

When water droplets fall in the air due to gravitational force, the maximum falling distance of the droplets is mainly controlled by droplet size and surrounding temperature, before they disappear into the hot gas due to the evaporation. Such maximum falling distance (X_{fall}), without considering the upward velocity produced by the fire, is given by Mawhinney et.al [184]:

$$X_{fall} = 2000 \frac{D_o L \rho}{2 K_g \Delta T C_2} \tag{5}$$

where D_o is the droplet diameter, L is the Latent heat of vaporization, ρ is the surrounding density, ΔT is the temperature difference between the droplet and surroundings and C_2 is the coefficient.

Table 5.2 Typical Falling Distance of Droplets with Droplet Sizes at Different [184].

D_o (Droplet Diameter, μm)						
T_g (^{o}C)	1	10	50	100	500	1000
400	1.5 pm	15 nm	9.1 μm	146 μm	2.5 m	9.9 m
600	0.88 pm	9 nm	5.5 μm	87 μm	1.5 m	6.0 m
800	0.63 pm	6 nm	3.9 μm	63 μm	1.1 m	4.3 m
1000	0.49 pm	5 nm	3.0 μm	49 μm	0.8 m	3.3 m

The falling distances are significantly reduced with the droplet size and with the increase in the surrounding temperature. Hence, with a high ceiling, the momentum of fine water droplets will become very small before they reach the fire. Such fine water mist with low momentum will not penetrate the strong upward fire plume to reach the region of the fuel surface, resulting in failure to suppress the fire.

To avoid having the mist (and the water vapour) carried away by the fire plume, the momentum of the mist must be at least equal in magnitude, and opposite in direction, to the momentum of the fire plume [148]. This relationship is given by:

$$M_{wy} \geq M_{fy} \qquad (6)$$

where M_{wy} and M_{fy} are the 'y' component of water mist and fire plume momentums, respectively.

The fire plume momentum, M_f, can be expressed as follow [148]:

$$M_f = (m_{fp} + m_{fg} + m_{fa}) \times V_f \qquad (7)$$

where m_{fp}, m_{fg}, and m_{fa} are mass of combustion products, fire gases and air entrained by the fire plume, respectively, and V_f is associated to the velocity vector of the fire plume.

Spray momentum is also particularly important for zoned water mist fire suppression systems and for fires with a high degree of obstruction. For such fire challenges, water mist must be directly discharged onto the fire and extinguish it by flame and fuel cooling. Recent experimental tests conducted by Kim et al [168], for the protection of electrical equipment by water mist, showed that effective fire suppression was achieved only by exercising rigorous control over spray direction by laying out atomizers to suit the physical arrangement of the obstructions or structural elements.

5.2.4 Enclosure Effects

When a fire occurs in an enclosed compartment, the room is heated and the oxygen concentration in the compartment is gradually reduced. In addition, the hot gases from the fire tend to concentrate near the ceiling. With the discharge of water mist downward from ceiling level, a maximum amount of water is converted to vapour and displaces oxygen and fuel vapour around the fire, as fine water droplets quickly absorb heat from their hot surroundings [167]. The capability of the compartment to capture heat and confine combustion products and water vapour has an important impact on the extinguishing performance of water mist, which is described as “enclosure effects” in fire suppression [148, 168]. With enclosure effects, it is possible to extinguish even shielded fires with low-momentum mist in heavily obstructed compartments. The flux density required for extinguishment can be as much as 10 times lower than that required for unconfined and well-ventilated fires [169].

The degree of “enclosure effects” in fire suppression is mainly dependent on the fire size in relation to the compartment size. ‘Large’ and ‘small’ fires are defined loosely in terms of whether the fire will affect the average temperature and oxygen concentrations in the compartment within the activation time of the water mist system [141]. A ‘large’ fire reduces the ambient oxygen concentration to the point that the combustion efficiency of the fire is reduced, prior to introducing water mist. A ‘large’ fire also releases more heat in the compartment to evaporate the fine water droplets, and further reduces the oxygen concentration in the compartment. With the enclosure effect, the main extinguishing mechanism of water mist for ‘large’ fires is oxygen displacement. Test results have shown that, in a compartment with large fires, small fires in a cabinet with a low ventilation rate were also extinguished by water mist due to the depletion of oxygen in the compartment by fires and steam. The extinguishing times were significantly reduced with the increase in the fire size [157,158].

For a ‘large’ fire challenge, the use of a Total Compartment Application (TCA) Water Mist System can quickly extinguish fires with low flux densities. This is because the use of a TCA water mist system maximizes the benefits of oxygen depletion and fuel vapour dilution for fire suppression by combining vitiated combustion products with a large amount of water vapour.

When the fine droplets are discharged into a very hot enclosure due to the existence of large fires, however, the rapid cooling by water mist will result in an overall negative pressure inside the compartment, because the hot air or gases contract faster than the steam can expand [152, 172]. The very high negative pressure produced could cause some damages to the compartment, such as the implosion of double-glazed windows, and lead to fresh air being drawn into the room [139, 157]. The cooling effect of water mist on the room pressure must be carefully assessed when designing a system for a “large” fire challenge.

With ‘small’ fires in the compartment, however, less heat and combustion products are released. The reduction in oxygen concentration and the increase in gas temperature in the compartment are small prior to the activation of the water mist system [157]. The “enclosure effect” no longer has important effect on the extinguishing performance of water mist, because less heat, water vapour and vitiated gases are available for confinement. The extinguishment of a ‘small’ fire by water mist will depend almost entirely on direct fire plume or fuel cooling. Water mist must be discharged directly on the fire. For ‘small’ fire challenges, the use of a Local Application (LA) water mist system might extinguish the fire more efficiently.

5.2.5 Dynamic Mixing

During water mist discharge, strong dynamic mixing is produced in the compartment, as the discharge of water mist entrains surrounding gases and pushes the combustion products and water vapour in the hot layer near the ceiling downward to mix with the gases near the floor of the compartment [157]. The dynamic mixing created by water mist discharge reduces oxygen concentration in the lower portion of the compartment and increases the convective mixing of mist, water vapour and combustion gases near the fire, resulting in the enhancement of the mist’s extinguishing capability. The gas concentrations (O_2, CO_2, CO, etc.) and temperatures throughout the compartment tend to be uniform after water mist discharge.

Test results showed that a water mist system in which the atomizers were directly below the compartment’s overhead had a better extinguishing performance than a system whose atomizers were 2 m below the overhead or whose atomizers were vertically installed on the side wall [170]. This is because the water mist system whose atomizers were near the ceiling could effectively produce more water vapour in the hot layer and redirect the vitiated gases and water vapour near the ceiling back to the fires by dynamic mixing. Test results also showed that a water mist system that could produce strong dynamic mixing in the compartment performed better against fires under ventilation conditions than a system that could not produce strong dynamic mixing, leading to short extinguishing time and less water required for fire suppression [171]. Another example is a water mist system developed by Marioff for the protection of a gas turbine enclosure where only two atomizers are installed in the compartment, one located near the ceiling and the other located near the floor [172]. It is claimed that such a configuration can increase the dynamic mixing in the compartment and enhance the extinguishing capability of water mist.

Recent research showed that the cycling discharge, i.e., the on/off action of water spray discharge, could substantially improve the efficacy of water mist in fire suppression [157, 173]. In comparison with the continuous application of mist, the use of the cycling discharge mode achieved rapid extinguishment and used less water. In some cases, the water requirement was one-third and the time to extinguish the fire was one-half that of the continuous discharge. The use of cycling discharge also improved the water mist’s capability against fires under ventilation conditions [170]. One important factor for the improvement of the mist’s extinguishing capability was that using the cycling discharge created a strong recurrent dynamic mixing in the compartment [173], increasing the convective mixing of mist, water vapour and combustion gases near the fire. The degree of dynamic mixing in the compartment created by water mist discharge is determined by spray characteristics (e.g., spray momentum, velocity), the atomizer characteristics (pressure, cone angle), the spacing of atomizers, the atomizer configuration in the compartment, the ventilation conditions and the compartment’s volume. The ability to influence convective mixing in a compartment is a design parameter that can be deliberately worked into the design of a water mist system [148]. However, it is not clear yet how to design a water mist system that achieves the optimum dynamic mixing in the compartment. This may be achieved by the application of a computational fluid dynamics (CFD) field model.

5.2.6 Water Mist with Additives

Using additives in the water mist system or combining water mist with inert gases and gaseous agents may improve the efficacy of water mist in fire suppression through chemical or physical means. It may also affect the droplet vaporization and generation processes by reducing surface tension or acting as a wetting agent.

Recent test results showed that water mist made with "sea water" (2.5% by weight sodium chloride solution) and the addition of a low percentage of a film-forming agent (e.g., 0.3% AFFF) greatly improved the effectiveness of water mist for suppressing hydrocarbon pool fires [174].

With the proper additives in water, not only the problem of freezing water could be avoided but also the fire suppression effectiveness of water mist could be improved [175 -177]. This increases the potential application of water mist for the protection of aircraft engine nacelles and combat vehicles.

In addition, water mist systems can be combined with other gas agents for fire extinguishment. Test results showed that the firefighting capabilities of a water mist system could be increased by substituting nitrogen or other inert gases for air as the second fluid [156, 21].

When water mist was used in conjunction with a gaseous agent, such as HFC227ea and Halon 1301 [178], the use of water mist, whether initiated at the same time, prior to or later than the discharge of gaseous agents, could enhance the performance of the gaseous agents in preventing re-ignition of the combustibles. The combination of a gaseous agent with water mist also significantly reduced the level of acid decomposition products generated in a fire. The initiation of the water mist system one minute prior to agent discharge limited HF generation to a peak value of 200 ppm, compared to values over 4000 ppm for tests without the discharge of water mist. As well, the overhead temperature was reduced from over 250 ^{o}C to less than 60 ^{o}C in less than 5 seconds from water mist discharge initiation. For comparison, the overhead temperature over the same interval dropped only 50 ^{o}C with agent discharge alone.

The use of additives in water mist and the addition of chemicals or a combination of inert gases/liquids with water mist, however, increase the operating cost and equipment corrosivity as well as the level of toxicity, in comparison to plain water [156]. In some cases, if most of the droplets are deflected away from the fire, the chemical suppression effectiveness of the additives would be minimized. Furthermore, the reduction in water evaporation rate by additives would impose an additional penalty, because, for a given time, less water vapour would be generated and entrained into the adjacent fire for suppression [178]. These factors must be considered in evaluating water mist systems with additives or combinations of inert gases/liquids with water mist.

5.3 METHODS OF GENERATING WATER MIST

The transformation or break up of bulk liquid fuel into a mist is of great importance in various industrial processes. The mist, comprising of a multitude of droplets, provides a much larger surface area compared to the bulk liquid, thus greatly enhancing the liquid evaporation rate. Numerous spraying devices, which operate on different principles and are broadly designated as atomizers or injectors, have been developed over the years. Atomization is often accomplished by discharging the liquid at a high velocity into a relatively slow-moving stream of air or gas or by destabilizing the liquid column using mechanical or electrostatic devices.

In general, water mist generating systems can be divided into three basic categories based on the atomizing mechanisms used to produce the fine droplets: impingement atomizers; pressure jet atomizers; and twin fluid atomizers [156]. Any other type of atomizer is a combination of these three basic types.

These three types of atomizers work under different operating pressures and can produce different spray characteristics. NFPA 750 [92] defines three pressure regions for water mist generating technologies: low, intermediate and high pressure systems. Low pressure systems operate at pressures of 12.0 bar (175 psi) or less, intermediate pressure systems operate at pressures greater than 12.0 bar (175 psi) and less than 34.0 bar (500 psi), and high pressure systems operate at pressures greater that 34.0 bar (500 psi).

The choice of the water mist generating method could influence factors such as mist characteristics, cost-effectiveness and reliability of the system. The method of generating water mist also affects the suppression capability of the system but it is not the only factor [156]. Matching the mist characteristics of drop size distribution, flux density and spray momentum to the fire hazard plays a more important role in fire suppression.

5.3.1 Impingement Atomizers

Impingement atomizers, operated with a single fluid, consist of a large diameter orifice and a deflector. They include standard sprinklers and atomizers used in traditional water spray and deluge systems. Small droplets can be produced as a high velocity jet of water from the large diameter orifice strikes a deflector and breaks up. The shape of the deflector and the jet velocity determine the size of drops and their distribution, the cone angle, flux density and spray momentum. Operating pressures for impingement atomizers range from low to intermediate pressures. [156].

The design of this type of atomizers is relatively simple and its manufacturing cost is less than that for atomizers that require precise machining. Impinging jet atomizers, however, have limited axial spray penetration momentum. As the jet strikes the deflector, the velocity of the spray is greatly reduced and randomized and may not be increased by increasing the atomizer pressure. The deflector supports also cause irregular flux distribution because of shielding.

Impingement atomizers have been widely used to control Class A (combustible solids) fires as well as fire scenarios where large droplets are required to extinguish fires [156]. They have demonstrated good extinguishing performance for use in ship cabins and crew areas and in residential buildings [18, 68]. The impingement atomizers has also been effective in extinguishing a wide variety of hydrocarbon pool and spray fires that might occur in a machinery space [18, 69], where enclosure effects make spray momentum less critical.

5.3.2 Pressure Atomizers

As their name suggests, pressure atomizers rely on the conversion of pressure into kinetic energy to achieve a high relative velocity between the liquid and the surrounding gas. Most of the atomizers in general use are of this type. They include plain-orifice and simplex atomizers, as well as variable-geometry, duplex and dual-orifice injectors. Disintegration of liquid jet, emerging from pressure atomizers, is promoted by an increase in flow velocity, which enhances both the level of turbulence in the liquid jet and the aerodynamic drag forces exerted by the surrounding medium. In simplex or pressure-swirl atomizers, a swirling motion is imparted to the liquid so that, under the action of centrifugal force, it spreads out in the form of a conical sheet as soon as it leaves the orifice. This sheet then breaks up into liquid droplets under the influence of the external and internal forces. Since the flow rates and droplet sizes obtained from pressure atomizers depend on the pressure drop across the injector, the quality of atomization is very poor at low flow rates. The lower limit of this flow rate depends on the atomizer design. At high flow rates the operating pressures are very high, e.g., in the range of 1500 psi. Thus, poor atomization at low flow rates and high operating pressures at high flow rates bound the range of operation of pressure atomizers. Furthermore, since the fuel flow rates and droplet sizes are directly related to each other through the operating pressure, these two parameters cannot be controlled independent of each other.

Pressure jet atomizers, operated with a single fluid, consist of small diameter orifices or swirl chambers [156, 180]. When a high velocity jet of water leaves the orifice, the sheet or thin jet of water becomes unstable and disintegrates into fine droplets.

The orifice diameter for this type of atomizer ranges from 0.2 mm to 3 mm [156]. The atomizer can have multi-atomizer heads that operate at relatively low pressures. The mass flow rates vary from 1 Lpm for a single atomizer to 45 Lpm for a multi-orifice assembly. The operating pressures range from low pressure (5.1 bar) to high pressure (272 bar) [156, 181]. The spray cone angle produced by pressure jet atomizers is between 20° and 150°.

Pressure jet atomizers can produce fine droplets, wide spray angles and good spray projection. Using a multi-orifice assembly can further increase cone angle and flux density of pressure jet atomizers. The size and distribution of droplets produced by a pressure jet atomizer are mainly determined by the discharge pressure used. Droplet sizes become finer as pressure increases. The droplet momentum and flux density of pressure jet atomizers are also increased by increasing the operating pressure [148]. However, there is an upper limit, at which point any further increase in pressure has little effect on the drop size distribution but may only increase mass flow rate or momentum.

Pressure jet atomizers have been widely used to suppress a variety of fires, including Class B fires in machinery spaces and in gas turbine enclosures [181, 182] and Class A fires in ship cabins and crew areas [183]. Their performance for the protection of electronic equipment has also been evaluated [183]. It has been shown that pressure jet atomizers with high discharge pressures are effective in suppressing fires under various fire scenarios and can reduce the effect of ventilation on fire suppression [157]. However, the advantage of working with high pressures must be weighed against the cost of operating a high pressure system, which may require special pipes and pumps.

5.3.3 Internally Mixed Air-Assisted Atomizers

In internally mixed, air-assisted, atomizers the atomizing air interacts with the liquid inside the injector and assists in the atomization process. It is believed that two effects induce atomization in an internally mixed injector. First, as both the liquid and the atomizing air share the same flow passage inside the injector, the liquid is restricted to a smaller available flow area. The reduction in flow area accelerates the liquid and, thus, increases its kinetic energy. This increase in the kinetic energy of liquid induces fine atomization. Second, the relative motion between gaseous and liquid phases produces a shear force at their interface. This force strips liquid droplets from the liquid filaments and thus, induces atomization. Since most of the atomizing energy is supplied by the atomizing air, this injector requires a very small pressure drop of liquid across the injector to produce a fine spray, in contrast to the large pressure drop required in pressure atomizers. Furthermore, internally mixed atomizers need a significantly lower flow rate of atomizing air compared to airblast atomizers. An atomizing air flow rate of only 10 – 20 percent of the liquid flow rate (by mass) can produce very fine atomization in internally mixed atomizers. The disadvantage of this injector is that it requires additional compression of the atomizing air. Conceptually, internally mixed atomizers are similar to effervescent atomizers. However, instead of forming a bubbly air-liquid mixture inside the injector, a low flow rate of pressurized air is impinged upon the liquid, a short distance upstream of the injector's exit in an internally mixed injector. Since the interactions between air and liquid occur over a very short distance, eliminating the possibilities of bubble formation, the resulting atomization process is expected to be less sensitive to acceleration.

Twin-fluid atomizers operate with compressed air and water. They consist of an air inlet, water inlet and internal chamber [156, 185]. The sheet of water formed in the chamber is sheared by the compressed air and becomes unstable and disintegrates into droplets. After the droplets exit the atomizer, the high turbulent jet can cause a second atomization of droplets, resulting in the further improvement of the droplet size distribution [185,186].

The discharge pressures of water and atomizing medium (air) from a twin-fluid atomizer are separately controlled. Both water and atomizing medium lines operate in the low pressure regime (from 3 bar to 12 bar) [156, 181]. The cone angle of this type of atomizer varies between 20° and 120°.

Drop size distribution, cone angle, spray momentum and discharge rates can be efficiently controlled using twin-fluid atomizers. Also, the compressed air discharged from twin-fluid atomizers can carry small water droplets into the combustion zone in sufficient quantities while producing strong turbulence to mix droplets with fires. Both effects increase the effectiveness of twin-fluid atomizers in fire suppression [187].

Twin-fluid atomizers have been widely used in industrial spray systems for many years [156,185]. They have good reliability, are less likely to clog due to their larger orifice sizes and are easy to maintain due to their low operating pressure. Twin-fluid atomizers can also substitute gaseous halon alternatives or inert gases for air as the atomizing fluid. The twin-fluid water mist system operates in the low pressure range, so that commonly available pipe fittings and valves can be used. One twin-fluid water mist fire suppression system has been listed by Factory Mutual for use in turbine enclosures [188].

The primary disadvantage of the twin-fluid water mist system is the system's cost, since it requires two supply lines for air and water and the storage of a sufficient quantity of compressed air [156, 181]. Its spray momentum is also relatively low due to its low discharge pressure, in comparison with those types of atomizers with high discharge pressures, which could affect its effectiveness against fire challenges.

5.3.4 Rotary Atomizers

In the rotary atomizers, liquid is supplied through a stationary tube to the inner part of a rotating surface. The friction between the liquid and the rotating surface causes the liquid to rotate with the surface and the centrifugal force causes it to flow towards the periphery. Under the action of this centrifugal force, the liquid leaves the edge of the surface with a high velocity, producing a fine spray. In rotary atomizers, even high flow rates of liquid can be atomized with relatively low pressure. They can be cleaned readily and display minimal flow blockage. However, the design is complex, including a rotating element with accompanying transmission and lubrication systems. They require high rotational speed of the surface to achieve good quality of atomization. Such high speeds reduce the reliability and require appropriate protections.

5.3.5 Air Blast Atomizers

The drive to improve the quality of generated sprays has resulted in an increase in the use of air blast atomizers in modern times. In such injectors, atomization is induced by blasting of liquid sheets and ligaments by slow moving, high-pressure air. However, they require large quantities of air (typically 500 to 600 percent of the liquid mass) to attain satisfactory atomization. But, this additional air is not wasted, because after atomizing the liquid it conveys the drops into the required zone. Airblast atomizers have many advantages over pressure atomizers. They require lower liquid pump pressures and produce finer sprays. The main disadvantage of airblast atomizers is that the large quantities of atomizing air required by these injectors. Furthermore, the “drowning” and “blasting” of the liquid jet by huge quantities of air leaves very little room for any kind of control of the atomization process.

5.3.6 Effervescent Atomizers

In effervescent atomizers a small amount of air or gas is introduced into the bulk liquid in a mixing chamber upstream of the discharge orifice. The injected gas forms a bubbly two-phase, gas-liquid flow when it mixes with the liquid in the mixing chamber inside the injector. When the gas bubbles emerge from the injector they “explode”. This rapid expansion of gas bubbles shatters the surrounding liquid ligaments, resulting in the formation of very fine droplets. The method of operation of effervescent atomizers is similar to that exhibited by “flashing” atomizers, where the atomization is caused by the explosion of cavitation bubbles. Quality of atomization obtained from effervescent atomizers is very good even at very low injection pressures. They have large holes and passages and can thus atomize “dirty” liquids without plugging of the injectors. These injectors are reliable, simple and cheap. However, effervescent atomizers are sensitive to acceleration owing to the sensitivity of air bubbles to acceleration. Consequently, they cannot be safely employed in airborne applications.

5.3.7 Advanced Atomizers

In order to rectify the flaws of the conventional atomizers, many advanced concepts of atomization were used in various process industries over the years. These atomizers, e.g., ultrasonic atomizers, acoustic atomizers, induced atomizers, electrostatic atomizers, use different physical mechanisms to produce liquid sprays. For example, ultrasonic atomizers use capillary break up of liquid sheets vibrating at ultrasonic frequencies to produce fine liquid spray. In acoustic atomizers, atomization is achieved by de-stabilizing the liquid column in an acoustic field. In electrostatic atomizers, the bulk liquid is charged and the droplets are believed to be produced by the instabilities induced by the repulsion of charged molecules. These advanced atomization concepts provide very good control of the atomization process and they produce very fine sprays with mono-sized droplets. However, all of them suffer from the same drawbacks. They need additional supply of electrical energy and additional electrical components to generate the actions responsible for atomization and the flow rate over which they can operate is severely restricted. They cannot handle the high fuel flow rates required in most of the application, which limits their use to special low flow rate applications such as drug delivery, ink-jet printers and spray painting.

5.4 COMPUTATIONAL TECHNIQUE OF ATOMISATION PROCESS

The process of atomization is one in which liquid is disintegrated into droplets by the action of internal and/or external forces. In the absence of such forces, surface tension tends to pull the liquid molecules together to form liquid jets or sheets. According to Lefebvre[189], “Atomization can be considered as a disruption of the consolidating influence of surface tension by the action of internal and external forces”.

The literature on the theory of droplet formation [190-193] is quite extensive, but it deals with fairly low velocity and low Reynolds’s number flows, which are not very important in practice. Currently, there is no known model of the disintegration of a high velocity liquid discharge. This is due to the highly complex, turbulent and random flow phenomena occurring during disintegration, which is not well understood.

Existing theory of spray formation are based on instability of liquid jets and sheets and are generally based on method of small disturbances. It is believed that the disintegration of liquid jet or sheet is caused by the waves that form on the surfaces of the jets and sheets of liquids. During instability, these waves rapidly grow into finite amplitude waves that eventually break the liquid jets or sheets into a multitude of small droplets. Reitz and Bracco [194] have classified the atomization process into Rayleigh breakup, first wind induced, second wind induced and atomization regimes. The Rayleigh regime is governed solely by capillary instabilities, while in the first wind-induced regime; the capillary instabilities are enhanced by the aerodynamic interaction with the surrounding gas. For the second wind-induced and atomization regimes, the breakup is characterized by the formation of drops significantly smaller than jet diameter. It is unfortunate that the atomization regime, which is most important for practical applications, is the least understood one and no theory that adequately describes the processes occurring in this regime exists. Table 5.3 shows a classification of jet break up regimes:

Table 5.3: Classification of jet breakup regimes (Source Lefebvre)

Regime	Description	Predominant drop formation mechanism
1	Rayleigh breakup	Surface tension force, capillary waves
2	First wind-induced breakup	Surface tension force; dynamic pressure of ambient air
3	Second wind-induced breakup	Dynamic pressure of ambient air opposed by surface tension force initially
4	Atomization	Unknown

The theoretical basis for the capillary instability was first investigated by Rayleigh [195], who conducted a linear, inviscid analysis neglecting the effects of gas pressure variations on jet distortion. He obtained the following relationship between the initial jet diameter and the droplet diameter:

$$D = 1.89d \tag{8}$$

Thus, for the Rayleigh breakup mechanism, the average drop size is nearly twice the diameter of undisturbed jet.

Weber [196] developed a linear theory similar to Rayleigh's that included the effects of both the liquid viscosity and the pressure of the surrounding gas on the jet behavior. He assumed that any disturbance causes rotationally symmetric oscillations of the jet. If the wavelength of the initial disturbance is less than a particular wavelength, the surface forces tend to damp out the disturbance. However, if λ is greater than λ_{min}, the surface tension forces tend to increase the disturbances, which eventually lead to disintegration of the jet. There is, however, one particular wavelength, λ_{opt}, that is most favorable for drop formation. For viscous liquids

$$\lambda_{\min} = \pi d \tag{9}$$

$$\lambda_{opt} = \sqrt{2}\pi d\left(1 + \frac{3\mu_l}{\sqrt{\rho_l \sigma d}}\right)^{0.5} \tag{10}$$

After breakup, a cylinder of length λ_{opt} and diameter d forms a spherical drop of diameter D, so that

$$\frac{\pi}{4}d^2\lambda_{opt} = \frac{\pi}{6}D^3 \tag{11}$$

No simple expressions, relating droplet size to other parameters, exist for the wind-induced regimes and atomization regime. To predict the behavior of these regimes, basic fluid dynamics conservation equations for both the liquid and air flows are numerically solved, along with matching boundary conditions at their interfaces [197-199]. Small perturbations or disturbances are imposed on the surface of the liquid jets or sheets and the optimum wavelengths of disturbances that cause maximum instabilities are estimated numerically, which are then correlated to the droplet sizes. Although these theories can predict the conditions suitable for the initiation of jet or sheet disintegration, they cannot accurately predict the size spectrum of the generated droplets. These theories have successfully predicted the formation of droplets in well-controlled laboratory conditions, as in the case of capillary droplet formation, but they have not yet succeeded in accurately modeling the actual droplet formation in a practical system. These fundamental studies have identified, however, an important criterion that governs the formation and breakup of droplets. Specifically, the above discussed research points to the existence of a critical value of the Weber number, which is the ratio of inertial and surface forces acting on the surface of a liquid jet or sheet, above which the liquid flow is very unstable and disintegrates into droplets. The Weber number is defined as

$$We = \frac{\rho_a V_r^2 D}{\sigma} \tag{12}$$

Therefore,

$$D = \frac{We * \sigma}{\rho_a V_r^2} \tag{13}$$

Experimental studies of the disintegration of liquid jet and formation of droplets also suggest the existence of a critical Weber number. Griffin and Muraszew [200] suggested that the magnitude of the critical Weber number between 7 and 12, depending on the flow conditions.

Sutherland, Sojka and Plesniak [201] have developed a model that describes the performance of a ligament-controlled effervescent atomizer. Their model describes the spray formation process as the breakup of individual cylindrical ligaments subject to a gas stream and solves for the fastest growing disturbance, which is then correlated to the droplet diameter. However, their model relies upon empirical relationships to estimate the ligament diameters and the slip velocity between the gas and liquid streams. Therefore, their model cannot be used to model the atomization process in an air blast atomizer. Therefore, a new model has been developed to study the behavior of the investigated atomizer.

The atomization modeling effort in the present study was primarily focused on the modeling of a design newly developed air blast atomizer. This atomizer is a multi-hole, siphon fed, air-blast atomizer.

The major parameters required for the modeling effort are the number and size of air injection holes, the number and size of water supply holes and the air pressure used in the study [148]. Although the information regarding the water head would have been beneficial in estimating the mist generation rate, in the absence of that information a physical model for the pressure drop across the water head was developed to predict the water flow rate. The model used fundamental physical relationships to predict the atomizer performance and a novel model, based on energy, force and mass balance was developed to predict the droplet SMD. Some physical relaxation variables were introduced in the model to compensate for the real flow effects.

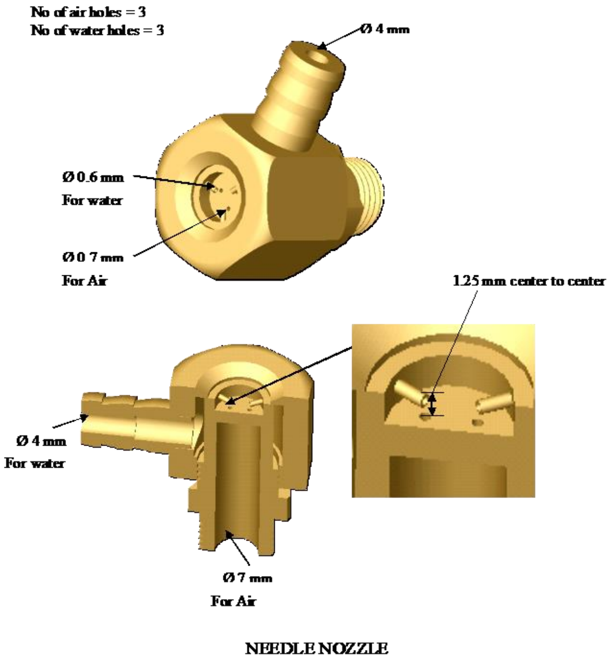


Fig. 5.1: Sectional solid drawing of the externally mixed twin fluid atomizer

A sectional drawing of the atomizer assembly is shown in Fig. 5.1. The basic geometric parameters of the investigated atomizer used in this study are:

No. of air injection holes = 3
No. of water ports = 3
Diameter of air injection holes = 0.7 mm
Diameter of water injection holes = 0.6 mm
Total area of air orifice = $n(\pi/4)*d^2 = 1.154 \times 10^{-6}\ m^2$
Total area of water orifice = $8.48 \times 10^{-7}\ m^2$

5.4.1 COMPUTATIONAL MODELING

For the computational modeling of the atomizer, three sub-models were developed. These sub-models are:

1. Model for predicting the air flow rate
2. Model for predicting the water flow rate
3. Model for predicting the droplet SMD

Out of these three models, the model for predicting the air flow rate is most critical as it provides the required air velocity and pressure that is used to model the mist generation rate and the droplet SMD.

5.4.1.1 Model for prediction the air flow rate

The first attempt to predict the air flow rate was by using standard Bernoulli's equation and continuity equation, which assumed the flow to be subsonic and hence incompressible. The equations used were:

$$\begin{aligned} &\dot{m}_a = \rho A v \\ &\frac{1}{2}\rho v^2 = \Delta P \\ &\Rightarrow \dot{m}_a = A\sqrt{2 * \rho * \Delta P} \end{aligned} \tag{14}$$

The density of the incoming air was estimated using perfect gas equation of state:

$$\rho = \frac{P}{RT} \tag{15}$$

The value of temperature was taken to be 300 K (27^0 C)

The compressible flow equations need to be used to model the flow properly. In order to use the compressible flow relations, first we needed to estimate the exit Mach Number of air. This was done by using the isentropic relationship between the supply pressure (P_0) and ambient pressure (P). The relationship used was

$$\begin{aligned} &\frac{P_0}{P} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}} \\ &M = \sqrt{\frac{2}{\gamma - 1}\left(\left(\frac{P_0}{P}\right)^{\frac{\gamma - 1}{\gamma}} - 1\right)} \end{aligned} \tag{16}$$

Value of γ was taken to be equal to 1.4. From the physics of compressible flows it is well known that the flow cannot become supersonic without going through a throat area (the minimum area) and the Mach number at the throat must be equal to 1.0. Therefore, following condition was used for the rest of the model

$$
\begin{aligned}
M_a &= M_i \ldots M_i < 1 \\
M_a &= 1.0 \ldots M_i > 1
\end{aligned}
$$

Where M_a is the actual Mach number and M_i is the isentropic Mach number.

Next, we estimate the static temperature (assuming total temp. T_0 = 300 K), the local speed of sound and the air velocity using the relations

$$
\begin{aligned}
&\frac{T_0}{T} = 1 + \frac{\gamma - 1}{2} M^2 \\
&a = \sqrt{\gamma R T} \\
&v = Ma
\end{aligned}
$$

Then, the exit air density is estimated using

$$\frac{\rho_0}{\rho} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{1}{\gamma - 1}} \qquad (17)$$

Next, the flow rate of air was calculated using the equation

$$\dot{m}_a = C_f \rho A v \qquad (18)$$

Where, C_f is a constant to take care of the real gas and other un-modeled effects. The value of C_f was chosen to be 2.35 for this study.

5.4.1.2 Model for prediction of water flow rate

Since the water was sucked into the flow domain by siphon effect, the information regarding the water head was crucial to model the process. However, that data was not available. Therefore, the head was assumed to be equal to zero. The air coming out of the air injection whole expands rapidly to the available larger area at the point of interaction between the water and air. This expansion leads to a pressure drop at that point. Therefore, the pressure differential between the water supply (which is at ambient pressure) and the lowered pressure at the point of interaction forces the water into the flow domain.

The given water flow rate data was used to form a neural network based model to estimate the pressure drop due to the flow. The pressure at the exit air orifice was considered to be equal to ambient pressure. The actual pressure ratio at the point of interaction was estimated using the relationship

$$\frac{P_0}{P_i} = \left(\frac{P_0}{P_a}\right) * N_f$$

$$N_f = \left(0.0034 * \frac{P_0}{P_a} + 0.9868\right) \qquad (19)$$

Where N_f is the factor estimated in the neurons by training the system with the data available. After estimating the pressure ratio across the water supply, the pressure drop was estimated using the relation

$$\Delta P = P_a - P_i \qquad (20)$$

Then, the water flow rate is calculated using the continuity equation, i.e.,

$$\dot{m}_w = C_d A_w \sqrt{2 * \Delta P * \rho_w} \qquad (21)$$

The value of C_d used in this study was equal to 1.0.

5.4.1.3 Model for prediction of droplet SMD

The size of the droplet produced by an atomizer depends on various factors like atomizer design, atomization mechanism, supply pressure, liquid properties (viscosity and surface tension) etc. Therefore, it is not possible to propose a unified theory for droplet formation. Most of the droplet size correlations available in the literature are empirical relations that work over a limited range of operating conditions and for specific atomizer designs. Keeping this in mind, a new phenomenological model to predict the droplet SMD for the atomizer being investigated was developed. The model uses basic mass and energy balance as well as the Weber number to predict the droplet SMD. The details of the developed model are given in this section.

Let

Surface Energy of the droplets = $E_S = \sigma S$

Total number of drops = N

Surface area of a single drop (assuming spherical drops) = $S_i = \pi D_i^2$

Where the subscript ‘I’ represents individual drops

Therefore, Total Surface Area = $S = \sum_i S_i = \sum_{i=1}^{N} \pi D_i^2 = \pi \sum_{i=1}^{N} D_i^2$ (22)

Total mass of the atomized liquid = $M = \sum_{i=1}^{N} M_i$ (23)

Where, mass of individual droplets = $M_i = \rho V_i$ (24)

Here, volume of a drop = $V_i = \frac{4}{3}\pi r_i^3 = \frac{\pi}{6} D_i^3$ (25)

$$\therefore M_i = \rho_l V_i = \frac{\pi}{6}\rho_l D_i^3$$
$$\Rightarrow M = \sum_{i=1}^{N} M_i = \frac{\pi}{6}\rho_l \sum_{i=1}^{N} D_i^3 \qquad (26)$$

Surface energy per unit mass = $\frac{E_S}{M} = \frac{\sigma S}{M} = \frac{\sigma \sum_{i=1}^{N} S_i}{\sum_{i=1}^{N} M_i} = \frac{\sigma \pi \sum_{i=1}^{N} D_i^2}{\frac{\pi}{6}\rho_l \sum_{i=1}^{N} D_i^3}$ (27)

By definition, SMD = $D_{32} = \frac{\sum_{i=1}^{N} D_i^3}{\sum_{i=1}^{N} D_i^2}$ (28)

Therefore, $\frac{E_S}{M} = \frac{6\sigma}{\rho_l D_{32}}$ (29)

Now, Total energy of the liquid per unit mass = surface energy of liquid per unit mass + kinetic energy of liquid per unit mass

$$\Rightarrow \frac{E_T}{M} = \frac{E_s}{M} + \frac{E_k}{M} \tag{30}$$

Kinetic energy per unit volume of liquid can be given as

$$\frac{E_k}{V} = \frac{\sum_{i=1}^{N} \frac{1}{2} M_i v_i^2}{\sum_i V_i} = \frac{\sum_{i=1}^{N} \frac{1}{2} (\rho_l V_i) v_i^2}{\sum_i V_i} \tag{31}$$

Assuming $v_i^2 = \bar{v}^2$ = average droplet velocity

$$\frac{E_k}{M} = \frac{\bar{v}^2}{2} \tag{32}$$

Again, by definition

$$\begin{aligned}
&We = \frac{E_k}{E_s} \\
&\Rightarrow E_k = We * E_s \\
&\Rightarrow E_T = E_s + E_k = (1 + We) E_s = (1 + We) \frac{6\sigma}{\rho_l D_{32}} M \qquad (33) \\
&\frac{M}{\rho_l} = \sum_i V_i = V \\
&\Rightarrow E_T = (1 + We) \frac{6\sigma V}{D_{32}}
\end{aligned}$$

Therefore, total energy per unit time of the droplets =

$$\frac{dE_T}{dt} = \frac{(1 + We) 6\sigma}{D_{32}} \frac{dV}{dt} = (1 + We) \frac{6\sigma}{D_{32}} \dot{Q}_l \tag{34}$$

Now, the energy of the droplets is primarily coming from the atomizing air blast. Therefore, from energy conservation one can write

$$\eta \frac{1}{2} \dot{m}_a v_a^2 = (1 + We) \frac{6\sigma}{D_{32}} \dot{Q}_l \tag{35}$$

Where η = fraction of air energy transferred to the atomized liquid

Now,

$$\frac{1}{2}\eta \dot{m}_a v_a^2 = \left(\rho_l \dot{Q}_l\right)\left(1+We\right)\frac{6\sigma}{\rho_l D_{32}} = \dot{m}_l\left(1+We\right)\frac{6\sigma}{\rho_l D_{32}}$$

$$\Rightarrow \eta(ALR)v_a^2 = \frac{12\left(1+We\right)\sigma}{\rho_l D_{32}}$$

$$ALR = \frac{\dot{m}_a}{\dot{m}_l}$$

Therefore,

$$D_{32} = \frac{12\left(1+We\right)\sigma}{\eta\left(ALR\right)v_a^2 \rho_l} \qquad (36)$$

In order to use this model to estimate the droplet size, one has to specify the We as well as the efficiency (η). In order to estimate the We, the air velocity and density estimated in the first section of the model as used along with the measured droplet size. The relationship used was

$$We = \frac{\rho_a v_a^2 D}{\sigma} \qquad (37)$$

Chapter 6

RESULTS AND DISCUSSIONS

6.0 INTRODUCTION

In this chapter, the results obtained from the experiments are presented and discussed. The experiments were carried out in standard cup burner apparatus for measuring the critical concentration (minimum extinguishing concentration – MEC) of flame suppressing agents (Halon 1301 & HFC227ea) for suppression of diffusion flames of different fuels (n-heptane & ethyl alcohol). The critical concentration was measured at various flow conditions of air and flame suppressing agent rates, and both agent & air flow rate was controlled using needle valves and measured using rotameters. The critical concentration of water mist was experimentally measured in modified cup burner apparatus. The was mist was introduced into the chimney using siphon fed (air blast) atomizer. The effect of air flow rate on critical concentration of water mist was evaluated and air flow rate was controlled using needle valves and measured using rotameters. The twin fluid siphon fed atomizer was developed for generating mist of low through-put required for carrying out experiments in modified cup burner apparatus.

The scaled up experiments were also carried out in large enclosed space to understand the mechanisms responsible for the suppression of pool fires using water mists. Experiments were conducted in a compartment of size 3.5m X 3.6m X 3.1m for n-heptane pool fires of different heat release rates. The temperature variations in the compartment were measured using K-type thermocouples fixed at two locations. A multi gas analyzer was used to measure gas concentrations. The test results indicate that the water mist suppress the diffusion flame in the enclosed space mainly through the evaporating cooling and oxygen displacement by water vapors resulting in inefficient combustion. The fire suppression time decreases with a decrease in droplet diameter. It is much easier to suppress a larger fire due to faster rates of evaporation of water droplets and therefore, the critical mist concentration decreases with an increase in the fire size. The water mist was generated using twin fluid internally mixed generator as high generation rate was required for carrying out experiments in large enclosed space. In this type of mist generators, atomization is attained by injecting a small amount of compressed air into a liquid stream in a mixing chamber inside the mist generator. Since most of the energy for atomization is supplied to the liquid by the atomizing air, a significantly small pressure drop can produce a fine spray. The dependence of droplet size upon the liquid supply pressure and the air liquid mass ratio was studied in detail using a Malvern Particle size analyzer. The results presented suggest that the investigated injector could be used to control the flow rate (mist through put) and spray characteristics independent of each other by simultaneously varying the supply pressure of the liquid and the atomizing air. The controlled atomization reported in this paper for a twin-fluid internally mixed atomizer makes it attractive to be used for fire suppression applications in particular because of the high mist generation rate and for various other commercial applications in general, as the atomizer is capable of providing spray of different characteristics depending upon the application requirements.

6.1 Performance of Internally Mixed twin fluid mist generator

In the present study, the liquid supply pressure was kept constant and the air flow rate through the mist generator was varied over a range by changing the air supply pressure to obtain the variation in Air to Liquid Mass Ratio (ALR). The liquid supply pressure was then varied and the entire procedure was repeated for different values of air supply pressure. The spray characteristics corresponding to a range of liquid supply pressures (i.e., 34.3 kPa to 171.2 kPa), air supply pressure (206 kPa to 756 kPa) and ALR (0.16 to 2.9) were studied and the results are presented in the next section. The full operating envelop reported in this paper is given in Fig. 6.1.

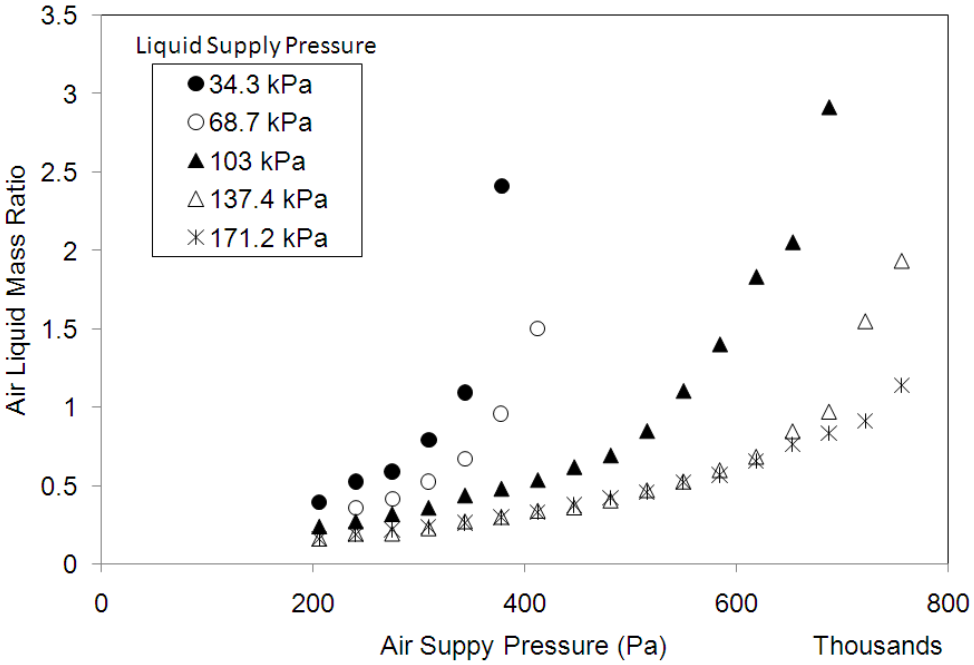


Fig. 6.1: Full operating envelop of the atomizer

The variation of liquid flow rate with ALR for different liquid supply pressures is shown in Fig. 6.2. The data presented in this Fig. show that the liquid flow rate decreases with an increase in ALR. At lower values of ALR the decrease is quite rapid. But, at higher values of ALR, the change in liquid flow rate is quite small with an increase in ALR for a particular liquid supply pressure.

Furthermore, the liquid flow rate is seen to increase with an increase in liquid supply pressure, which is expected due to the increase in incoming liquid velocity with the increase in supply pressure. The liquid flow rate is seen to vary between 0.2 LPM and 1.8 LPM. In order to establish a functional relationship between the liquid flow rate, the ALR and the liquid supply pressure, the discharge coefficient variation with respect to ALR was estimated using Eq (1) and the results are plotted in Fig. 6.3.

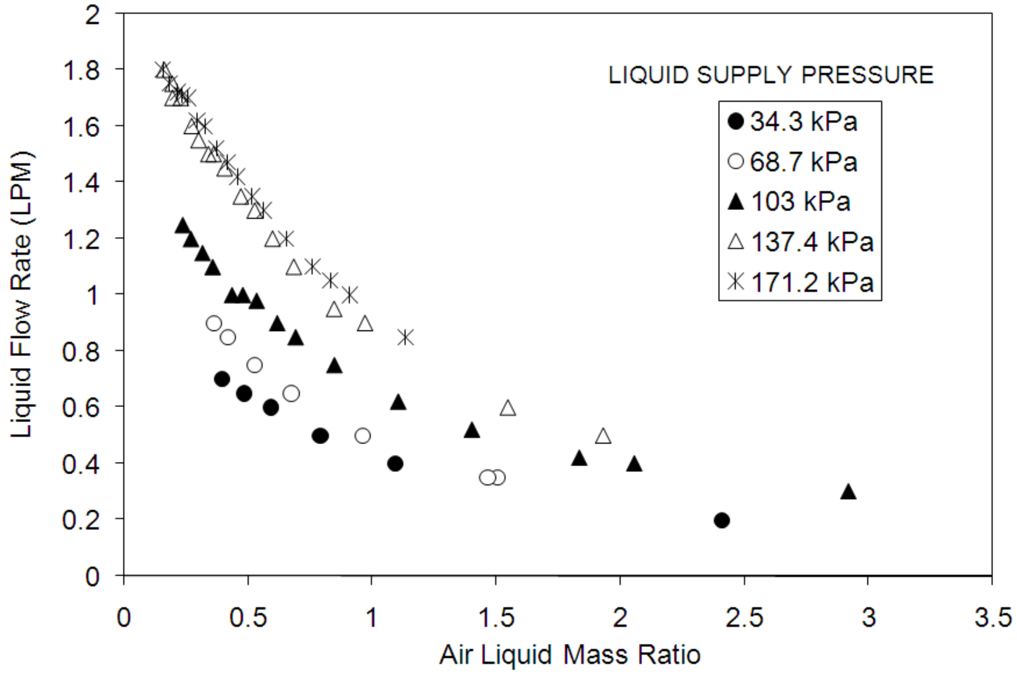


Fig. 6.2: Variation of liquid flow rate with ALR for different liquid supply pressures.

$$C_D = \frac{\dot{m}_W}{A_0(2\rho_W P_W)^{0.5}} \qquad (1)$$

The functional relationship between the discharge coefficient and ALR is given by

$$C_D = -0.01\ln(ALR) + 0.29, \qquad R^2 = 0.952 \qquad (2)$$

The data presented in Fig. 6.3 show that the discharge coefficient decreases with an increase in ALR. Lefebvre [202] has defined the discharge coefficient to be a measure of the extent to which the liquid flowing through the final discharge orifice makes full use of the available flow area. Therefore, the reduction in discharge coefficient with ALR points to the fact that the flow area available for liquid decrease with an increase in ALR as the liquid is “squeezed” to smaller available area by air, and, the reduction in water flow rate with an increase in ALR, seen in Fig. 6.2, can be safely attributed to the reduction in flow area of the liquid.

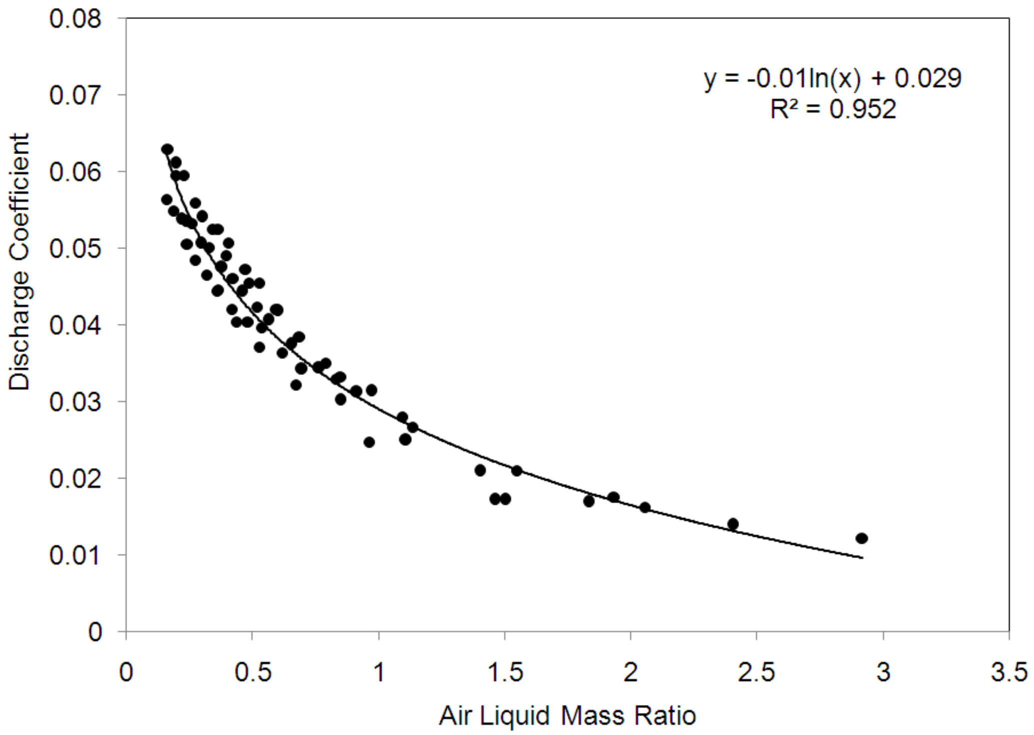


Fig. 6.3: Variation of discharge coefficient with ALR

According to Eq. (2), the rate of change of C_D with ALR ($i.e., dC_D/d(ALR)$) is inversely proportional to ALR. Therefore, the rate of change decreases with an increase in ALR, which is responsible for slower rate of decrease in the liquid flow rate at higher values of ALR as seen in Fig. 6.2. This behavior may be attributed to the change in two-phase flow regime with ALR. At higher values of ALR the two-phase flow is expected to be an annular flow or a dispersed flow [203], which are less sensitive to external forces [204].

The dependence of droplet Sauter Mean diameter (SMD) on ALR for different liquid supply pressures is shown in Fig. 6.4, which is seen to vary between 85 μm to 15 μm over the entire operating range reported in this paper. The data presented in Fig. 6.4 show that the droplet size decreases with an increase in ALR for a given liquid supply pressure.

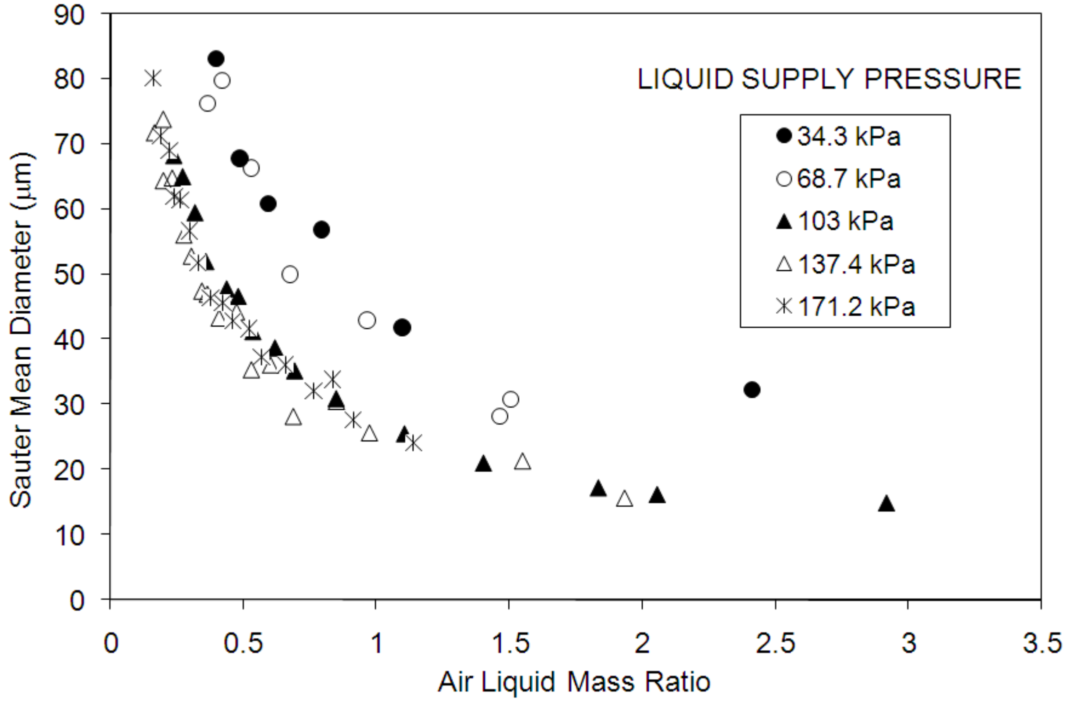


Fig. 6.4: Variation of droplet SMD with ALR for different liquid supply pressures.

In order to further elucidate this behavior, the droplet size distribution parameters (D_{v10}, D_{v50}, D_{v90} and Span = $(D_{v90} - D_{v10})/D_{v50}$) corresponding to different ALR for a constant liquid supply pressure of 103 kPa are shown in Fig. 6.5.

$$We_l = \frac{Inertial\ forces\ due\ to\ air\ flow}{Surface\ forces\ on\ the\ ligements} = \frac{\rho_a {V_a}^2 D_l}{\sigma} = \frac{2P_a D_l}{\sigma} \qquad (3)$$

$$Re_l = \frac{Internal\ inertial\ forces\ on\ liquid\ ligaments}{Shear\ forces\ on\ the\ liquid\ ligaments} = \frac{\rho_w V_w D_l}{\mu_w} = \frac{\sqrt{2\rho_w P_w} D_l}{\mu_w} \qquad (4)$$

where, the effective diameter of the liquid ligament D_l is estimated as

$$D_l = \sqrt{\frac{4C_D A_0}{\pi}} \qquad (5)$$

It should be noted that the inertial forces are scaled as the supply pressures in Eqs. (3) and (4).

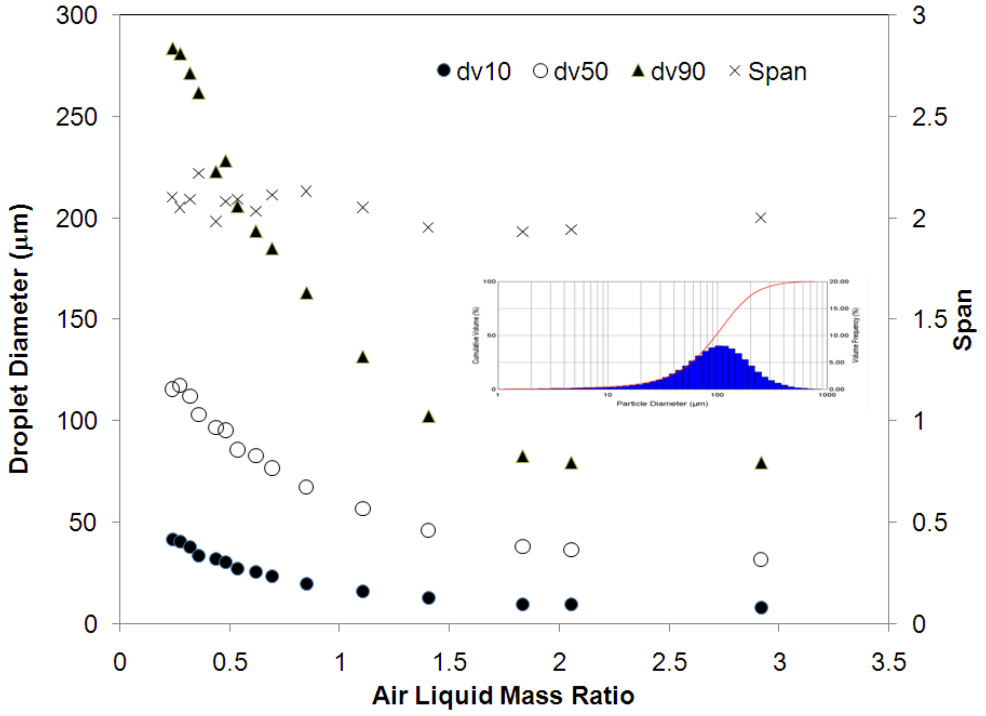


Fig. 6.5: Variation of droplet distribution parameters with ALR for a constant liquid supply pressure of 103 kPa. A representative volumetric droplet distribution is shown in the insert.

The data presented in Fig. 6.6(a) show that in general We_l increases with an increase in liquid supply pressure. This observation suggests that at a constant ALR, there is an increase in the inertial forces acting on the liquid ligaments with an increase in liquid supply pressure, which can be considered to be responsible for the decrease in droplet size with an increase in liquid supply pressure as seen in Fig. 6.4. However, for a given liquid supply pressure, there is a rapid increase in We_l at lower values of ALR. But, at higher values of ALR, We_l is almost constant. The sharp increase in We_l, i.e., inertial forces acting on the ligaments, with ALR at lower values of ALR is responsible for the rapid decrease in droplet diameter with ALR at lower ALR values. The inertial and surface forces balance each other at higher values of ALR rendering the droplet diameter almost constant with ALR. Looking at the variation in Re_l presented in Fig. 6.6(b), one can observe that the Reynolds number increases with an increase in liquid supply pressure for a constant ALR, once again suggesting the increase in inertial forces with an increase in supply pressure. On the other hand, for a constant liquid supply pressure, Re_l decreases with an increase in ALR. This suggests that the internal shear forces increase with an increase in ALR, resulting in an enhancement of instability leading to the rapture of the ligaments, producing smaller droplets.

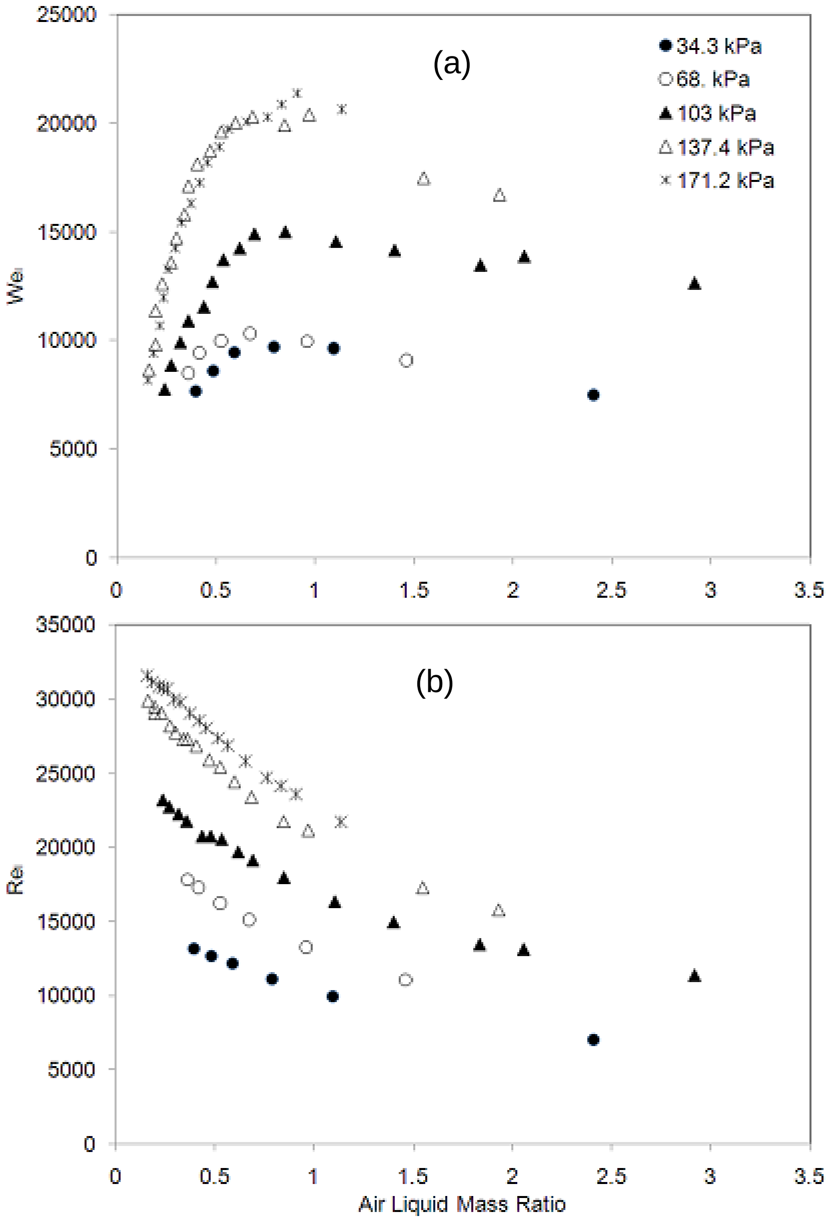


Fig. 6.6: Variation of ligament (a) Weber number and (b) Reynolds number with ALR for different liquid supply pressures.

Next, the droplet SMD was non-dimensionalized using Eq. (6) and its variation with ALR is presented in Fig. 6.7. It can be seen that using such non-dimensalization, all the values of D* for different supply pressures collapse onto each other. The functional relationship between the non-dimensional droplet diameter and ALR is given in Eq. (7).

$$D^* = Non - dimensional\ droplet\ diameter = \frac{D_{32} P_W}{D_0 P_a} \qquad (6)$$

$$D^* = 324(ALR)^{-1.13}, \qquad R^2 = 0.952 \qquad (7)$$

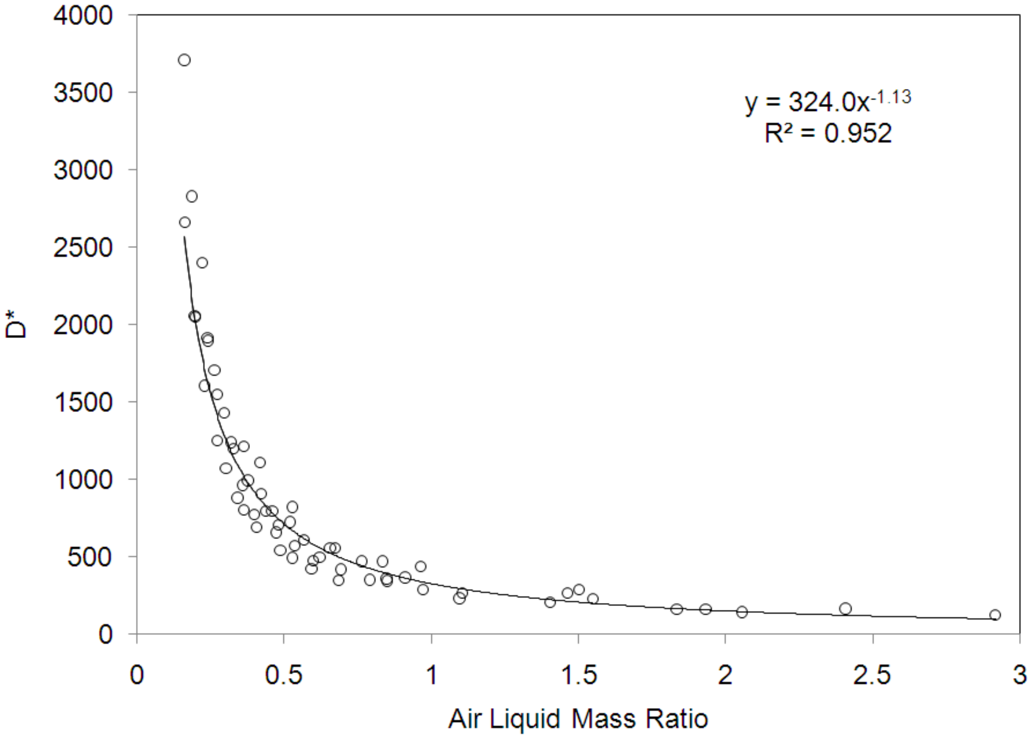


Fig. 6.7: Variation of non-dimensional droplet diameter with ALR for all the supply pressures

The performance plot for the atomizer is given in Fig.. 6.8 in which the variation of liquid flow rate is plotted against the SMD for different liquid supply pressures. By moving along a vertical line in the plot, one can vary the liquid flow rate over a range while keeping the droplet SMD constant. Similarly, a horizontal line in the performance plot corresponds to different droplet diameters for a constant liquid flow rate. Therefore, the presented atomizer can be used to achieve independent control over the droplet size and the liquid flow rate.

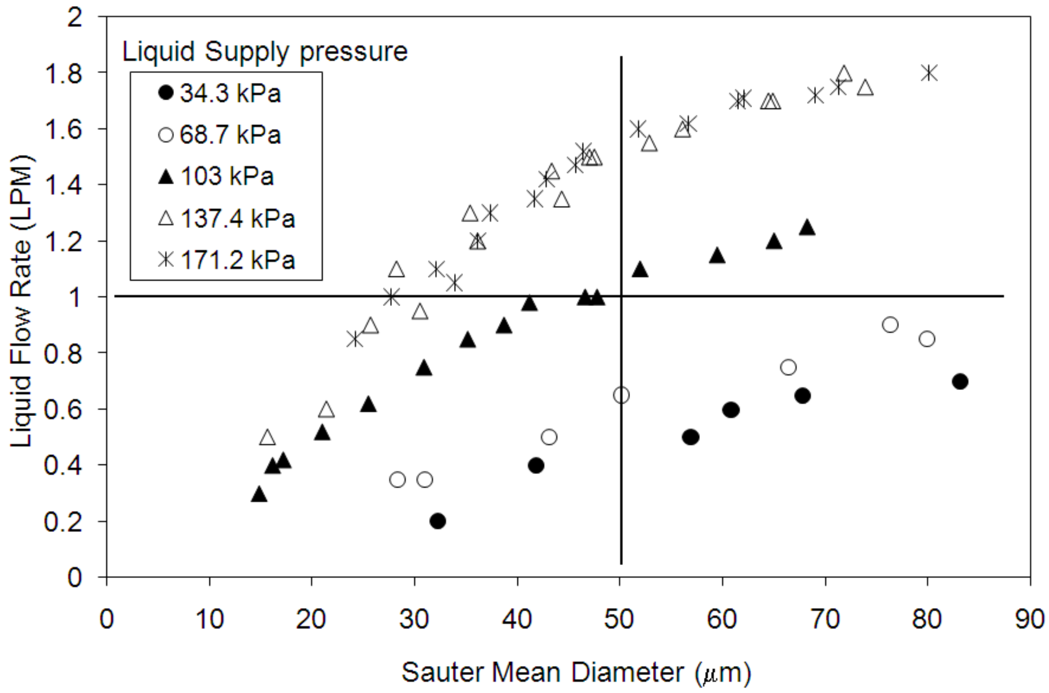


Fig. 6.8: Performance map of the atomizer

The operation map corresponding to the performance map is shown in Fig. 6.9. It can be seen that the air supply pressure must be increased in order to maintain a constant SMD with increasing liquid supply pressure (i.e., correspondingly increasing liquid flow rate). Furthermore, increasing the liquid supply pressure at a constant air supply pressure causes an increase in the droplet SMD, as seen in Fig. 6.9, due to a decrease in ALR**.** Therefore, the liquid as well as the air supply pressure needs to be increased simultaneously in order to achieve an increase in flow rate accompanied with a decrease in droplet diameter.

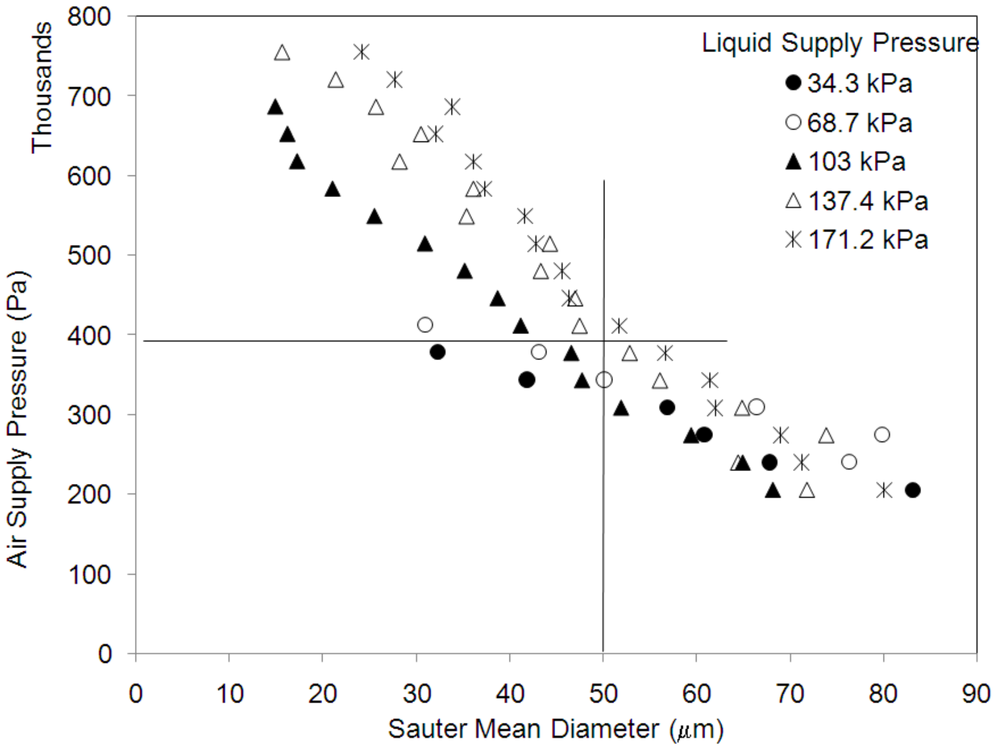


Fig. 6.9: Operation Map of the atomizer

The results presented in this section suggest that the investigated twin-fluid mist generator can be used to produce controlled sprays over a range of operating conditions. Therefore, the presented mist generator can provide fire engineers the flexibility to achieve optimum control over fire in confined spaces, pool fires and even small and medium open fires by varying the mist through put rate and the spray characteristics depending on the type and intensity of the fire as well as during different stages of a fire fighting operation.

6.2 Performance of Externally Mixed Atomizer

The measured and predicted values of air flow rate are shown in Fig. 6.10. The data in Fig. 6.10 shows that Bernoulli's equation not only under predicts the flow rate (which can be very easily corrected using a correction factor of 1.5) but it is also unable to capture the proper slope of the curve. As can be seen from the measured data, there is a change in the slope of the curve after a pressure of about 0.8 bar. This deviation in slope is primarily due to the compressibility of air, which brings in a change in air density and velocity [127].

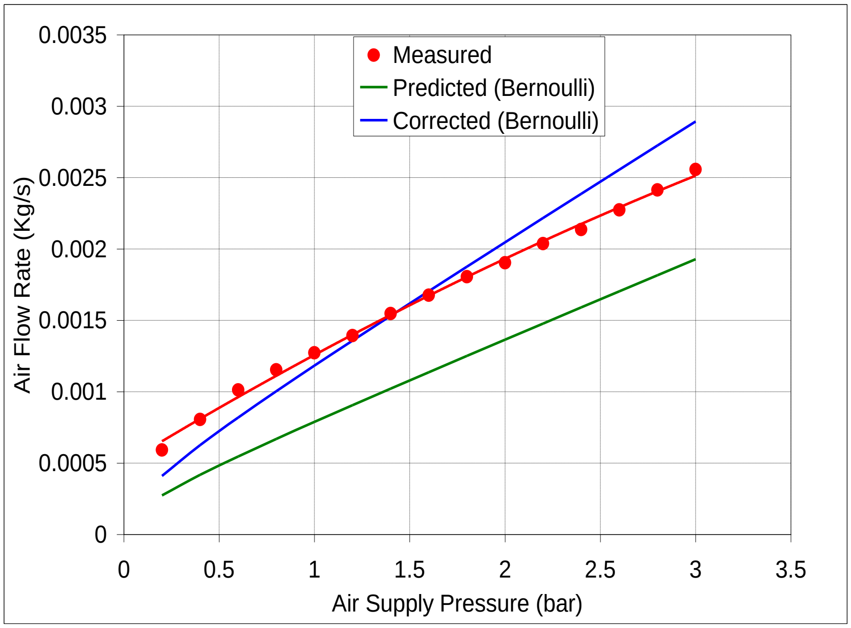


Fig. 6.10: First estimate of air flow rate.

The estimated exit Mach number is plotted in Fig. 6.11 with respect to the air supply pressure. The results in Fig. 6.11 show that the flow becomes supersonic beyond a supply pressure of 0.8 Bar (the same point were the air flow rate slope changes).

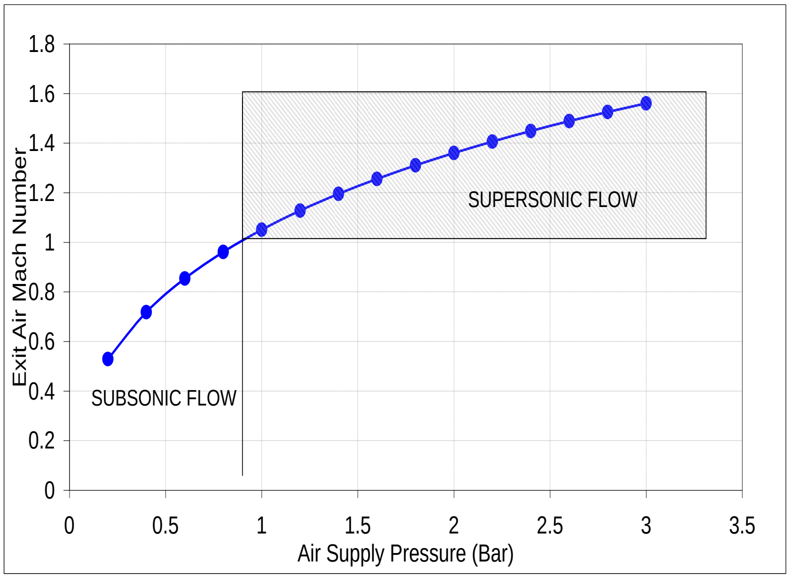


Fig. 6.11 : Estimated exit Mach Number

The estimated air flow rate was converted to LPM within proper pressure correction and the results are plotted in Fig. 6.12. The data in Fig. 6.12 shows excellent matching between the experimental values and the model predictions capturing all the details of the flow rate variation.

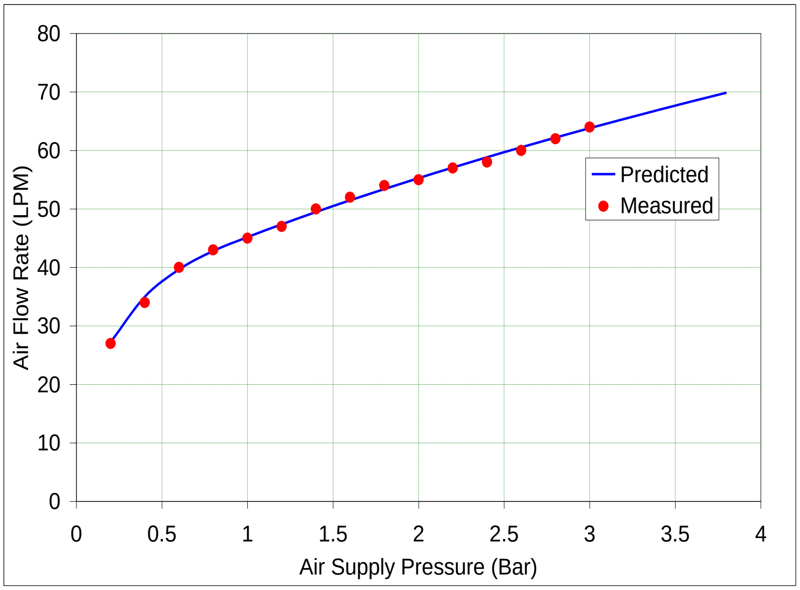


Fig. 6.12: Measured and predicted variation of air flow rate with supply pressure.

The estimated water flow rate (kg/s) was converted into LPM and the results are shown in Fig. 6.14. The data presented in Fig. shows remarkable matching between the measured value and the model prediction (except for higher values of P_{supply}, the reason for which is explained earlier).

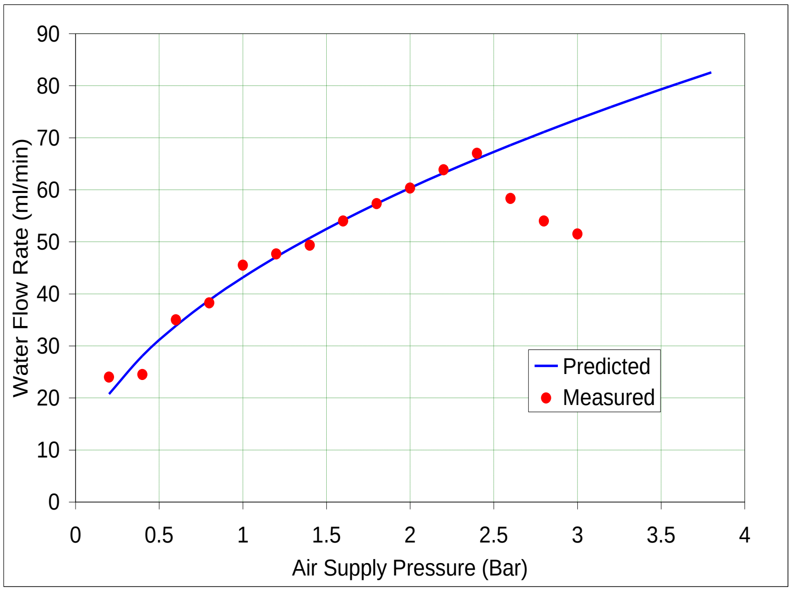


Fig. 6.14 : Measured and predicted water flow rate

It should be point out that the last three points in the given data shows a dip in the water flow rate with an increase in air supply pressure. This is physically impossible. This dip can be attributed to an appreciable change in the water head during the course of experimentation. Therefore, those data points were excluded while training the model. It should be pointed out that if the neurons were trained using the full data set available, then the model will reproduce the exact experimental data.

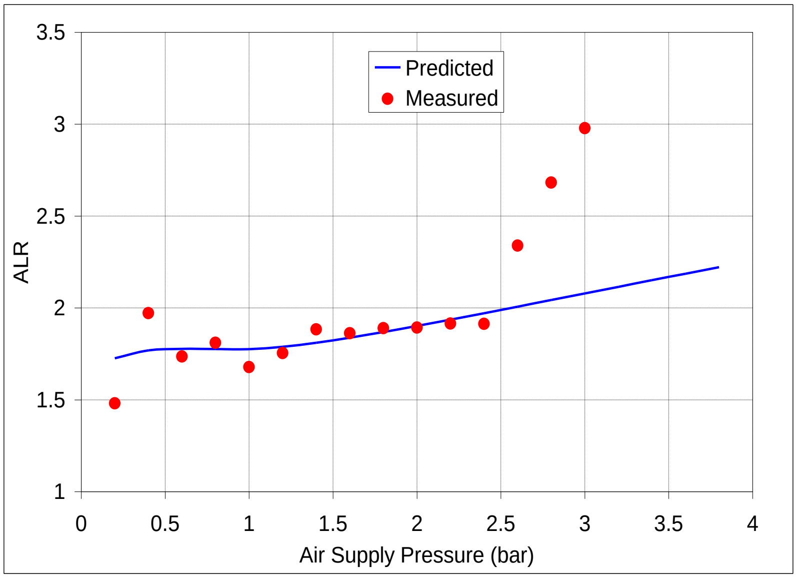


Fig. 6.15 : ALR vs. Air Supply Pressure

The predicted ALR $(=\frac{\dot{m}_a}{\dot{m}_w})$ was estimated and is presented in Fig. 6.15 along with the measured values. The deviations at higher air supply pressures are due to the variation in water head.

The average We for the entire data set was calculated and that was found to be equal to 43. Therefore, that value was used in the model. Similarly, the average value of η was estimated to be equal to 0.013 and that was used in the model. Using these numbers and the value of ALR estimated in the previous section, the droplet SMD was calculated and the predicted droplet diameter were compared with the measured values. The model predictions, along with the measured values are shown in Fig. 6.16.

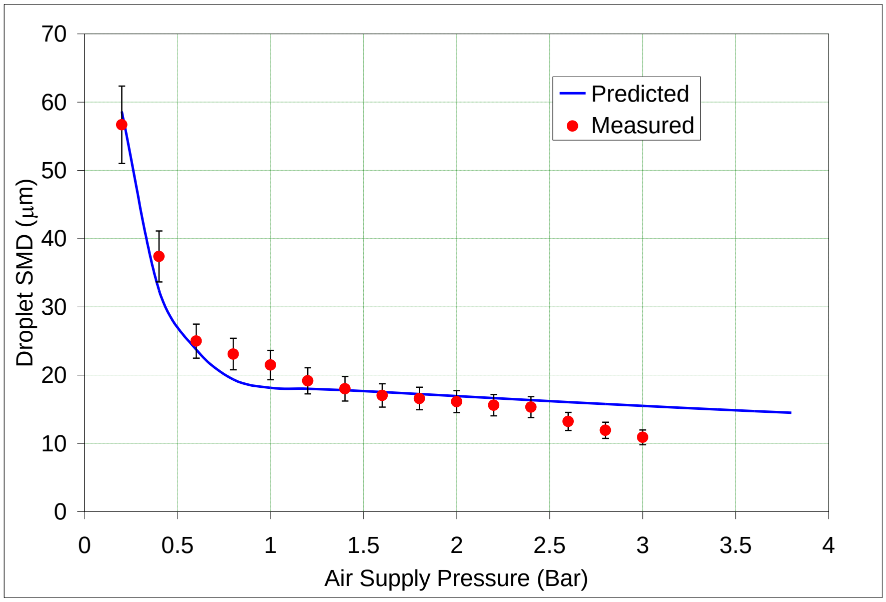
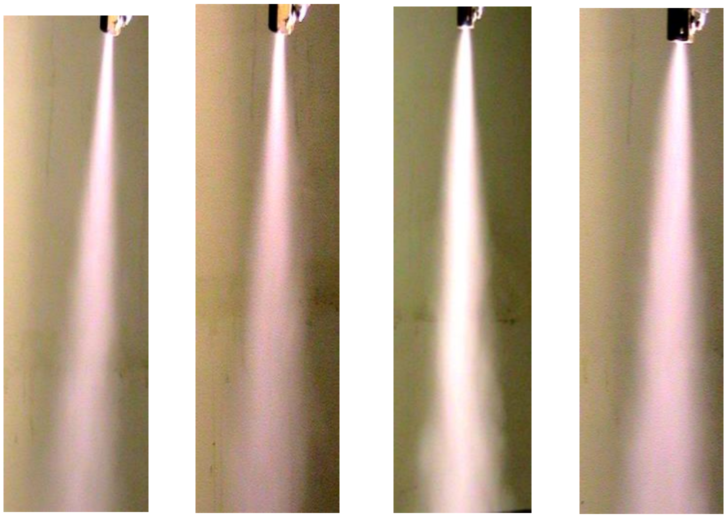


Fig. 6.16 : Predicted and measured droplet SMD.

The data presented in Fig. 6.16 shows very good agreement between the model predictions and the measured SMD. It should be noted that the model inputs were only the atomizer exit geometry and the air supply pressure and the model estimated the air flow rate, the water flow rate, the ALR as well as the droplet SMD. The deviation of the model prediction from the measured data at higher values of ALR was again due to the change in water head, which brings about an error in the prediction of ALR. It should be pointed out that the model prediction will be better if the atomized liquid is also pressurized and the liquid head information is made available.



(a) (b) (c) (d)

Fig. 6.17 : Spray Images at different ALR [(a) ALR = 1.147., (b) ALR = 1.117., (c) ALR =1.057., (d) ALR = 1.004]

Fig. 6.17 shows images of the spray produced by the presented atomizer at different air flow rates. It is observed that with an increase in air flow rate, the kinetic energy of the flow keeps on increasing causing a increase in spray cone angle. It was observed that spray forms the solid cone at all the operating conditions.

In the present study, the liquid supply pressure was kept constant and the air flow rate through the atomizer was varied over a range of air supply pressure to obtain the variation in ALR. The spray solidity was studied by taking pictures of the spray at different liquid air supply pressures. The liquid flow rate corresponding to a particular air flow rate (i.e .ALR) was measured using a calibrated rotameter. The liquid supply pressure was then varied and the entire procedure was repeated for different values of air supply pressure and a performance map was obtained.

6.3 MEC of Halon 1301 and HFC 227ea – Standard Cup Burner Apparatus

The experiments were conducted to measure MEC of Halon 1301 and HFC 227ea required for suppression of diffusion flame of n-Heptane and ethyl alcohol. Fuel is filled in fuel reservoir and fuel level is adjusted in the cup in such a way that fuel is filled up to the lip of the cup and in no case fuel is allowed to be less than 1 mm from the lip of the cup.

Once the fuel level is maintained, air is injected into to sustain the combustion inside the flame tube, air flow is fixed and measured using rotameters. Flame is established and then flame tube is placed at its position. A pre-burn time of 60 seconds is given for full growth of the diffusion flame. Once fully developed diffusion flame is established, extinguishing agent is added in steps till the flame is extinguished. This agent flow rate is measured using rotameter. Using measured flow rate values of the air and agent, extinguishing concentration of the agent is calculated. Minimum Extinguishing Concentration (MEC value) of three extinguishing agents are experimentally measured at different air flow rates such as 10, 15, 20 and 25 lpm. The Reynold number of the flow within the flame tube is calculated for all the cases in order to compare and interpret the increasing values of MEC with the increasing air flow rates. The entire procedure is repeated for different fuels and for different extinguishing agents. Table 6.1 indicates the MEC of halon 1301 for n-heptane diffusion flame. and Table 6.2 indicates the MEC of Halon 1301 for ethyl alcohol diffusion flame. Table 6.3 & 6.4 indicate the MEC of HFC 227ea for n-heptane & ethyl alcohol diffusion flames in cup burner apparatus.

Table 6.1: MEC of Halon 1301 for n-heptane diffusion flame

S.No	Air Flow (lpm)	Agent Flow (lpm)	Extinguishing Conc. (% V/V)	Average Extinguishing Conc.(%V/V)	MEC (gm / m^3)
1.	10	0.30, 0.30, 0.30	2.90, 2.90, 2.90	2.90	177.77
2.	15	0.455, 0.46, 0.455	2.94, 2.97, 2.94	2.95	180.86
3.	20	0.65, 0.63,0.54, 0.60	3.14, 3.05, 2.61, 3.01	2.95	180.86
4.	25	0.81, 0.82, 0.82	3.13, 3.16, 3.16	3.15	193.12

Table 6.2: MEC of Halon 1301 for Ethyl Alcohol diffusion flame

S..No.	Air Flow (lpm)	Agent Flow (lpm)	Extinguishing Conc. (% V/V)	Average Extinguishing Conc.(%V/V)	MEC (gm / m^3)
1.	10	0.47, 0.47, 0.47	4.50, 4.50, 4.50	4.5	275.89
2.	15	0.70, 0.70, 0.70	4.45, 4.45, 4.45	4.45	272.85
3.	20	0.94, 0.95, 0.95	4.49, 4.52, 4.52	4.51	276.50
4.	25	1.35,1.34,1.35	5.12,5.08,5.12	5.09	312.06

Table 6.3: MEC of HFC 227ea for n-heptane diffusion flame

S.No.	Air Flow (lpm)	Agent Flow (lpm)	Extinguishing Conc. (% V/V)	Average Extinguishing Conc.(%V/V)	MEC (gm / m^3)
1.	10	0.68, 0.70	6.40, 6.50	6.44	454.59
2.	15	1.0,1.02, 1.08	6.25, 6.36, 6.72	6.45	455.30
3.	20	1.33, 1.41, 1.41	6.23, 6.60, 6.60	6.47	456.71
4.	25	1.92, 1.91, 1.91	7.13,7.09,7.09	7.10	501.18

Table 6.4: MEC of HFC 227ea for Ethyl Alcohol diffusion flame

S.No	Air Flow (lpm)	Agent Flow (lpm)	Extinguishing Conc. (% V/V)	Average Extinguishing Conc.(%V/V)	MEC (gm / m^3)
1.	10	0.90, 0.92,0.91	8.25,8.43,8.34	8.34	588.72
2.	15	1.40, 1.32, 1.40	8.50, 8.10, 8.50	8.40	592.95
3.	20	1.85, 1.85, 1.90	8.46, 8.46, 8.67	8.53	602.13
4.	25	2.45, 2.43, 2.45	8.92,8.86,8.92	8.90	628.25

Fig. 6.18(a) and 6.18(b) indicates the value of MEC does not change with increase in air flow rate in laminar region (Re < 2000). For the transitional flow (Re 2000 to 4000) , there is not appreciable increase in MEC value. With further increase in air flow rate inside the flame tube tends to change flow from transitional flow to turbulent flow(Re>4000), resulting in increase in MEC value.

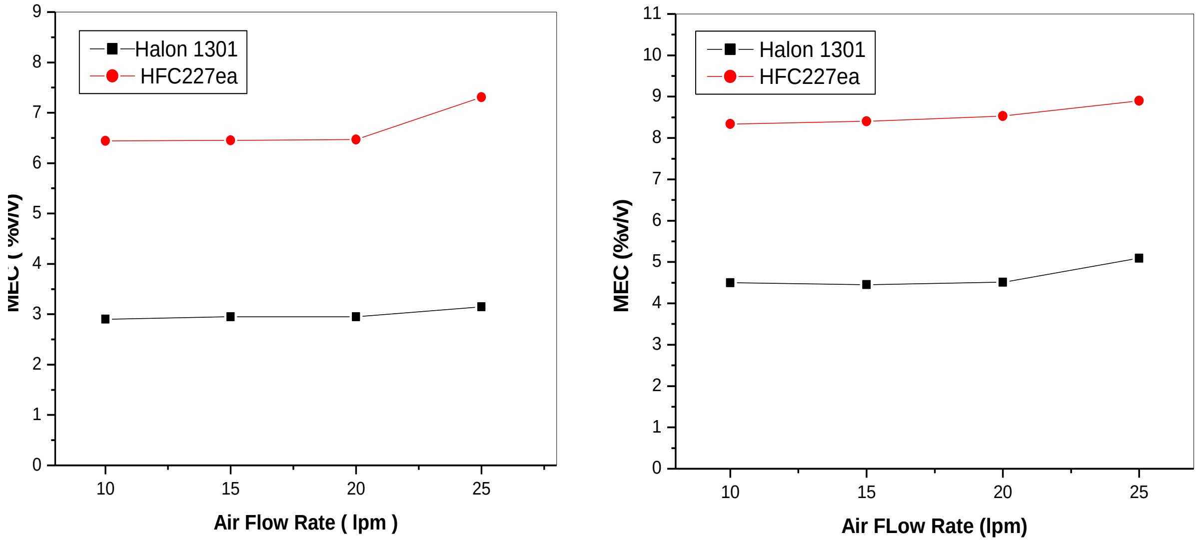


Fig. 6.18 : Minimum Extinguishing Concentration with respect to air flow rate (a) MEC of Halon 1301 and HFC227ea for n- heptane diffusion flame, (b) MEC of Halon 1301and HFC227ea for Ethyl Alcohol diffusion flame]

Fig. 6.18(a) indicates increase in MEC value of 7.9% for Halon 1301 and 9.29% for HFC 227ea for suppressing n-heptane diffusion flame, when flow inside flame tube changes from transitional flow to turbulent flow. Fig. 6.18(b) indicates similar trend and increase in MEC value of 11.59% for Halon 1301 and 6.29% for HFC 227ea for suppressing ethyl alcohol diffusion flame, when flow inside flame tube changes from transitional flow to turbulent flow.

It is observed that flame stability is influenced directly by the air flow past the cup, a higher total flow rate would carry relatively more air & logically may affect the flame stability and resulting in stronger flame [205]. The fuel vaporization and preparation of air-fuel mixture depends on convective Mass Transfer Coefficient as indicated by *Gilliand* :

$$\mathrm{Sh} = \frac{h_{mc} l}{D} = 0.023(\mathrm{Re})^{0.83}(\mathrm{Sc})^{0.44}$$

This equation is applicable for the condition mentioned below

$2000 < Re < 35000$ and $0.6 < Sc < 2.5$

Increasing value of Reynold no. will increase h_{mc} leading to stronger flame

The fuel burning rate is observed to increase with elevated air flow rate. This phenomena is well explained by using Frossling equation for fuel evaporation. This equation states that ratio of evaporation rate under forced convection to free convection is given as :

$$\frac{\dot{m}}{\dot{m}_0} = 1 + 0.276\,\mathrm{Re}^{1/2}\,Sc^{1/3}$$

As evaporation rate is function of Reynold number and Schmidt number, the evaporation rate is calculated for n- heptane fuel and is given in table 6.5

Table 6.5: Evaporation rate of fuel under forced convection

Air flow rate lpm	Reynold Number	MEC % v/v	Fuel evaporation rate
10	1382	6.44	$m=13.4\ m_o$
15	2072	6.45	$m=15.6\ m_o$
25	3485	7.10	$m = 20.6\ m_o$

Results in table 6.5 can be explained on the basis of flow transition to turbulent regime. These conditions increase the air entrainment in the flame and result in higher concentration rate. This in turn increases the fuel evaporation rate through radiation feed back coupling making the flame stronger and therefore 9.29 % more agent is required for extinction of flame at higher value of Reynold number.

The increased MEC value observed for higher value of Reynold number may be because of the two important factors (a) With increase in velocity gradient, burning rate is increased making flame more stronger, hence higher concentration of extinguishing agent is required. (b) The overall increase in flow rate would lead to a reduced agent residence time to some extent, thus at higher air flow rates, higher agent concentration is required leading to higher MEC value.

For suppressing ethyl alcohol diffusion flame with Halon 1301, increase of 11.59% MEC value is observed as compared to increase of 7.9% for n- heptane diffusion flame, when flow inside the flame tube changes from transient region to turbulent region. This higher MEC value for ethyl alcohol fuel is because ethyl alcohol flames are clean i.e no in situ soots are formed leading to low IR emission rates from the reaction zone and consequently low radiative cooling rate. Thus basic thermal quenching burden on the agent is increased and is achieved only at higher agent concentration which leads to increased value of MEC. The cup burner flames are more difficult to extinguish than full scale fire of same fuel. Hence the cup burner is ideally suited for the establishment of design concentration for halocarbon fire suppressant agents. For a same extinguishing agent, the value of MEC is different with different fuels. This indicates there exists different mechanics of flame extinguishment in case of different fuels.

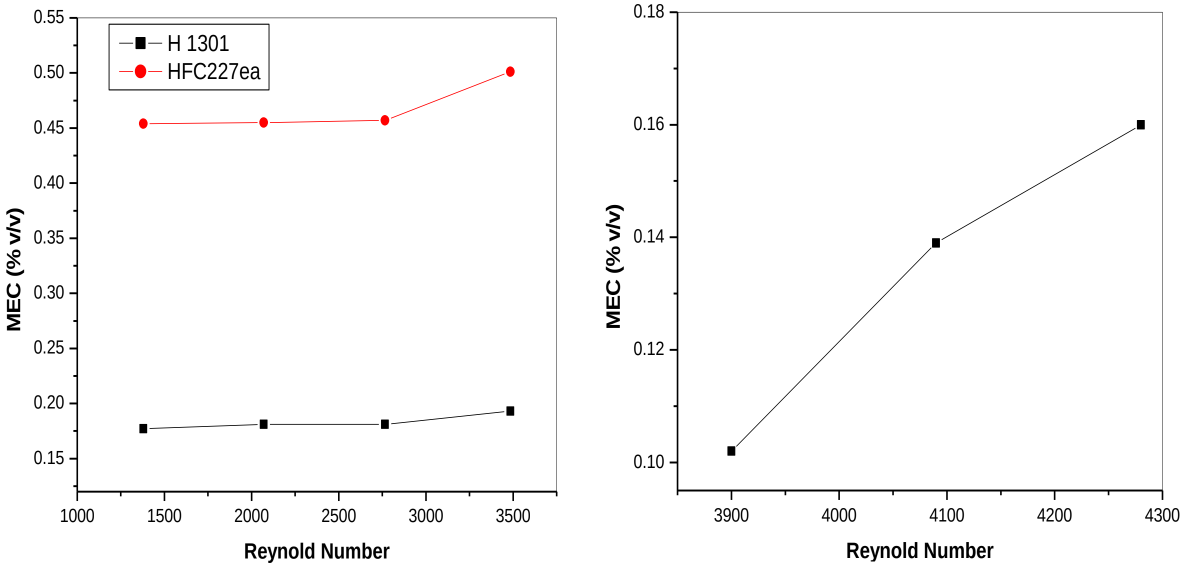
6.4 MEC of Water Mist - Modified Cup Burner Apparatus

All the mist generated by the atomizer did not reach the diffusion flame for carrying out the interactions for fire suppression. Some quantity of mist deposits on internal surfaces of the chimney and floor of the inlet chamber and is considered as losses from the feed concentration. These wall losses are measured and subtracted from the inlet mist feed concentration to obtain effective mist concentration in the flame tube and same is used for calculating the minimum extinguishing concentration (MEC) These are given in the Table-6.6

Table 6.6: MEC of water mist for n- heptane diffusion flame

S.No	Atomizing air (lpm)	Mist Generation rate (gm / sec)	Mist Losses (gm / sec)	MEC (gm/ m^3)
1	26	0.45	0.325	102
2	28	0.5	0.35	139
3	30	0.58	0.40	160

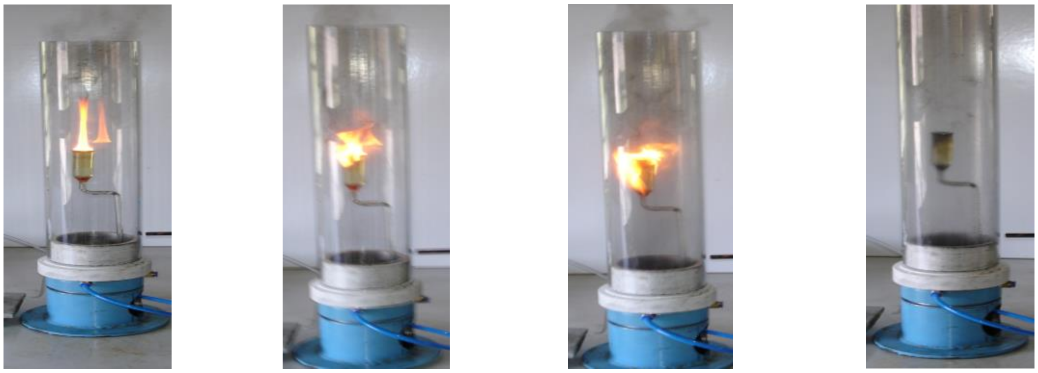
The combustion air flow is kept at 15 lpm into chimney for sustaining the combustion and is measured using a rotameter. The MEC of water mist was 102 gm /m^3 where as MEC of CF_3Br (Halon 1301) and C_3F_7H (HFC227ea) was 177.77 gm/m^3 and 454.59 gm/m^3 respectively for suppressing of n – heptane diffusion flame. For H 1301 and HFC227ea MEC value does not change in laminar region up to Re~1447 and remains unchanged in transient region up to Re~2873 as indicated in figuer 6.19(a). For flow in the near turbulent region with Re~3680, 7.9% increase in MEC value is observed for n-heptane flame. Similar trend is observed for ethyl alcohol diffusion flame. Results of other authors also indicate increase in MEC value at higher value of Re [206-210]. In case of water mist, the experiments were carried out at Re more than 3900 because of higher flow of atomizing air. In the Re~3900 to Re~4280, it was observed that MEC increased with increasing Re number as indicated in Fig. 6.19(b).



(a) (b)

Fig. 6.19 : Suppression of diffusion flame using suppressing agents (a) with Halon 1301 and HFC227ea (b) with mist.

Based on the above results, it is estimated that on mass to mass basis comparison, water droplets having average diameter of 40 µm is 1.7 times more effective then H 1301 and 4.4 times more effective then HFC227ea. It is evident from Fig. that during flame-mist interaction Fig. 6.20(b) and 6.20(c) that flow conditions were turbulent when the mist was introduced in the flame tube, because of higher air flow rates. (Re~3900 to Re~4281) results in starching of the diffusion flame which required higher mist concentration for suppression of flame. The studies on effect of droplet size in suppressing the diffusion flame are carried out during diffusion flame suppression in 40 m^3 enclosed chamber.



(a) t =60 Sec (b) t =62 Sec (c) t =70 Sec (d) t =75 Sec

Fig. 6.20 : Diffusion flame at different time intervals (a) with pre burn time (b) Injection of mist in co flow direction (c) Interaction of flame and mist inside the chimney (d) suppression of flame.

6.5 SUPPRESSION OF DIFFUSION FLAMES IN LARGE ENCLOSED SPACE

6.5.1 Effect on compartment temperature

In order to understand the effect of mist on the fire dynamics two tests were carried out for an 800 kW fire burning at a corner of the fire room. The first test was conducted without the mist and the fire was allowed to burn freely. It was observed that the fire plume reaches its full design height in 20 seconds. Therefore, 20 second pre-burn time was provided for the tests with water mist. The second test was conducted at the same heat release rate, but, water mist at a rate of 1 lpm/atomizer having a corresponding cold spray SMD of 40 µm was introduced into the chamber after the pre-burn time of 20 seconds, from the top of the fire room as mentioned earlier.

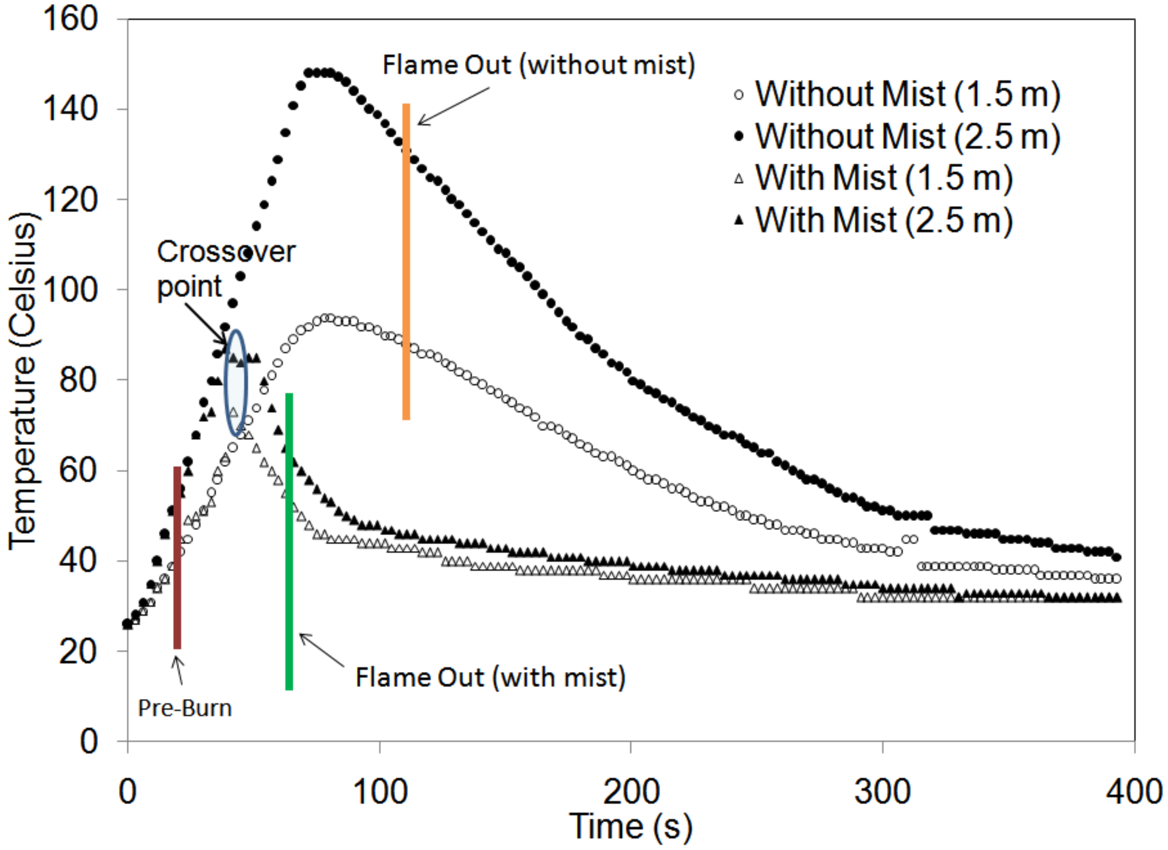


Fig. 6.21: Temporal variation of temperature at two measurement location with and without water mist for 800 kW fire.

The temporal variation of temperature (at 1.5 m and 2.5 m from the floor at a distance of 1 m from the fire) and

6.5.2 Effect on compartment gas concentration

The concentration of O_2, CO_2 and CO inside the large enclosed compartment was measured with and without water mist and the data are plotted in Fig. 6.21 & 6.24. The gas sampling probe was positioned at a height of 1.88 m from the floor and at a distance of 1 m from the diffusion flame.

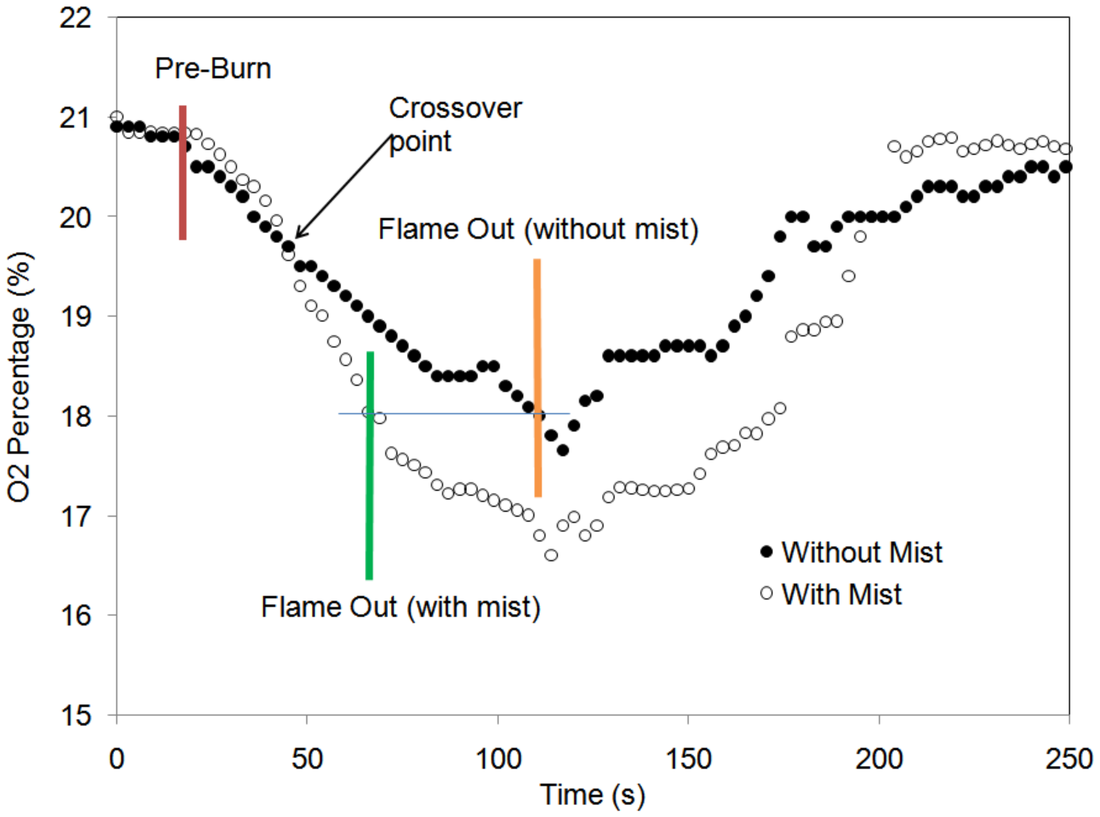


Fig. 6.22: Temporal variation of oxygen concentration with and without water mist for 800 kW fire.

Before discussing the data for the effect of mist on the fire, it is important to discuss the dynamics of freely burning fire. The temporal variation of temperature presented in Fig. 6.21 shows that without the mist, the temperature at both the measurement locations first increase with time, reaches a maximum and then starts to decrease leading to flame out. However, the concentration of O_2 decreases very gradually during the initial 20 seconds (i.e., during the suggested pre-burn for the other test case, see Fig. 6.22) followed by a sharp decrease. On the other hand the concentrations of CO_2 and CO first increase and then reach a state where their concentrations are almost constant as seen in Figs. 6.23 and 6.24 respectively.

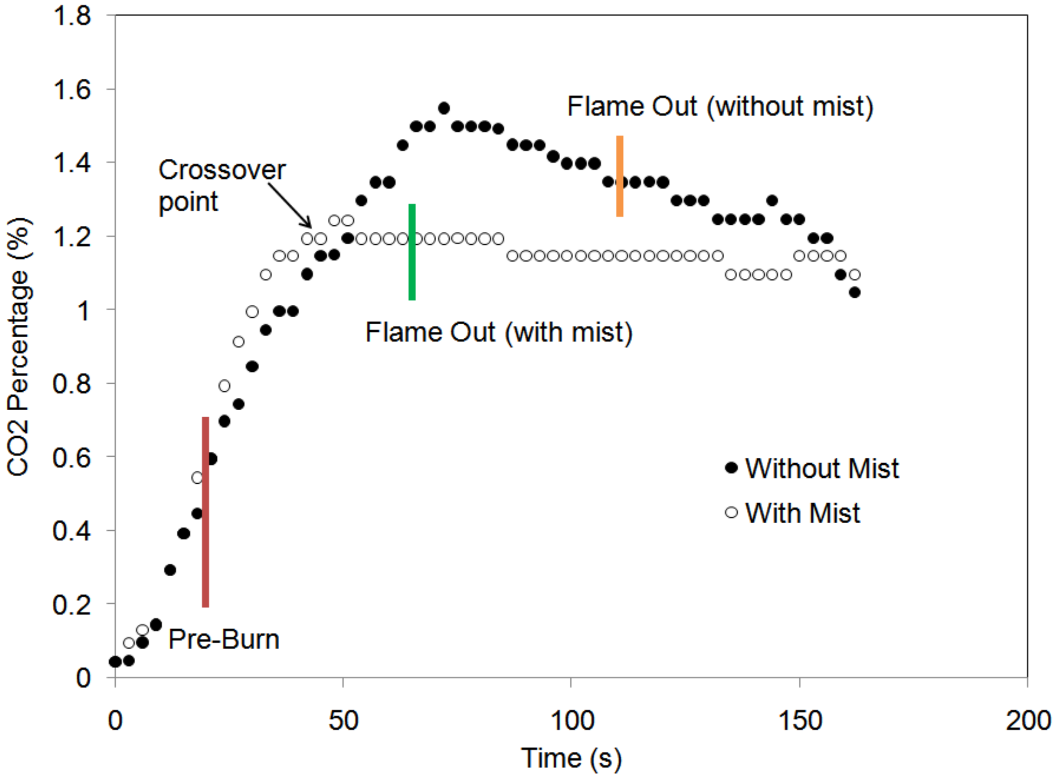


Fig. 6.23: Temporal variation of CO_2 concentration with and without water mist for 800 kW fire.

Another interesting feature seen in Fig. 6.21 is that the temperature recorded at 2.5 m from the floor is higher than that recorded at 1.5 m. This can be attributed to the rising of the hot plume and burned products of combustion towards the ceiling of the fire room, creating a high temperature layer closer to the ceiling and establishing a thermal current from the ceiling towards the floor of the room manifested by the temperature gradient between the two measurement locations. This thermal current establishes a re-circulating flow path of air inside the room resulting in an increased rate of entrainment of air into the fire, causing the fire to burn more vigorously. Therefore, the fire burning rate in an enclosure in faster than that observed in a pool fire burning in open as discussed by Drysdale [205]. It should be pointed out that at the time of flame out after 110 seconds from ignition (as seen in Fig. 6.21), there was still some unburned fuel left in the fire pan. Therefore, the flame out was not because of scarcity of fuel. But, as can be seen in Fig. 6.22, the oxygen concentration in the chamber reduces to almost 18 percent, starving the fire of oxygen and hence the flame out in this case is primarily due to the scarcity of oxygen.

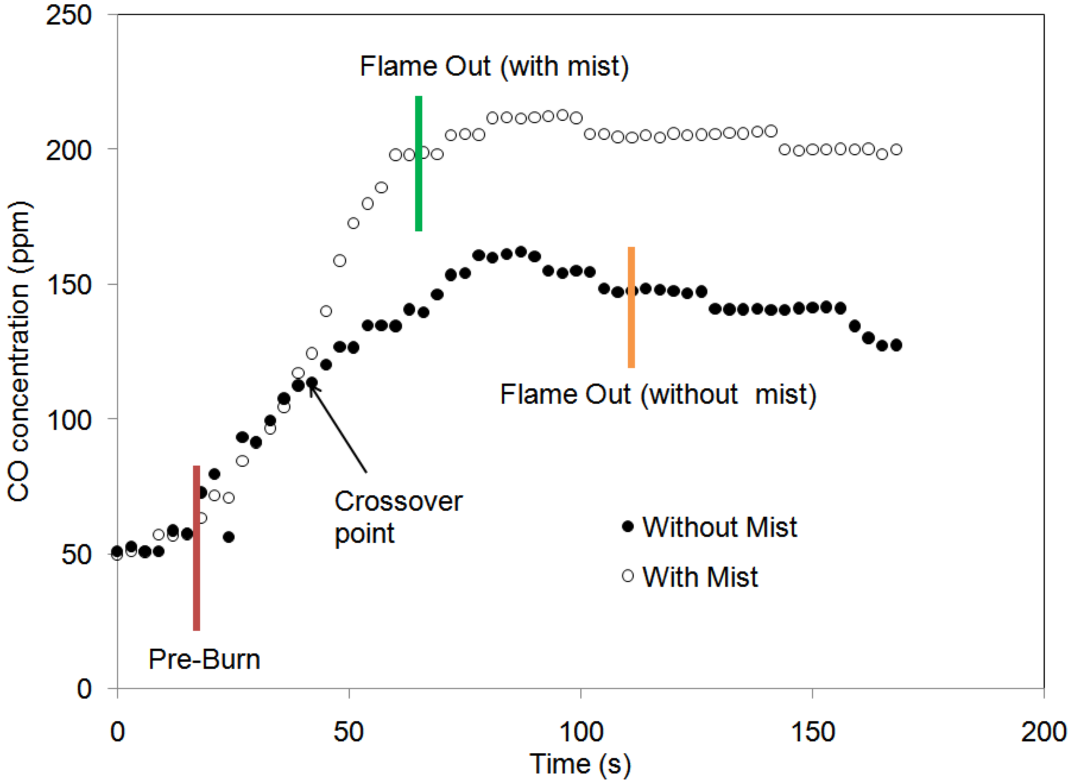


Fig. 6.24: Temporal variation of CO concentration with and without water mist for 800 kW fire.

When the water mist was introduced into the compartment after the specified pre-burn time, it was observed that the fire spreads side wise. Looking at the data presented in Figs. 6.21 and 6.22, one can see that it takes a finite time for the water mist of have substantial effect on the fire. For the first 22 seconds after the introduction of the mist, the temperatures at both the locations remain same as in the case without the mist. However, the concentration of oxygen is higher during this period with the mist. This can be attributed to the use of twin-fluid air-assisted atomizers, which introduce 960 lpm of air into the fire room along with the water mist. But, the rate of decrease of oxygen concentration is higher in the presence of the mist as compared to the one without the mist. Water mist absorbs heat from hot surrounding gas and evaporates quickly. The presence of water vapor in the reaction zone works as a deterrent to the fire by diluting the air and hence reducing the overall concentration of oxygen in the enclosed room. At the same time water mist along with atomizing gas makes a strong dynamic mixing in the compartment and consequently the temperature between upper and lower layer decreases. With regard to the temperature increase initially with water mist, it is expected since the production of thermal energy is normally associated with the mixing of fuel vapor and oxidizer and this phenomenon is enhanced by the entrainment of air from the leaner side of the flame, therefore, one would expect to find an increase in temperature and a decrease in oxygen concentration.

Looking back at the data presented in Fig. 6.22, it can be seen that beyond 42 seconds from the ignition, the oxygen concentration in the case with the mist falls below the concentration measured without the mist. This point is defined as the cross over point in this study. Interestingly, beyond this point, the temperature measured at both the locations (seen in Fig. 6.21) start to fall rapidly leading to a flame out after 65 seconds (or 45 seconds after the pre-burn time). Furthermore, the data in Fig. 6.22 show that the concentration of oxygen at the flame out is same for both the test cases, again suggesting that the scarcity of oxygen is the primary cause of flame out in enclosed fires as has been discussed in the previous paragraphs.

It is probable that there are three effects: (1) diluting effect due to the addition of significant amounts of water vapor causing a reduction in oxygen concentration, (2) exothermic effect associated with the combustion chemistry due to enhanced mixing and hence faster and more energetic combustion leading to rapid consumption of available oxygen and (3) the evaporation and cooling effect due to the presence of water which play the role of a heat sink. The reduction of temperature due to the heat absorption by water is expected to slow down the chemistry and hence slow down the decrease in the concentration of oxygen. But, as seen in Fig. 6.22, the concentration of oxygen continues to decrease at a faster rate, suggesting that the cooling effect is not the dominant effect. Therefore, the combustion chemistry, dictated by the presence of water vapor and the enhanced rate of entrainment, play the crucial role in the decrease in the concentration of oxygen leading to flame out.

The effect of chemistry can be further elucidated by the CO and CO_2 concentrations presented in Figs. 6.23 and 6.24. The data in Fig. 6.23 show that just after the introduction of the mist, there is a marked increase in the concentration of CO_2 till the crossover point and Fig. 6.24 shows a reduction in the concentration of CO at the introduction of the mist till the crossover point with respect to the values measured for freely burning pool fire without the mist. Gas phase oxidation involves a great number of elementary steps in which highly reactive atoms or radicals such as H* and OH* take part. With regard to the combustion products, the reaction

$CO + OH^* \rightarrow CO_2 + H^*$ is a significant reaction by which CO is oxidized, in the temperature ranges generally encountered in fires and, indeed, is the main source of CO_2 [211,212].

Thus carbon monoxide is released if the concentration of OH* radicals is not sufficient to permit the preceding reaction to be complete. In general, there is always competition, for the hydroxyl radical OH between CO and other partially burned products of combustion, which tends to limit the conversion of CO to CO_2. This is a well documented effect [205, 211, 212]. In addition, the rate of this conversion is also limited by the presence of soot particles which are known to react with hydroxyl radicals [213]. The increase in CO_2 concentration and the decrease in CO concentration before the cross over time suggest that during this period, the combustion is more efficient resulting in the conversion of CO to CO_2 following the water gas reaction. Therefore, the second effect mentioned in the previous paragraph, i.e., the enhanced rate and efficiency of chemical reaction due to the improved entrainment of air into the fire seems to be the dominant effect in this period and is responsible for the rapid decrease in oxygen concentration as well as the increase in temperature.

Beyond the cross over period, the concentration of CO_2 remains almost constant but the concentration of CO increases rapidly in comparison to the case without the mist suggesting incomplete combustion. It can be argued that the combined effect of the flame cooling due to the evaporation of water and the presence of water vapor that dilutes the concentration of the oxidizer around the fire results in slowing down the reaction and impeding the conversion of CO to CO_2. Therefore, the final flame out is facilitated by the first mechanism, i.e., dilution of air due to water vapor resulting in incomplete combustion due to scarcity of oxygen leading to an increase in the final concentration of CO and a decrease in the concentration of CO_2 as seen in Figs. 6.22, 6.23 and 6.24.

6.5.3 Effect of Heat Release Rate

As has been suggested by Grant et al [214], the optimum droplet size for most efficient fire suppression depends on the type of fire and hence, the heat release rate is expected to play a crucial role in fire suppression using water mist. In order to elucidate the effect of heat release rate in fire suppression, experiments were carried out for three different cases (i.e., 300 kW, 500 kW and 800 kW) as discussed earlier and the effect of 40 µm SMD droplets at a rate of 1 lpm/atomizer on the fire dynamics were studied and the results are presented in Figs.6.25 – 6.28. The data in Fig. 6.25 show that the flame out time decreases with an increase in the heat release rate. This phenomenon seems to be counter intuitive as one expects that the time taken to suppress a bigger fire will be more than that required to suppress a smaller fire.

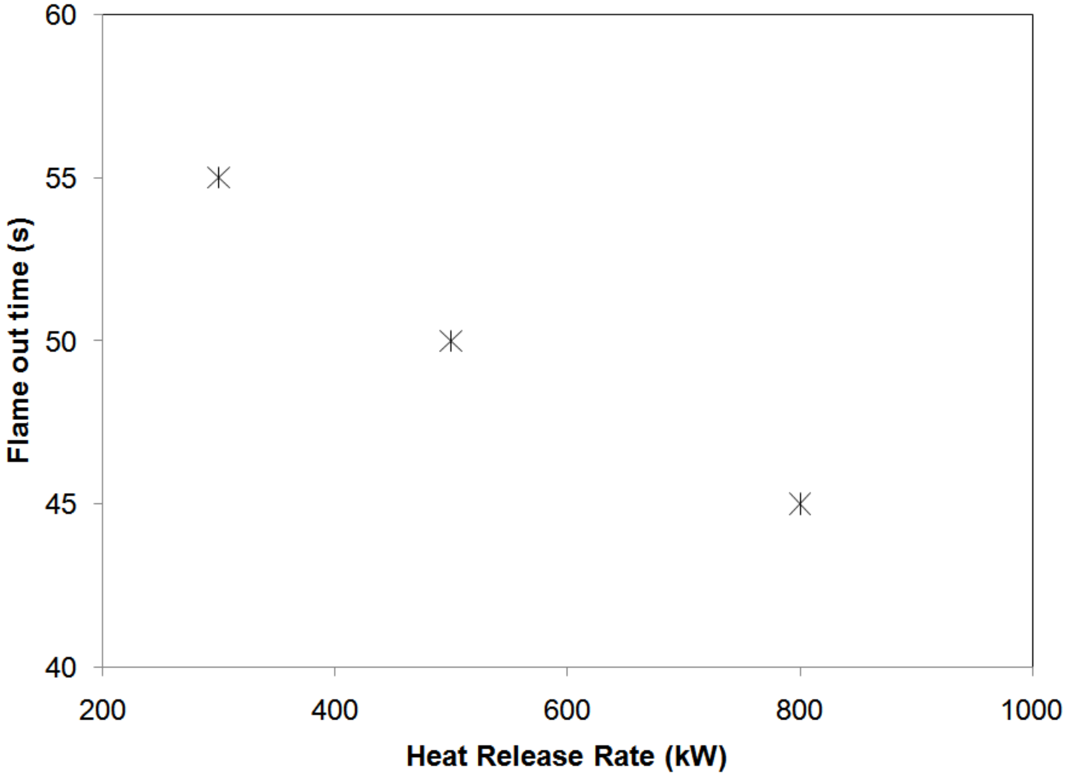


Fig. 6.25 : Effect of the Heat Release Rate of the pool fire on the fire suppression time using 40 µm SMD water mist.

The temporal variation of temperature at 2.5 m from the floor (as discussed earlier), O_2 concentration and CO concentration for 300 kW and 800 kW fires are compared in Figs. 6.26, 6.27 and 6.28. The data in Fig. 6.26, i.e., the temporal variation in temperature show a much stepper gradient in the increase in temperature and a higher temperature during the pre-burn for the 800 kW fire, which is expected due to the higher heat release rate. Larger heat release rate produces stronger thermal currents inside the enclosure, improving the entrainment of air into the flame and thus, causes a faster rise in the temperature as seen in Fig. 6.26.

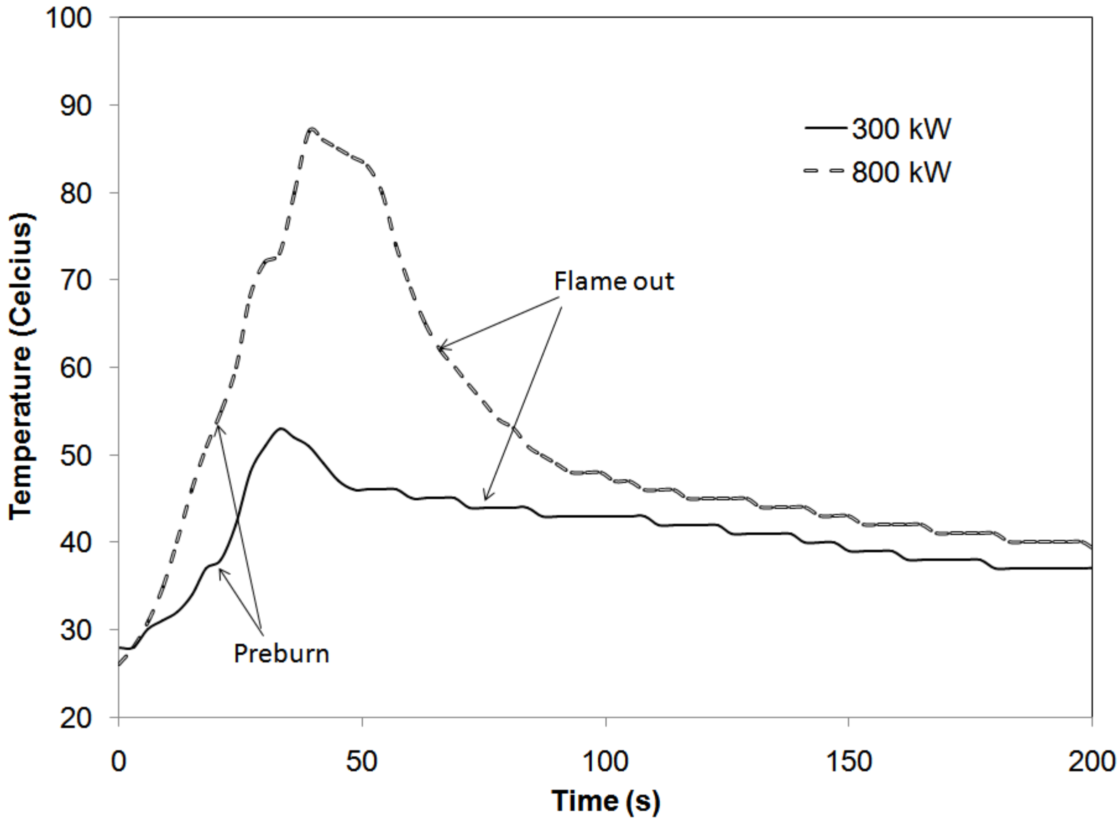


Fig. 6.26 : Temporal variation of temperature at 2.5 m from the floor for 300 kW and 800 kW fires with 40 µm SMD water mist.

The maximum temperature attained at the measurement location for 800 kW fire is also higher, followed by a sharper decrease in temperature before the flame out. However, the temperatures are substantially lower for the 300 kW fire, which is expected to reduce the rate of vaporization of water mist. Therefore, in the case of 300 kW fire, the oxygen concentration starts to increase immediately after the flame out as the reduction in O_2 concentration due to the dilution by water vapor stops. Whereas, the presence of higher temperature for 800 kW fire ensures that the vaporization continues for a while after the flame out and the oxygen concentration continues to decrease before it can increase again as seen in Fig.6.29. The concentration of CO after the introduction of the water mist is substantially higher in the case of 800 kW fire as can be seen in Fig. 6.28, suggesting incomplete combustion in the presence of water vapor as has been discussed earlier. Therefore, the earlier flame out in the case of 800 kW fire, as compared to the fires with lower heat release rates, can be attributed to the change in chemistry due to the presence of water vapor leading to inefficient combustion.

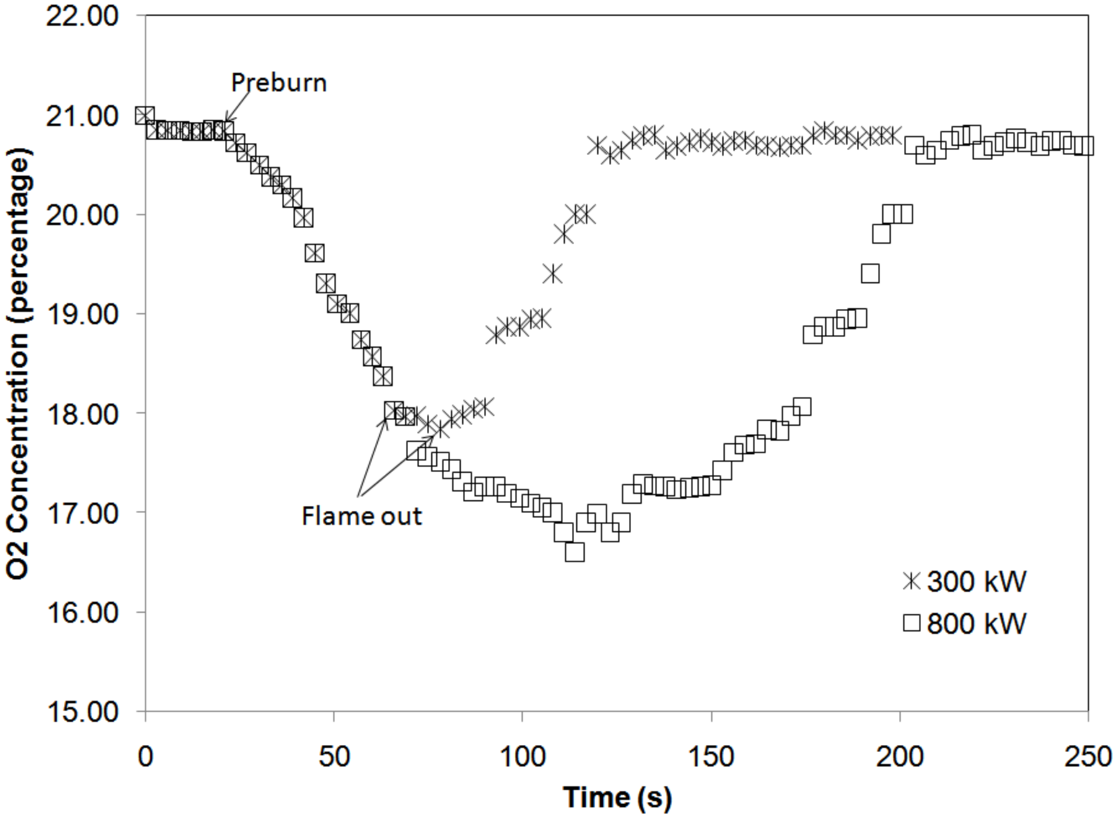


Fig. 6.27 : Temporal variation of oxygen concentration for 300 kW and 800 kW fires with 40 µm SMD water mist.

One may argue that the rate of oxygen consumption in the case of more intense fire (i.e, fire with higher HRR) will be more than that with lower HRR as the oxygen requirement for a larger fire is more. However, the rate of vapor formation is also expected to be higher for a larger fire that can substantially reduce the efficiency of the combustion process and thus, reduce the rate of oxygen consumption and increase the rate of production of CO (as seen in Fig. 6.28). Therefore, the opposing effect of higher oxygen requirement and slower chemistry at higher HRR seems to balance each other and therefore, the rate of consumption of oxygen is same for both the fires, as can be seen in Fig. 6.27.

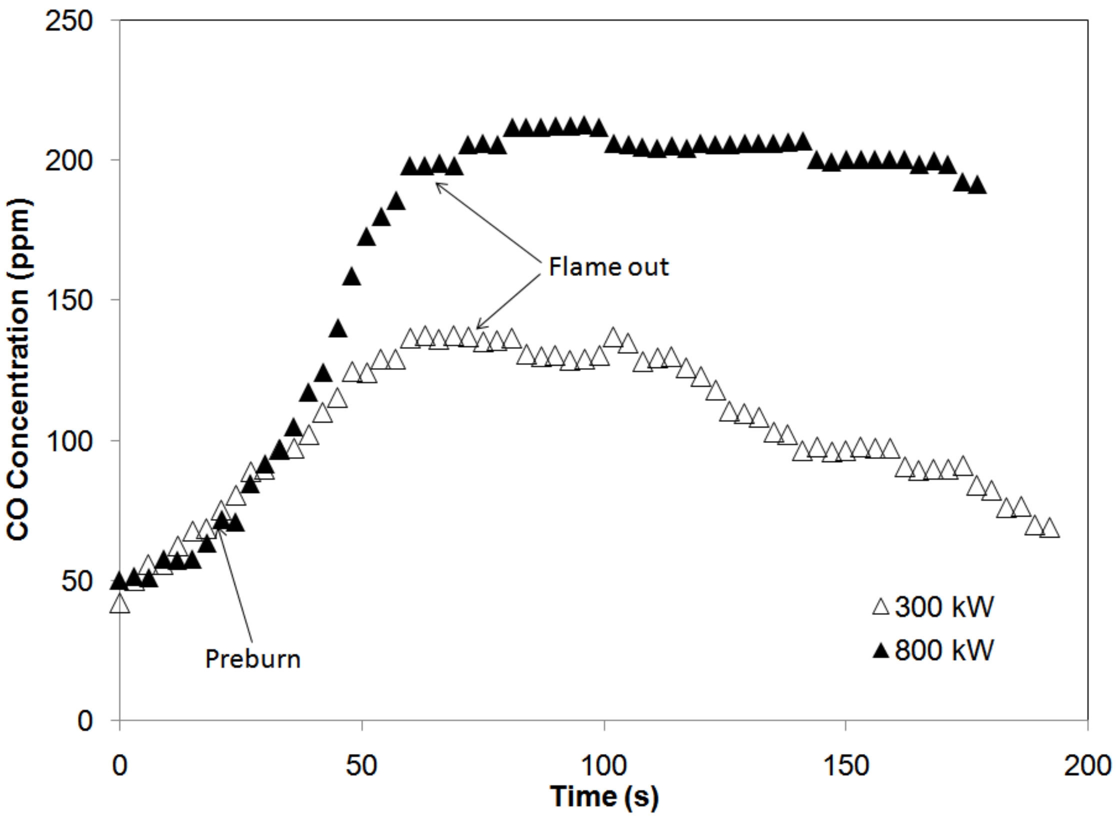


Fig. 6.28: Temporal variation of CO concentration for 300 kW and 800 kW fires with 40 μm SMD water mist.

6.5.4 Effect of droplet size

Since it takes longer to suppress a smaller fire using water mist, the effect of droplet size on the flame out time for a 300 kW fire was studied and the results are plotted in Fig. 6.29. The fire suppression experiments were carried out with water mist of three different Sauter mean diameters, i.e, 40, 80,120 μm. The droplet size in these experiments was varied by changing the supply pressure of the atomizing air, while keeping the same water through-put. Water mist with Sauter mean diameter of 40 μm is observed to be most effective in suppressing the fire. The extinction time increases with an increase in droplet diameter. The mist with larger droplets did not interact with flame in combustion zone and hence took longer time to suppress the pool fires due to lower rate of vaporization, where as 40 μm droplets took minimum extinction time as they were easily entrained into the flame with air, which resulted in slowing the combustion process and hence, smaller fire extinction time.

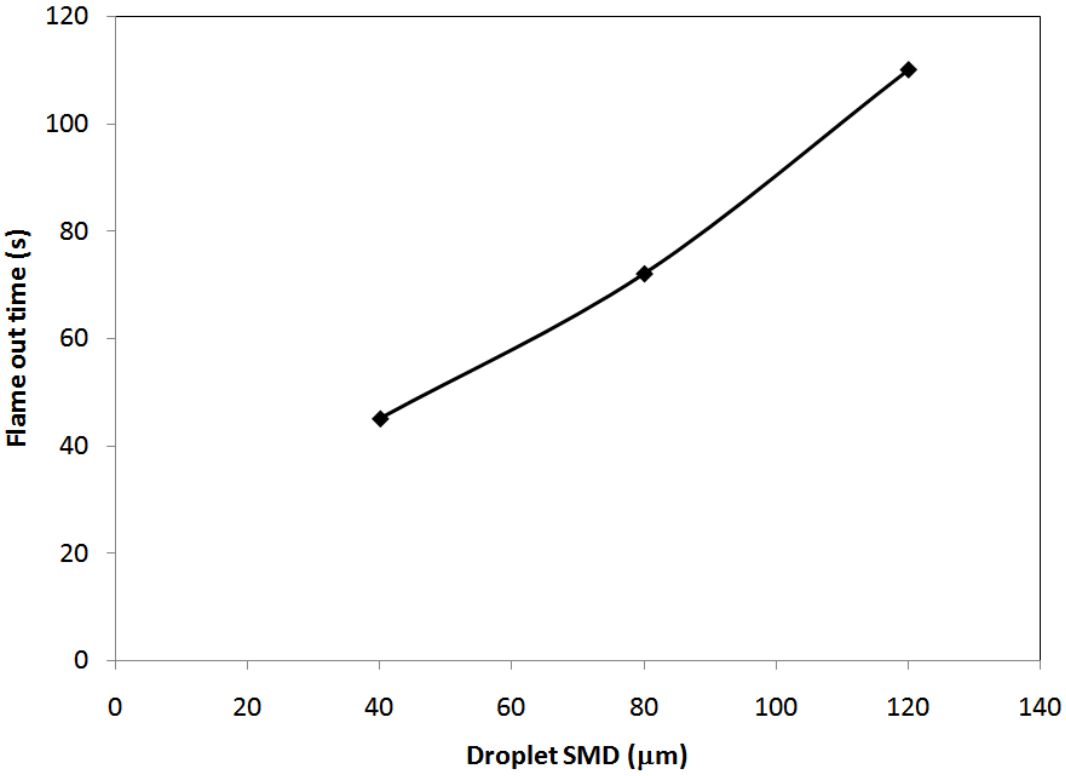


Fig. 6.29: Dependence of fire suppression time on droplet diameter for 300 kW fire.

6.5.5 Critical mist concentration

In order to estimate the amount of mist required to suppress a pool fire in a room, the total amount of mist (with 40 μm SMD droplets) supplied into the chamber to suppress the fire, i.e. the amount of mist supplied after the pre-burn and up to the time when the fires were out, were estimated by multiplying the flow rates of water with the flame out time. The total mass of water used to suppress the fire were then divided by the enclosure volume to estimate the critical mist concentration required to suppress the fires of different heat release rates. The variation of critical mist concentration with heat release rate for 40 μm SMD mist is shown in Fig. 6.30. As has been discussed earlier, the rate of vaporization is enhanced with an increase in heat release rate, thus, reducing the combustion efficiency and impeding the burning of fire. Therefore, the amount of mist required to suppress a pool fire in an enclosure reduces with an increase in the heat release rate.

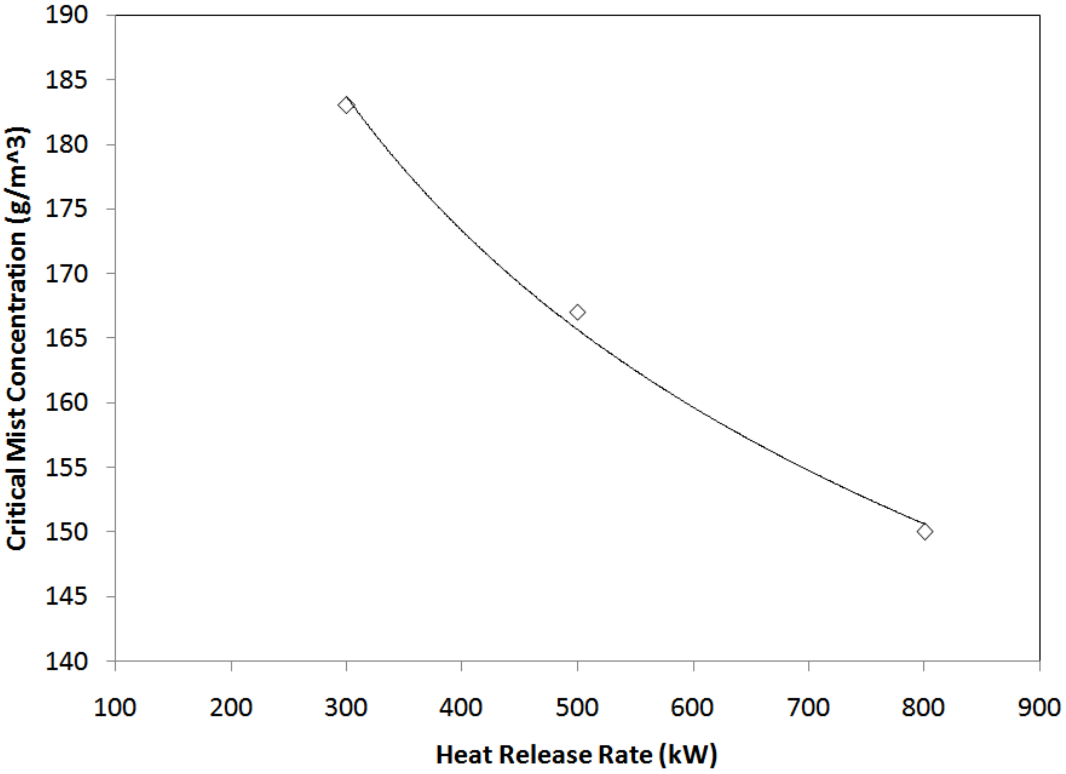


Fig. 6.30: Dependence of critical mist concentration on the heat release rate of the fire for 40 μm SMD water mist.

6.5.6 Effect of atomizing gas

An experimental investigation on the effectiveness of nitrogen as atomizing gas for suppression of diffusion flames of different heat release rate in the large enclosed spaces is conducted. As mist critical concentration and diffusion flame extinction time are used as a measure of flame suppression effectiveness, therefore experiments carried out in the 40 m^3 chamber with diffusion flame having different heat release rate. The water mist with droplet size of 40 μm was generated using nitrogen as atomizing gas.

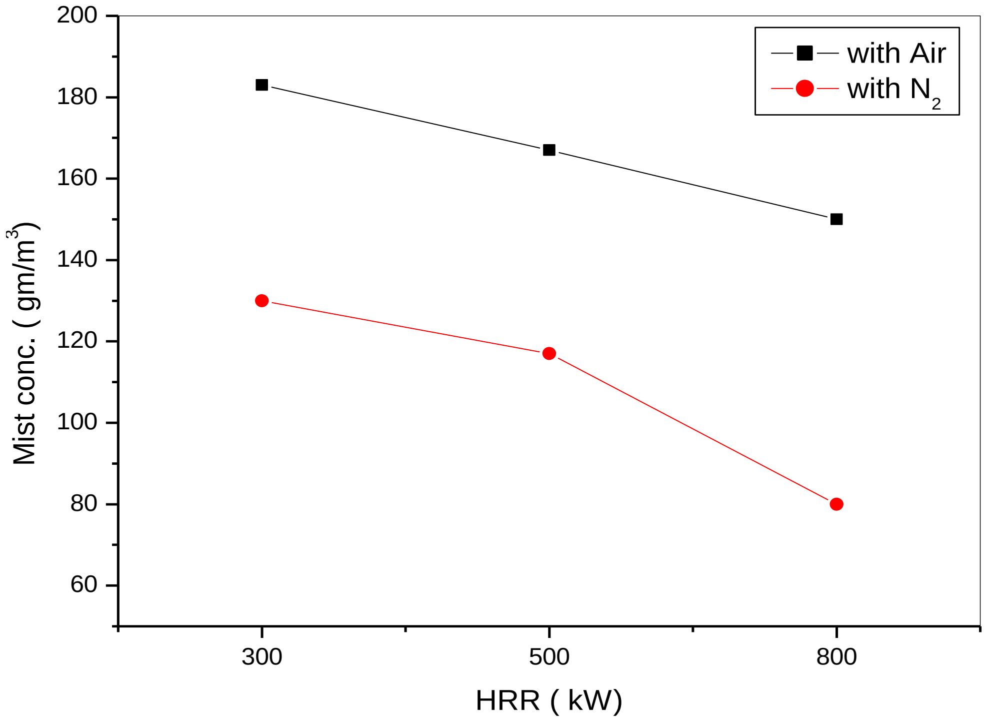


Fig. 6.31: Critical mist concentration for diffusion flames unobstructed pool fires

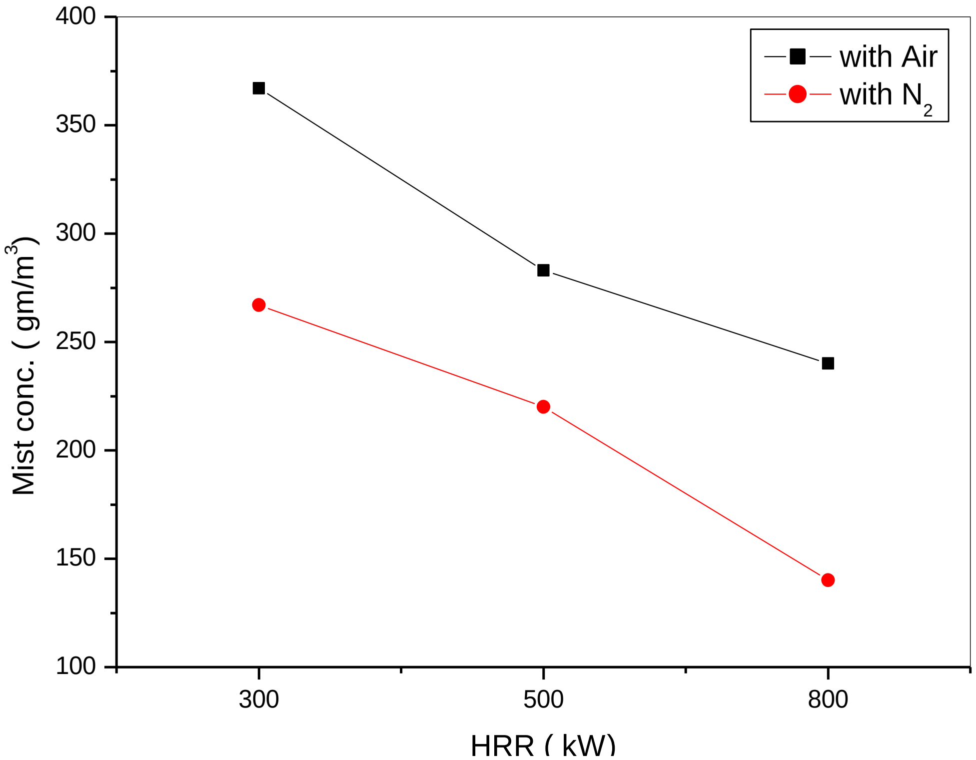


Fig. 6.32: Critical mist concentration for diffusion flames obstructed pool fires

The use of nitrogen as atomizing gas, the critical concentration required for suppression of diffusion flames with heat release rate of 300 & 500 kW is reduced by 30 % for unobstructed and obstructed pool fires Fig 6.31 & 6.32 . Where as for diffusion flames with higher heat release rate i.e 800 kW, the critical concentration required was reduced by 50 % with nitrogen as compared to air. The use of nitrogen creates inert environment in the enclosed space and helps in lowering the compartment oxygen concentration along with formation of water vapour. The formation of water vapous is higher in case of diffusion flames with higher heat release rate, leading to smaller concentration of water mist required for suppression as compared to diffusion flames with lower heat release rate.

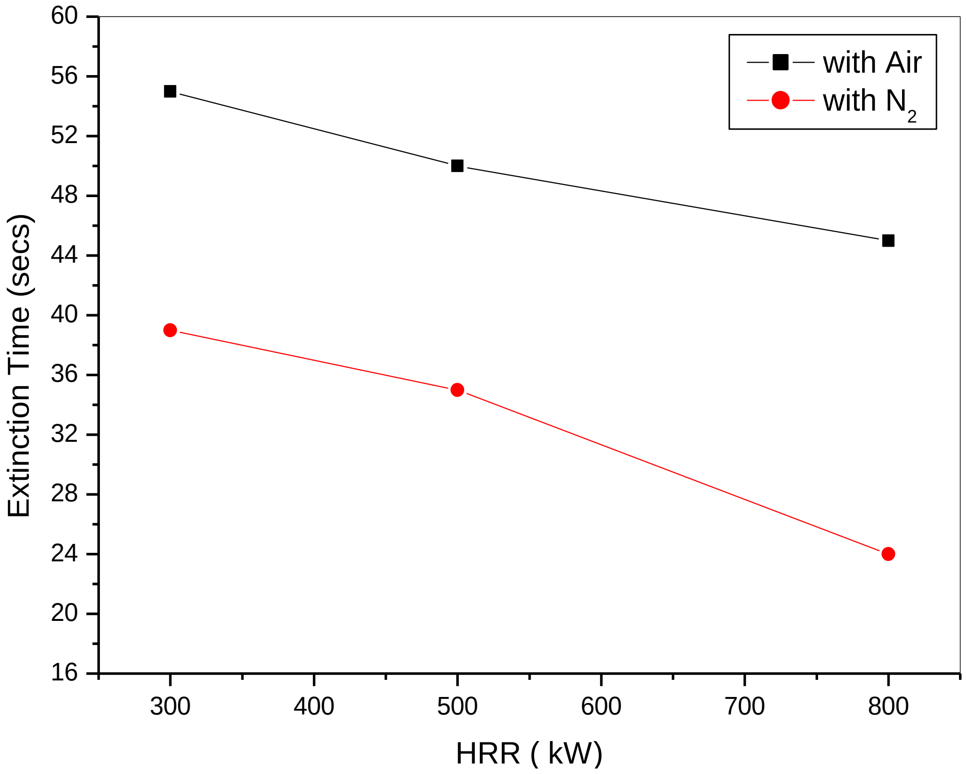


Fig. 6.33: Diffusion flame extinction time unobstructed pool fires

The flame extinction time for diffusion flames of different heat release rates are presented in Fig 6.33 for unobstructed & 6.34 for obstructed pool fires. The use of nitrogen as atomizing gas resulted in reduction in flame extinction time upto 30% for diffusion flames with heat release rates of 300 & 500 kW and upto 45% for diffusion flames with higher heat release rate i.e 800 kW. This reduction in flame extinction time is because of reduction in oxygen concentration in the compartment leads to entrainment of nitrogen in the flame zone along with the water vapours. As the concentration of air in the enclosed compartment is reduced to a large extent leading to slow combustion process and finally extinction of diffusion flame.

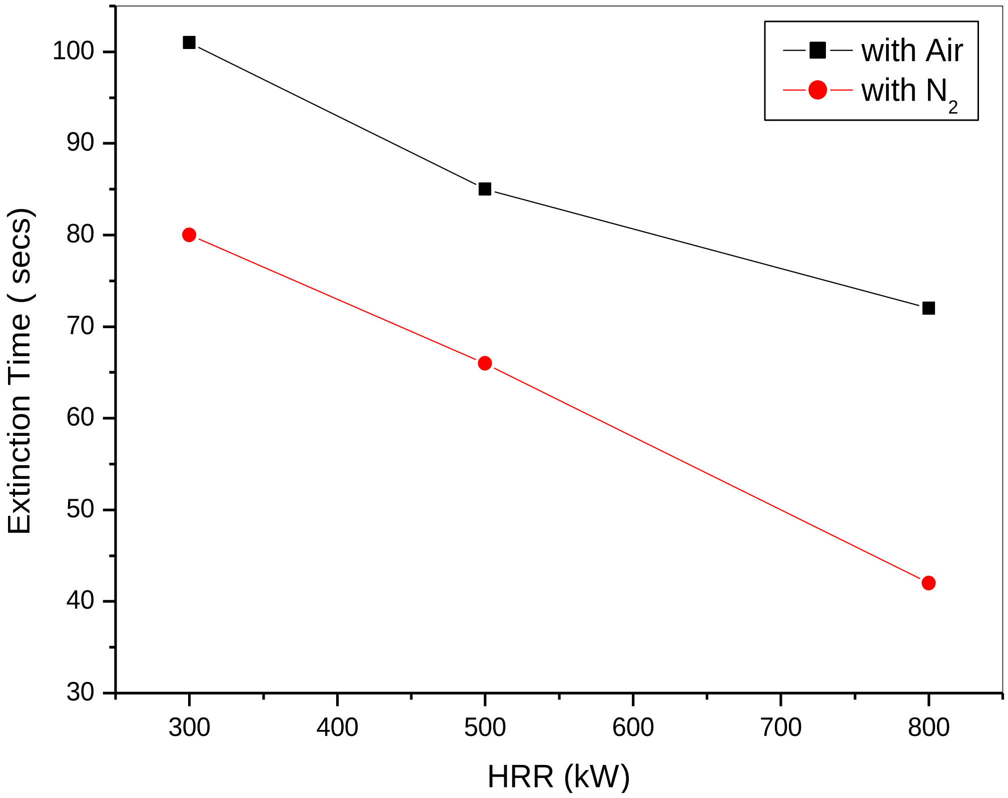


Fig. 6.34: Diffusion flame extinction time obstructed pool fires.

It should be noted that the large scale of experimentation restricts the number of cases that can be studied. Therefore, the presented study is primarily focused on understanding fire dynamics in the presence of water mist and the suppression of fire using water mist in a large room. It is realized that the parametric study (i.e. effect of HRR, droplet diameter and critical mist concentration) is limited in its scope and therefore, any proposed scaling law can be inadequate. However, the present study provides a guideline for further research in this field to come up with an optimum design of the mist generation system for enclosure fires.

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APPENDIX – I

Instrument for the Measurement of Droplet Size Distribution

An Ensemble Particle Concentration and Sizing apparatus (EPCS, Insitec/Malvern®, Worcestershire, U.K.) was used to measure the average droplet diameter of the spray. The operating principle of this apparatus is based on low angle laser light scattering. The dynamic measurement range for this system was between 2 microns to 850 microns. To determine droplet diameter from the input signals, EPCS uses a computer program (RTSizer, Insitec/Malvern®, Worcestershire, U.K.), which is based on the Mie theory of light-particle interactions. The instrument uses 670 nanometer He-Ne laser with a beam diameter of 10 mm. The accuracy of the instrument was ± 3% of full scale (specified by the manufacturer) and it could measure the size distribution of sprays with obscurations up to 95%. The measurement rate of equipment was one measurement every 400 microseconds. Measurements were taken along the centerline of the spray cone at a distance of 1 meters below the exit of the atomizer. Sauter mean diameter (SMD) was used as a meaningful quantity to represent the average of droplet diameter. SMD represents an average droplet diameter with the same volume to surface area ratio as that of the entire spray. It should be noted that for fuel combustion applications, emphasizes is given to the use of this average diameter criteria, since it is least susceptible to a large spread in the droplet diameter distribution.

The spray was required to be separated from the electronic noise and the background. In order to filter out the electronic noise, a sample snap (keeping the lens of the camera covered) was captured. This image was then subtracted from the spray images in order to deduct the effect of the electronic components. To filter the background optical noise, an image, containing only the background (keeping the spray off), was taken and the pixel wise intensity distribution was estimated. Once the spray was turned on, the zone containing the spray got brighter than the background resulting in an increase in the corresponding pixel intensities in the image matrix. Thus, a pixel, in an image containing the spray, with an intensity value higher than the corresponding values in the image containing solely the background was considered to be the one representing the spray.

Figure A-1 Droplet Size Analyzer in Operation

APPENDIX – II

Instrument for the Measurement of Gas Concentrations

MRU Air Emission Monitoring System GmbH (model no : DELTA 1600 V) NDIR (Non Dispersive Infra-red) based multi gas analyzer was used to measure the concentration of CO, CO_2 and paramagnetic method for measure of O_2 in the test compartment (40 m^3 chamber). In the NDIR analyzer the gas species being measured is used to detect itself. This is done by selective absorption. The infrared energy of particular wavelength or frequency is peculiar to certain gas in that the gas will absorb the infrared energy of this wavelength and transmit infrared energy of other wavelengths. For example, the absorption band of carbon monoxide is between 4.5 to 5 microns. So the energy absorbed at this wavelength is an indication of concentration of CO present in the combustion emission. The Oxygen is measured using paramagnetic method, which has oxygen sensor built inside the gas analyzer.

The NDIR analyzer is shown in Figure A-2 consists of two infrared sources, interrupted simultaneously by the optical chopper. Radiations from these sources pass in parallel paths through a reference cell and a sample cell to opposite side of a common detector. The sample cell contains the compound to be analyzed, whereas this compound is not present in reference cell. The latter usually filled with an inert gas, usually nitrogen, which does not absorb the infrared energy for the wavelength corresponding to the compound being measured. A closed container filled with only compound to be measured works as detector.

The detector is divided into two equal volumes by a metallic diaphragm. When the chopper blocks the radiation, the pressure in both parts of the detector is same and the diaphragm remains in the neutral position. As the chopper blocks the unblocks the radiation, the radiant energy from one source passes through the reference cell unchanged whereas the sample absorbs infrared energy at the wavelength of the compound in the cell. The absorption is proportional to the concentration of the compound to be measured in the sample cell. Thus unequal amount of energy are transmitted to the two volumes of the detector and the pressure differential so generated causes movement of the diaphragm of the detector. This changes the capacitance between the diaphragm and a fixed probe, thereby generating an a.c signal which is amplified and, after rectification to d.c., displayed on a meter. The signal is a function of the concentration of the compound to be measured.

Figure A-2   Schematic diagram of NDIR analyzer

APPENDIX – III

Instrument for the Measurement of Spatial Temperature

Temperature measurement was carried out using K type thermocouples installed on thermocouple tree. Two thermocouples on the thermocouple tree gives the spatial temperature inside the enclosed chamber at different heights. K Type (inconel sheath) thermocouples having response time of 1 sec (mineral insulated, grounded junction) with a accuracy of 1 % of full scale was used for temperature measurement. The thermocouple tree made of stainless steel having height of 2 .7 meter was used to position the thermocouples at different heights. Figure A-3 indicate the schematic of the thermocouple tree.

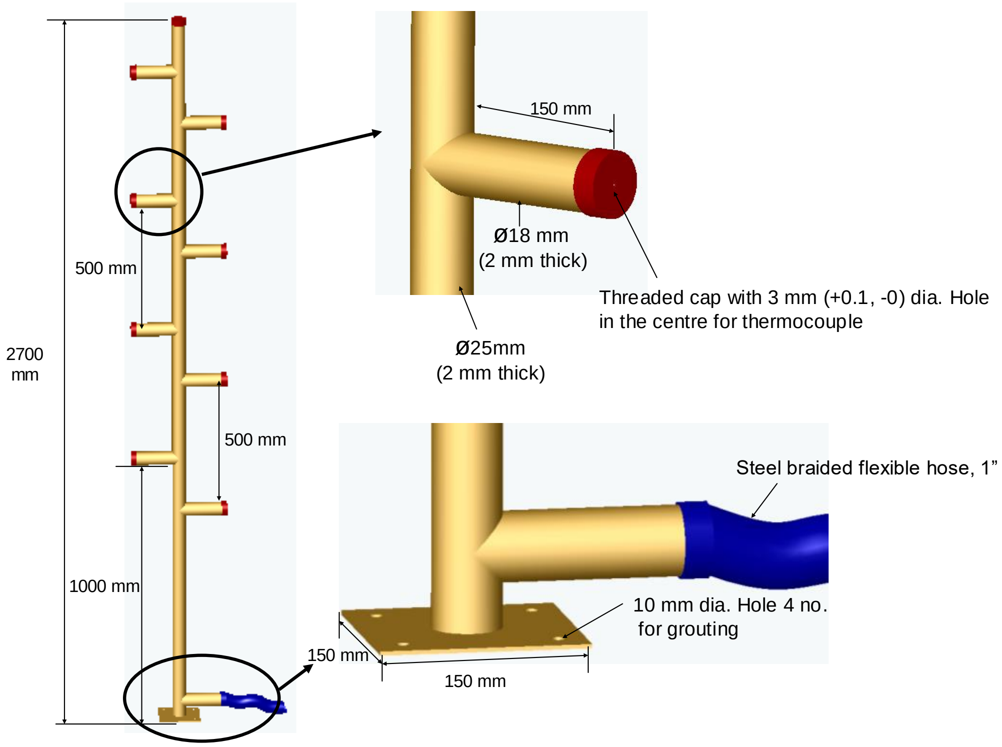

Figure A-3 Thermocouple tree for spatial temperature measurement

SUPPRESSION OF DIFFUSION FLAMES WITH WATER MIST

A THESIS
SUBMITTED IN FULFILMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE OF

DOCTOR OF PHILOSOPY

BY

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APRIL, 2010

Chapter 7

CONCLUSIONS

The twin-fluid internally mixed mist generator is very versatile kind of atomizer having great control on atomization process. In this type of mist generators, atomization is attained by injecting a small amount of compressed air into a liquid stream in a mixing chamber inside the mist generator. Since most of the energy for atomization is supplied to the liquid by the atomizing air, a significantly small pressure drop can produce a fine spray. The dependence of droplet size upon the liquid supply pressure and the air liquid mass ratio was studied in detail using a Malvern Particle size analyzer.

The results suggest that the atomizer could be used to control the flow rate (mist through put) and spray characteristics independent of each other by simultaneously varying the supply pressure of the liquid and the atomizing air. The controlled atomization of such atomizer makes it attractive to be used for fire suppression applications in particular because of the high mist generation rate and for various other commercial applications in general, as the atomizer is capable of providing spray of different characteristics depending upon the application requirements.

An internally mixed twin –fluid mist generator that can be potentially used in the suppression of diffusion flames was experimentally investigated. The investigated mist generator provided droplets with SMD in the 15-85 μm range. The measured data suggest that such injectors can be employed to control the atomization process by simultaneously varying the liquid and air supply pressures. The liquid flow rate is seen to decrease with an increase in air liquid mass ratio, which is attributed to a decrease in available area for liquid flow with increasing air flow rate. The droplet diameter is seen to decrease with an increase in air liquid mass ratio and liquid supply pressure due to an increase in inertial forces.

Another type of atomizer that was used for generating mist with low through-put for carrying out experiments in modified cup burner apparatus was siphon fed externally mixed air blast atomizer. In this type of the atomizer, atomization is attained by injecting a air stream at tip of the water injection port. The water is siphon fed because of the pressure difference. The result of experimental and theoretical studies of an siphon fed externally mixed air blast atomizer indicate that flow becomes supersonic beyond the supply pressure of 0.8 bar. The the prediction of mathematical model that depics the two phase flow in externally mixed atomizer. The model uses compressible flow relationships to predict the air flow rate, a neural network based model to predict the water flow rate and a novel droplet formation model to predict the droplet SMD. A statistically distributed Weber number criterion is used to estimate the sizes of the droplets produced in the atomization process. The liquid flow rate, air flow rate and sauter mean diameter predicted by model are compared with the experimental data and they are found to be in fair agreement with each other, suggesting that model properly describes the physics of two- phase flow within the atomizer.

The standard cup burner method was used for experimentally measuring the Minimum Extinguishing Concentration (MEC) of fire extinguishing agents (Halon 1301 and HFC 227ea) for suppression of n-heptane & ethyl alcohol diffusion flames. The MEC was measured, which does not change with increase in air flow rate in laminar region (Re ~ 2000). For the transitional region (Re 2000 - 4000), there is not appreciable increase in MEC value and increase in MEC is observed near turbulent region (Re ~ 4000). The increase in air flow rate inside the flame tube increased the burning rate of fuel making diffusion flame stronger. The agent residence time is reduced requiring higher concentration of agent for suppression of diffusion flame. The increase in MEC value of 7.9% for Halon 1301 and 9.29% for HFC 227ea for suppressing n-heptane diffusion flame, when flow inside flame tube changes from transitional flow to near turbulent flow. The increase in MEC value of 11.59% for Halon 1301 and 6.29% for HFC 227ea for suppressing ethyl alcohol diffusion flame, when flow inside flame tube changes from transitional flow to near turbulent flow. The MEC of CF_3Br (Halon 1301) and C_3F_7H (HFC227ea) was 177.77 gm/m^3 and 454.59 gm/m^3 respectively for suppressing of n – heptane diffusion flame.

The MEC of water mist was experimentally measured in modified cup burner apparatus for suppression of n-heptane diffusion flame. The mist with droplet size of 40 µm was injected into flame chimney in the turbulent region (Re ~ 3900-4200). It is observed that MEC increases with increase in the air flow rate and 34% increase in value of MEC was observed. The MEC of water mist was 102 gm /m^3 for suppression of n-heptane diffusion flame. It is also observed that on mass to mass basis water mist is 1.7 times more effective then Halon 1301 and 4.4 times more effective then HFC227ea in suppressing a n- heptane diffusion flame.

The pool fire suppression tests were conducted in large enclosed space using water mist and results indicate that the water mist suppress the diffusion flame in the enclosed space mainly through the evaporating cooling and oxygen displacement by water vapors resulting in inefficient combustion. The fire suppression time decreases with a decrease in droplet diameter. It is much easier to suppress a larger fire due to faster rates of evaporation of water droplets and therefore, the critical mist concentration decreases with an increase in the fire size.

The temporal variation of temperature in the enclosure increase with time without the mist, reaches a maximum and then starts to decrease leading to flame out. However, the concentration of O_2 decreases very gradually during the initial 20 seconds (i.e., during the suggested pre-burn for the other test case) followed by a sharp decrease. On the other hand the concentrations of CO_2 and CO first increase and then reach a state where their concentrations are almost constant . When the water mist was introduced into the compartment after the specified pre-burn time the rate of decrease of oxygen concentration is higher as compared to the one without the mist. Water mist absorbs heat from hot surrounding gas and evaporates quickly. The presence of water vapor in the reaction zone works as a deterrent to the fire by diluting the air and hence reducing the overall concentration of oxygen in the enclosed room. The sharp reduction in the temperature was observed after injection of mist.

The results reported show that the evaporation of water droplets into vapor, causing dilution of air and the subsequent slow down of the combustion process, leading to inefficient combustion manifested by an increase in the concentration of CO, is the primary mechanism for fire suppression using water mists in enclosed spaces. Larger the fire size less is the time required to extinguish the fire. This can be attributed to the larger heat available for evaporation of the water mist droplets leading to attaining the inert environment faster by formation of water vapor and causing dilution of oxygen concentration below that required for sustained combustion reaction. Therefore, the critical mist concentration reduces with an increase in HRR of the fire. As has been discussed earlier, the rate of vaporization is enhanced with an increase in heat release rate, thus, reducing the combustion efficiency and impeding the burning of fire. Therefore, the amount of mist required to suppress a pool fire in an enclosure reduces with an increase in the heat release rate.

Smaller droplets are more effective in the suppression of fire because of their ease of convection to the flame zone and faster and easier evaporation. The droplet size in the experiments was varied by changing the supply pressure of the atomizing air, while keeping the same water through-put. Water mist with Sauter mean diameter of 40 µm is observed to be most effective in suppressing the fire. The extinction time increases with an increase in droplet diameter. The mist with larger droplets did not interact with flame in combustion zone and hence took longer time to suppress the pool fires due to lower rate of vaporization, where as 40 µm droplets took minimum extinction time as they were easily entrained into the flame with air, which resulted in slowing the combustion process and hence, smaller fire extinction time.

The variation of critical mist concentration with heat release rate for 40 µm SMD mist was studied, as has been discussed earlier, the rate of vaporization is enhanced with an increase in heat release rate, thus, reducing the combustion efficiency and impeding the burning of fire. Therefore, the amount of mist required to suppress a pool fire in an enclosure reduces with an increase in the heat release rate. The minimum critical concentration (MEC) was 150 gm/m^3 for 800 kW n-heptane pool fire.

The use of nitrogen as atomizing gas and its effect on diffusion flame suppression performance was evaluated. The critical mist concentration required for suppression of unobstructed & obstructed diffusion flame reduced by 30-50% by use of nitrogen as atomizing gas. This clearly indicate that atomizing nitrogen caused the further lowering in compartment oxygen concentration along with formation of water vapors at diffusion flames with higher heat release rates. Similar trend was observed in case of flame extinction time, as nitrogen is entrained into flame zone leading to incomplete & slow combustion process due to absence of sufficient oxygen in the compartment which finally results in extinction of diffusion flame.

The presented study is primarily focused on understanding fire dynamics in the presence of water mist and the suppression of diffusion flame using water mist in a large room. It is realized that the parametric study (i.e. effect of HRR, droplet diameter and critical mist concentration) is limited in its scope and therefore, any proposed scaling law can be inadequate. However, the present study provides a guideline for further research in this field to come up with an optimum design of the mist generation system for enclosure fires.