IMPACT ANALYSIS OF FIRECRACKERS ON ULTRAFINE AND QUASI ULTRAFINE PARTICLE NUMBER CONCENTRATION DURING DIWALI FESTIVAL IN DELHI

A PROJECT REPORT

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Submitted by:

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CANDIDATE'S DECLARATION

I, Ajay Singh, Roll No. 2K18/ENE/01 student of MTech Environmental Engineering, hereby declare that the Project Dissertation titled "Impact Analysis of Firecrackers on Ultrafine and Quasi Ultrafine Particle Number Concentration During Diwali Festival in Delhi" which is submitted by me to the Department of Environmental Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

Place: DTU, Delhi, India **(AJAY SINGH)**

Date: JULY 2020

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CERTIFICATE

I hereby certify that the Project Report entitled "Impact Analysis of Firecrackers on Ultrafine and Quasi Ultrafine Particle Number Concentration During Diwali Festival in Delhi" which is submitted by Ajay Singh, Roll No. 2K18/ENE/01, Department of Environmental Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

PLACE: DELHI **Dr. Rajeev Kumar Mishra**

DATE: JULY 2020 **SUPERVISOR**

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ABSTRACT

This study is carried out in Delhi Technological University, (DTU) campus, which is an institutional cum residential area in the megacity of Delhi. To assess the effects and variation in ultrafine range aerosols in terms of their particle numbers and mobility equivalent diameter during the episodic event of Diwali (with fireworks) and non-episodic (lesser or without fireworks) event days, monitoring has been conducted. The usage of moderately high burning of fireworks shows the significant growth in the pattern of nucleation, aitken, along with individual accumulation mode particles. The different peaks ($1.35\text{-}3.41\times10^5$ /cm^3) that occurred in and about Diwali occasion can attribute to meteorology and other local emission sources. With the surge in an overall total concentration of particles and accumulation mode, the ultrafine aerosols size distribution received a single peak ranging from 35-110 nm. For most of the scenario, the maxima of total particle concentration superimposed with the minima of geometric mean diameter likely in ultrafine particles (<100 nm). During the extreme bursting of fireworks in peak time, there was found a rise in accumulation mode particles with the parallel evolution of new particles in nucleation and small- aitken mode ranges. This study makes a difference in Particle number dynamics (PSD) of occasional events and non-occasional days with a clear shift of UFP along with accumulative mode particles. The study will help in generating public awareness about the human health risks due to bursting of fireworks during Diwali festival.

Keywords: *Firework, Nucleation mode, Size distribution evolution, Ultrafine Particles*

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LIST OF ABBREVIATIONS

UFP	Ultrafine Particles
PNC	Particle Number Concentration
PSD	Particle Size Distribution
IGP	Indo Gangetic Plain
PM	Particulate Matter
RH	Relative Humidity
WS	Wind Speed
ETC	European Topic Centre
ACM	Air pollution and Climate Change Mitigation
SMPS	Scanning Mobility Particle Spectrometer
DMA	Differential Mobility Analyser
Dp	Particle Diameter
GMD	Geometric Mean Diameter
WHO	World Health Organization
CPC	Condensation Particle Counter
TSP	Total Suspended Particle

CHAPTER 1 INTRODUCTION

Ambient air quality is a cause of concern for researchers and policymakers for a long time. Increasing man-oriented activities and selfish approaches have led us to survive in a severely polluted environment. The urban population experiences a heterogeneous mixture of ambient air pollutants as of their extreme variability in terms of time and space (Singh et al., 2011). Serious implications such as climate change decreased visibility, and health issues are on high due to ambient air pollution (Kong et al., 2015; Kumar et al., 2016). Specifically, the finer aerosols and UFP form of pollutants induce maximum deterioration in the ambient air as well as to health (Joshi et al., 2016, 2019). Transformation of aerosols generated from various sources follows nucleation, coagulation, and accumulation processes (Banerjee et al., 2015). This transformation caused by the variability in emission sources and meteorological parameters (Murari et al., 2014; Tiwari et al., 2013). Emissions generated by the vehicles and industries add majorly to the ambient air pollution levels through happenings like Festivals (Diwali in India), and forest fires have a crucial role in creating adverse impacts on air quality (Parkhi et al., 2016; Perrino et al., 2011; Rohra et al., 2018; Sati & Mohan, 2014; Srinivas et al., 2016; Yadav et al., 2019). For megacities like Delhi, the situation of ambient air quality is even critical as Delhi stands as one of the highly polluted megacities in the world in consideration to particulate matter pollution (Parkhi et al., 2016). At the early start of winters (Oct-Nov) every year, Diwali is celebrated with great pomp and show, filling the sky with firecrackers burning neglecting associated pollution with it.

1.1 SCENARIO OF FINER AEROSOLS IN CONCERN WITH DIWALI CELEBRATION

India, also known as the jewel of the crown, is well known for its festivities across the world. Diwali is one of the most important festival of India and falls every year during the month of October-November and celebrated on a grandiose scale with pomp and fervor since ages. The celebration is never complete without the majestic display of fireworks across the states and, study even show that 80 percent of the population of India are seen to be indulging in this massive celebration (Matawle et al., 2015). Needless to say, the National capital of India, New Delhi, the second largest urban area, does not lack behind in the participation of the festivity. However, in the past decades, numerous studies have highlighted the deterioration of the air quality as an aftermath of pollutants loading, chiefly elevated levels of Particulate Matter (PM) in the ambient air. In fact, the association of festivities and increased aerosol formation in the ambient atmosphere is known to affect both the environment, for instance reduced visibility, and the quality of life (Ambade, 2013), be it directly or indirectly. As far as the Indian context is concerned, various studies have been carried out to illustrate the release of high level of pollutants (Ravindra et al., 2003; Sahu et al., 2014; Barman et al., 2008) during such period. On the other hand, festivities across the globe such as National day celebration in United States (Seidel and Birnbaum, 2015), Lantern festival across the Chinese population (Zhang et al., 2017; Lin , 2014), Guy Hawkes in England (Godri et al.,2010) and New year celebrations across the world (Drewnick et al., 2006; Wehner et al., 2010) are often being linked with short –term air quality deterioration along with ascent in the pollution level. Though referred to as short-term deterioration of the air quality, the impacts on human health are severe, namely respiratory morbidity (Atkinson et al.,2015), cardiovascular diseases (Shah et al.,2015) and deaths (Dominici et al.,2006; Janssen et al.,2013), dementia (Chen et al.,2016), child brain structural alterations and cognitive impairment (Guxens et al., 2018) and acute eosinophilic pneumonia due to inhalation of smoke for three consecutive nights (Hirai et al.,2000). In addition to this, the festival of lights coincides with the winter season, the air pollutants tend to remain in suspension state and the temperature drop and wind speed also tend to influence the same.

Short term celebration leads to high air pollution levels (Mandal et al., 2012). Particulate emissions occurring at major celebrations are related to the deteriorated quality of ambient air (Kumar et al., 2016; Sarkar et al., 2010). Diwali event emissions are generally local and short term but instigate the respiratory and health illness for a longer duration with the increased UFP (finer aerosols) (Joshi et al., 2016; Singh et al., 2019). Scientists have been working on different aspects of firework generated emissions considering the significant impacts caused by them (Hirai et al., 2000; Kumar et al., 2016; Singh et al., 2010). Transformation of finer aerosols from nucleation to accumulation mode passing through the Aitken modes and its size characterization during Diwali is discussed by (Yadav et al., 2019). Other Diwali related research work included the behavior of PM10 and various gaseous pollutants (Attri et al., 2001; Parkhi et al., 2016; Ravindra et al., 2003; Sati & Mohan, 2014). Results from (Dutschke et al., 2011; Zhao et al., 2014) showed the transformation of small and nucleation mode to large and accumulation mode of the size range. On the other hand, (Yadav et al., 2019) concluded the inefficiency of connection between the temporal variation of PNC and the emission of fireworks, considering the more variability in it. Limited analysis has been done for PNC characterization, size segregation pattern, and relationship with meteorological factors, particularly in urban cities like Delhi. The transformation pattern in different subdivided size ranges is the area that is still untouched.

1.2 OBJECTIVES OF THE STUDY

Finer aerosols generation during the Diwali period as of intense firecracker burning follows quiet distinctive patterns and composition as compared to usual urban aerosols in the background, which needs analysis (Kumar et al., 2016). PNC related research can be helpful in the determination of AQI in terms of particle number count (Joshi et al., 2016). As far as India is concerned recent studies done during Diwali (Joshi et al., 2016, 2019; Yadav et al., 2019) stated an apparent increase in finer aerosols particle number concentration, but lacked in the effect of meteorological factors on PNC pattern and unclear source apportionment considering other (vehicular and industrial) emissions. Seeing these present gaps, the study was conducted considering the following objectives:

1. To analyze the diurnal variations of finer aerosols and characterizes their Particle number concentration in terms of different size segregation.

2.To Compare the Episodic and Background Events during the monitoring period

3.To establish a relationship between meteorological factors (such as RH and wind speed) and finer aerosols.

CHAPTER 2 LITERATURE REVIEW

There is a growing concern among air and health experts about the ultrafine particles (diameter <200nm) and Quasi-Ultrafine Range (diameter 200-1000nm) and their effect on human health. Ultrafine particles emission sources range from combustion processes like burning of coal, wood and or natural phenomena like forest fires. The studies across world over firework emissions on several major occasions showed direct increase in Particle Number Concentration (PNC).

Ultrafine and Quasi-Ultrafine particles are measured on the basis of Particle number per unit volume as Particle number per cm^3 due to negligible mass (Baldauf et al.2016). As of present, no standard criteria are there to make Ultrafine particles (UFPs) as an indicator of Air Pollutants. Workshop was held in 2006 by WHO wherein UFP gained a lot of attention and base level work started after that (Baldauf et al. 2016).The term "Ultrafine Particle" in ambient atmosphere lacks a universal definition, though all particles in ambient air which are lesser that 200nm diameter can be considered as Ultrafine Particles (Solomon 2012).Since it is unclear about which standard to be used (number or area) for ultrafine particles size range (UFP), some studies (ETC/ACM technical paper 2013) proposed the standard as particle number/Surface area concentration (PNC) to analyze UFP as PM2.5/PM10 is not able to serve the purpose of understanding the effects and behavior of UFP fraction in particulate matter present in ambient air.

Study by Yadav et al. (2019) for Diwali specific firework in Varanasi over central IGP (Indo-Gangetic Plain) showed how PNC and mobility equivalent Diameter of Submicron Particles Evolved. Measurement was done for pre, during and post Diwali days to compare the concentrations in different modes of particles characterization. Results indicated new particle formation and transformation from Nucleation to Accumulation modes as well. PNC fluctuation was evident because of meteorological factors and local sources emissions. Distinctive Peaks in Particle number concentration ($3.1\text{-}4.5\times10^4$ /cm^3) during the period (18:00-23:00hr) of Diwali day was shown. Interestingly, at times of peak firework emission, new particle formation predominated over accumulation mode resulting from nucleation mode and small-Aitken mode particles increase, before coming back to background concentration of particles. In this study, Black Carbon

(BC) concentration fluctuations were noted on the Diwali day that showed similar behavior as of firework emissions.

In a study by Joshi et al., (2016), the impacts of bursting of firecrackers were studied. An interest was drawn to the trend with respect to the attributes of aerosol number in urban areas of a metropolis. To evaluate the changes brought about during the celebrations, readings were taken from a height of 50m. A surge in the UFP concentration and particle number was observed. The buildup attributes were equally monitored. The concentration with respect to number were portraying a peak almost daily, hence at a first glance difficulty were linked to differentiation between the changes at the atmospheric level and the periodic bursting of crackers. Nevertheless, the demarcation between the aforesaid issue, was possible owing to the analysis of size around the peaks obtained. The outcomes of the study corroborate with previous ones dealing with aerosols formation associated with firework. Emphasis was focused on the threats linked to breathing of UFP. It was noted that short-term rise in Ultrafine Particles concentration can cause respiratory problems to humans. According to the results, it is not possible to differentiate between episodic (Firework emission period) and normal (Ambient atmospheric changes) events. So, the differential criteria were adopted on the basis of size evolution for Particle Number concentration peaks.

A study on Diwali, before Diwali and after Diwali days in two consecutive years (Nov. 2010 and Oct. 2011) was done by (Parkhi et al., 2016) wherein large number of fireworks was established during Diwali days. The observation showed 5 to 10 times peak in Particulate Matter concentrations. The large difference in pollutant concentration in two years is controlled by weather parameters. Mandal et al. (2011) accessed effects of Diwali celebration on Delhi Urban Air Quality, during the month of pre-Diwali, Diwali month and Post Diwali Month during period of 2006-2008. During Diwali day, use of firework showed 1.3 to 4.0 times rise in PM10 concentration and 1.6 to 2.5 times increase in TSP (Total suspended particulate matter) than concentration during the month of pre-Diwali. Statistical Analysis was also done to correlate between the different parameter of air pollutants and analyze them.

Furthermore, Singh et al., (2009) studied the chronological deviation of the ambient air quality, during the festival of lights in Delhi. Some of the parameters studied are: PM_{10}, SO_2, NO_2, TSP (Total Suspended Particle). The study was carried out in four segments namely: before, after, the

Diwali day as well as on days where foggy conditions prevailed. Readings were taken from the year 2002 to 2007. The TSP was seen to be practically the same as that of an industrialized area of Delhi all year round. However, upon comparison against the data collected at industrial sites, the concentration for the rest three parameters depicted a two to six folds rise during Diwali. As far as foggy days are concerned, a rise could be equally observed. Meteorological conditions such as a decline in the mixing height, temperature and wind velocity have been contributing to the poor ambient quality on the D-day, hence explaining the increasing trend of the parameters before the respective peaks are attained on the day of festival. On a similar note, a decline in the concentration was registered after the festivities. A remarkably high surge was observed for PM_{10} in 2007, whereby the recorded value was 3.6 times higher than stipulated limits of NAAQS, unlike the other years of study. Overall, the study concluded that firecrackers bursting certainly emits PM_{10}, SO_2, NO_2 and TSP, which eventually undergoes buildup, along with triggering conditions leading to poor air quality.

Concurrently, Srinivas et al., (2016), have favored the use of a sensitive as well as interactive weather- chemistry prototype to forecast the air quality both 24hrs and 72hrs ahead of time. The same was carried out twice, namely for the episodic event of Diwali in 2012 and 2013 in Delhi. Assessment of $PM_{2.5}$ was carried out 3 days before and after the massive celebration dealing with fireworks. The prediction of 2012 was reported as accurate, unlike in 2013 whereby the quick accumulation of $PM_{2.5}$ was reportedly taking place at 1500 µg m^{-3} on an average hourly basis, post the Diwali day. Failures in terms of inability to record the unfamiliar low temperature during the wee hours. Slashed boundary layer height was also reported. One important conclusion of this study is that abrupt variations in the meteorological parameters can divert the forecasts, particularly in a highly localized region.

In a case study by Tiwari et al., (2013), $PM_{2.5}$ was studied over a period of 3 years (2007-2009) and same was subjected to statistical evaluation. The daily average of $PM_{2.5}$ was well above the stipulated guidelines of NAAQS. The concentration varied between 12 to 367.9 µg m^{-3}. In fact, analysis show that almost 69 % of the samples crossed the 24h threshold while 85 % of the samples was above 40 µg m^{-3} i.e. exceeded the yearly average. In terms of seasons, the $PM_{2.5}$ values recorded were following the trend: post monsoon > winter > summer > monsoon, while on a yearly basis, the values recorded was highest in 2008. A negative correlation was observed between $PM_{2.5}$

and temperature (r = - 0.59), likewise with respect to wind (r = -0.38). The maxima were registered when no adverse weather conditions were prevailing, unlike the minima which was recorded when the wind velocity was 5 km h^{-1}. Chance of risks are higher during winter owing to the stable weather conditions.

The particle size distribution and water-soluble in-organic ion (WSII) and carbonaceous species in size-segregated aerosols, Dp < 0.95, 0.95 < Dp < 1.5,1.5 < Dp < 3.0, 3.0 < Dp < 7.2, and 7.2 < Dp < 10 μm was studied by Kumar et al., (2016) in Delhi. Higher concentrations of $PM_{0.95}$ was observed unlike for $PM_{0.95-1.5.}$ Similarly, Dp < 0.95 and 0.95 < Dp < 1.5 were seen to be contributing 39 and 40% respectively towards the WSII. The ions - Mg^{2+}, Cl^{-}, and K^{+} were found to be more prevalent during the measurement of $PM_{0.95.}$ Besides, Cl^{-}/Na^{+} (5.6) and OC/EC (3.4) are helpful as indicators. Lowering of the mixing height by 50m was witnessed on the day of Diwali, unlike the days preceding and following the event. Changes in the temperature profile was noted. The alveolar, respirable, and inhalable fractions were responsible for 64.6, 90.8, and 97.8 %, respectively, of the total PM_{10} mass. People exposed even for short duration (6-8h) are likely to develop health complications.

One of the important constituents of Earth's atmosphere is aerosols which greatly influences the climate, visibility, human health and the ambient air quality (Kumar et al., 2015). For a fast-growing country like India, the effects of aerosols on human health is of great concern (Burnett et al., 2018). Henceforth, understanding aerosols evolution and formation from finer particles to coarser particulate matter is necessary. Recently, study over south Asia region for finding primary sources of fine particulates is done in which vehicular emissions was found to be dominating contributors, followed by industrial emissions and secondary aerosols in ambient air. However ,one of other major sources which has capability of modifying the local/regional ambient air quality is extensive fireworks and is discussed in wide literature (Kumar et al., 2016; Joshi et al., 2016) .As far as other parts of the world is concerned, large firework emissions is observed on i.e. New year's eve in Europe, Lantern festival in china, Independence day celebration in USA (Retana et al.2019). As far as all studies are concerned, it has been established that there is increase in the aerosol concentration (especially finer aerosols) during fireworks and corresponding increase in firework traces like P, K, Mg, Cu and S as well.

A lot of work has been done on measurement of aerosol characteristics and their effects on air quality as a result of which the background aerosol characteristics of ambient air have been discussed in the research work (Kumar et al., 2011; Gurjar et al., 2010). Although, relatively few studies are done for studying the number concentration characteristics of finer aerosols and their size distribution evolution. Studies from Zhao et al., (2014) and Dutshke et al., (2011) have shown increase in large Aitken (50-100nm diameter) and accumulation mode of particulate matter (100-300nm diameter) with a simultaneous decrease in nucleation (20-50nm diameter) and small Aitken mode (50-100nm diameter) of particle number distribution.

CHAPTER 3 METHODOLOGY

3.1 SITE SELECTION

Delhi Technological University (DTU) situated in the north-west part of New Delhi. The location selected for the study is depicted in Figure1. The instrument was placed at the height of around 1 m in the outer boundary of the campus (Figure 3.2 and 3.3). The location was so selected that it covers both residential and commercial areas maintaining the homogeneous environment far away from the road traffic. This way, we can neglect the vehicle generated smaller Particle number concentration, hence focusing majorly on characteristics of fireworks emitted aerosols number concentration in ambient air. Aerosols measurement was done on 4 consecutive days from 25th October to 28th October 2019. The main event day i.e., Diwali festival was on 27th October 2019. The bursting of firecrackers was mainly witnessed from 18:00-22:00 hrs on 26th -28th October 2019.

Figure 3.1: Google earth view of DTU campus in New Delhi

3.2 INSTRUMENTATION

The monitoring was conducted with the help of SMPS (Scanning mobility particle spectrometer) manufactured by the Grimm model: 5420C with a DMA controller and a particle counter, which is called Condensation particle counter and used for the measurement of dynamic aerosol number particles in ambient air. SMPS works with a technique called electrical mobility detection for measuring number and size distributions. It has three parts as follows

1.A neutralizer (charger) for charging of particles.

2.A DMA (Differential Mobility Analyser), used for classification of particle by virtue of their electrical mobility.

3.A Condensation Particle Counter (CPC) for detection and particle count.

The Grimm- SMPS works on the principle of light scattering. This light scattered by each aerosol droplet at 90° and focused on the mirror in which the electrical pulse counted as a signal. With this instrument, the aerosol size range, which can be measured, is from 10 nm -1100 nm (Table 3.1). The average estimated time for each cycle is 7 minutes. The SMPS placed in the portable cabin at the boundary of the campus. A small pipe was attached to that instrument in which one mouth related to the instrument, and the other nozzle kept outside the cabin. Any loss of the particles was minimized in the instrument because all protocols followed during the monitoring (Burkart et al., 2010; Joshi et al., 2012). The size distribution which observed during the experiment was nucleation mode, small-Aitken mode, large- Aitken mode, and final accumulation mode. During the monitoring period, both the wind speed and Relative humidity recorded for all the days using the data available from the monitoring station of CPCB at the DTU campus only.

Table 3.1: Specifications of SMPS instrument

Model	**Size Range**	**Detection concentration (particle/cm^3)**	**Real time Analysis (Yes/No)**	**Aerosol Flow rate**	**Application**	**Sheath flow Rate**
SMPS+C (CPC5420)	10-1100nm	150000	yes	0.3 lpm	Accurate for UFP measurement	3 lpm

Figure 3.2: Sampling at the monitoring site

Figure 3.3: Instrumentation employed in study

CHAPTER 4 RESULTS AND DISCUSSION

Monitoring of Ultrafine and Quasi ultrafine Particle number concentration (PNC) in concern with the firework emissions was done over a span of four days, from 25th October to 28th October. The days were divided into pre Diwali days(25th and 26th October), the Diwali day(27th October) and post Diwali day(28th October).For all the four days ,monitoring was done from 8 a.m. in the morning to 10 p.m. at night except for the Diwali day when the night monitoring was done up to 12 a.m. in order to attain more information regarding the Diwali day and associated fireworks.

4.1 DIURNAL VARIATION OF PARTICLE NUMBER CONCENTRATION AND GEOMETRIC MEAN

The temporal variation of Total Aerosol concentration of particle number and their geometric mean is presented in Figure 4. On the celebration day (27th October 2019), a sudden rise in Total particle number concentration (PNC) during 17:00-22:00 hrs was seen with an average peak of 4.5 × 104 cm^{-3}, which validates the maximum burning of firecrackers in this period. The total number of aerosol particulates during the day was 1.6×10^{5} - 1.1×10^{4} /cm^{3}. Peak A denotes the highest peak on Diwali day in Figure 4.1, which reached the maxima at late night from 19:00-21:00 hrs. While analyzing post and pre- Diwali days, similar peaks were obtained with an average particle number concentration of 5.4×10^{3} and 5.5×10^{3} /cm^{3} i.e. on 26th October & 27th October 2019, respectively. This shows comparatively lesser burning of firecrackers was done on these days, keeping the background concentration the same. The peaks for pre and post-Diwali days were denoted by peak B & C, respectively. The peak occurring on the other day i.e., on 25th October 2019 indicated by peak D represents the background concentration of Particle number in ambient air, possibly from other sources like vehicular emission, commercial emission sources and may be due to the influence of meteorological conditions (Zhao et al., 2017) like wind speed and relative humidity(Figure 4.2) which we have discussed later. During morning hours of each day, several peaks were seen, which may be the contribution from local anthropogenic activities or vehicular emissions. We have not discussed these peaks as they are not concerned in the scope of our study.

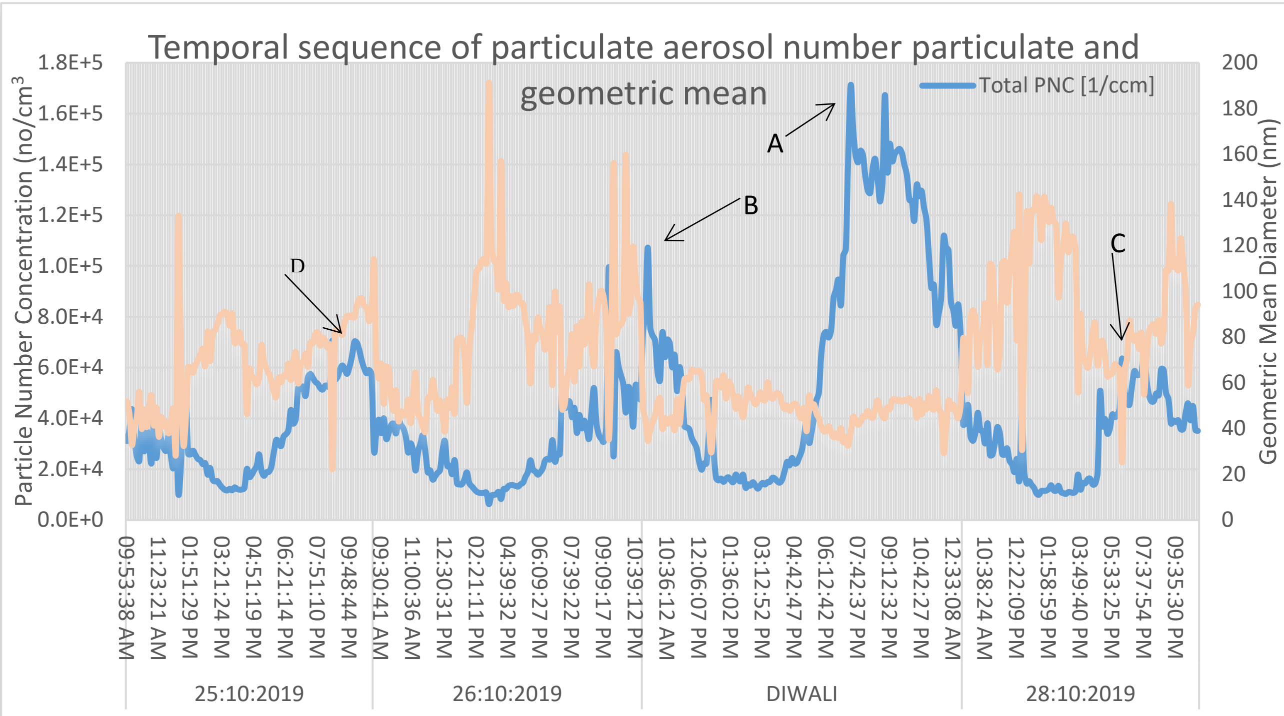


Figure 4.1: Temporal sequence of aerosol particulates number and their geometric mean during the study

In Figure 4.1, relationship has been established between total particle number concentration of finer aerosols with its geometric mean diameter, which describes that the number concentration maxima coincide with the geometric mean diameter (nm) minima. It interprets that the smaller the diameter of the finer aerosols larger is its particle number concentrations. Similar trends for temporal variation of number concentration were also shown by Yadav et al., (2019). According to the geometric mean diameter of the pre and post-Diwali days, peaks B (14nm) and C (14.5) clearly show that they lie in small- Aitken mode of well-established ultrafine range particles. The peaks occurring at other timings also coincided with the minimum geometric mean diameters.

4.2 ANALYSIS OF RELATIONSHIP BETWEEN METEOROLOGICAL FACTORS WITH THE FINER AEROSOLS

As far as the pattern for meteorological factors like wind speed and relative humidity is concerned (Figure 4.2), high wind speed disperses PNC while low RH and wind speed lowers the dispersion and increases the PNC concentrations. The graph clearly shows the wind speed maxima of 0.83m/s with minima of 0.22m/s. The average hourly value of wind speed for Diwali day comes out to be 0.62m/s. On Diwali day at evening time, it is seen that the wind speed reached towards the peak (0.74m/s) and became constant, which implies the large distance travel of the finer particles as well as suspension of particles at receptor location (Tiwari et al., 2013). Also,

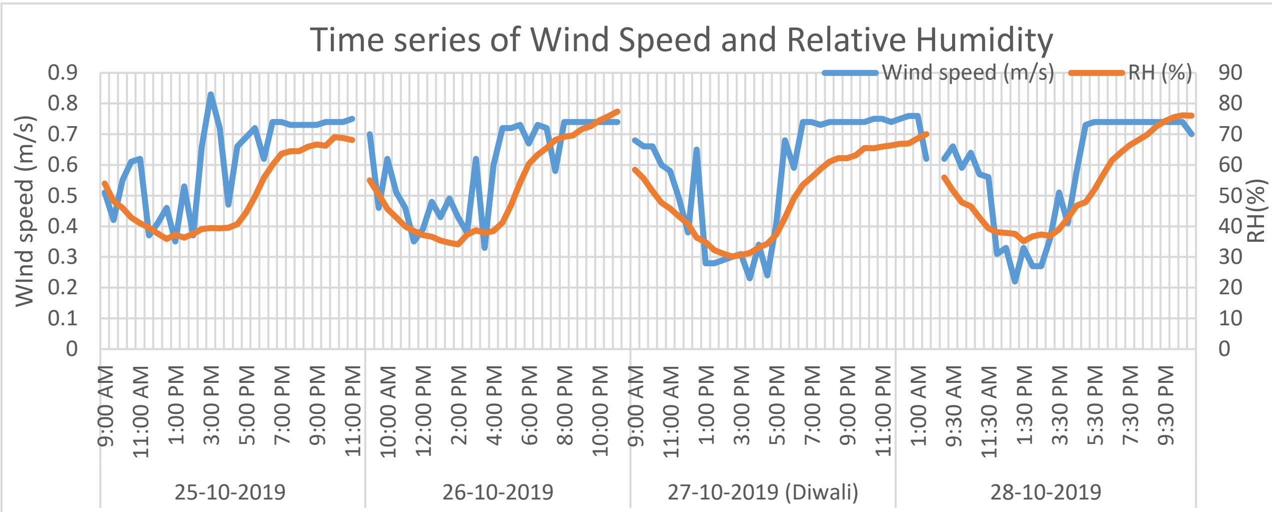


Figure 4.2: Time series of wind speed (m/s) and relative humidity (%)

relative humidity shows the same trend as wind speed with maxima and minima of 80.84% and 30.14%, respectively.

To understand the distinctive growth of particle number concentration during the monitoring time of the all the days, we have plotted the graph (Figure 4.3) between the lognormal distribution of concentration of aerosol particles with the corresponding diameter size ranging from 10nm up to 1000 nm for all the days. Most of the aerosol particles are found in the size range of 60-110 nm, which is a large Aitken and accumulation particle size range. It means that the maximum particle formations were lying in the size range of finer aerosols (UFP). These formations attributed to new nucleation formations because of firework emissions during Diwali. For further analysis, we took the different distribution of size modes (in the span of 4 hrs each) to gain more information on the particle formation in ultrafine range and other modes during the monitoring period on Diwali mentioned as mentioned in table 2. The 4 hrs span took to differentiate the particle transformation from nucleation to accumulation in the morning (09:30-13:30) hrs, afternoon (14:00-18:00) hrs and the night (18:00-22:00) hrs period during the monitoring days (Kumar et al., 2016; Yadav et al., 2019). For Figure 4.4 (a, b & c), the average of 09:30-13:30, 14:00-18:00 and 18:00-22:00 hrs are taken respectively for all the days. When the night slot compared for different modes of particle number concentration on Diwali day, it shows that the PNC for nucleation mode is highest (45077#/cm^3) (From table 4.1). Consequently, the small Aitken and large Aitken mode showed the same increasing trend, which is indicative of the new particle formation at night of Diwali day as a result of firecrackers burning. A similar trend followed on pre and post-Diwali days in the different modes of particle formations. Also, for all the days, from 18:00-22:00, the concentration of particles kept on increasing, specifically in small Aitken and nucleation mode. It concludes that there is an increment of particles in size 45-50 nm range, which is shown in Figure 4.4(b-c). In figure 4.4(c), a clear maximum increment seen in the nucleation mode and small- Aitken mode particles, also with a spike in accumulation mode particles too for the Diwali day (27th October 2019). Further analysis on Diwali day showed the increase in particle concentration from evening to midnight (18:00-22:00 hrs), which is nucleation (554%), and small Aitken (107%) mode particles against pre- Diwali day (25th October 2019).

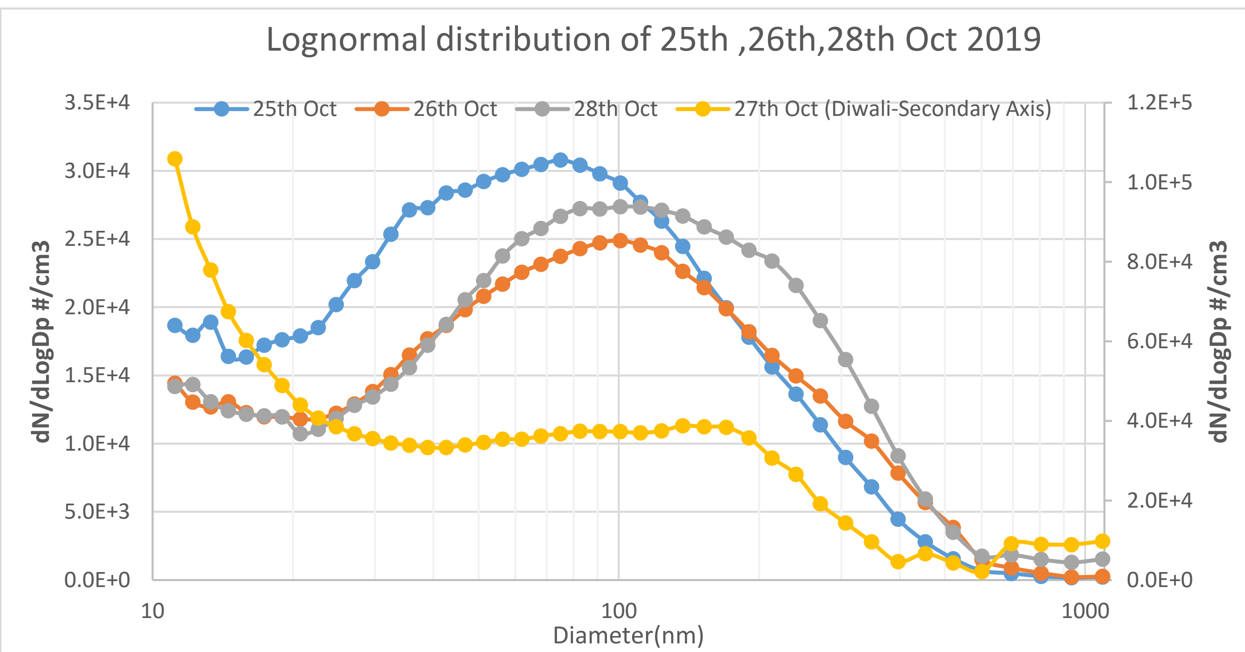


Figure 4.3: Average of aerosol particulates distribution of size during the experiment days

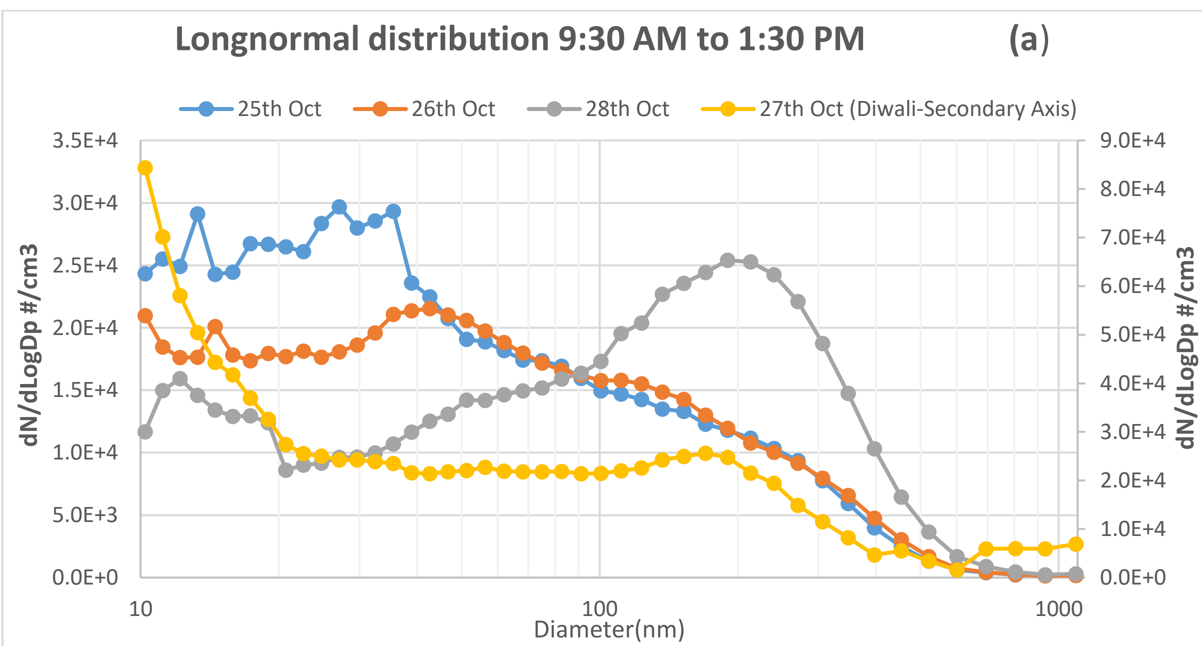
4.3 COMPARATIVE ANALYSIS OF BACKGROUND WITH THE EPISODIC EVENT

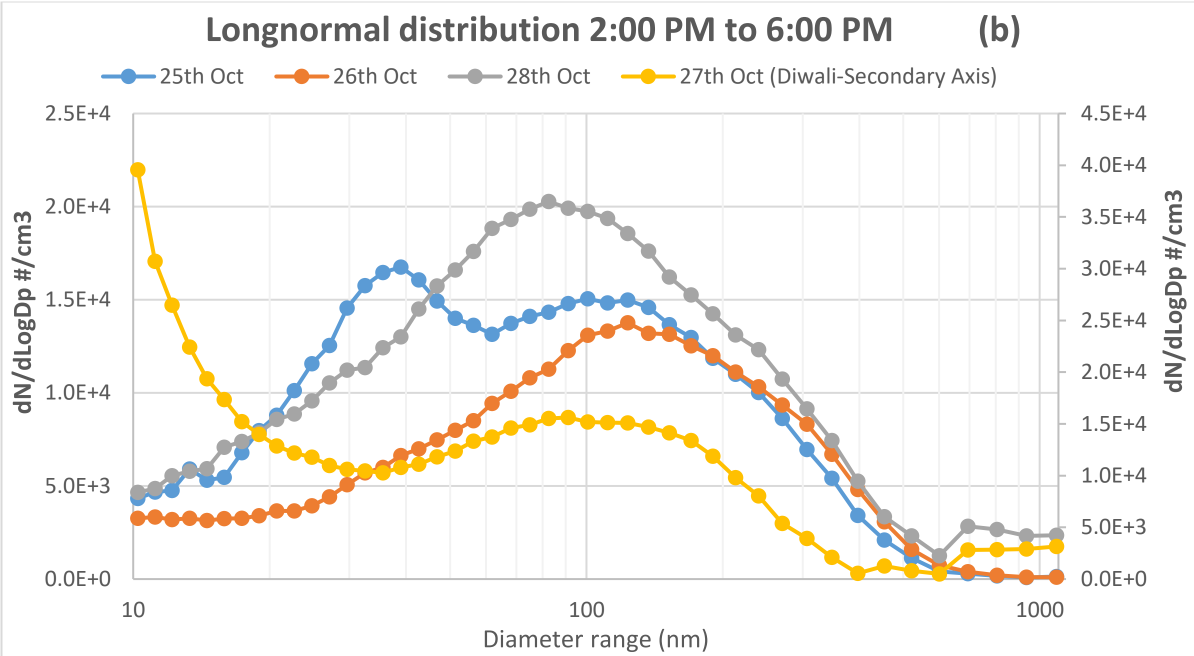
There is found a similar kind of relationship between small Aitken, Large Aitken mode particles, and the accumulation range particles (Table 4.1). The growth of small and large Aitken particles formation is matching to the accumulation mode particle growth. From duration 18:00-22:00 hrs, there is a positive shift in the accumulation mode particles with GMD of 223.7 nm for Diwali day (Table 4.1). To study this relationship more deeply, we have drawn a temporal variation graph in Figure 8 between ultrafine particles and accumulation mode particles.

Table 4.1: Different distribution of size modes (mean of 4 h)

Time Divisions	**Study days**	**Nucleation mode ~ (10-20 nm)**		**Small Aitken mode~ (20- 50 nm)**		**Large Aitken mode ~(50-100nm)**		**Accumulation mode ~ (100-1000)**	
		N_{Total} (#/cm^3)	**GMD (nm)**	**N_{Total} (#/cm^3)**	**GMD (nm)**	**N_{Total} (#/cm^3)**	**GMD (nm)**	**N_{Total} (#/cm^3)**	**GMD (nm)**
9:30 AM to 1:30 PM	**25-Oct**	7894.5	14.6	10336.8	32.2	5140.1	71.2	7274.6	197.5
	26-Oct	5468.7	14.6	7792.4	33.5	5484.7	70.9	8119.5	200.1
	27-Oct	16025.4	13.7	9364.6	32.0	6374.7	72.3	14135.1	232.3
	28-Oct	4169.7	14.4	4094.5	34.3	4389.1	73.2	14087.6	220.1
14:00 PM to	**25-Oct**	1733.5	15.2	5415.4	34.0	4065.1	72.7	7177.2	192.2

18:00 PM	**26-Oct**	1040.1	14.8	2195.3	35.0	3051.1	74.2	7272.7	203.7
	27-Oct	7081.7	13.5	4562.0	32.2	4289.7	73.2	7048.6	228.4
	28-Oct	1882.5	14.9	4719.0	33.9	5510.2	73.5	9721.6	220.8
18:00 PM to 22:00 PM	**25-Oct**	6888.9	15.5	13181.2	36.2	17503.0	72.1	19708.9	173.7
	26-Oct	5475.2	14.0	7031.8	35.5	10370.5	73.4	17197.8	192.2
	27-Oct	45077.2	13.6	27356.3	32.1	20585.8	72.2	36110.1	223.7
	28-Oct	5585.0	14.5	10754.7	35.9	13713.8	73.1	21425.2	225.1





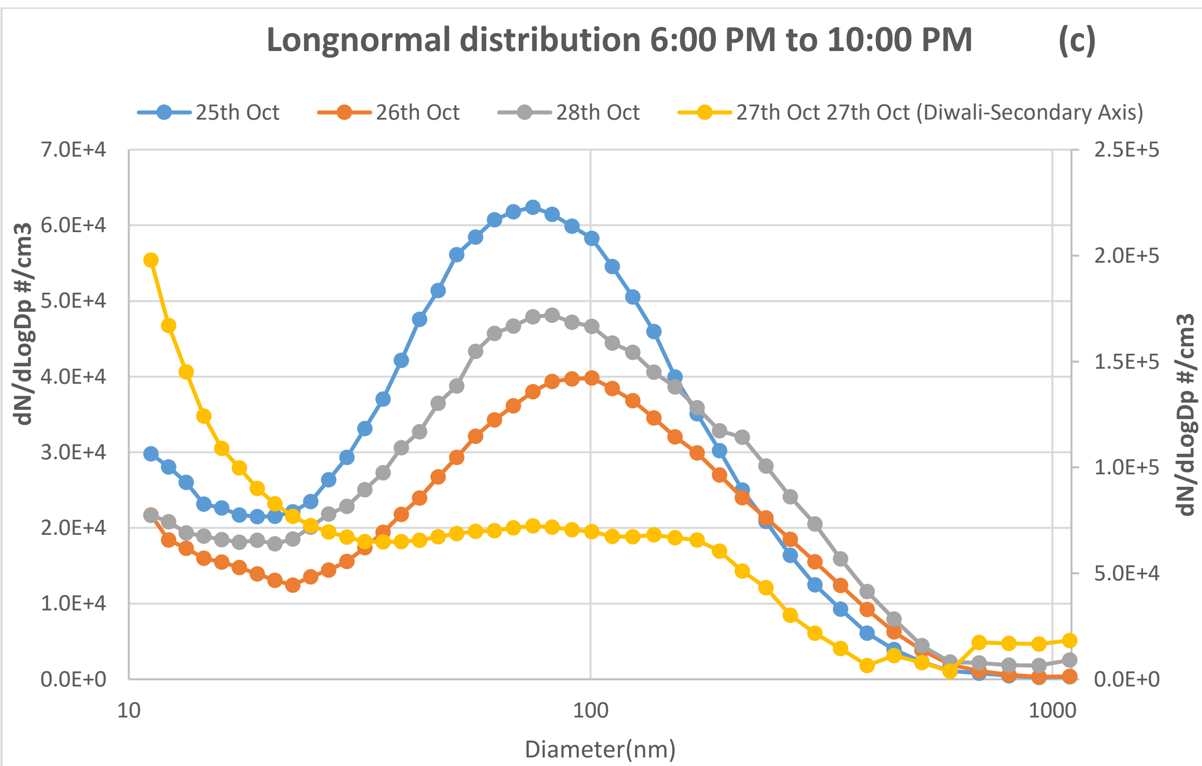


Figure 4.4(a-c): Mean of particle size number distribution during the experimental days (arithmetic mean over 4 h).

In Figure 4.5, The evolution of Ultrafine particles (diameter <100nm) with the accumulation mode of particles (>100nm) is shown. Both particle ranges showed rising patterns during the extensive burning of firecrackers from 18:00-22:00 (shown with black arrows), and both got parallel after some time (shown with green arrows). Both types of variations can be seen on pre and post-Diwali days. The formation of large amounts of ultrafine particles leads to the formation of accumulation mode particles as they are getting dispersed into the atmosphere by getting sunk and coagulated in the background aerosols concentration, which is already present (Anand & Mayya, 2011).

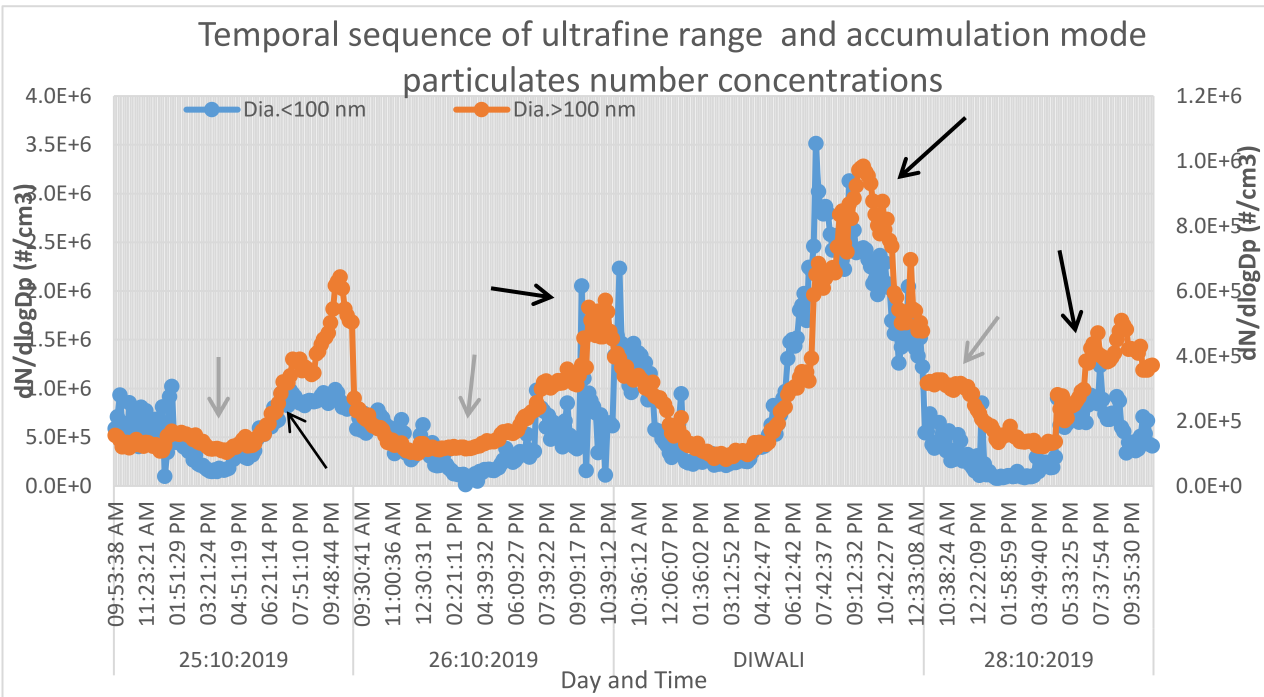


Figure 4.5: Temporal sequence of ultrafine range and accumulation mode concentrations of aerosol particulates

Till now, the study explains the different size distributions of the finer particles taking the 4-hour mean. More detail about the evolution of the distribution of the particles for each peak can be seen in Figure 4.6(a-b) and Figure 4.7(a-b). A distinction of the transformation of the PSD of the individual peak during Diwali and other regular days, check if there is a possible distinction, the time resolution of evolution peaks taken (more than 1 hr). The size distribution, which measured concerning the presence of the below peaks, was taken (0, 30, 60, 90 minutes), 180 min average, and finally 360 min average. Joshi et al. 2016 took time resolution of evolution peaks up to 90 mins averaging 30 minutes each, but to attain more clarity, analysis was done up to 360 min average (Joshi et al., 2016). It was done so that no hike in particle distribution was missed. In Figure 4.6(a-b), there is peak A (3.41×105 /cm^3 at 7:21 pm night) with GMD ~ 11nm and peak D (9.07×104/ cm^3 at 10:02 pm night) with GMD ~111nm on the night of 27th October 2019 and 25th October 2019 respectively to compare the firework emission and non-firework emission scenario. Peaks A & D were not similar in particle number concentration, but they were highest on their respective days. In Figure 4.6(a), there was a significant rise in the concentration of the ultrafine particles (< 45nm), which included nucleation, small & large- Aitken range particles from 18:00-22:00 hrs. Continuous formation of a new particle in the UFP range was seen, indicating large firecrackers burning at night. The transition of particle formations from t=-360min (background concentration) reaching peak A and then again reaching the background concentrations within 90 min of the peak attained was shown. If we see the peak D in Figure 4.6(b) for25th October, the trend of particle concentration evolution followed a different path compared to one in Figure 4.6(a). Similar trends were also shown by (Joshi et al., (2016) in their study. There was a clear transition from nucleation towards small and large Aitken modes. It contained all ranges of particle size distribution from nucleation to accumulation range particles. The presence of spike in the particles of accumulation range ~110 nm noticed in Figure 4.6(b). Similarly, in other figures 4.7 (a-b), there was found a rise in the transition of particle number concentration on pre-Diwali (26th October 2019) and post-Diwali day (28th October 2019). However, it was not the same as occurred on Diwali day having low strength in the evolution of particles. There was an increment of ultrafine particles in peak B of Figure 4.7(a), but after 60 mins, all the particle size range added up and showed a proper formation of accumulation particles. In peak C of Figure 4.7(b), it was showing a similar pattern of rising in particle number concentration but without any other significant modes. So, from the above study, we can say that festivals like the Chinese New Year, forest fires or Diwali festival, etc. can lead to the release of a significant amount of ultrafine, fine particles concentration and even accumulation range particle concentration also. These types of events can increase the background aerosol concentration, which leads to short term air quality deterioration, ultimately harming human life through its deposition in the alveolar region of the respiratory system (Manigrasso & Avino, 2012). From our detailed study, we are in a position to say that extreme burning of firecrackers can lead to an increase in the finer aerosol concentration on post-

Diwali days also. Still, if we talk about emissions in big cities like New Delhi, complexity in different processes in the atmosphere requires a longer duration of the study.

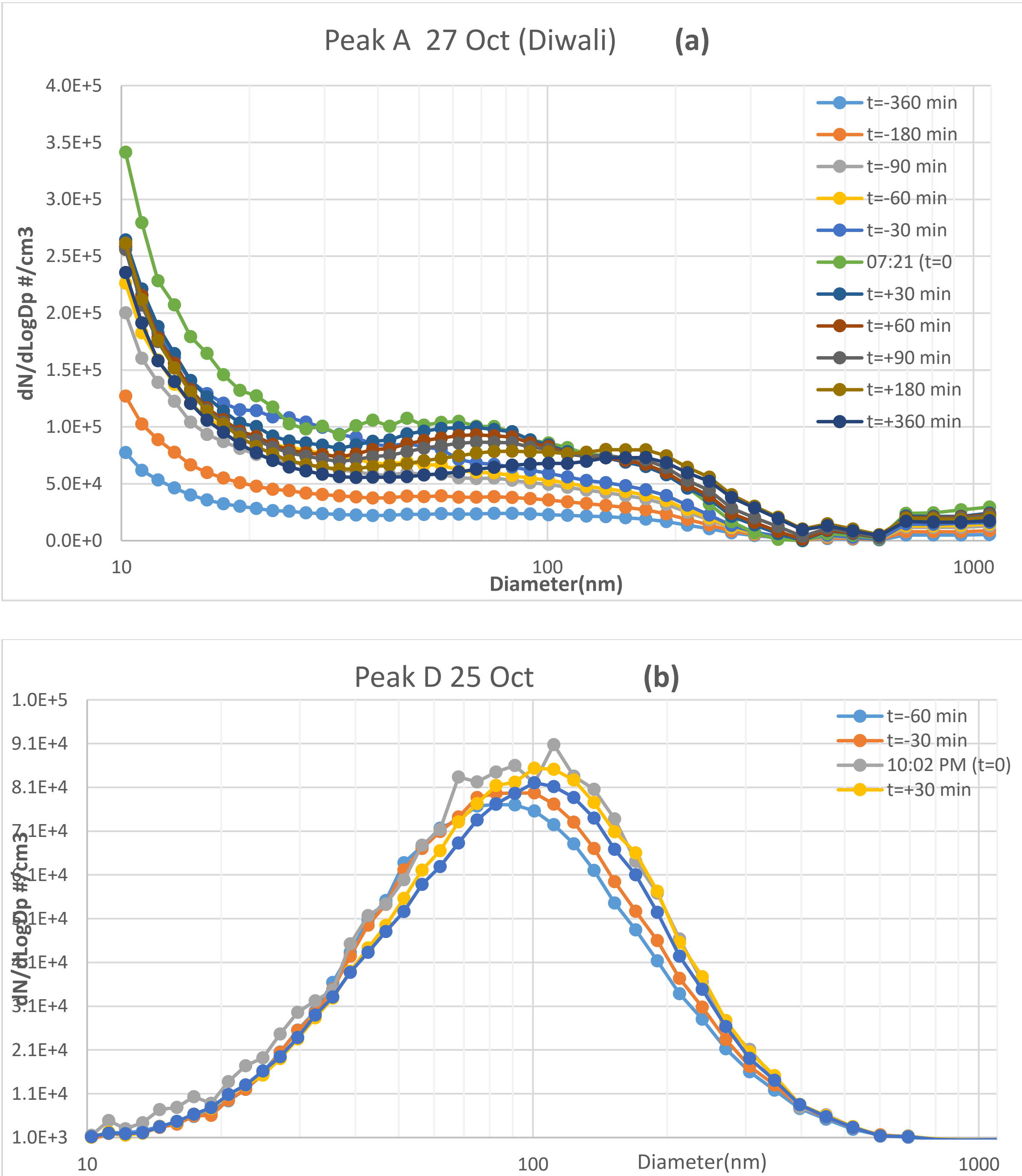


Figure 4.6 (a-b): Progression of aerosol particulates in a resolved time manner during Diwali and non- Diwali days at peaks of A & D of Fig.4

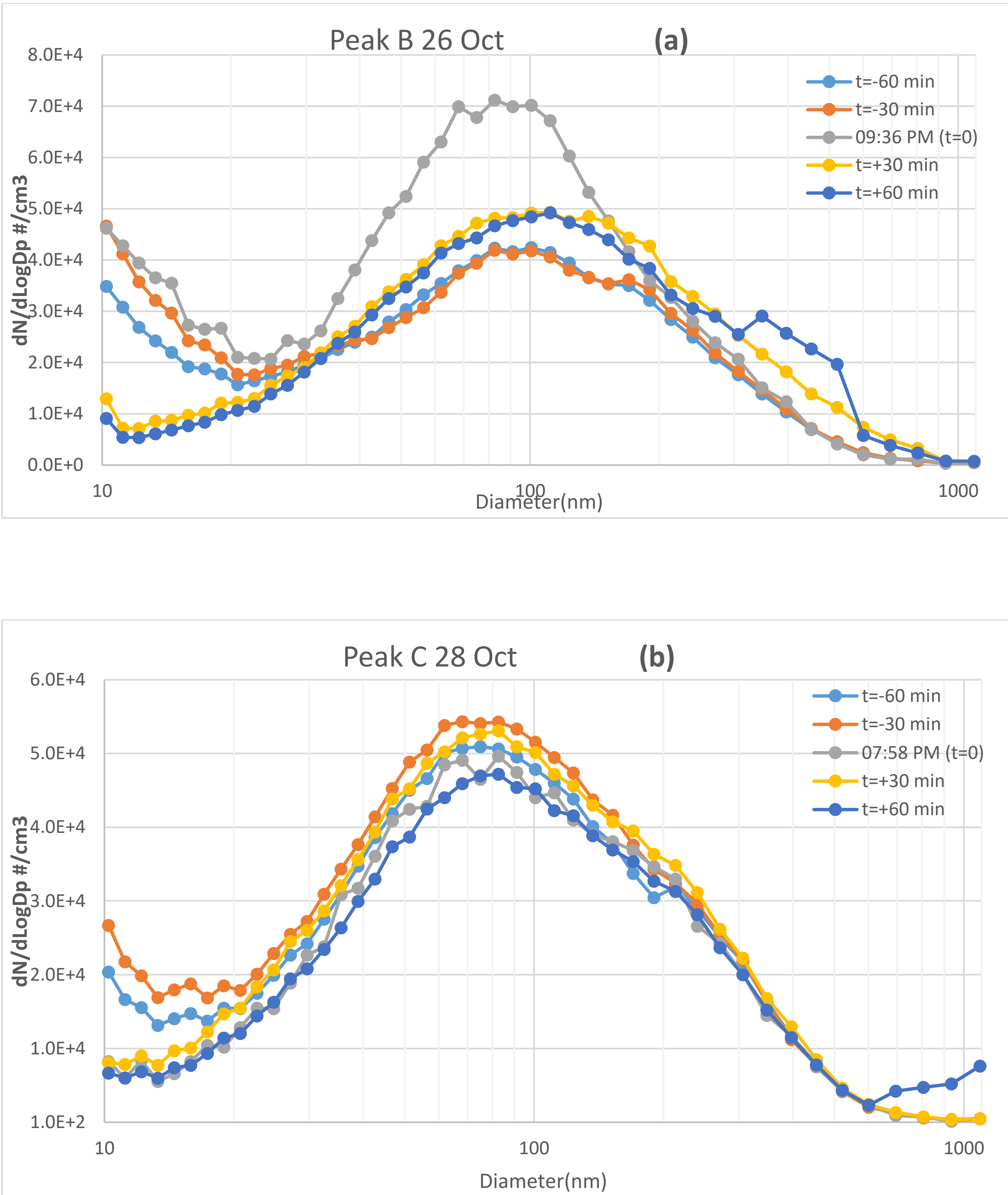


Figure 4.7 (a-b): Progression of aerosol particulates in a resolved time manner during Diwali and non- Diwali days at peaks of B & C of Fig.4

CHAPTER 5 CONCLUSION

The particle number concentration of finer aerosols was monitored during Diwali from 25th October to 28th October 2019 at DTU, Delhi. The study indicated the firework influence on the particle number concentrations. Total PNC was maximum for Diwali day, reaching an average peak of 4.5×105 $\#/cm^3$, showing direct effects of Diwali emissions on urban air. On Diwali day, there was an increase in particle formation, especially in nucleation (554%) and small Aitken mode (107%) against the pre-Diwali day (25th October 2019). Though, these concentrations came back to the levels of background concentrations after some time. The transformation of different modes of the particle distribution of size range was the same for all the days. Still, a distinctive comparison of non-episodic event days with the episodic event day was observed. Meteorological factors like wind speed and relative humidity found to play a vital role in instigating the firecracker's emissions effects with lower traffic and industrial activities. Interestingly the higher wind speed on Diwali night, reaching the peak value of 0.74m/s, may have carried the firework emissions from longer distances and got suspended at the receptor location. With the dynamics of Delhi being densely populated and other anthropogenic activities causing pollution, the locally produced Diwali emissions are felt to a larger extent, directly affecting the sensitive part of the population. This study will help to evaluate the adverse effects of firecrackers burning during Diwali on urban ambient air quality precisely for cities like Delhi and change in public opinion henceforth. Recommendations for using Green Crackers for Diwali celebrations could be a better alternative in years to come to reduce the deterioration in urban air quality and associated health risks of people.

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