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“EFFECT OF FOULING ON THE PERFORMANCE OF
VAPOUR ABSORPTION REFRIGERATION SYSTEM”

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This is to certify that report entitled “**EFFECT OF FOULING ON THE PERFORMANCE OF VAPOUR ABSORPTION REFRIGERATION SYSTEM**” by **ANURADHA** is the requirement of the partial fulfilment for the award of Degree of **Master of Technology (M.Tech)** in **Thermal Engineering** at **Delhi Technological University**. This work was completed under my supervision and guidance. She has completed her work with utmost sincerity and diligence. The work embodied in this project has not been submitted for the award of any other degree to the best of my knowledge.

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ABSTRACT

The incessant increase in the cost and demand for energy has directed to more research and development to consume available energy resources proficiently by minimizing the waste energy. Absorption refrigeration systems gradually attract interest of the researchers. Absorption cooling bids the possibility of using heat to provide cooling. Furthermore due to fouling of heat exchangers its performance deteriorate results in lag in rate of heat transfer and hence consuming more energy in a refrigeration system. For the fact that an absorption refrigeration system uses more number of heat exchangers as compared to other such systems, the effect of fouling on its performance is investigated. The objective of this report is to present empirical relations for evaluating the characteristics and performance of a single stage Ammonia water ($\text{NH}_3\text{-H}_2\text{O}$) vapour absorption system under normal as well as fouled conditions. The essential heat and mass transfer equations and appropriate equations recounting the thermodynamic properties of the working fluid at all thermodynamic states are evaluated. An energy scrutiny of each component has been carried out and numerical results for the cycle. Finally the variations of several thermodynamic parameters are replicated and examined. The main effect of the fouling is to decrease the effectiveness of the heat exchanger. Thus, the overall conductance (UA) of the heat exchanger is decreased. In the present work COP of the vapour absorption refrigeration system is decreased under fouling by keeping the constant value of overall conductance. Due to the fouling in the heat exchangers performance of the vapour absorption refrigeration system is degraded by 8.81%.

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NOMENCLATURE

C_{min}	Minimum value of thermal capacitance rate(kW/°C)
COP	Coefficient of Performance(-)
ε	Heat exchanger effectiveness(-)
TR	Ton of Refrigeration
H	Efficiency (%)
\dot{m}	Mass flow rate (kg/s)
H	Enthalpy (J/Kg)
T	Temperature(K)
P	Pressure(bar)
UA	Overall conductance(kW/K)
Q	Heat transfer (Joule)
W	Work Transfer(Joule)
°C	Degree Celsius
x	Dryness fraction
ξ	Circulation rate or mass fraction
ΔS	Entropy(J/Kg)
U	Internal energy(J/Kg)
v	Specific volume(m ³ /kg)
R	Refrigerant
kW	Kilo watt
Kg	Kilogram
K	Kelvin

ASHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineers
s	Second
J	Joule
IC	Internal combustion
VARs	Vapour Absorption Refrigeration System
m	Mass
q_h	Heat added in generator
M	Molecular weight
q_o	Refrigerating effect
H ₂ O	Water
ψ	Mole fraction
NH ₃	Ammonia
1, 2, 3,	State points

Subscripts

A	Absorber
c	Condenser
P	Pump
O	Ambient
G	Generator
E	Evaporator
f	Fouled condition
II rev	Second law reversible
act	actual

A	Ammonia
W	Water
total	Total
mix	Mixture
evap	Evaporator
gen	Generator
Cl	Clean condition
Di	Dirty condition
P	Percentage
Abs	Absorber

Superscripts

V	Vapour
L	Liquid

CHAPTER 1

INTRODUCTION

1.1 Introduction

Due to scarcity of energy's production and consumption of fast growing energy, It will be required to reduce the use of energy and preserve it for all the possible ways. Conservation of energy (i.e., energy saving is more desirable than the production energy) is today becoming a eye catcher of the present time and new processes to save energy, excluding of being fruitless, are being explored. Recapturing or recycling energy from the waste heat and/or using it effectively for improvement of the system efficiency (is fast) becoming frequent scientific temper and industrial practice today. The present energy issue has made the engineers and scientists around the world to encompass the energy conservation measures in various industries. Reduction in the thermal energy and electric power exhaustion are also advisable but cannot be avoided in a view of the rapid moving and competitive industrial progress all over the world. Refrigeration systems form important component for the industrial progress and effects the energy problems of the country at large. Hence, it is suggested to subject the base for conservation of energy and recuperation of energy from Vapour Absorption Refrigeration System (VARs). Although, the reviews noted in this work are kind of applied research but certainly can create a base for further (R&D) Research and Development activities in direction of conservation of energy and recovery of heat options for the refrigeration systems and the analysis can be also utilized to other Refrigeration and Air Conditioning Systems. Now, the main focus of the researchers is to emphasize how to upgrade the absorption refrigeration systems. As, we know that the vapour compression refrigeration requires high grade of thermal energy for its operation. Coming apart from this, now recent studies have shown that the conventional working fluids which we are using in the vapour compression system are the main cause of the green house effects and ozone depletion . However, Absorption Refrigeration Systems (ARS's) requires low grade of energy for their performance. The harmless sources like, low cost waste heat, solar energy, biomass or geothermal energy where in many of the cases the cost of the supply is almost negligible . Also, the working fluids of these systems are eco-friendly. The net performance of the absorption cycle in terminology of refrigerating effect per unit of energy input

normally taken to be poor, the waste heat that was rejected out from the power can also be further utilized attaining the better overall utilization of the energy. When the temperature requirement is lesser there we are mainly using the ammonia-Water ($\text{NH}_3\text{-H}_2\text{O}$) mixture solutions and where we wanted the normal temperature there we may use water-lithium Bromide ($\text{H}_2\text{O-LiBr}$). For e.g. in the case of air conditioning, and then the new constructed system is very much efficient than that of the previous one.

1.2 Refrigeration

Refrigeration can be defined as the process of sustaining the space at temperature below the surroundings. Hence, heat should flow from lesser temperature space to surroundings of greater temperature.

Refrigeration effect (R.E.): It is defined as the total quantity of absorption of heat from the refrigerated space so that this maintains it at a lesser temperature than that of the surroundings. It is the acquired effect of the refrigerator. It is stated in KJ/Kg or KJ.

Energy performance ratio/ COP/ Energy ratio: It is stated as the ratio of the desired effect or in the other words refrigerating effect to the work input.

$$\text{COP} = \text{Desired Effect (R.E.)} / \text{Work Input}$$

It is analogues to ‘ η ’ in heat engine, but COP can be greater than 1 ($\text{COP} > 1$). More the COP, smaller is the work input required for the same desired effect and due to this the higher COP is desired.

UNIT OF REFRIGERATION (Ton of Refrigeration) : It is the amount of heat absorbed by 1US ton (900 Kg) of ice at 0°C turns to water at 0°C in the 24 hours. Tonnage of refrigeration i.e., the unit of refrigeration represents the heat transfer rate.

$$\begin{aligned} 1\text{TR} &= 3.5167\text{KW} \\ &= 221 \text{ KJ/min} \\ &= 50.4 \text{ Kcal/min} \end{aligned}$$

1.3 Methods of Refrigeration Systems

Methods of refrigeration mainly classified as

- (a) Non cyclic refrigeration.
- (b) Cyclic refrigeration.

Cyclic refrigeration is further classified as

- (a) Vapor cycle refrigeration.
- (b) Gas cycle refrigeration.

Now, vapour cycle refrigeration is further classified as

- (a) Vapour Compression Refrigeration Cycle.
- (b) Vapour Absorption Refrigeration Cycle.

1.4 Vapour Absorption Refrigeration cycle

Vapour Absorption Refrigeration Systems (VARs) are like vapour compression refrigeration systems only. But the requisite input in case of the vapour absorption refrigeration system is in the form of heat which is different from vapour compression refrigeration systems. That is why these systems are stated as either heat operated or thermal energy driven systems. The traditional absorption refrigeration systems are using liquids for the absorption of the refrigerant, due to this, these are also called as the wet absorption systems. Now, the vapour absorption refrigeration system are being commercialized and used widely in the applications of air-conditioning as well as various refrigeration applications. These systems are operated on the low grade thermal energy, they are only preferable when the low grade thermal energy like waste heat or solar energy is easily available. The purpose of compressor is to withdraw the refrigerant vapour continuously from the evaporator in the vapour compression system and then raising its temperature as well as pressure, due to this the heat which is immersed on the evaporator with the compression work, may get rejected in the condenser over the surroundings.

Since conventional absorption refrigeration systems use the natural refrigerants for example water or ammonia. These are ecofriendly refrigerants.

In vapour absorption refrigeration system, Compressor's function is accomplished in the three stage process by the help of absorber, pump and generator or boiler.

These are as follows :

1. **Absorber:** Absorption of the refrigerant by its poor or a weak solution in a appropriate adsorbent or absorbent forming a rich or strong solution of the refrigerant in the adsorbent/absorbent.
2. **Pump:** When the pumping of the rich solution is done it will raises its pressure to the pressure corresponding to the condenser pressure.
3. **Generator:** Here the distillation of the vapour from the rich solution which is leaving the poor solution from recycling is done.

Simple vapour absorption system comprises of

1. Absorber.
2. Generator.
3. Heat exchanger.
4. Pump.
5. Expansion device.
6. Condenser.
7. Evaporator.

1.5 Refrigerant absorption combinations for vapour absorption refrigeration system (VARS)

The required properties of the refrigerant absorbent solution for the VARS are as follows:

- i. There should be high solubility of the refrigerant with the solution in the absorber. That is, it should exhibits negative deviation from the Raoult's law at the absorber.
- ii. In order to boiled off the refrigerant, there must be high difference in the boiling points of the refrigerant and absorbent (higher than 200°C), in the refrigerator. However, which certified that only the pure refrigerant is flowing over the refrigerant circuit which leads to isothermal transfer of heat in condenser and evaporator.
- iii. In the process of achieving the higher COP, there should be very less intermixing of heat. However, this requirement contradicts with the very first requirement. Hence, in the actual practice a trade-off is necessary between the solubility and heat of mixing.
- iv. The refrigerant-absorbent mixture must have low viscosity and high thermal

conductivity for the better operation.

v. There should not be any kind of crystal formation or solidification inside the system.

vi. The mixture must exhibit these qualities like, safe, low-cost, chemically stable, non-corrosive and also should be easily obtainable.

The most often refrigerant-absorbent pairs that are used in the commercial systems are mentioned below:

1. Water-Lithium Bromide (H₂O-LiBr): These systems are used where the temperature are above 0°C. For example such as in the case of air conditioning. Here lithium bromide is the absorbent and water is the refrigerant.

2. Ammonia-Water (NH₃-H₂O): These systems are used for the refrigeration applications with ammonia as refrigerant and water as absorbent.

To overpower the limitations from the (H₂O-LiBr) and (NH₃-H₂O) systems later, by the help of using the natural and synthetic refrigerants as refrigerant-absorbent mixtures many others efforts are been made .

Presently, for the large scale, we extensively uses water-lithium bromide (H₂O-LiBr) for the applications of air-conditioning, and the refrigeration applications are desirable then we effectively uses ammonia-water (NH₃-H₂O) systems, while for the small scale, like in the domestic refrigerators ammonia-water systems with a third inert gas are used in the pump less form.

In this project ammonia-water (NH₃-H₂O) Refrigerant-absorbent mixture is being taken into consideration.

1.6 Basic Vapour Absorption Refrigeration System

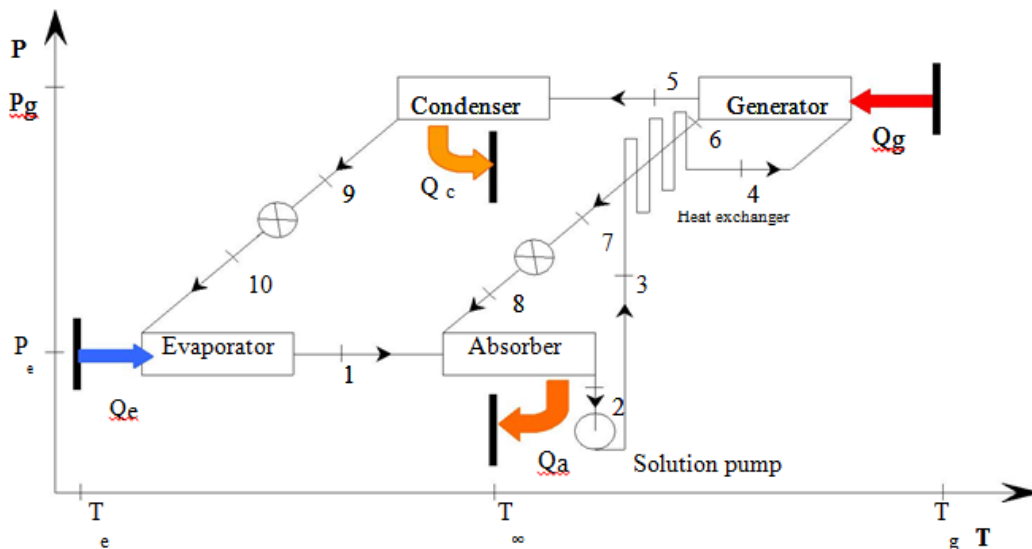


Figure 1.1: Basic vapour absorption refrigeration system alongwith solution heat exchanger.[14]

Ammonia water leaves the evaporator and enters the absorber where it dissolves and react with water to form $\text{NH}_3 \cdot \text{H}_2\text{O}$ solution. This is an exothermic reaction; the quantity of NH_3 that can be dissolved in H_2O is inversely proportional to the temperature. The liquid $\text{NH}_3 \cdot \text{H}_2\text{O}$ solution is then driven to the generator. As in the generator, the temperature is very high so that the NH_3 separates from the H_2O . Thus, producing great pressure. Vapour which in NH_3 passes through the analyzer (attached to the generator). Where, H_2O breaches from the NH_3 vapours. This NH_3 vapours is then passed through rectifier where traces of H_2O are removed and sent back to the generator. High pressure pure NH_3 vapour continues its cycle by reaching to condenser where pressure is very high as well as temperature, followed by expansion device where temperature drops and then evaporator where pressure and temperature are very less.

1.7 Fouling

Fouling is the process of incorporating the deposit of unwanted material over the heat transfer surface during the long lasting of the heat exchanger. Whatever may be the cause or the exact essence of accumulation of the material, by adding the extra resistance to heat transfer which inaugurates over the surface and it correspondingly reduces the functional potential of the

heat exchanger. but mostly we can see that the accumulation of the unwanted material over the surfaces are large enough to interfere the fluid flow significantly and thereby, gain momentum in the pressure drop which requires to sustain the required flow rate through the heat exchanger. For this reason while the designing of the heat exchanger, the effect of fouling upon the heat exchanger fouling during the desired operational lifetime must be considered by the designer and make planning in his design for the sufficient additional capacity to make certain that the heat exchanger will definitely meet process details up to shut down for cleaning. Also, the designer must consider what are the necessary mechanical arrangements to authorize easy cleaning.

There are two types of fouling phenomenon.

(a) Macro fouling

(b) Micro fouling

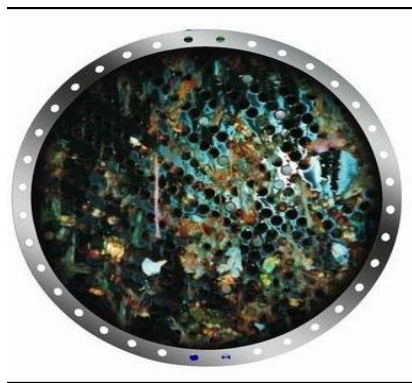


Figure 1.2: Heat exchanger used in steam power plant fouled by macro fouling. [14]

MACRO FOULING: Macro fouling is developed by the rough matter of either biological or non-organic origin. For example, refused particles that are fabricated industrially. Such a particle entering into the cooling water circuit through cooling water pumps from sources like the rivers , open sea or lakes. In the closed circuits (cooling towers) the addition of macro fouling into the cooling tower basin is the any and every possible way through open canals or by the wind. At times, components of the cooling system internals disengaged themselves and area unit carried into cooling water circuit. Such substances then foul the surfaces of warmth exchangers and will cause the degradation of their heat transfer constant. They will additionally manufacture flow blockages, reapportion the flow within the parts, or

causing the fretting destruction. Examples: Detached internal components of element, manmade refuse . Etc.

MICRO FOULING: There are several types of micro fouling, these are classified below

1. Scaling or precipitation fouling
2. Composite fouling
3. Chemical reaction fouling
4. Solidification fouling
5. Corrosion fouling
6. Bio fouling
7. Particulate fouling

PRECIPITATION FOULING: Scaling or precipitation fouling including the solid salts, crystallization of the oxides and hydroxides from solutions. These are in the main liquid solutions, however non-liquid precipitation fouling is additionally proverbial Precipitation Fouling. Precipitation fouling may be a terribly acquainted downside in boilers and warmth exchangers acting with hard water and customarily ends up in lime scaling.

Through changes in temperature, or solvent or degasification or solvent evaporation, the concentration of salts might overshoot saturation, resulting in precipitation of solids (usually crystals).



Figure 1.3: Condenser tube with calcium carbonate scaling. [14]

PARTICULATE FOULING: Fouling by particles which are suspended in water (crud), or by gas progresses by a mechanism aside from the precipitation fouling. These processes are largely vital for colloidal solution i.e. particle size lesser than $1\mu\text{m}$. By a variety of mechanisms particles are then shipped to the surface and that they will hitch themselves by coagulation.

CORROSION FOULING: If the metal of the heat transfer surface gets corroded by the stream, the corrosion outcome is also significant to guard the remaining metal against the more corrosion, within which case any trial to scrub the surface could solely end in the accelerated corrosion and then collapse of the heat exchanger may occur.

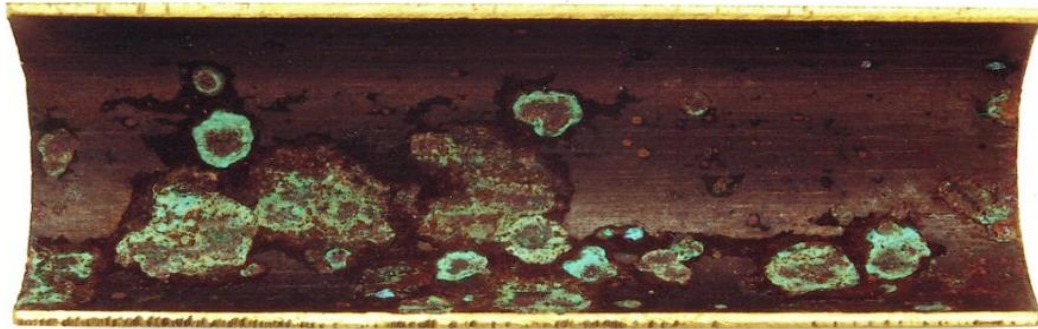


Figure 1.4: Brass tube with corrosion traces. [14]

CHEMICAL REACTION FOULING: Chemical reactions may occur while contacting the chemical species in method fluid at the side of the heat transfer. In that cases, the metallic surface acts as a role of catalyst. As an example, corrosion polymerization happens in the cooling water for chemical industry that has having slight content of the hydrocarbons in it. Systems in petroleum processing are at risk to the polymerization of olefins or accumulation of significant fractions. If the wall temperatures are higher, it could steer to the carbonizing of organic matter. Food business, as an example of process of milk, jointly experiences fouling problems by these chemical reactions. Fouling through an ionic reaction with a progression of an inorganic solid is usually classified as precipitation fouling (not chemical reaction fouling).

SOLIDIFICATION FOULING: Solidification fouling may takes place once a part of the flowing fluid "freezes" over the surface which makes a solid fouling deposit. For examples, it incorporates solidification of wax (with the high melting point) from a hydrocarbon solution or of molten ash (carried inside the furnace exhaust gas) onto a exchanger surface . The surface needs having a temperature not up to a particular threshold; therefore, it's said to be subcooled in regard to point of solidification of the foulant.

BIOFOULING: Several cooling water headsprings and some method streams contain organisms that may hitch to solid surfaces and grows. This organism ranges from barnacles and mussels to algae and microbial slimes. Even once there's solely a very sender film can

present, the heat transfer resistant is terribly considerable. narrow film will present, the heat transfer resistant can be very appreciable. Where the microscopic forms like mussels are present, the problem will no longer be considered to the heat transfers .



Figure 1.5: Condenser tube with residue of biofouling.[14]

COMPOSITE FOULING: Composite fouling is the type of fouling which is very usual. In this type of fouling more than one fouling mechanism of the fouling are working simultaneously . By adding the numerous foulants or different mechanisms together communicating with each other which results in the synergistic fouling which shows that that is not even a simple arithmetic sum when we consider components individually.

1.8 EFFECT OF FOULING ON HEAT TRANSFER

1. Thermal efficiency of the heat exchanger decreases.
2. It reduces the heat flux.
3. On the hotter side temperature rises.
4. On the colder side temperature reduces.
5. Under-deposit corrosion may induced.
6. Use of the cooling water increases, and many more.

Above all the factors are well enough to decrease the operation of the heat exchanger and then heat exchanger will not perform its operation properly. Also may damage the diversity of components due to very high temperature. In order to prevent the heat exchanger from fouling we have to make some allocation for its periodic removal.

1.9 REMOVAL OF FOULING

If we cannot arrest the fouling from forming, then it is very necessary to make the allocations for removal of fouling periodically. By the means of chemical actions some deposits can be removed totally for e.g., with the help of chlorination we can totally remove the carbonate deposits. There are so many cleaning techniques that are the specialized art and must be undertaken only under the supervision of the specialist. However, in the process of chemical cleaning that is to use where it does not require for the removal of equipment or disassembly of their piping, chemical cleaning is one of the most of cleaning techniques in those cases.

Mechanically, there are numerous of techniques for the removal of fouling. Also, Scraping and rotary brushes are limited to the surfaces which can be reached by the scraping tool uses the trick so that it can be eased by the shell side or by the use of very large clearances between tubes or the using the rotating square tune layout.

As the high velocity water jets are used to both inside and outside of the tubes, the jets will not be that much affective for the shell side, deep inside a large tube tank.

The objective of this report is to evaluate thermodynamic properties. Heat rate and mass flow rate in each components of the system are obtained in this report. For the various range of temperature the coefficient of performance (COP) of the system is determined. The result of this dissertation can be used for calculating the COP for fouled condition for heat exchangers.

1.10 Solution Methodology in Engineering Equation Solver (EES)

Dr. Sanford Klein from the University of Wisconsin established the software package which is known as EES. It includes the various programming structures of C and FORTRAN incorporated with iterator in itself, thermodynamic property relations, numerical integration, transport property relations graphical capacities and many more other useful mathematical functions are inbuilt in itself. The assembly of equation that has to be solved simultaneously, with the very high rate of computational speed EES is proficient to function. By using the correlations which are developed by Ibrahim and Klein in 1993 properties of ammonia-water mixture properties can easily be calculated. The main difference between EES and the existing numerical equations solving programs is; First, EES discovers and group the equations automatically that has to be solved simultaneously. Due to this feature sim the

process for the user get simplified and there is certainty that the solver will always operate at optimum level of efficiency. Second, EES also provides many useful functions i.e., incorporated mathematical and thermo-physical property functions for engineering calculations. The very fundamental function is the numerical solution of non-linear algebraic and differential equations provides by the engineering equation solver (EES). EES is incorporated with many thermodynamic and transport property functions for different fluids including dry and moist air and water. In the property database are thermodynamic properties for R134a, R1234yf and R1234ze mixtures are also incorporated. Any information between quotation marks [“] or braces [{}] is an optional remark. Variable names must start with a letter.

A code containing a quality library of working fluid properties suitable for heat pumps is the Engineering Equations Solver (EES). Here the user must write the equations governs the cycle and make sure the set is well-defined. In the case of a non-linear set of equations, the user must examine the results to make sure that the mathematical solution is also a physical one. In one form or another, the user has to do a fair amount of programming to steer the simulator toward convergence to the correct solution.

Computer Program and Its Output

The computer program for the thermodynamic analysis of the system elaborated in EES has been given in Appendix A along with its flow diagram for computation procedure.

CHAPTER 2

LITERATURE REVIEW

2.1 LITERATURE REVIEW

Most of the research has been carried out by the scientists and researchers across the globe on the effect of fouling on vapour compression system and on the performance of various vapour absorption systems. Some of their research findings are as follows:

[1] **Bultman et al. (1995)** simulated the effect of partially blocked condensers of a 3-ton vapour compression system and reported that the COP was predicted to decrease by 7.6 percent when the airflow across over the condenser was reduced by 40% for a constant speed fan. It was noted that the increase in the power consumption had a logarithmic nature as did the decrease in COP. Pressure rise across the compressor is increased by 19 percent which is above its standard value of 1151 kPa, suggesting that reduction in the life of compressor might be the major economic consequence of condenser air flow blockage.

[2] **Siegel (2002)** explained that the impact of fouling on vapour compression systems is an important outlook because one of the main components of any cooling system are heat exchanger and a decrease in performance, due to fouling, can potentially increase the energy consumption and/or decrease the efficiency and cooling capacity of the heat exchanger. Airborne particulate matter, textile fibers, human hair and dust etc. all constitute foulants. Later, he found that the impact of fouling is a decrease in the air flow rate of 5-6 percent and a decrease in the system efficiency by 2-4 percent.

[3] **Pak et al. (2005)** investigated experimentally the effects of air-side fouling on the performance of numerous condenser coils found in unitary air-conditioning systems and inveterate that, under fouled conditions, the heat transfer performance degraded by 7-12 percent at the standard air face velocity of 1.53 meter per second. He also concluded the fouling on the front face of the coil is a mixture of dust and fibres in non-uniform distribution and decreases gradually from the front face to the first tube row. On the rear face, the fouling is in uniform distribution over the fins.

[4] **Ali and Ismail (2008)** experimentally investigated evaporator air-side fouling of room air-conditioners showing that COP decreased by more than 57 percent due to 300 g of real foulant collected from the numerous evaporator coils. Although it was noticed that 110 g of this material did not deposit over the coils and R12 was used as the refrigerant before, which has now been phased out of use.

[5] **Bell and Groll (2010)** studied the effect of fouling on air-side pressure drop in plate-fin and micro channel coils. The heat exchanger were tested with two different dust's type, ASHRAE standard dust and Arizona road test dust, concluded that, ASHRAE dust results in much larger increase in air-side pressure drop, and Arizona dust results in much larger decrease in heat transfer than the ASHRAE dust.

[6] **Raghuvanshi and Maheshwari (2011)** performed the analysis of ammonia-water ($\text{NH}_3\text{-H}_2\text{O}$) vapor absorption refrigeration system based on first law of thermodynamics and concluded that as the temperature of condenser, generator and absorber gets increased the system COP gets decreased, as the effectiveness of the heat exchanger increases, COP of the system also increases.

[7] **Qureshi and Zubair (2012a, 2012b)** performed fouling simulation work for a simple vapour compression cycle employing an integrate and dedicated mechanical sub-cooling cycle, respectively. It is noted that these simulations display a logarithmic variation in the various parameters when examined with respect to degradation in the conductance, i.e. the UA-value, of both the condenser and evaporator.

[8] **V.K. Bajpai (2012)** studied and designed an environment friendly vapor absorption refrigeration system of a unit capacity using R 717(ammonia) as a refrigerant and water as a working fluid and uses hot water as a heat source. Also, concluded that solar water heating unit can be usefully employed for the water cooling purposes. During summer days, when the solar potential is quite high, the units can be used for refrigeration.

[9] **V.D. Patel (2012)** investigated the desired capacity of 0.25 TR was not completely achieved due to the fact that certain parameters could not be achieved during the practical design as compared to the theoretical design, as there are less number of turns of condenser and tube length which resulted inefficient heat rejection. Concentration of ammonia fifty percent as per the design but in actual practice it is also came out to be 25 percent which is also a limitation.

[10] **Vazhappilly et al (2013)** experimentally investigated the performance of generator of a vapour absorption refrigeration system and concluded that the heating coil generator system of the absorption refrigeration system has been replaced by plate frame type heat exchanger, thereby, utilizing exhaust gases of IC Engine.

2.2 GAPS IN LITERATURE SURVEY

From the above literature survey it has been concluded that most of the work has been done on vapour compression system under fouled condition and almost no research work is available which has analyzed the performance of vapour absorption system under fouled condition. Therefore, I have chosen this topic for my project work.

CHAPTER 3

THERMODYNAMIC ANALYSIS

3.1 INRODUCTION

BASIC PRINCIPLE OF OPERATION

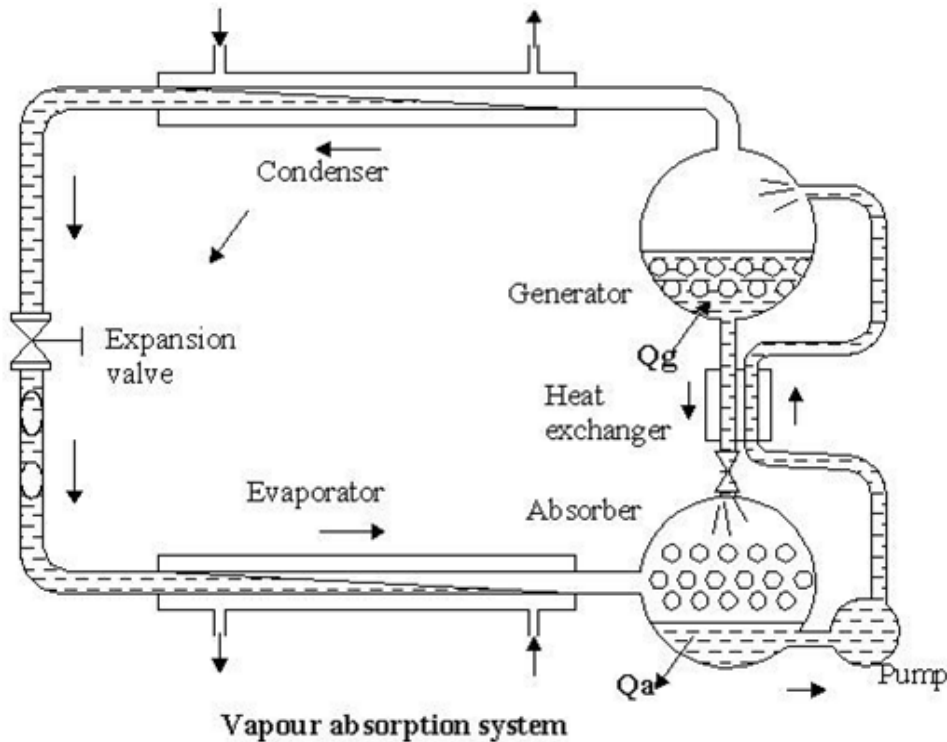


Figure 3.1: Simple vapour absorption system. [15]

Ammonia water leaves the evaporator and enters the absorber where it dissolves and reacts with water to form $\text{NH}_3 \cdot \text{H}_2\text{O}$. This is an exothermic reaction, the amount of NH_3 that can be dissolved in H_2O is inversely proportional to the temperature. Liquid $\text{NH}_3 \cdot \text{H}_2\text{O}$ solution is then propelled to the generator. As the temperature is high the NH_3 separates from the H_2O . Thus, creating high pressure. Vapour which is NH_3 passes through the analyzer (attached to the generator). Where, H_2O separates from the NH_3 vapours. This NH_3 vapour is then passed through rectifier where traces of H_2O are removed and sent back to the generator. High pressure pure NH_3 vapour continues its cycle by reaching to condenser where pressure is very high as well as temperature, followed by expansion device where temperature drops and then evaporator where pressure and temperature are very less.

In vapour absorption refrigeration systems based on ammonia-water pair where, ammonia is the refrigerant and water is the absorbent. This pair of systems are more adaptable than systems based on water-lithium bromide as this can be used for both sub-zero (refrigeration) as well as above 0°C (air conditioning) applications. However, ammonia-water systems are more complicated in design and operation due to the lesser boiling point temperature difference between the refrigerant and absorbent. Due to the smaller boiling point temperature difference the vapour generated in the generator consists of both ammonia as well as of water. If water is allowed to circulate with ammonia in the refrigerant circuit, then it results in:

- i. Heat transfer in condenser and evaporator becomes non-isothermal.
- ii. Evaporator temperature increases.
- iii. Evaporation will not be complete.
- iv. Water may get accumulated in the evaporator leading to malfunctioning of the plant.
- v. Circulation ratio increases.

Since all of the above effects are detrimental to the performance of the system, it is necessary to decrease the concentration of water vapour in ammonia at the inlet to the condenser. This requires additional components, namely a rectification column and a dephlegmator between generator and absorber, which later results in increasing the design complexity and cost and also minimizes the system COP compared to water-lithium bromide system.

3.2 IMPACT OF FOULING ON VAPOUR ABSORPTION REFRIGERATION SYSTEM

Fouling are of two types as discussed above i.e., micro fouling and macro fouling. The fouling can either be internal or external to the system. In this project, overall fouling effect has been taken into consideration i.e., both internal and external fouling effect.

3.3 COP OF VARS SYSTEM

$$\text{COP}_{\text{VARS}} = \frac{Q_e}{Q_g + W_p} \approx \frac{Q_e}{Q_g} \quad (3.1)$$

If, $W_p \ll Q_g$

Then, neglecting W_p

$$\text{COP}_{\text{VARS}} = \frac{Q_e}{Q_g} \quad (3.2)$$

3.3.1 MAXIMUM COP OF VARS SYSTEM

If we assume that heat rejection at the absorber and condenser takes place at same external heat sink temperature T_o , then a vapour absorption-refrigeration system operates between three temperature levels, T_g , T_o and T_e . Possibly, the maximum possible COP of a refrigeration system operating between three temperature levels can be obtained by applying first and second laws of thermodynamics to the system. Figure 3.2, shows the various energy transfers and the corresponding temperatures in an absorption refrigeration system.

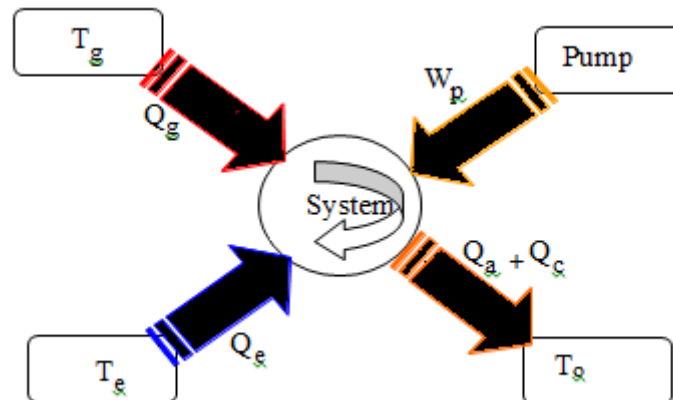


Figure 3.2: various energy transfer in VARS system. [15]

From 1st law of thermodynamics,

$$Q_g + W_p + Q_e = Q_a + Q_c \quad (3.3)$$

$$\text{Neglecting } W_p, \quad Q_g + Q_e = Q_a + Q_c \quad (3.4)$$

where Q_e is the heat transferred to the absorption system at T_e (evaporator temperature), Q_g is the heat transferred to the generator of the absorption system at temperature T_g , $Q_a + Q_c$ is the

heat transferred from the absorber and condenser of the absorption system at temperature T_o and W_p is the work input to the solution pump.

From the 2nd law of thermodynamics,

$$(\Delta S)_{\text{universe}} = (\Delta S)_{\text{system}} + (\Delta S)_{\text{surrounding}} \geq 0 \quad (3.5)$$

For maximum COP,

$$(\Delta S)_{\text{universe}} = 0 \quad (3.6)$$

$$(\Delta S)_{\text{system}} + (\Delta S)_{\text{surrounding}} = 0 \quad (3.7)$$

For a cycle; $(\Delta S)_{\text{system}} = 0$

$$-\frac{Q_e}{T_e} - \frac{Q_g}{T_g} + \frac{Q_a + Q_c}{T_o} = 0 \quad (3.8)$$

Since, evaporator and generator are external to the system i.e.; why -ve sign is there.

$$\frac{Q_g + Q_e}{T_o} = \frac{Q_e}{T_e} + \frac{Q_g}{T_g} \quad (3.9)$$

$$Q_g \left(\frac{1}{T_o} - \frac{1}{T_g} \right) = Q_e \left(\frac{1}{T_e} - \frac{1}{T_o} \right) \quad (3.10)$$

$$\frac{Q_e}{Q_g} = \frac{T_g - T_o}{T_o - T_e} \times \frac{T_e}{T_g} = \text{COP} \quad (3.11)$$

Thus an ideal vapour absorption refrigeration system can be considered to be a combined system consisting of a Carnot refrigerator and a Carnot heat engine (shown in Fig 3.3). Due to this, the COP of an ideal VARS increases as evaporator temperature (T_e) and generator temperature (T_g) increase and heat rejection temperature (T_o) decreases.

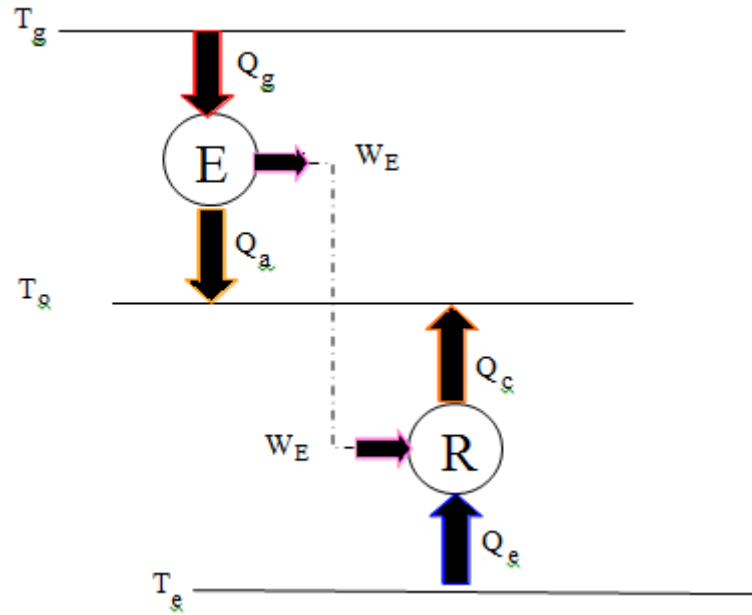


Figure 3.3: vapour absorption refrigeration system as a combination of heat engine and refrigerator. [15]

3.4 Properties of ammonia-water solutions

3.4.1 Composition

The composition of ammonia-water solution is manifested either in mass fraction (ξ) or mole fraction (ψ). However, for ammonia-water solutions, the mass and mole fractions are interpreted in terms of ammonia. For example the mass fraction ξ is defined as the ratio of mass of ammonia to the total mass of solution-

$$\xi = \frac{m_A}{m_A + m_W} \quad (3.12)$$

where m_A is the mass of ammonia and m_W is the water in solution.

Similarly, the mole fraction of ammonia-water solution is defined as:

$$\psi = \frac{n_A}{n_A + n_W} \quad (3.13)$$

where n_A and n_W are the number of moles of ammonia and water in solution, respectively. The number of moles of ammonia and water can easily be obtained from their respective masses in solution and molecular weights-

$$n_A = \frac{m_A}{M_A} ; \text{ and } n_W = \frac{m_W}{M_W} \quad (3.14)$$

where $M_A = 17.0 \text{ kg/kmol}$ and $M_W = 18.0 \text{ kg/kmol}$ are the molecular weights of ammonia and water respectively.

3.4.2 Vapour pressure of ammonia water solution

Liquid ammonia and water are completely miscible in all possible proportions, hence can form solutions of all concentrations varies from 0 to 1, at normal temperatures. The effect of ammonia in water is to lower the vapour pressure of water, likewise the water's effect in ammonia is to lower the vapour pressure of ammonia. Thus, the total pressure over ammonia water solutions is made up of water vapour's partial pressure and ammonia's partial pressure, and is always in between the saturation pressures of pure ammonia and water.

If Raoult's law is applied to ammonia-water mixtures (at any temperature), then the total pressure, P_{total} is given by:

$$P_{\text{total}} = \psi P_A + (1 - \psi) P_W \quad (3.15)$$

Where ψ is the liquid phase mole fraction of ammonia, P_A and P_W are the saturation pressures of pure ammonia and pure water at that temperature.

However, similar to lithium bromide-water solutions, ammonia-water solutions also deviate from ideal solution behavior foretell by Raoult's law in a negative manner, i.e., at a given temperature of the solution the actual vapour pressure will be less than that foretell by Raoult's law (activity coefficient is very much smaller than 1).

For example, mass fraction of 0.4 and temperature at 40°C , Raoult's law estimates a vapour pressure of 6.47 bar, whereas the measured value of vapour pressure is 3.029 bar.

The vapour pressure data of ammonia-water solutions is also available in the form of Duhring and other P-T- ξ plots.

3.4.3 Composition of ammonia-water vapour

Since the vapour above ammonia-water liquid consists of both ammonia and water vapour, it is necessary to distinguish between the composition in vapour phase and composition in liquid phase. The superscripts V and L will be used to distinguish between vapour and liquid phase compositions. This is why, ξ^L stands for mass fraction of liquid phase and ξ^V stands for mass fraction. Though the vapour phase composition can be procured by assuming ideal solution behavior, it is noticed that the actual vapour composition departs from that predicted by ideal mixture equations. Based on measurements by experimental data, charts have been created for obtaining composition of ammonia-water mixture in vapour phase in equilibrium with a solution of water and ammonia at variable temperatures. Figure 3.4 shows the construction of such a chart using which one can obtain the composition of mixture in vapour phase from known values of liquid phase mass fraction (ξ^L) and saturated temperature of pure ammonia or pressure.

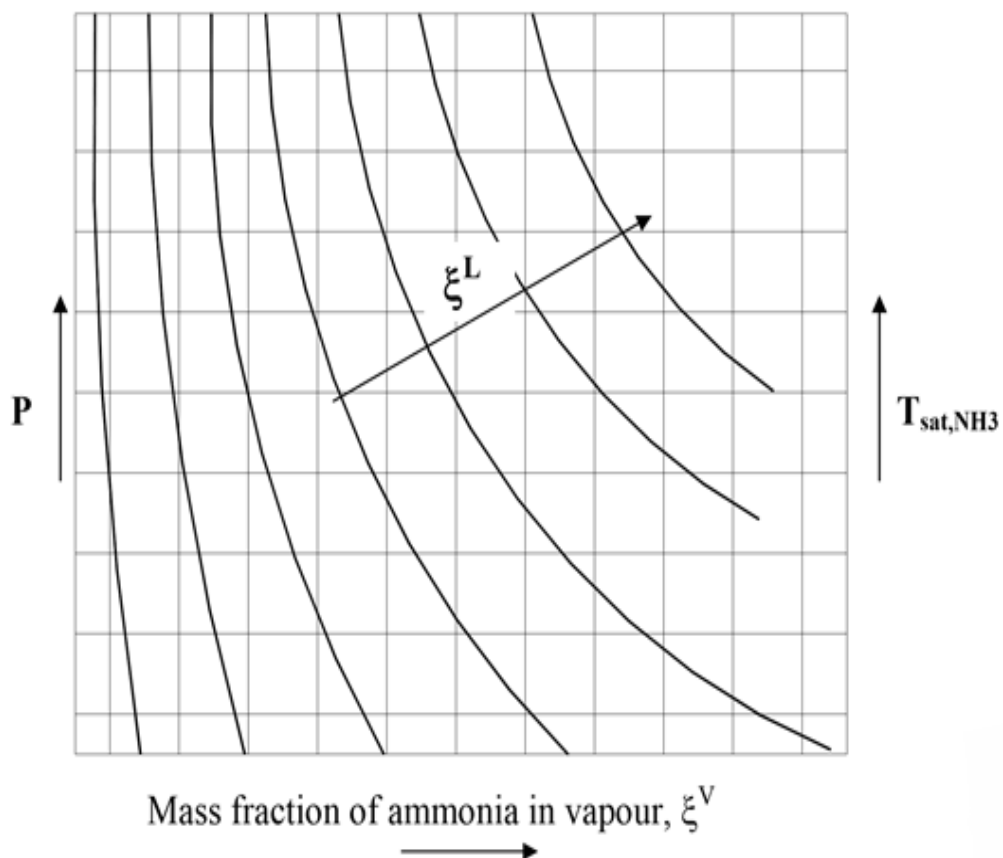


Figure 3.4: Vapour-liquid equilibrium chart for ammonia-water solution. [15]

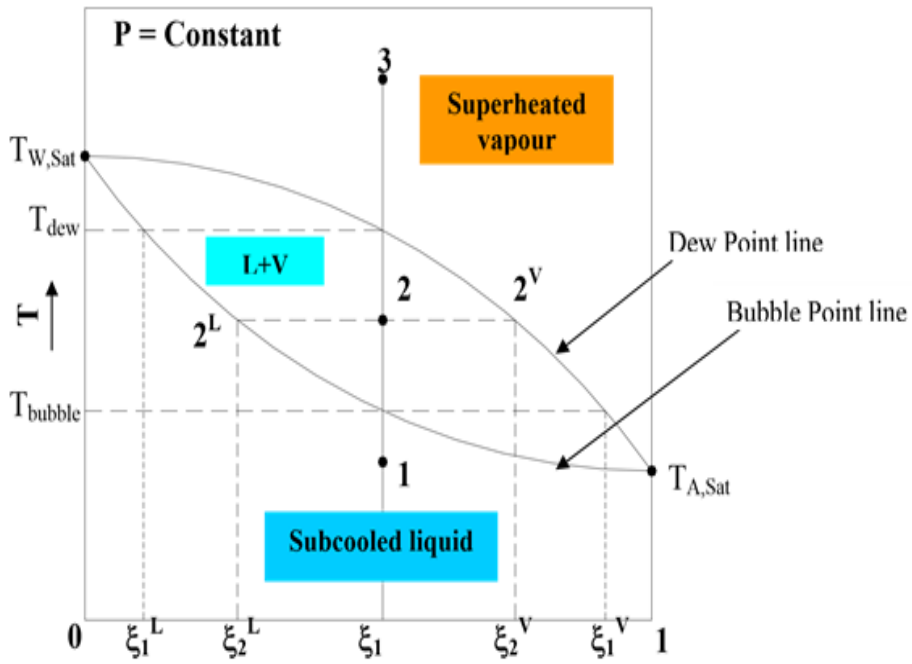


Figure 3.5: Equilibrium temperature-concentration curve for $\text{NH}_3\text{-H}_2\text{O}$ at a constant pressure.[15]

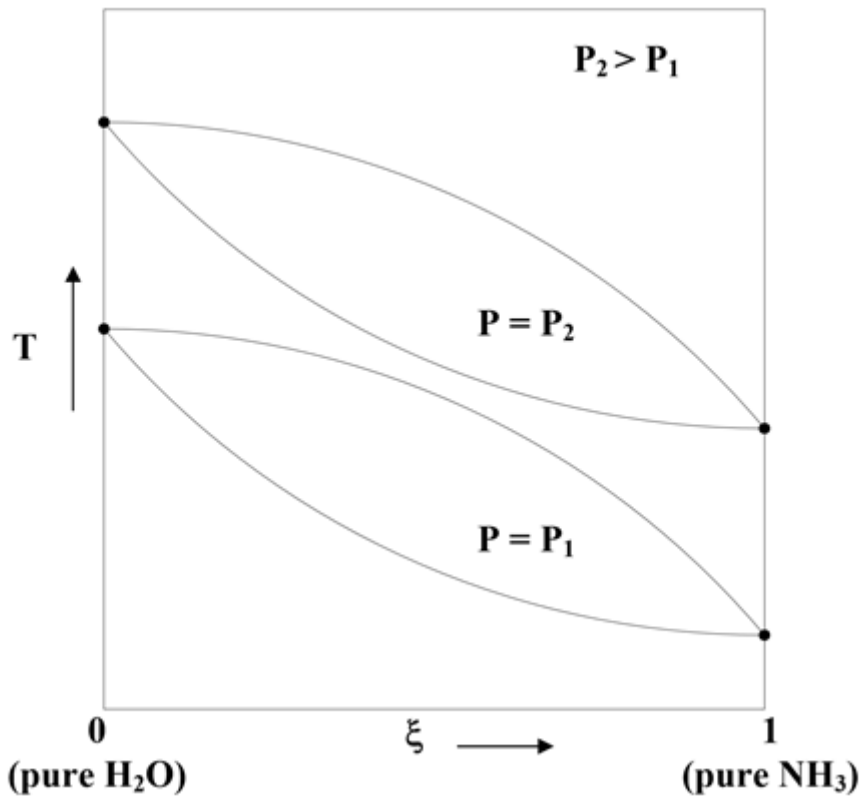


Figure 3.6: Bubble point and dew point curves at two different pressures. [15]

3.4.4 Enthalpy of ammonia-water mixtures

Liquid phase

The enthalpy of ammonia-water solution in liquid phase, ‘ h^L ’ is deliberated in a manner similar to that of the lithium bromide-water solutions, i.e., by the equation:

$$h^L = \xi^L h_A^L + (1 - \xi^L) h_W^L + \Delta h_{\text{mix}} \quad (3.16)$$

Where, ξ^L is the mass fraction of liquid phase of ammonia, h_A^L and h_W^L are liquid phase enthalpies of pure ammonia and water respectively. Δh_{mix} is the mixing heat, which is exothermic (negative) similar to lithium bromide-water mixtures.

Using the above equation one can deliberate the specific enthalpy of ammonia water solutions at any temperature and concentration provided the heat of mixing is known from the measurements. This is why enthalpy charts for solution are plotted as a field of isotherms against mass fraction by taking suitable reference values for enthalpy of water and ammonia. Since pressure does not have a remarkable effect on liquid enthalpy (except at that of critical point), in normal case pressure lines are not shown on typical solution enthalpy charts. Plus subcooled liquid’s enthalpy x is generally assumed to be equal to the saturated enthalpy at that temperature without loss of that much accuracy.

Vapour phase

Evaluation of enthalpy of vapour mixtures of ammonia and water is more complicated compared to that of liquid phase enthalpy. This is due to the dependency of vapour enthalpy on both pressure and temperature. However, to simplify the problem, it is generally assumed that water vapour and ammonia mix without any heat of mixing. Then the enthalpy of the vapour mixture, h^V is given by:

$$h^V = \xi^V h_A^V + (1 - \xi^V) h_W^V \quad (3.17)$$

Where ξ^V is the vapour phase mass fraction of ammonia and h_A^V and h_W^V are the specific enthalpies of ammonia vapour and water vapour respectively at the temperature of the mixture. However, since vapour enthalpies reliable on pressure as well as temperature, one has to evaluate the vapour enthalpy at suitable pressure, which is not equal to the total pressure. Approximately but practically useful method is to examine the vapour enthalpies of ammonia (P_A) and water at pressures (P_W), given by:

$$P_A = yP_{\text{total}} \quad (3.18)$$

$$P_W = (1-y)P_{\text{total}} \quad (3.19)$$

Where, y is the vapour phase mole fraction of ammonia and P_{total} is the total pressure. It should be remarked that P_A and P_W are equal to the partial pressures of ammonia and water only if they are behaving as ideal gases. Since water vapour and ammonia may not approach the ideal gas behavior at all pressures and temperatures, in general P_A and P_W are not equal to the partial pressures. Using this method, ammonia-water's enthalpies mixtures in vapour phase have been obtained as functions of mass fraction and temperatures.

3.5 The complete enthalpy-composition diagram for ammonia-water mixtures

Normally, charts of enthalpy-temperature-mass fraction are available which give both vapour phase as well as liquid phase enthalpy of mixtures. Figure 3.7 shows one of such chart. Figure 3.8 shows the enthalpy-composition diagram at a constant pressure P . In the figure point **a** characterizes the condition of saturated liquid mixture at a temperature T with a liquid phase mass fraction of ξ^L . The liquid phase enthalpy corresponding at this condition is given by h^L . The enthalpy and composition of vapour mixture in equilibrium with the liquid mixture at temperature T and pressure P are obtained by drawing a vertical line from point **a** up to the auxiliary line and then drawing a horizontal line right from the intersection of the vertical line with the auxiliary line. The junction of this horizontal line with the dew point line **a'** gives the vapour phase mass fraction ξ^V and the vapour phase enthalpy h^V as shown in the figure. The isotherm T in the two-phase region is obtained by joining these two points points **a** and **a'** together which is as shown in the figure. Point **b** in the figure lies in the two-phase region. The specific (h_b) enthalpy of this point is given by:

$$h_b = (1-x_b) h^L + x_b h^V \quad (3.20)$$

Where, x_b is the quality or dryness fraction of the two-phase mixture at b. Since points a, a' and b are co-linear, (x_b) the dryness fraction is given by:

$$x_b = \frac{\xi_b - \xi_L}{\xi_V - \xi_L} \quad (3.21)$$

In actual enthalpy-composition diagrams the isotherms are not shown in two-phase region as a different set of them exist for each pressure.

It is important to remark that it is not possible to fix the state of the mixture (i.e., subcooled, saturated, two-phase or superheated) just from temperature and mass fraction alone, though enthalpy of the mixture can be calculated from mass fraction and temperatures. This is due to the reason that at a given mass fraction and temperature, depending upon the pressure the point can be subcooled or saturated or superheated.

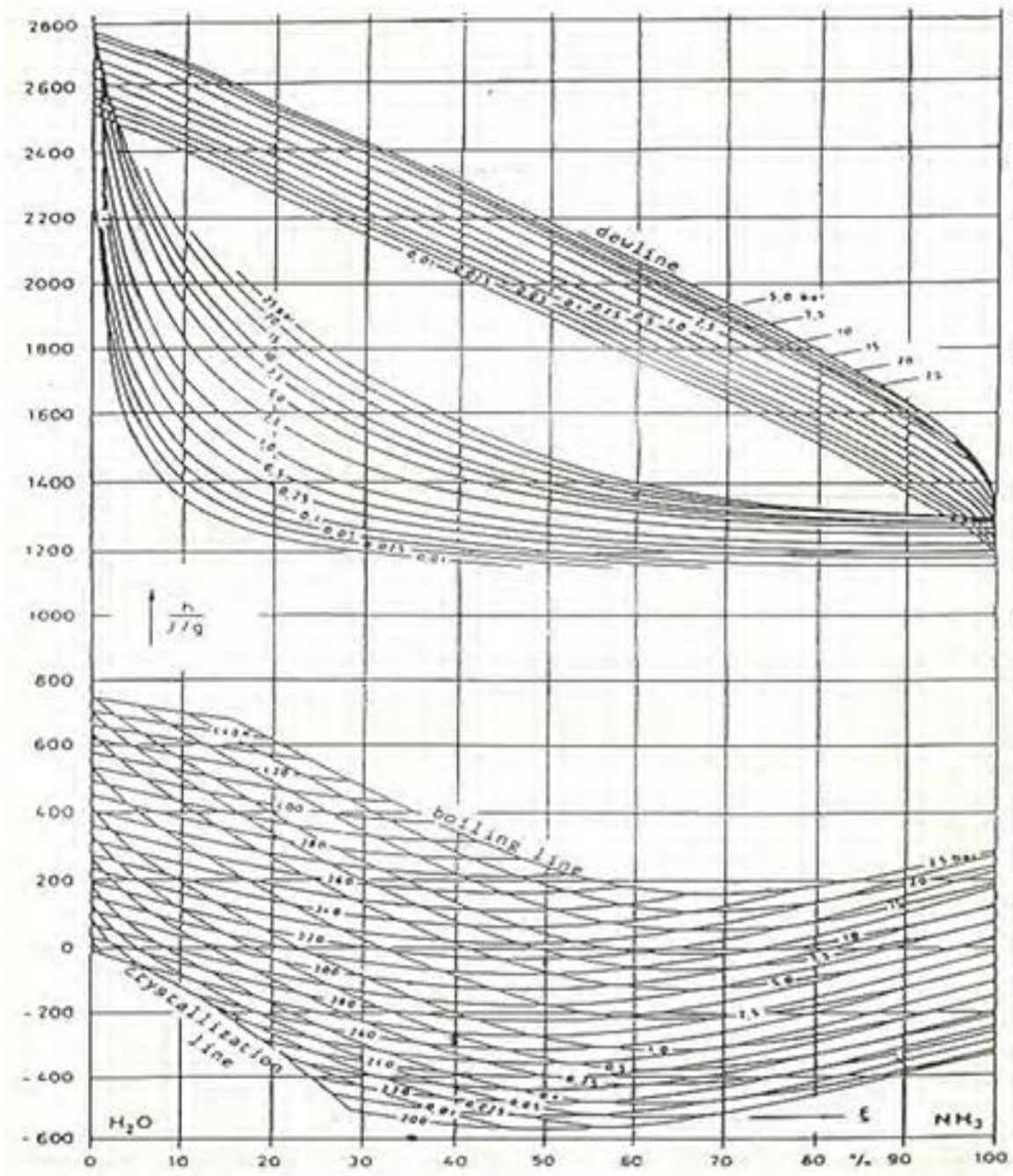


Figure 3.7: h-T-ξ chart for ammonia-water solution. [15]

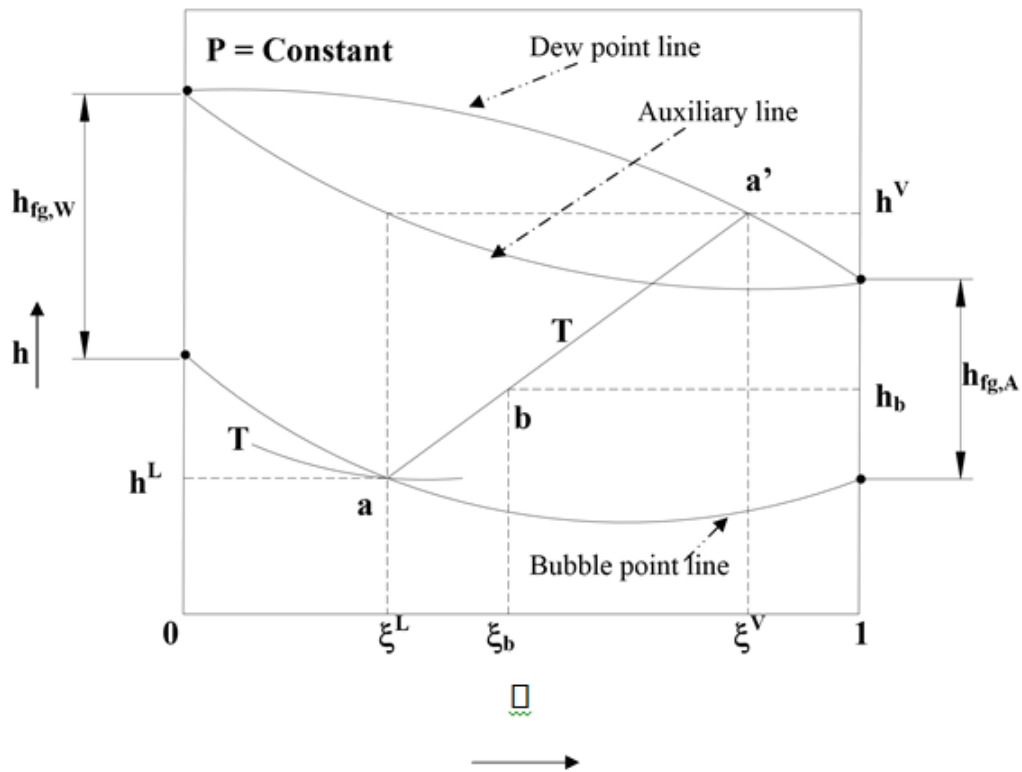


Figure 3.8: Enthalpy-composition diagram of NH₃-H₂O at a constant pressure P. [15]

3.6 Determination of temperature of mixture in two phase region

A trial and error method has to be used to determine the temperature of a point in two-phase region if its liquid phase mass fraction, enthalpy and pressure are known. The trial and error method can be numerical or graphical. Figure 3.9 shows a graphical method for detecting the temperature of point x in the two phase region which is at a known pressure P_x , liquid phase mass fraction ξ_x and also the enthalpy . To start with, point a' is obtained as shown in the figure by drawing a vertical line from point x upto the auxiliary line and then after drawing a horizontal line from the junction point a'' upto the dew point line, the junction of which gives a. Then a straight line a'- x- a is drawn as shown. Now, the point b' is obtained by drawing a vertical line upto the auxiliary line and then drawing a horizontal line from b'' upto the dew point line to get 'b' . Then line b'- x- b is drawn passing through x. This procedure is repeated h_x until convergence is acquired.

Numerically the temperature can be procured from the equation, which needs to be satisfied for each end of the isotherm passing through x,

$$\frac{h^V - h^L}{\xi^V - \xi^L} = \frac{h_x - h^L}{\xi_x - \xi^L} \quad (3.22)$$

To begin with guess values of h^L and ξ^L are presumed by taking some point on the bubble point line. Then saturated vapour properties h^V and ξ^V are acquired from the enthalpy composition charts using the supposed values of h^L and ξ^L . Then using the above equation, new values of h^L and ξ^L are acquired. Then these new values are used to get the next set of h^V and ξ^V . This procedure is recapitulated till the values converge. Once the converged values of h^L and ξ^L are acquired then the temperature is read from the enthalpy composition chart.

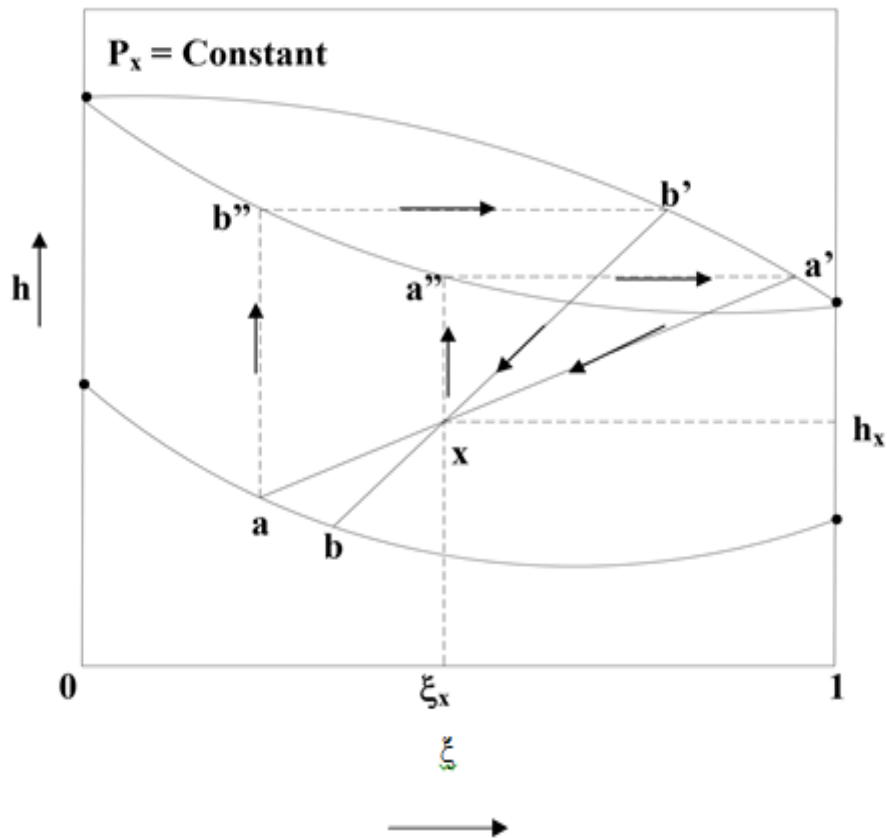


Figure 3.9: A graphical method for finding temperature of liquid-vapour mixture. [15]

3.7 THERMODYNAMIC MODELLING

The thermodynamic analysis of the vapour absorption refrigeration cycle is based on the following three equations which can be applied to any part of the system .

1. Mass balance

$$\sum m = 0 \quad (3.23)$$

2. Material balance

$$\sum m\xi = 0 \quad (3.24)$$

3. Energy balance

$$\sum Q + \sum mh = 0 \quad (3.25)$$

GENERATOR

Overall mass balance:

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3 \quad (3.26)$$

Ammonia balance:

$$\dot{m}_1 * x_1 = \dot{m}_2 * x_2 + \dot{m}_3 * x_3 \quad (3.27)$$

Energy balance:

$$h_1 * \dot{m}_1 - h_2 * \dot{m}_2 - h_3 * \dot{m}_3 + Q_{\text{gen}} = 0 \quad (3.28)$$

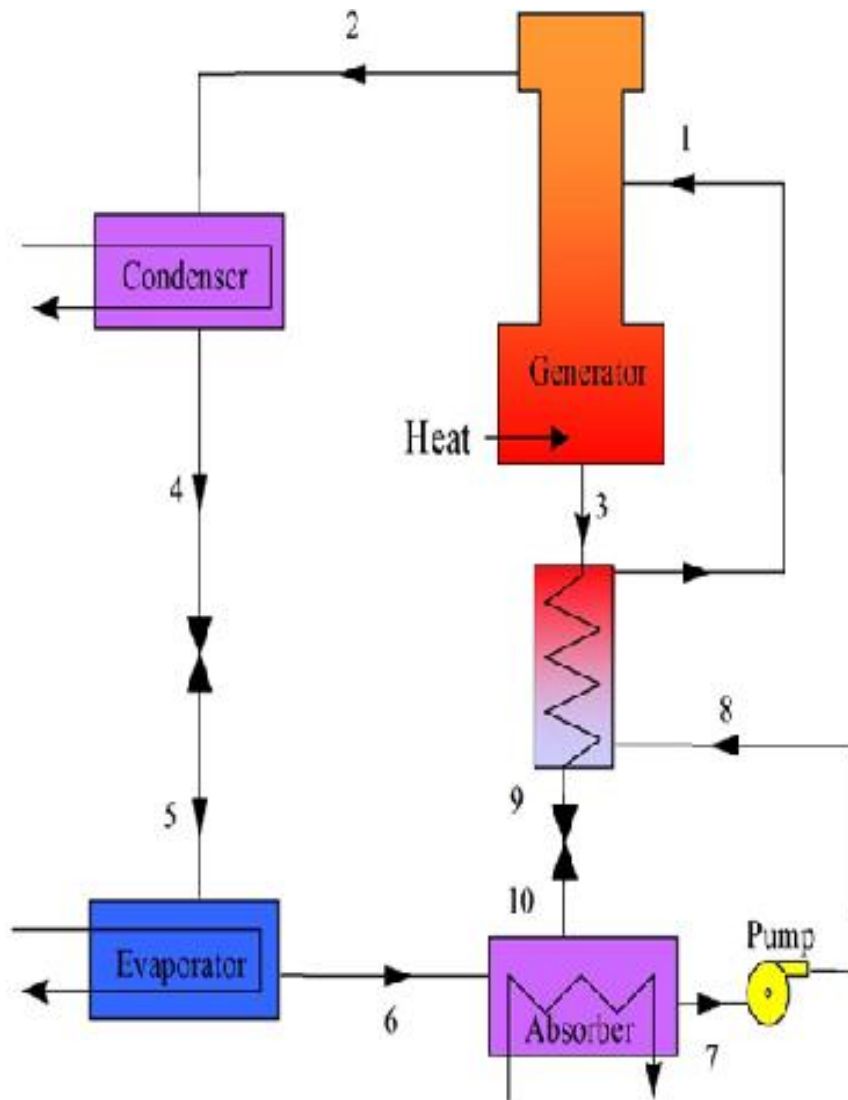


Figure 3.10: Schematic Diagram of Simple Vapour Absorption Refrigeration System. [16]

CONDENSER

$$Q_{\text{cond}} = (h_2 - h_4) \cdot \dot{m}_2 \quad (3.29)$$

THROTTLING VALVE (ISENTHALPIC)

$$h_4 = h_5 \quad (3.30)$$

EVAPORATOR

$$Q_{\text{evap}} = \dot{m}_2 \cdot (h_6 - h_5) \quad (3.31)$$

ABSORBER

Energy balance:

$$h_6 \cdot \dot{m}_2 + h_{10} \cdot \dot{m}_3 - Q_{\text{abs}} = h_7 \cdot \dot{m}_1 \quad (3.32)$$

$$h_9 = h_{10} \text{ (isenthalpic)} \quad (3.33)$$

GENERATOR HEAT EXCHANGER

$$h_7 = h_8 \quad \text{(neglecting pump work)} \quad (3.34)$$

$$\dot{m}_1 \cdot (h_1 - h_8) = \dot{m}_3 \cdot (h_3 - h_9) \quad (3.35)$$

$$\text{COP} = Q_{\text{evap}}/Q_{\text{gen}} \quad (3.36)$$

The first law efficiency alone can never tell about the accurate measure of the performance of any engineering device. To overcome from this deficiency, we introduce the second law efficiency, which is defined as the ratio between actual thermal efficiency to the maximum possible thermal efficiency or in other words, it can also be stated that the ratio of actual performance (COP) and the maximum possible Coefficient of Performance (COP_{rev}) under the same condition.

When we derive for an actual refrigeration system while considering a reversible one than the second law efficiency can be written in the form of

$$\eta_{\text{II}} = \text{COP}/\text{COP}_{\text{rev}} \quad (3.37)$$

From the heat conductance theory, the overall conductance, can be written as

$$UA = C_{\text{min}} \cdot \ln(1/1 - \epsilon) \quad (3.38)$$

The reduction in UA value is due to the increasing of the fouling effect on the air side and can be characterized as a percentage, UA %, in the subsequent manner:

$$UA\% = (1 - UA/UA_{\text{cl}}) \cdot 100 \quad (3.39)$$

TYPE OF FLUID	FOULING FACTOR(m² .°C/W)
Seawater, below 50°C	.00009
Above 50°C	.002
Treated boiler feed water above 50°C	.0002
Fuel oil	.0009
Quenching oil	.0007
Alcohol vapors	.00009
Industrial air	.0004
Steam, non-oil-bearing	.00009
Refrigerating liquid	.0002

Table 3.1: Table for selected fouling factors. [13]

In the present research work, by keeping the constant value of overall conductance how the fouling may effects on the various parameters of vapour absorption refrigeration system has been calculated. Also, when only evaporator is gone under fouling percentage decrease in the COP is also calculated. In addition to this, in the overall calculations heat leakages in the lines and pressure drop in heat exchangers will be considered as negligible. With the help of EES for solving the above of the equations where, a computer program will be written. In the programs, by the help of in built function will be obtained that are needed at every step of the calculation like, thermo physical properties of the refrigerants.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter deals with the results and discussion for single stage vapour absorption refrigeration system under normal condition and under fouled condition simultaneously. Methodology and formulation for these systems are already discussed in chapter 3.

4.1 Result from the given vapour absorption refrigeration system:

4.1.1 Input parameters:

Condenser pressure	:	20.3 bar
Evaporator pressure	:	2.1 bar
Generator temperature	:	156°C
Absorber temperature	:	40°C

4.1.2 Results:

(a) When condenser and evaporator both under fouling.

$$\text{COP} = 0.2579$$

$$\text{COP}_f = 0.2351$$

$$\eta_{II} = 6.951$$

$$\eta_{II,f} = 6.761$$

$$\begin{aligned} \text{Percentage decrease in COP} &= \frac{\text{COP} - \text{COP}_f}{\text{COP}} \times 100 \\ &= \frac{0.2579 - 0.2351}{0.2579} \times 100 \\ &= 8.81 \% \end{aligned}$$

$$\text{Percentage decrease in } \eta_{II} = 2.73 \%$$

4.2 Performance curves:

First of all, we are discussing the results when we consider the whole system is under with or without fouled condition.

(a) Variation of COP with q_0 under normal condition.

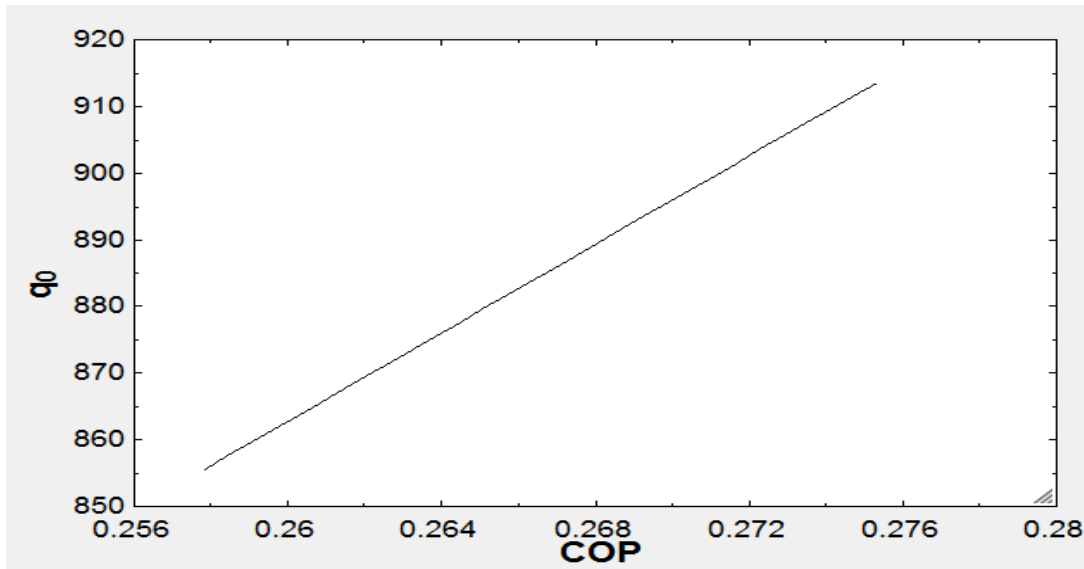


Figure 4.1: variation of COP with q_0 .

	1	2
1..30	COP	q_0
Run 1	0.2578	855.6
Run 2	0.2584	857.6
Run 3	0.259	859.6
Run 4	0.2596	861.6
Run 5	0.2603	863.6
Run 6	0.2609	865.6
Run 7	0.2615	867.6
Run 8	0.2621	869.6
Run 9	0.2627	871.6
Run 10	0.2633	873.6
Run 11	0.2639	875.6
Run 12	0.2645	877.6
Run 13	0.2651	879.6
Run 14	0.2657	881.6
Run 15	0.2663	883.6
Run 16	0.2669	885.6
Run 17	0.2675	887.6
Run 18	0.2681	889.6
Run 19	0.2687	891.6
Run 20	0.2693	893.6

Table 4.1: COP and q_0 .

(b) Variation of COP_f with $q_{0,f}$ under fouled condition.

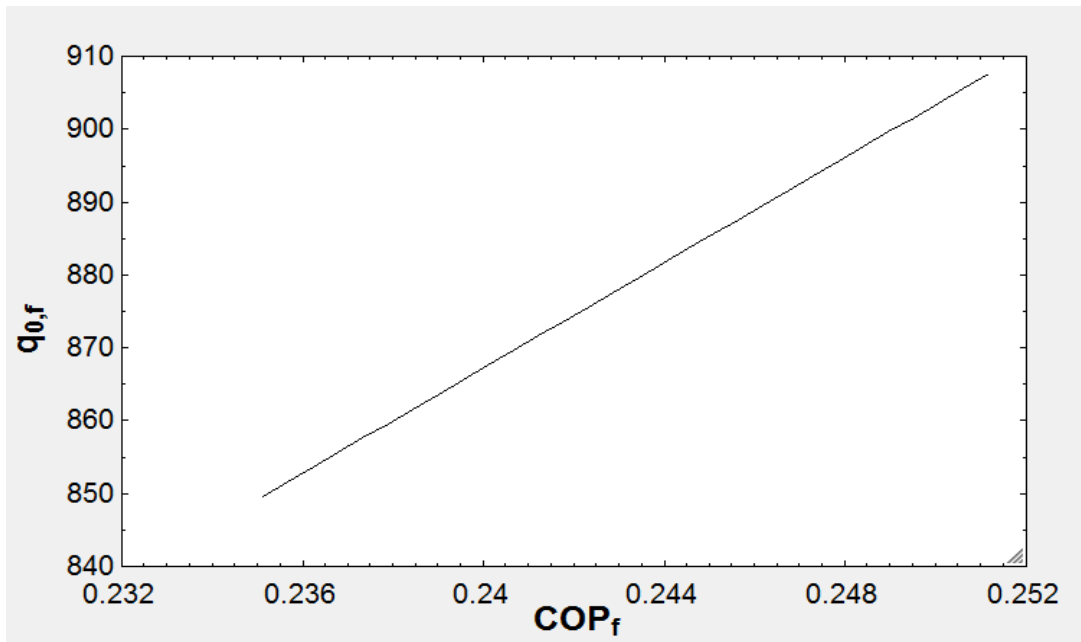


Figure 4.2: variation of COP_f with $q_{0,f}$.

	1	2
1..30	COP_f	$q_{0,f}$
Run 1	0.2351	849.6
Run 2	0.2357	851.6
Run 3	0.2362	853.6
Run 4	0.2368	855.6
Run 5	0.2373	857.6
Run 6	0.2379	859.6
Run 7	0.2384	861.6
Run 8	0.239	863.6
Run 9	0.2395	865.6
Run 10	0.2401	867.6
Run 11	0.2407	869.6
Run 12	0.2412	871.6
Run 13	0.2418	873.6
Run 14	0.2423	875.6
Run 15	0.2429	877.6
Run 16	0.2434	879.6
Run 17	0.244	881.6
Run 18	0.2445	883.6
Run 19	0.2451	885.6
Run 20	0.2456	887.6

Table 4.2: COP_f and $q_{0,f}$.

(c) Variation of ε with UA_{cl} under normal condition.

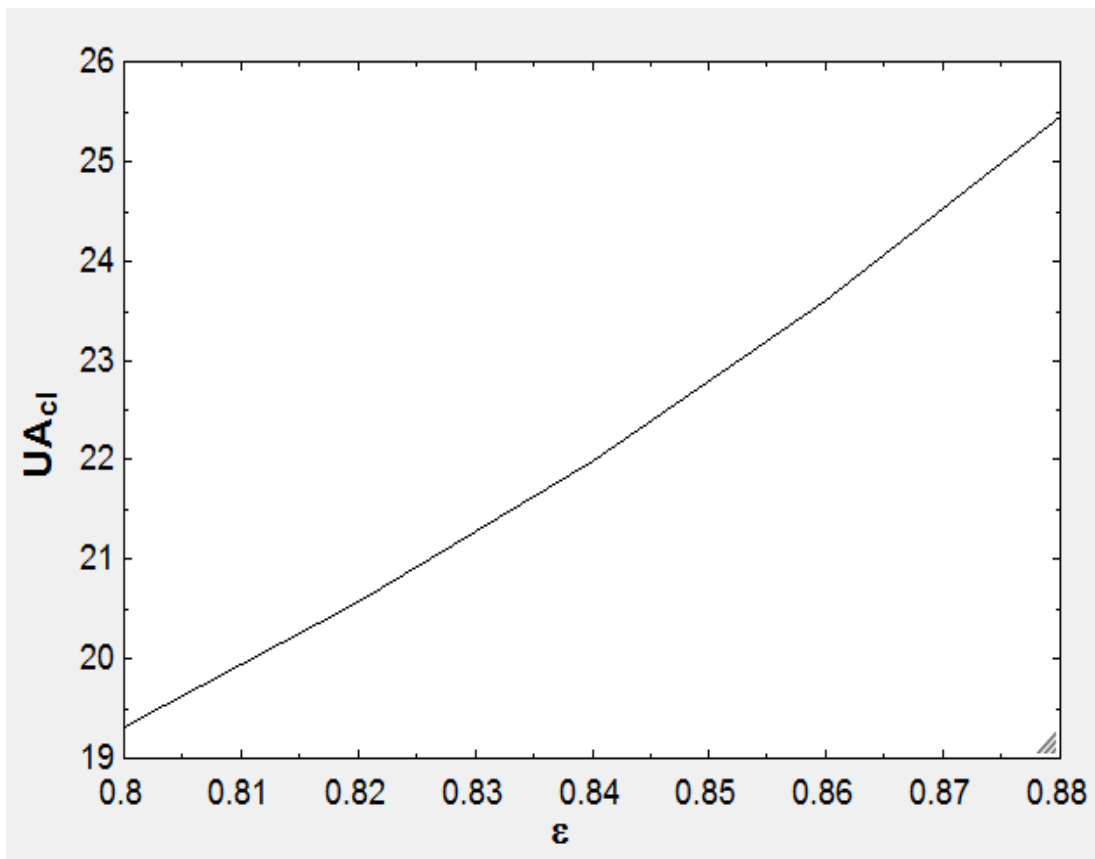


Figure 4.3: variation of ε with UA_{cl} .

	1	2
1.5	ε	UA_{cl}
Run 1	0.8	19.31
Run 2	0.82	20.58
Run 3	0.84	21.99
Run 4	0.86	23.59
Run 5	0.88	25.44

Table 4.3: ε and UA_{cl} .

(d) Variation of ε_f with $UA_{cl,f}$ under fouled condition.

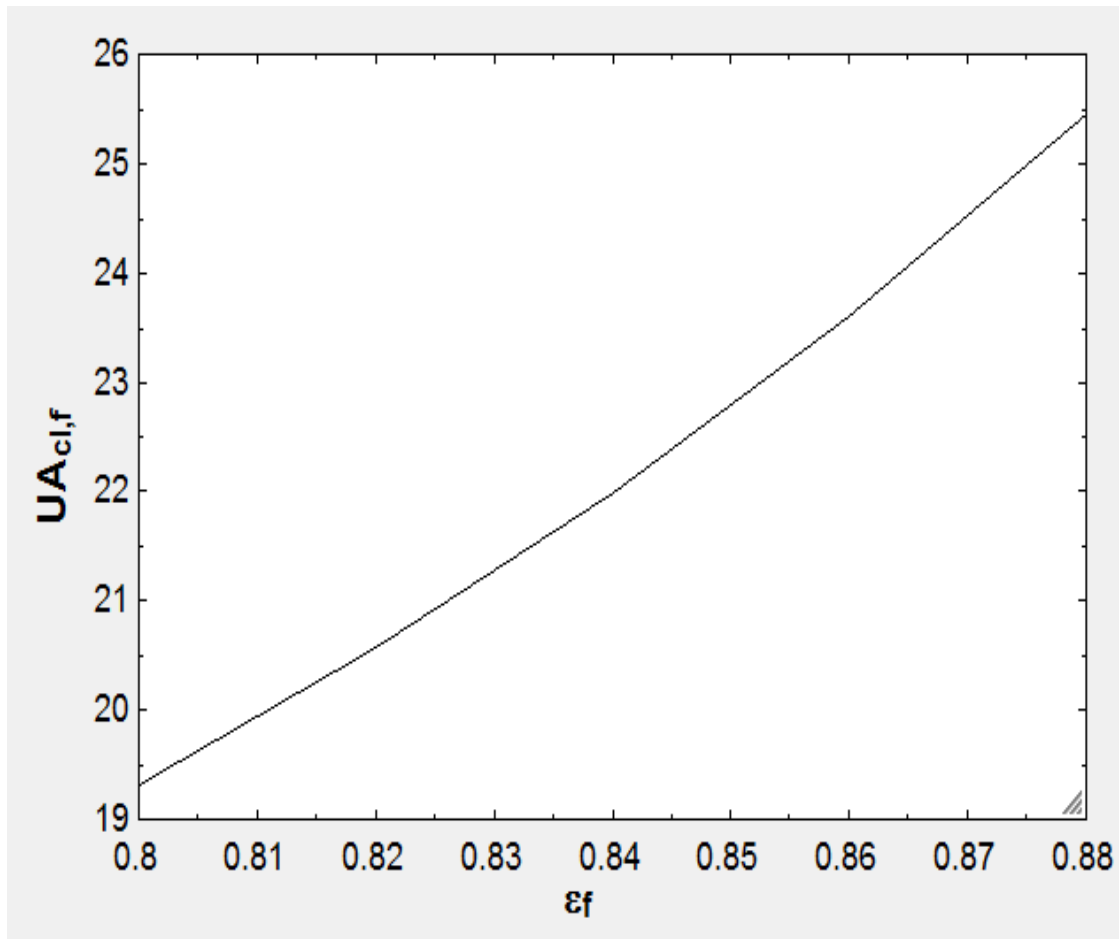


Figure 4.4: variation of ε_f with $UA_{cl,f}$.

	1	2
▶ 1.5	ε_f	$UA_{cl,f}$
Run 1	0.8	19.31
Run 2	0.82	20.58
Run 3	0.84	21.99
Run 4	0.86	23.59
Run 5	0.88	25.44

Table 4.4: ε_f and $UA_{cl,f}$.

(e) Variation of COP with q_h under normal condition.

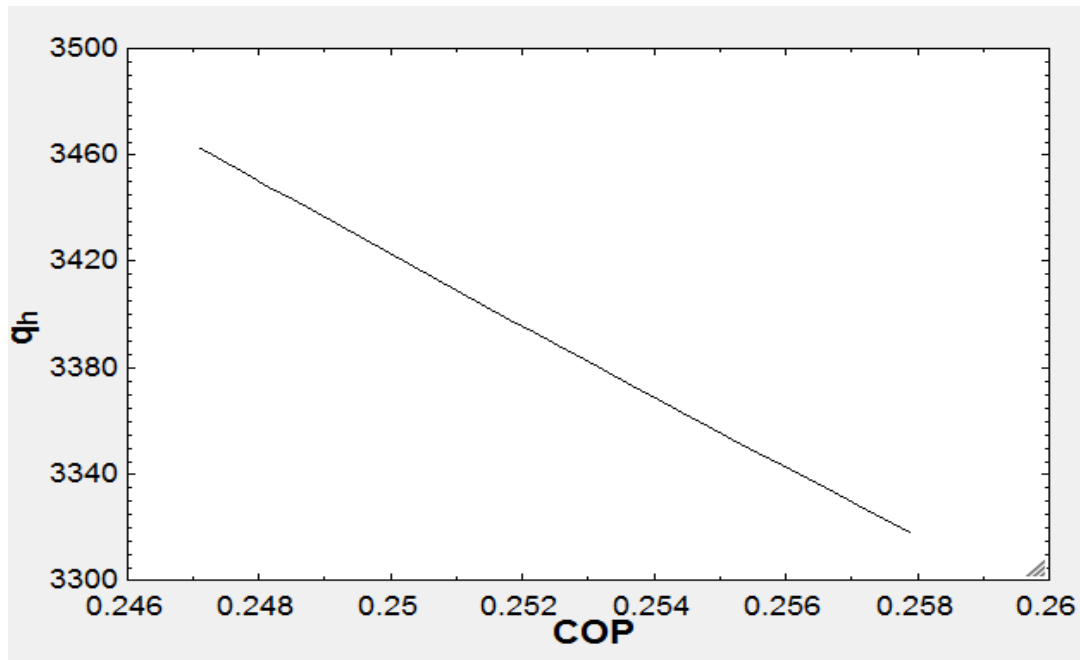


Figure 4.5: variation of COP with q_h .

1..30	1 q_h	2 COP
Run 1	3318	0.2579
Run 2	3323	0.2575
Run 3	3328	0.2571
Run 4	3333	0.2567
Run 5	3338	0.2563
Run 6	3343	0.256
Run 7	3348	0.2556
Run 8	3353	0.2552
Run 9	3358	0.2548
Run 10	3363	0.2544
Run 11	3368	0.2541
Run 12	3373	0.2537
Run 13	3378	0.2533
Run 14	3383	0.2529
Run 15	3388	0.2526
Run 16	3393	0.2522
Run 17	3398	0.2518
Run 18	3403	0.2514
Run 19	3408	0.2511
Run 20	3413	0.2507

Table 4.5: COP and q_h .

(f) Variation of COP_f with $q_{h,f}$ under fouled condition.

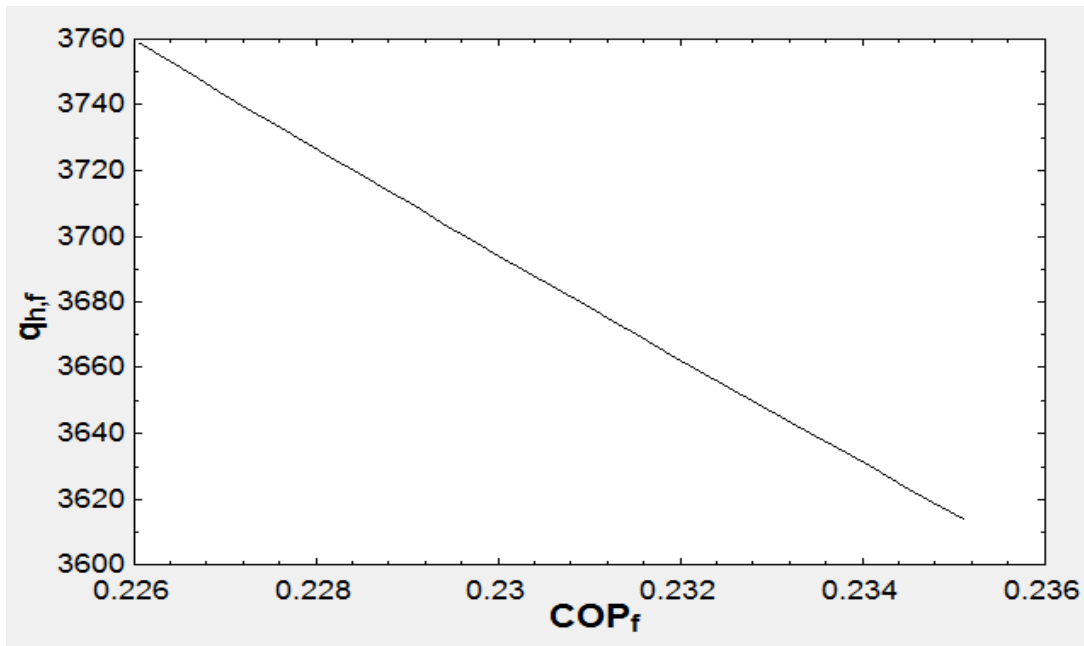


Figure 4.6: variation of COP_f with $q_{h,f}$.

1..30	1 COP_f	2 $q_{h,f}$
Run 1	0.2351	3614
Run 2	0.2348	3619
Run 3	0.2344	3624
Run 4	0.2341	3629
Run 5	0.2338	3634
Run 6	0.2335	3639
Run 7	0.2332	3644
Run 8	0.2328	3649
Run 9	0.2325	3654
Run 10	0.2322	3659
Run 11	0.2319	3664
Run 12	0.2316	3669
Run 13	0.2313	3674
Run 14	0.2309	3679
Run 15	0.2306	3684
Run 16	0.2303	3689
Run 17	0.23	3694
Run 18	0.2297	3699
Run 19	0.2294	3704
Run 20	0.2291	3709

Table 4.6: COP_f and $q_{h,f}$.

(g) Variation of C_{\min} with UA_{cl} under normal condition.

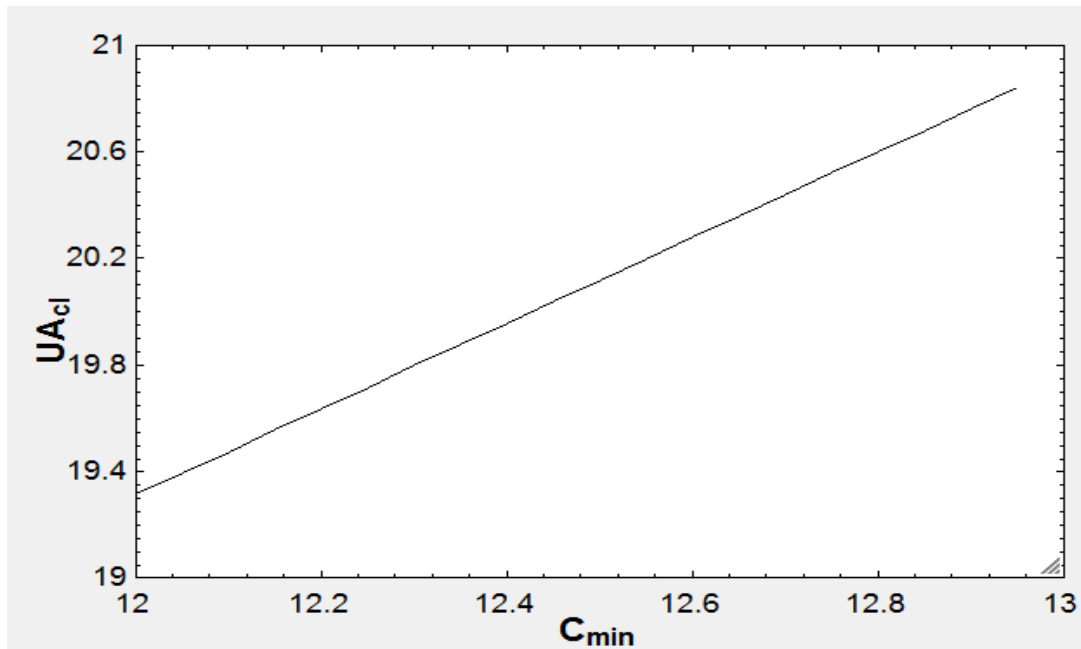


Figure 4.7: variation of C_{\min} with UA_{cl} .

	1	2
	C_{\min}	UA_{cl}
Run 1	12	19.31
Run 2	12.05	19.39
Run 3	12.1	19.47
Run 4	12.15	19.55
Run 5	12.2	19.64
Run 6	12.25	19.72
Run 7	12.3	19.8
Run 8	12.35	19.88
Run 9	12.4	19.96
Run 10	12.45	20.04
Run 11	12.5	20.12
Run 12	12.55	20.2
Run 13	12.6	20.28
Run 14	12.65	20.36
Run 15	12.7	20.44
Run 16	12.75	20.52
Run 17	12.8	20.6
Run 18	12.85	20.68
Run 19	12.9	20.76
Run 20	12.95	20.84

Table 4.7: C_{\min} with UA_{cl} .

(h) Variation of $C_{min,f}$ with $UA_{cl,f}$ under fouled condition.

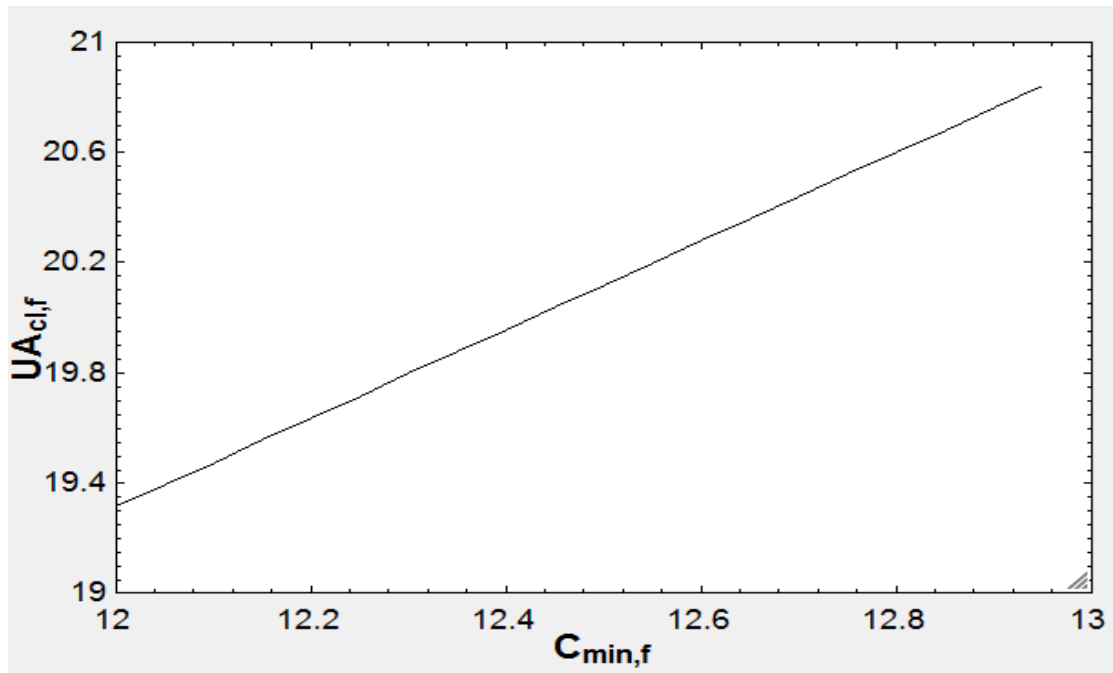


Figure 4.8: variation of $C_{min,f}$ with $UA_{cl,f}$.

▶ 1..20	1 $C_{min,f}$	2 $UA_{cl,f}$
Run 1	12	19.31
Run 2	12.05	19.39
Run 3	12.1	19.47
Run 4	12.15	19.55
Run 5	12.2	19.64
Run 6	12.25	19.72
Run 7	12.3	19.8
Run 8	12.35	19.88
Run 9	12.4	19.96
Run 10	12.45	20.04
Run 11	12.5	20.12
Run 12	12.55	20.2
Run 13	12.6	20.28
Run 14	12.65	20.36
Run 15	12.7	20.44
Run 16	12.75	20.52
Run 17	12.8	20.6
Run 18	12.85	20.68
Run 19	12.9	20.76
Run 20	12.95	20.84

Table 4.8: $C_{min,f}$ and $UA_{cl,f}$.

(i) Table for COP and η_{II} under normal condition.

▶ 1..30	1 COP	2 η_{II}
Run 1	0.2579	6.953
Run 2	0.3079	8.301
Run 3	0.3579	9.649
Run 4	0.4079	11
Run 5	0.4579	12.34
Run 6	0.5079	13.69
Run 7	0.5579	15.04
Run 8	0.6079	16.39
Run 9	0.6579	17.74
Run 10	0.7079	19.08

Table 4.9: COP and η_{II} .

(j) Table for COP_f and $\eta_{II,f}$ under fouled condition.

▶ 1..30	1 COP_f	2 $\eta_{II,f}$
Run 1	0.2351	6.761
Run 2	0.2851	8.198
Run 3	0.3351	9.636
Run 4	0.3851	11.07
Run 5	0.4351	12.51
Run 6	0.4851	13.95
Run 7	0.5351	15.39
Run 8	0.5851	16.83
Run 9	0.6351	18.26
Run 10	0.6851	19.7

Table 4.10: COP_f and $\eta_{II,f}$.

CHAPTER 5

CONCLUSIONS AND SCOPE OF FUTURE WORK

5.1 Conclusions

This present work has been set out to get the values of coefficient of performance of the vapour absorption refrigeration system under normal and fouled condition. In the present work the performance analysis of the ammonia-water ($\text{NH}_3\text{-H}_2\text{O}$) vapour absorption refrigeration system under fouled condition in the overall system has been carried out. Here, the performance of the VARS is degraded under fouled condition. So that it is necessary to clean the heat exchanger after the period of time. The obtained results from this analysis are permits the following remarks:

1. COP of the vapour absorption refrigeration system (VARS) under fouled condition is decreased by 8.81% than that of under normal condition.
2. η_{II} of the vapour absorption refrigeration system under fouled condition is decreased by 2.73%.
3. When heat is added to the evaporator, COP of the system gets increased.
4. COP of the system is also increasing while increasing the effectiveness of the heat exchanger.
5. As the temperature of Generator and Condenser temperature are of the increasing nature, COP of the system gets decreases.
6. As the temperature of the evaporator gets increases, COP of the system also increases.

5.2 Scope of future work

1. The performance analysis of the vapour absorption refrigeration system under fouled condition may be done with condenser fouling.
2. The performance analysis of the vapour absorption refrigeration system may be done by taking evaporator fouling into consideration.
3. This performance analysis may be done for double stage vapour absorption refrigeration system.
4. The result of theoretical analysis may be compared with the actual results of refrigeration system.
5. In actual practice, VARS is always equipped with one more heat exchanger, the fouling of that may be incorporated in the result of overall performance.
6. The result may be compared with the vapour absorption refrigeration system using Li-Br with water as a refrigerant.

REFERENCES

- [1] D.H.Bultman, 1995. Effects of condenser air flow blockage on vapor-compression refrigerator. *Journal of Energy Resources Technology-transactions of The ASME*, 117(4):349-353.
- [2] J.A.Siegel, 2002. Particulate fouling of HAVC Heat Exchangers, Ph.D. Thesis.
- [3] Pak, B. C., Groll, E. A., Braun, J. E., 2005. Impact of fouling and cleaning on plate fin and spine fin heat exchanger performance. *ASHRAE Transactions*. Vol. 111 PART 1. Orlando, FL, United states, pp. 496 – 504.
- [4] Ali, A.H.H., Ismail, I.M., 2008. Evaporator air-side fouling: effect on performance of room air conditioners and impact on indoor air quality. *HVAC&R Res.* 14, 209-219.
- [5] Bell, I.H., Groll, E.A., 2010. Air-side particulate fouling of microchannel heat exchangers. *Appl. Therm. Eng.* 31, 742-749.
- [6] Raghuvanshi, S., Maheshwari, G., 2011. Analysis of ammonia-water ($\text{NH}_3\text{-H}_2\text{O}$) vapour absorption refrigeration system based on first law of thermodynamics. *Int. J. of scientific and engineering*. Vol.2(8).
- [7] Qureshi, B.A., Zubair, S.M., 2012a. The impact of fouling on performance of a vapor compression refrigeration system with integrated mechanical sub-cooling. *Appl. Energy* 92, 750-762.
- [8] Qureshi, B.A., Zubair, S.M., 2012b. The effect of refrigerant combinations on performance of a vapor compression refrigeration system with dedicated mechanical sub-cooling. *Int. J. Refrigeration* 35 (1), 47-57.
- [9] Bajpai. V.K., 2012. Design of solar powered vapour absorption system. *World congress on engineering*. Vol 2. London. U.K.

[10] Patel. V.D., 2012. Theoretical and Experimental evaluation of Vapour Absorption Refrigeration System. Int. J. engineering research and application.

[11] Vazhappilly, CV., 2013. Modeling and Experimental Analysis of Generator in Vapour Absorption Refrigeration System. Vol.3(5), pp.63-67.

[12] ARORA.C.P. Refrigeration and Air Conditioning, Tata McGraw-Hill, Second Edition, 1981.

[13] HOLMAN.J.P. Heat and Mass Transfer, Tata McGraw-Hill, Ninth Edition, 2008.

[14] www.wikipedia.com.

[15] www.nptel.ac.in.

[16] EES Tutorial, V9.224-3D.