

Emissions from Cow Dung Cake Combustion: Particle & Gas Dynamics

Anurag Gupta

IIT BHU: Indian Institute of Technology BHU Varanasi

Sunil Kumar Yadav

suneelyadav24@gmail.com

University of Lucknow

Prasant Shukla

IIT BHU: Indian Institute of Technology BHU Varanasi

Yogesh Kumar Vishwakarma

IIT BHU: Indian Institute of Technology BHU Varanasi

Research Article

Keywords:

Posted Date: October 1st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11083883/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Emissions from Cow Dung Cake Combustion: Particle & Gas Dynamics

Anurag Gupta¹, S.K. Yadav^{2*}, P. Shukla¹, Yogesh Kumar Vishwakarma³

¹Department of Mechanical Engineering, Indian Institute of Technology (BHU), Varanasi, India

²Department of Mechanical Engineering, University of Lucknow, Lucknow, India

³Department of Chemical Engineering, Indian Institute of Technology (BHU), Varanasi, India

Abstracts

The burning of cow dung cakes in domestic stoves remains a prominent source of energy in rural regions of developing countries, though it is a major contributor to household air pollution, especially because of the fine sized aerosols that are generated. Despite the widespread use of domestic stoves, the generation of micron and nano sized ultrafine aerosols from them under controlled combustion conditions has been relatively less studied. In this study, aerosol and gaseous emissions from cow dung cake combustion were experimentally investigated with particular emphasis on the effects of fuel grain size and heating rate. Dung cake samples were prepared in three grain size ranges (BSS 10, BSS 25, and BSS 44) and combusted in a quartz tube furnace at heating rates of 4, 6, and 8 °C min⁻¹ under airflow conditions comparable to those in traditional stoves. Particle number, mass and size distributions spanning 10 nm to 10 µm were measured using scanning mobility particle sizer (SMPS), while CO, CO₂, emissions were simultaneously quantified. Results indicate particle number concentrations up to ~10⁹ particles/cm³ and mass concentrations on of the order of 10⁶ µg/m³. Ultrafine particles dominated the emissions, with nucleation-mode particles accounting for up to ~85% of total number concentration, particularly for finer fuel grains. Increasing heating rate reduced ultrafine particle formation and shifted the size distribution toward larger particles. Modified combustion efficiency values below 0.9 confirmed smouldering-dominated combustion. The findings provide a new perspective on aerosol formation from dung cake combustion is relevant to emission reduction and cleaner biomass energy strategies.

1. Introduction

Even in the time of computers and technological devices, globally nearly 2.6 billion people remain dependent on polluting cooking practices due to the lack of access to clean cooking facilities, with the problem being most pronounced in low and middle-income countries (LMICs)[1][2]. Nearly about 1460 million people depend on biomass for cooking and heating in Asia [3]. In sub-Saharan Africa (SSA), approximately 40% of people lived on less than US\$ 1.9 a day in 2018[4]. Cooking food with biomass has been a major practise for decades in SSA. Many communities in Asia and Africa rely on dung cakes as their main solid fuel. for example, in the villages surveyed in India, Nepal and Bangladesh, 62% of people use cow dung cakes for cooking [5]. For centuries, cattle and camel dung have been a major source to fulfil domestic demand such as cooking and fertiliser in Asia and Africa[6]–[8]. In the Delhi region, dung cakes may contribute more to household fuel consumption than firewood or crop residues, as approximately one in five households relies on dung cakes for cooking [9], [10]. In Inner Mongolia and China, households collected about 129 kg of dung per day, about a fifth of which was burnt for domestic fuel and the rest used as farm fertilizer[11]. In Tibet, over 70% of household daily energy comes from biomass sources, primarily consisting of livestock dung [12]. The emissions from burning of cow dung can have harmful consequences on health [13]. These include the release of particulate matter (PM), CO₂, CO, polyaromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs)[14]. According to epidemiological research, adults and children who are exposed to smoke from the burning of biomass fuels are more likely to get respiratory diseases[15], [16]. Because women are primarily responsible for cooking at home, so they are at greater risk of indoor air pollution. Indoor biomass smoke, a significant contributor to home air pollution, is thought to be responsible for over 39 million years of living with a disability and over 500,000 premature deaths from acute respiratory tract infections annually[15], [17], [18]. Furthermore, more than half of respiratory infections globally are caused by inhalation of biomass smoke[15], [16]. Biomass burning can be a major producer of ambient nanoparticles. Emissions of small particles into the atmosphere are a major human health concern[19]. Dung cake has been found in various studies to emit more carbon monoxide (CO) than wood and crop residues. Burning cow dung cakes releases twice as much CO as burning wood[20]. In contrast, reported slightly higher carbon monoxide (CO) emissions in dung cake as compared to fuelwood[21]. Combustion of dung cakes has been reported to emit higher levels of sulphur dioxide, suspended particulate matter, and polycyclic aromatic hydrocarbons (PAHs) compared to fuelwood and crop residues[22]. emission of NO_x from

dung cake combustion was also higher as compared to other solid fuels[23]. The combustion of cow dung cakes has been recognized as a significant contributor to the air pollution crisis in the New Delhi region of India[24], [25]. The combustion of dung generates three to four times greater amounts of secondary organic aerosols (SOAs) compared to fuelwood[26], and produces three times more non-methane volatile organic compounds (NMVOCs) than fuelwood and twice the amount emitted from crop residues[27]. Burning of biofuels in Delhi areas produces 23 NMVOCs which is 1.158 kg/year by weight, of which more than half (58%) is from burning of cow dung[28]. The majority of previous investigations have focused primarily on quantifying emissions of PAH, CO, and CO₂ from dung cakes. Most of the literature on particle and mass concentration measurements of particles produced during burning is in the micron size. Nonetheless, ultrafine particles are capable of penetrating the cellular lining of the lung alveoli and are deposited deep within the pulmonary tissue via diffusion[29]. Therefore, the physical characterization in nano size range is essential to accurately estimate the size distribution and its subsequent health impacts. Particulates that are respirable (<5 µm) are most abundant in animal dung and it produces higher levels of carbon monoxide (CO) and particulate matter (PM) than wood burning and fuel briquette[30].

As per the available literature on burning of animal dung, the emphasis in the past has been mostly directed toward studying chemical composition and its effects on the environment and human health. Very few literatures are available on aerosol generation and its characterization during burning at different conditions. Studying the oxidation behaviour of dung cake at different heating conditions and the characterization of its size and size distribution is essential to evolve strategies for mitigation of the harmful effects on human health. In this study, dung cake is pulverized into three different grain sizes and burned in a high-temperature facility at three different heating rates. Also, the air flow rate at which the samples are oxidized is comparable to the actual flow rate that exists in real-life stoves used in households. Size distribution and mass concentration are measured in the nanometre to micrometre size spectrum using spectrometers – a Nanoscan SMPS and OPS for nano and micron range aerosols respectively. Additionally, the study measures the concentration of CO and CO₂ gases released during the burning process.

2. Material and methods

2.1. Experimental setup

The experimental setup schematically represented in fig-1. The system consists of a quartz tube with a length (L) of 1200 mm and an internal diameter (I.D.) of 70 mm, which was heated using a split furnace having a heating zone of $210 \times 130 \times 220 \text{ mm}^3$. The quartz tube was designed to allow the insertion of a quartz boat for holding the dung cake samples. The tube was supported by flanges mounted at both ends. Compressed air was supplied to the heated quartz tube through an 8 mm diameter pipe. The air supply line was equipped with a flow regulator to precisely control the air flow rate, a damping chamber to minimize flow fluctuations, a rotameter for flow measurement, and a high-efficiency particulate air (HEPA) filter (filtration efficiency 99.97%) to ensure the supply of clean air into the heating tube. The filtered air acted as a carrier gas, facilitating the transport of aerosol particles generated during the combustion of the dung cake samples. Further details of the experimental setup (facility) have been described elsewhere[31]. The flange at the outlet of quartz tube was connected with an exhaust tube to remove extra smoke.

An isokinetic is employed to sample aerosol from the quartz tube. Before analysis, the sampled aerosol was cooled with the help of a heat exchanger and then passed through a dilution system. The diluted sample was subsequently directed via a flow splitter to the two spectrometers- a scanning mobility particle sizer (NanoScan SMPS 3910, TSI) and an optical particle sizer (OPS 3330, TSI). The sampling flow rates were maintained at 0.8 L/min for the NanoScan SMPS and 1.0 L/min for the OPS. These instruments size the aerosol in the ranges of 10–420 nm and 0.3–10 μm , respectively. Since these spectrometers operate satisfactorily below an inlet sample temperature of 40°C, a heat exchanger was used to cool the sampled air. A diluter with a dilution ratio of 1:100 was placed before the spectrometers to ensure that the maximum aerosol concentration at the inlet to the spectrometers remained below the maximum measuring range of the instruments. A gas analyser (Model- AVL DIGAS 444) which measures CO and CO₂ gases with least counts of 0.01% v/v) and 0.1% v/v respectively. were used to measure the concentrations of these gases.

2.2. Experimental procedure

a schematic diagram of the experimental setup is shown in fig 1. Before the experiments, the quartz tube and quartz boat were initially purged with an air jet supplied by a high-flow-rate compressor and cleaned tube was set horizontally into the furnace and an empty boat was also

placed inside the tube. The inlet of the quartz tube was sealed using a flange, and air was supplied at a flow rate of 20 L/min under atmospheric temperature and pressure conditions. The particle number concentration was continuously monitored using aerosol measurement instruments. If the number concentration from the empty tube was found to be more than 10^3 cm^{-3} (background particle concentration) for nanoscan and 10 cm^{-3} for OPS, the experimental setup was cleaned again to ensure the particle concentration became less than the above value. After that the dung cake sample in the boat was inserted inside the quartz tube at mid position of furnace and thereafter, the inlet was closed and heating started. and the particle and gaseous concentrations were measured at the outlet ports of the experimental setup. The furnace temperature and heating rate were precisely maintained and controlled using a proportional–integral–derivative (PID) controller, which minimized offset and oscillations in the corrective response. This test was carried out at gradual heating (from 30°C to 500°C) for three heating rates ($4^\circ\text{C}/\text{min}$, $6^\circ\text{C}/\text{min}$, $8^\circ\text{C}/\text{min}$). Each experiment was repeated three times in order to ensure that the results obtained are accurate and reliable. After completion of the experiment, the furnace was allowed to cool naturally, and the residual samples were removed and weighed using an electronic balance (least count= 0.1 mg).

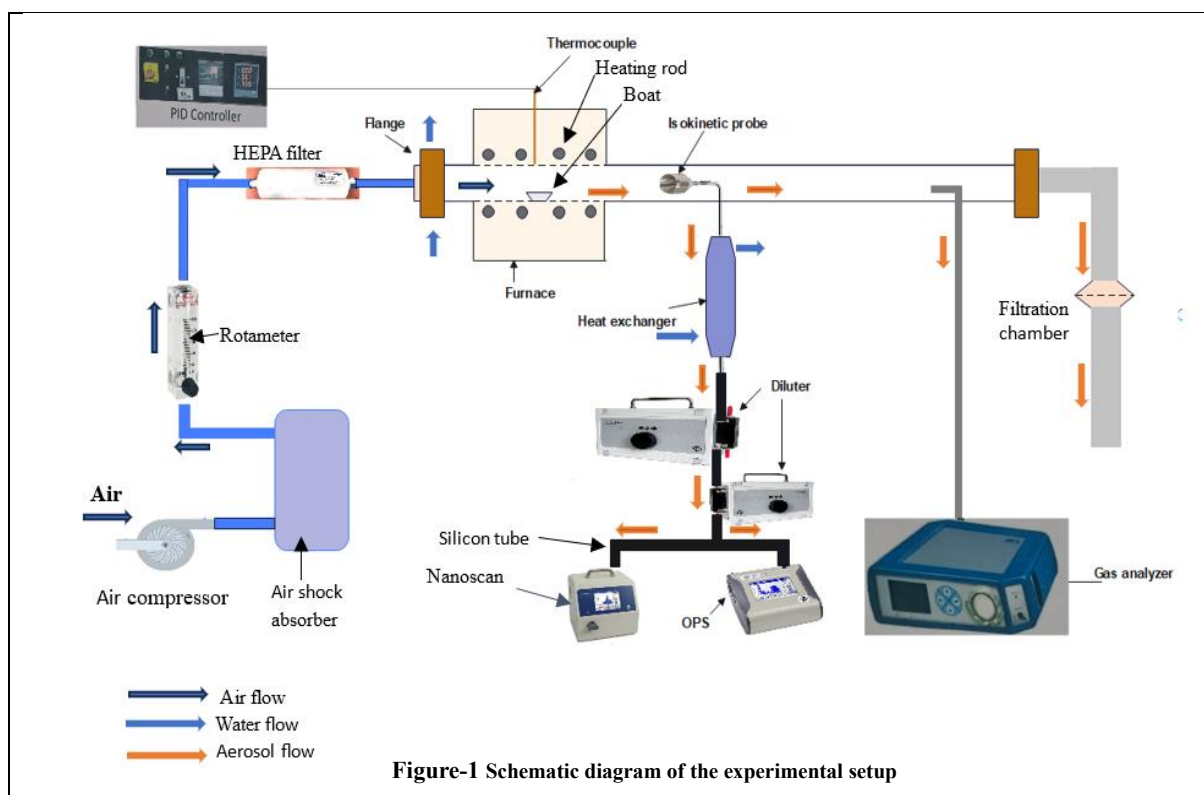


Figure-1 Schematic diagram of the experimental setup

2.3. Sample preparation

Cow dung cakes for the experiments were collected from a milk dairy in Varanasi, India. Collected sample was then properly dried in sunlight. After sun drying, the dung cakes were pulverized. The pulverized sample was then sieved into three different grain sizes- BSS 44, BSS 25 and BSS 10 (specification are mentioned in table-1 below) followed by sun drying again for 2 days to remove moisture. Since the sun-dried sample still retained some moisture, it was further dried in an oven at 80°C for 24 hours to ensure thorough drying.

Table-1 Sample specifications in terms of size

BSS (British slandered Sieve system)	Grain size range (mm)
BSS 44	0.355 - 0.6
BSS 25	0.6 - 1.7
BSS 10	1.7 – 2

2.4. Fuel characterisation

The sample was characterized by performing the proximate, ultimate and thermogravimetric analysis (TGA). The details of the characterization results are presented in tables 2 and 3.

Table-2 proximate analysis of sample (dung cake)

Sample	Component (wt. %)			
	Volatile matter	Ash content	Moisture content	Carbon content
Dung cake	61.1	22.8	10.4	5.7

Table-3 components of dung cake by ultimate analysis

Sample	Component (wt. %)				
	N	C	H	S	O
Dung cake	1.9	27.8	4.33	1.9	65.58

2.5 Thermo-Gravimetric Analysis (TGA)

Thermo-Gravimetric Analysis (TGA) (conducted in nitrogen) is a method used to assess the thermal stability and quantify the volatile components in materials by monitoring the weight changes as the sample is heated at a constant rate in presence of nitrogen. fig-2 illustrates a TGA of the substance's pyrolytic properties. The pyrolysis process of dung is divided into three

distinct stages: (a) drying, (b) main pyrolysis, and (c) carbonization. In the drying stage, which occurs from room temperature to 250°C, there is a weight loss of 10-11% of the original weight, primarily due to the evaporation of moisture (with the moisture content of dried manure being around 10.4%) and a minor contribution from volatile compounds. The main pyrolysis stage, occurring between 250°C and 350°C, is critical for the process. During this stage, there is a significant weight loss of about 35% from the preceding stage, caused by the thermal degradation of cellulose, hemicelluloses, proteins, starch, and microbial cell walls[32]. Finally, in the carbonization stage, from 350°C to 500°C, the mass loss rate is slower compared to the main pyrolysis stage, with a weight loss of about 25% of the original weight present in the second stage. This stage is mainly governed by the pyrolytic decomposition of lignin, which occurs in the temperature range of approximately 350 °C to 500 °C[29].

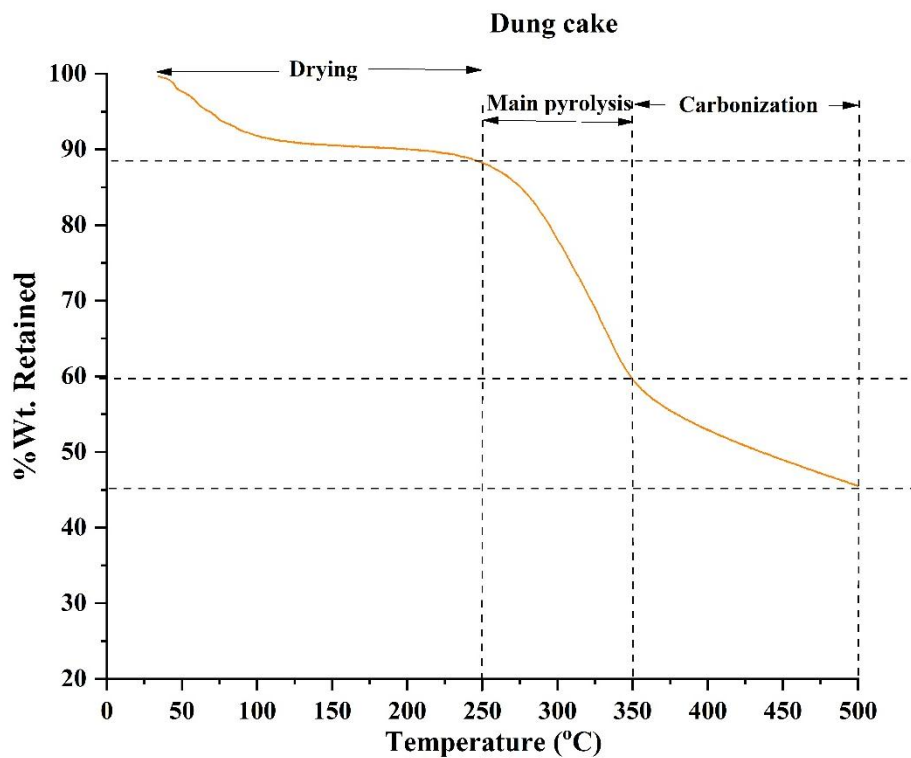


Figure-2 TGA of dung cake

2.6 Estimation of volume flow rate of air in the stove:

A critical factor in determining the generation of aerosol during the burning of the sample is the air velocity in the stove. Earlier experiments conducted on graphite [33] have demonstrated that the air velocity around the heated sample has a significant role in the determining the size and size distribution of the aerosol generated. A larger air velocity ensures a more abundant

oxygen supply for oxidation and vice versa. Most of the past studies on burning of cow dung have not sufficiently paid attention to this critical aspect[34].

In the present work, a home-made earthen stove was built and the air flow velocity at the exit of the stove was measured using an anemometer. Calculations were performed to convert the air velocity in terms of a volumetric air flow which would produce an identical flow velocity in the heating tube used in the experiment. The details of the calculation are given in appendix-1 while the dimensions of the stove used are shown in fig-4 and original picture in fig-3.

Besides the air velocity, the heating rate to which the sample is subjected also plays a vital role in determining the size of the aerosol generated[33]. In the present work, the sample has been heated at 2, 4 and 6 degree per minute heating rate.

2.7 Picture and Design of Indian domestic chulha

2.7.1 Picture

Chulha with attached chimney is constructed to meet the most efficient and realistic conditions inside rural household.



Figure-3 (a) picture of original chulha, (b) Anemometer

2.7.2 Design

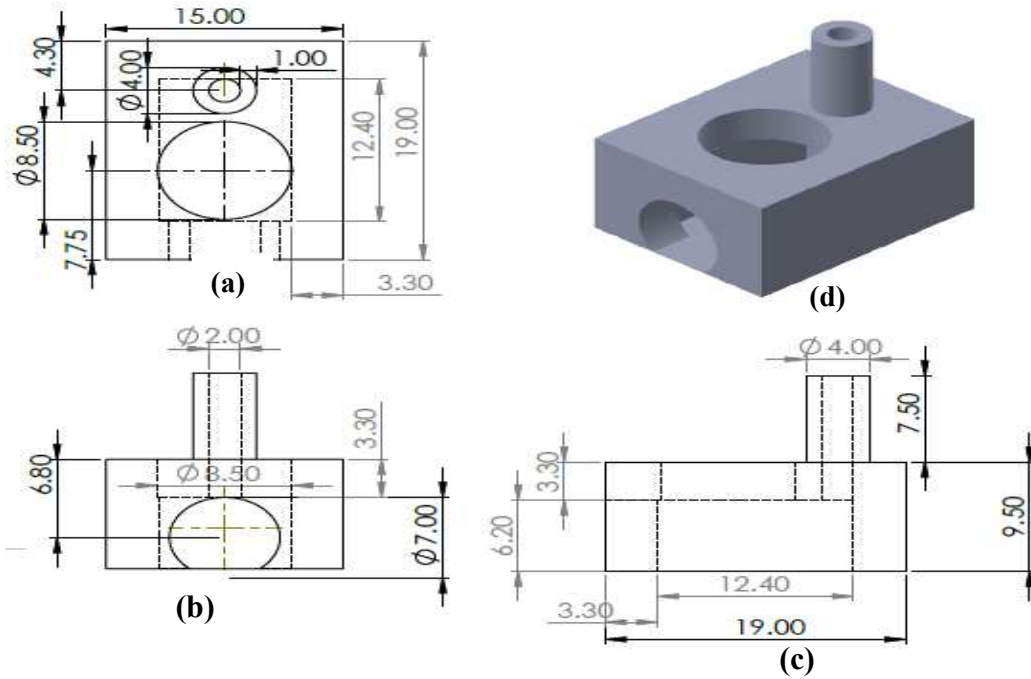


Figure-4 (a) Top view, (b) front view (c) side view of the stove (d) 3-D design of stove

3. Results and discussion

During combustion of different samples of varying grain sizes, total particle concentration was found to be approximately $\sim 10^9$ particles/cm³ and total mass concentration of particles generated in order of 10^6 μ g/m³ (fig-8). The majority of the aerosol generated fall within the nucleation mode (<50nm), accounting for about 70-80% of the total particles produced (table 4). Specifically, for the sample burned at a heating rate of 4°C/min (BSS 44), the percentage contribution of nucleation mode particles is about 85.53%, the highest observed among all tested samples. Though the particle generation peaks in nucleation mode but the mass concentration is found to be maximum for accumulation mode due to the large particle size of the latter for all cases (fig-6 a-f). We used the measurements from OPS and Nanoscan (SMPS) to study the evolution of mass concentration in addition to the number characteristic features of the generated particles. Modified combustion efficiency (MCE) curves are plotted for different grain size of dung cake sample at different heating rates and it was found that MCE is less than 0.9 (fig-5) indicating smouldering dominated burning for which particles have a very narrow range of effective density (1.03-1.21 g/cm³)[35], [36].

Average value of effective density (1.12 g/cm³) is used for calculating particle concentration data into mass concentration. MCE give information about effective density of generated aerosol, Particles generated under smouldering-dominated combustion conditions,

characterized by a modified combustion efficiency (MCE) of less than 0.9, exhibit a narrow range of effective density (ρ_{eff}), varying from 1.03 g/cm³ to 1.21 g/cm³.

$$MCE = \frac{\Delta CO_2}{\Delta CO + \Delta CO_2}$$

Where ΔCO_2 = Background corrected carbon dioxide

ΔCO = Background corrected carbon mono oxide

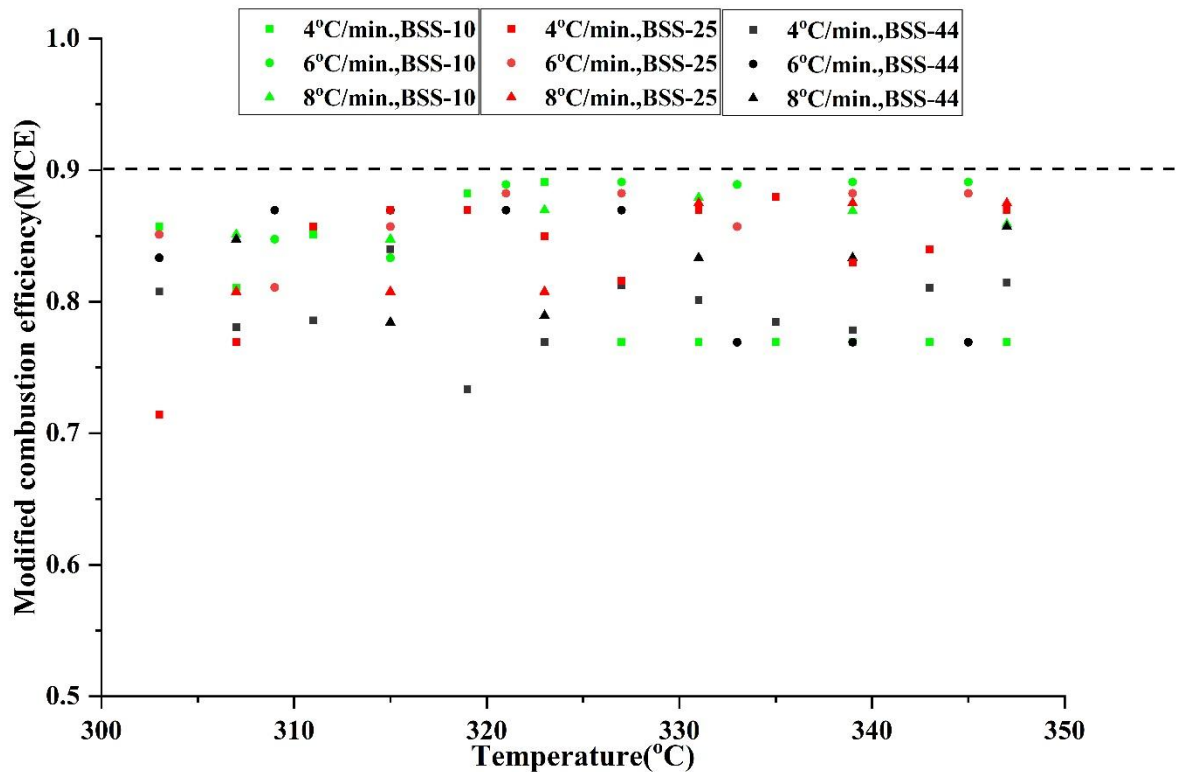


Figure-5 Modified Combustion Efficiency at different heating rate for different grain size

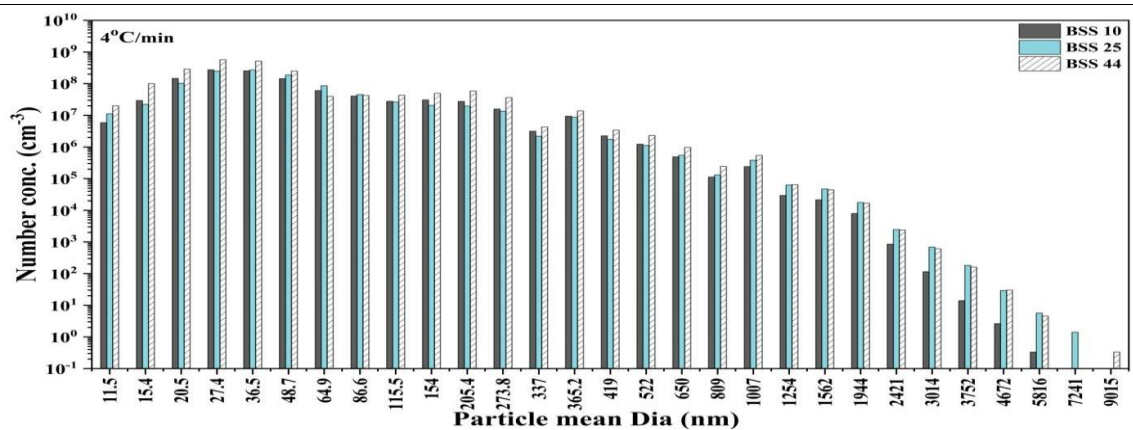
3.1 Effect of grain size on particle generation at constant heating rate

Three different grain dung sample-BSS 44, BSS 25 and BSS 10 (specification provided in table-1) was burned at different heating rate (4°C/min, 6°C/min, 8°C/min) and it was seen that when burning finer dung grain (BSS 44) more particle was produced(fig-8(a)). The impact of grain size can be understood in two contrasting ways. Firstly, as grain size of sample increases, heat transfer resistance decreases, which enhances heat transfer and accelerates the decomposition process. the surface to volume ratio decreases Consequently, more light volatile compounds are release[37]. On the other hand, smaller grain sizes delay the release of volatile

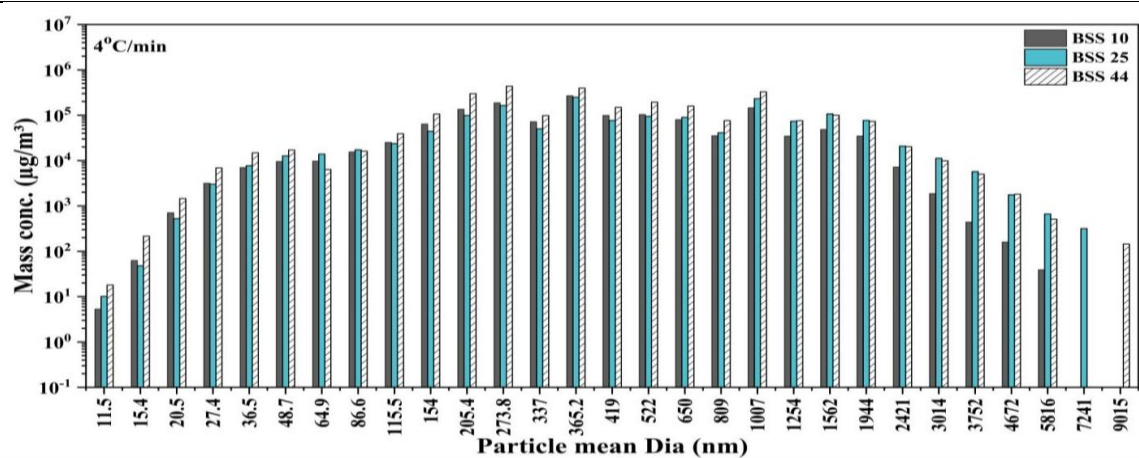
matter due to a larger surface area. This extensive surface area slows down the decomposition process, leading to increased char production at the final temperature. This indicates that finer grains, when burned at a consistent rate, predominantly produce large number of particles, with a significant proportion of them being in the nucleation mode(table-4). The reason for high concentration of aerosol particles for BSS 44 is due to early ignition of small grain particles present on the top layer of sample and the high ash content of cattle manure particles restricts internal heat transfer, whereas their low volatile matter and fixed carbon content make ignition difficult at low ambient temperatures. As a result, ignition occurs only after the particles are heated to sufficiently high temperatures[38]. Same trend is observed for mass concentration i.e. as the grain size of sample is decreased mass concentration of generated particles increases for all heating rate (fig-6 b,d,f).

Table 4- Percentage of nucleation, Aitken and accumulation mode particle in total particle concentration generated from burning of dung cake

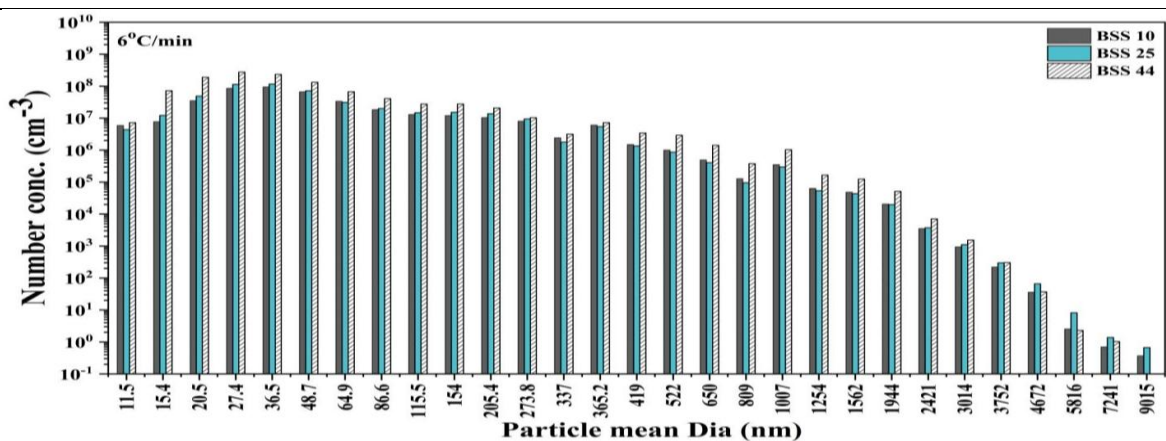
Mode of particle Generation	BSS-10			BSS-25			BSS-44		
	4°C/min.	6°C/min.	8°C/min.	4°C/min.	6°C/min.	8°C/min.	4°C/min.	6°C/min.	8°C/min.
Nucleation mode (<50nm) (%)	79.52	73.33	75.28	79	76.24	72.41	85.53	81.01	70.87
Aitken mode (50-100nm) (%)	9.4	12.8	13.4	12.3	10.6	12.8	4	9.52	20
Accumulation mode (>100nm) (%)	11.08	13.87	11.32	8.7	13.16	14.79	10.47	9.47	9.13



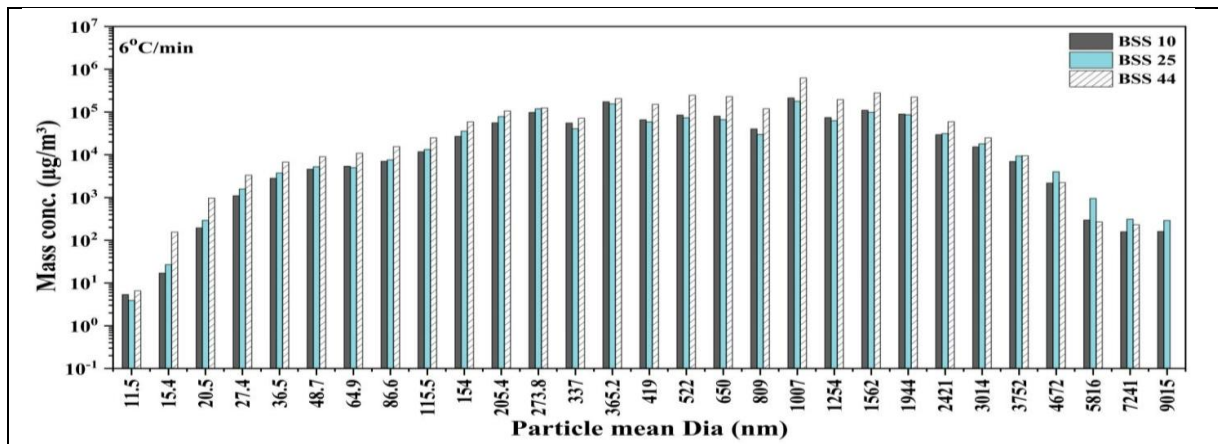
6(a)



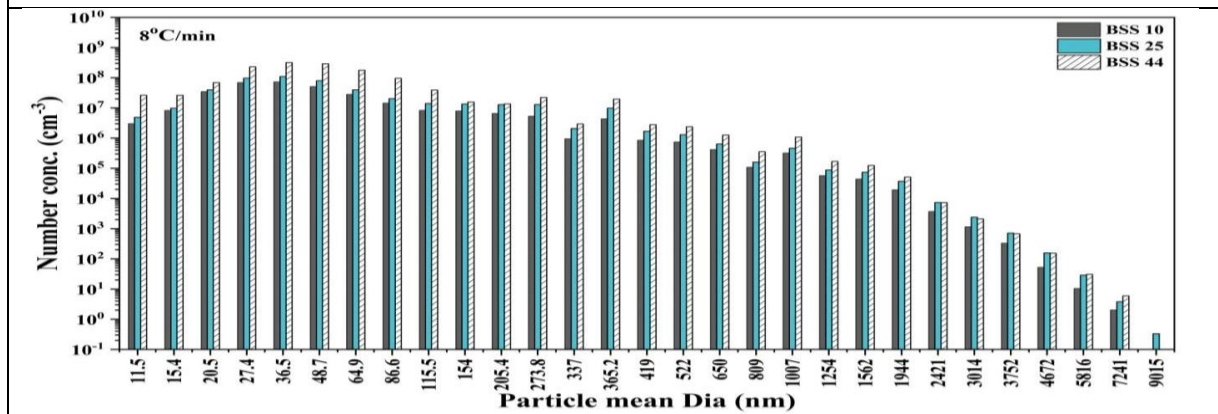
6(b)



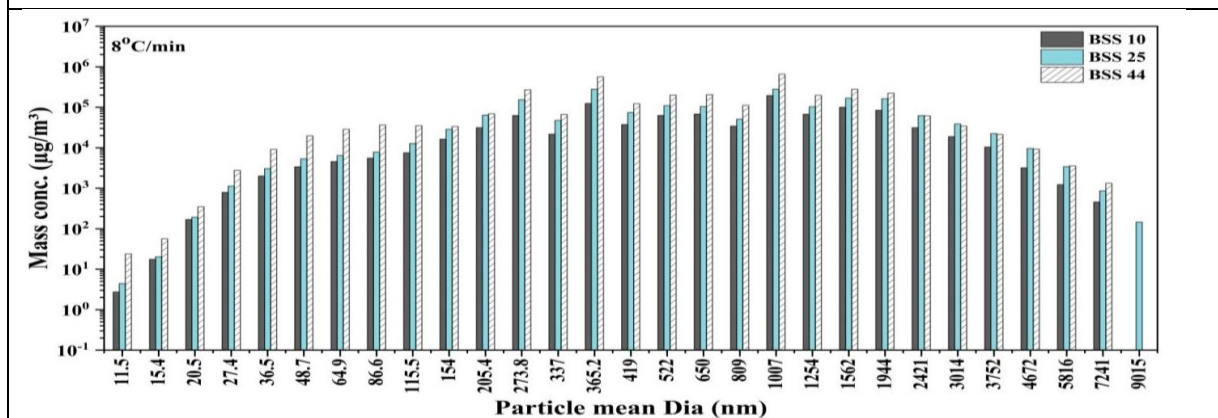
6(c)



6(d)



6(e)

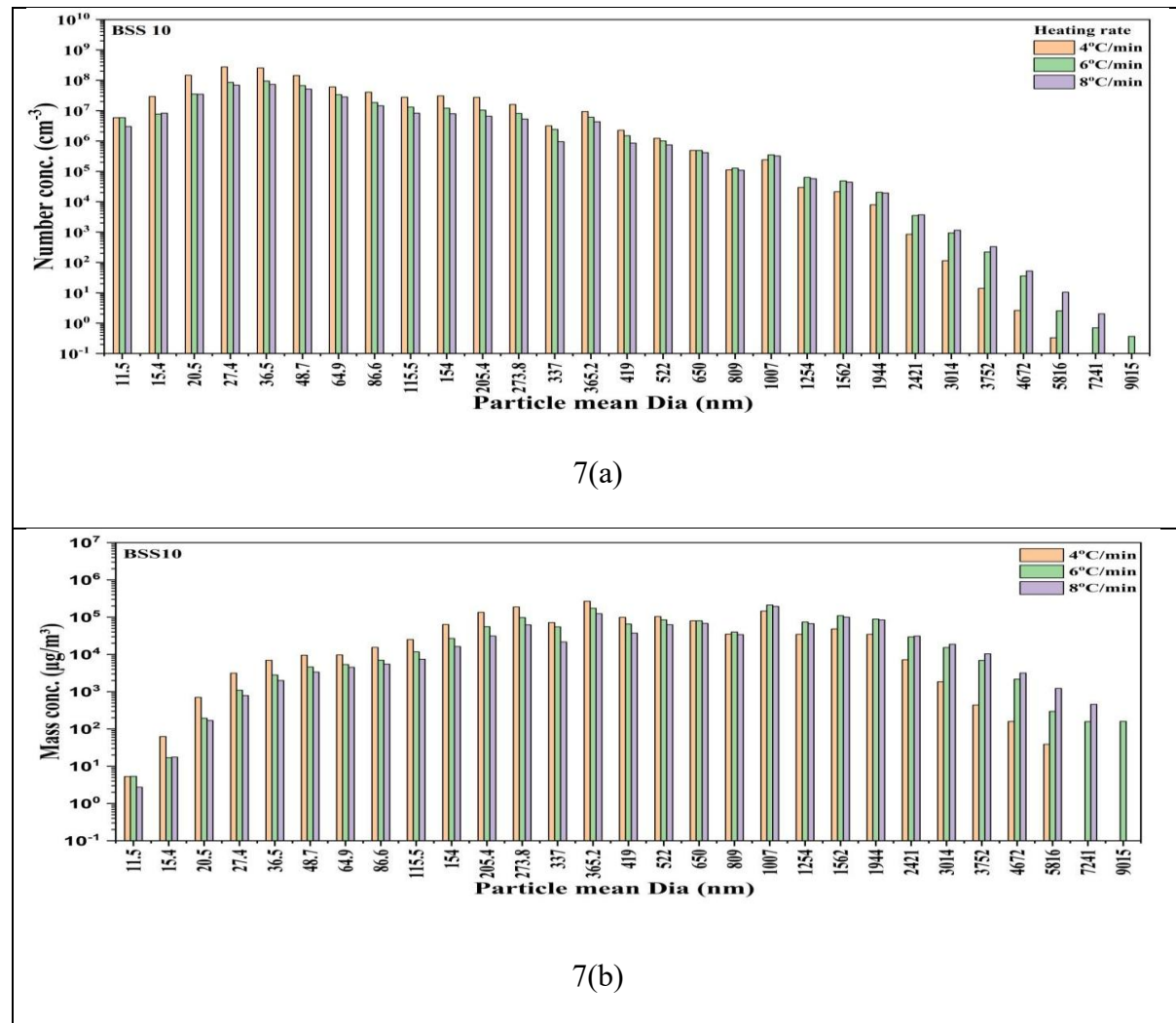


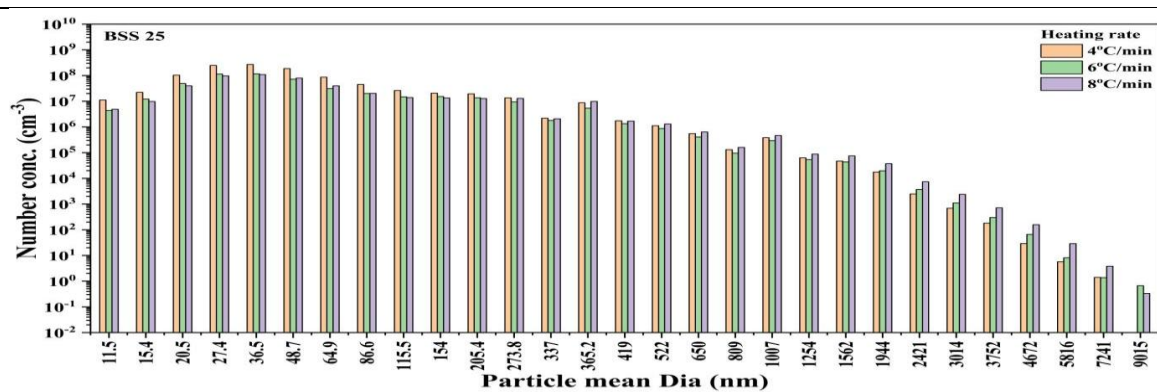
6(f)

Figure-6 Evolution of different diameter particles at 4°C/min, 6°C/min 8°C/min during burning of different grain size (BSS 10, BSS 25, BSS 44) of sample

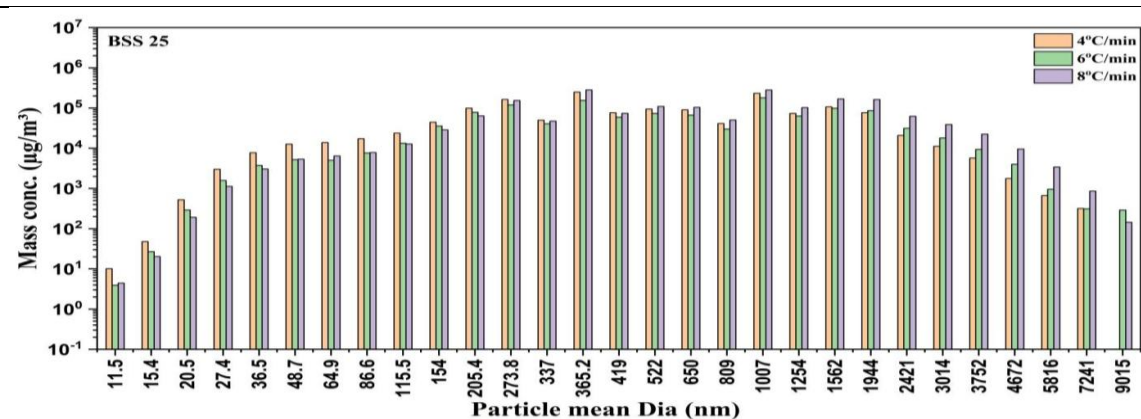
3.2 Effect of heating rate on particle generation for particular grain size

For fixed grain size of dung cake sample, it was observed that as the heating rate increases the particle concentration in the ultrafine range decreases and at higher heating rates, particles with a mean diameter exceeding 500nm become predominant in concentration for all case (fig-7 a,c,e), this is because sample must reach greater temperatures in order to have adequate time for the overall decomposition to be completed, since a higher heating rate translates into shorter exposure to a particular temperature or temperature domain[39]. This relationship highlights the impact of heating rate on the size distribution of aerosol particles generated from burning dung cake, with significant implications for optimizing combustion conditions to manage particle emissions effectively.

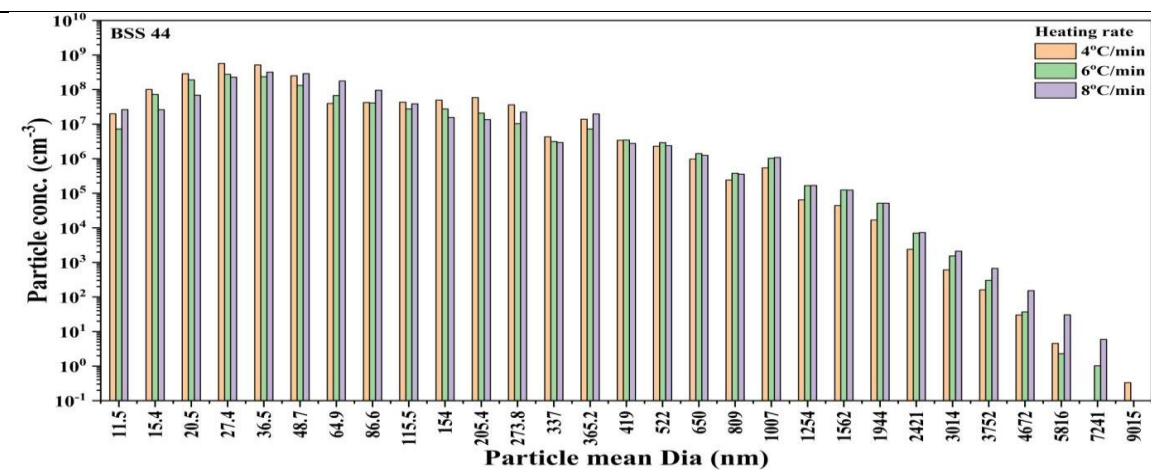




7(c)



7(d)



7(e)

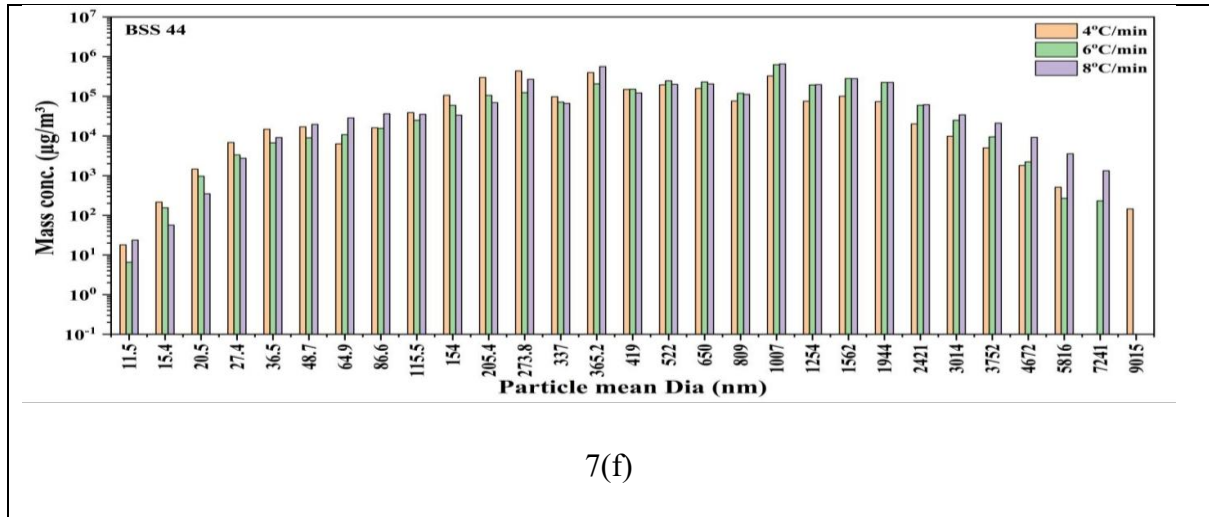


Figure-7 Effect of heating rate (4°C/min, 6°C/min 8°C/min) on grain size (BSS 10), (BSS 25), (BSS 44)

3.3 Total particle and mass concentration

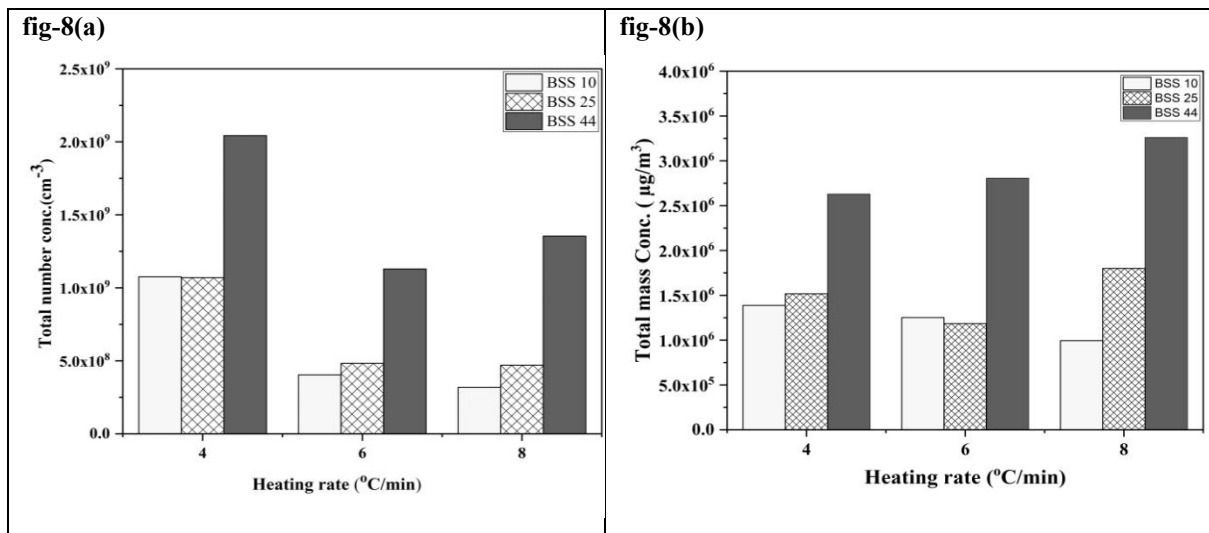


Figure-8 Total particle and mass concentration with heating rate of different grain size

The total number concentration graph indicates that at a fixed heating rate, the total concentration increases as the grain size of the sample decreases and the highest particle generation is observed at a lower heating rate for smaller grain-sized samples during burning (fig-8(a)). Similarly for fixed heating rate as grain size of sample decreases mass concentration of emitted particle increases and highest mass concentration was observed at higher heating rate for finer grain size (fig-8(b)).

3.4 Gas analysis

The fig-9 shows that no gaseous emissions are detected before 200°C. This observation is supported by the TGA (Thermogravimetric Analysis) of the dung cake sample(fig-2), which indicates that up to 200°C, there is primarily evaporation of moisture with only minor traces of volatile organic compounds (VOCs). During the combustion process a general trend in the emissions of carbon monoxide (CO) and carbon dioxide (CO₂) is observed, with minor CO emissions indicating incomplete combustion at the beginning, now as the temperature increases by 25°C, the combustion process moves towards complete combustion. Complete combustion occurs at higher temperatures, which can break down larger particles into smaller, finer particles. The intense heat causes the remaining organic material to volatilize and combust more thoroughly, resulting in smaller residual particles[40], [41]. During complete combustion, various chemical reactions can occur, leading to the formation of secondary particles. Maximum concentration of Carbon monoxide (CO) was about 0.04% by volume. These measurements were taken using a gas analyser with a least count of 0.01% by volume. Similarly, carbon dioxide (CO₂) emissions follow a comparable trend, with their maximum concentration reaching around 0.2% by volume. The gas analyser used for measuring CO₂ had a least count of 0.1% by volume(fig-9). This data highlights the significant levels of pollutants emitted during burning, emphasizing the importance of monitoring and controlling these emissions to mitigate their impact on health and the environment.

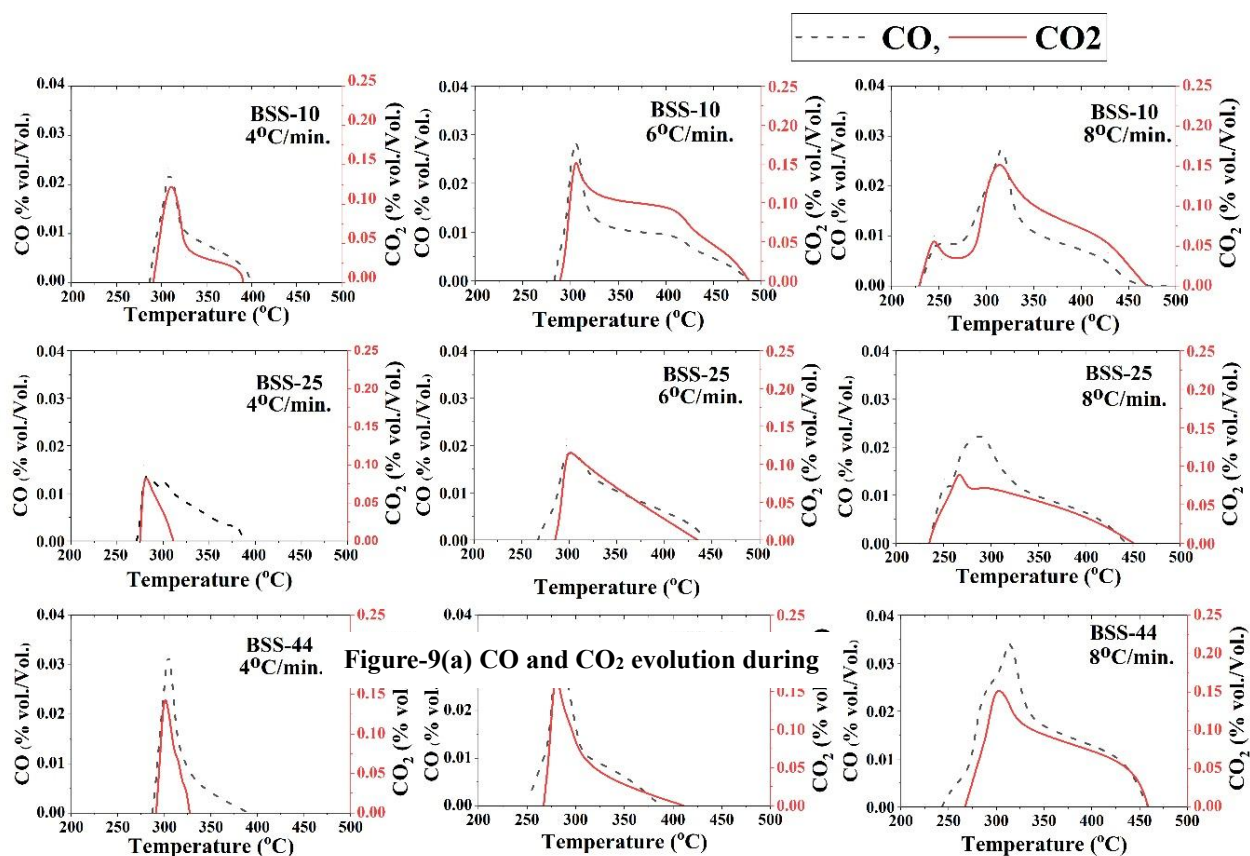


Figure-9 CO and CO₂ evolution during

Conclusion

This research presents a comprehensive analysis of the combustion characteristics and emissions of aerosol particles from dung cake, a prevalent biomass fuel in rural regions. Through proximate analysis, CHNS analysis, and Thermogravimetric Analysis (TGA), we characterized the dung cake samples to understand their combustion behaviour and emissions. The study investigated aerosol particle number concentration and mass concentration by burning different grain size of dung cake at varying heating rates. This study investigates the effects of grain size and heating rate on number and mass concentration of generated aerosols during the combustion of dung cake samples. For fine grains (BSS-44) of dung, the maximum particle concentration reaches approximately $\sim 10^9$ particles/cm³ and mass concentration in order of 10^6 μ g/m³, with the particle number concentration peaking in the 20-40nm range. Constant heating rate results in higher particle generation when burning finer dung grains. Most particles generated fall within the nucleation mode, with finer grains producing a significant proportion of small particles. Additionally, as the heating rate increases, the particle concentration in the ultrafine range decreases, higher heating rates lead to the dominance of larger particle concentrations. Since smaller particles are more harmful to human health due to their ability to penetrate deep into the respiratory system, controlling their formation is important. therefore, the findings suggest that using larger dung grain sizes and higher heating rates can help reduce the formation of harmful ultrafine particles. Optimizing these combustion parameters can be an effective approach to minimize nanoparticle emissions and associated health risks, while gaseous pollutants such as carbon monoxide (CO) and carbon dioxide (CO₂) were simultaneously detected using a gas analyser during the combustion process.

Acknowledgment

The authors are grateful for BRNS (Project No. 2013/36/67-BRNS/0577), DAE's financial assistance.

Competing Interests Statement

Author(s): Anurag Gupta, S.K. Yadav, P. Shukla, Yogesh Kumar Vishwakarma

I declare that I have no significant competing financial, professional, or personal interests that might have influenced the performance or presentation of the work described in this manuscript.

References:

- [1] “World Energy Outlook 2012 – Analysis - IEA.” <https://www.iea.org/reports/world-energy-outlook-2012> (accessed Jan. 26, 2026).
- [2] “Financing Clean Energy Transitions in Emerging and Developing Economies – Analysis - IEA.” <https://www.iea.org/reports/financing-clean-energy-transitions-in-emerging-and-developing-economies> (accessed Jan. 26, 2026).
- [3] “Tracking SDG7: The Energy Progress Report, 2020 – Analysis - IEA.” <https://www.iea.org/reports/tracking-sdg7-the-energy-progress-report-2020> (accessed Jan. 26, 2026).
- [4] “Tracking SDG 7: The Energy Progress Report 2020,” *Track. SDG 7 Energy Prog. Rep. 2020*, May 2020, doi: 10.1596/33822.
- [5] B. Behera, D. B. Rahut, A. Jeetendra, and A. Ali, “Household collection and use of biomass energy sources in South Asia,” *Energy*, vol. 85, pp. 468–480, Jun. 2015, doi: 10.1016/J.ENERGY.2015.03.059.
- [6] “The Cultural Ecology of India’s Sacred Cattle [and Comments and Replies] on JSTOR.” <https://www.jstor.org/stable/2740230> (accessed Jan. 26, 2026).
- [7] C. Lancelotti and M. Madella, “The ‘invisible’ product: developing markers for identifying dung in archaeological contexts,” *J. Archaeol. Sci.*, vol. 39, no. 4, pp. 953–963, Apr. 2012, doi: 10.1016/J.JAS.2011.11.007.
- [8] M. S. GILL, J. P. SINGH, and K. S. GANGWA, “Integrated farming system and agriculture sustainability,” *Indian J. Agron.*, vol. 54, no. 2, pp. 128–139, Oct. 2009, doi: 10.59797/IJA.V54I2.4790.
- [9] C. Navinya *et al.*, “Heating and lighting: understanding overlooked energy-consumption activities in the Indian residential sector,” *Environ. Res. Commun.*, vol. 5, no. 4, Apr. 2023, doi: 10.1088/2515-7620/ACCA6F.
- [10] A. Swarnkar and B. R. Gurjar, “GIS-based emission inventory of heavy metals from road transport and NMVOCs associated with biomass burning for megacity Delhi,” *Urban Clim.*, vol. 51, p. 101600, Sep. 2023, doi: 10.1016/J.UCLIM.2023.101600.
- [11] Z. Wang *et al.*, “Assessing the burning of household dung-cake as an energy source in different rangeland regions of Inner Mongolia,” *J. Clean. Prod.*, vol. 292, p. 125827, Apr. 2021, doi: 10.1016/J.JCLEPRO.2021.125827.
- [12] Q. Xiao, E. Saikawa, R. J. Yokelson, P. Chen, C. Li, and S. Kang, “Indoor air pollution from burning yak dung as a household fuel in Tibet,” *Atmos. Environ.*, vol. 102, pp. 406–412, Feb. 2015, doi: 10.1016/J.ATMOSENV.2014.11.060.
- [13] K. R. Smith *et al.*, “Energy and human health,” *Annu. Rev. Public Health*, vol. 34, pp. 159–188, Mar. 2013, doi: 10.1146/ANNUREV-PUBLHEALTH-031912-114404.
- [14] A. Masih, A. S. Lall, A. Taneja, and R. Singhvi, “Exposure levels and health risk assessment of ambient BTX at urban and rural environments of a terai region of northern India,” *Environ. Pollut.*, vol. 242, no. Pt B, pp. 1678–1683, Nov. 2018, doi: 10.1016/J.ENVPOL.2018.07.107.
- [15] S. B. Gordon *et al.*, “Respiratory risks from household air pollution in low and middle

- income countries,” *Lancet Respir. Med.*, vol. 2, no. 10, pp. 823–860, Oct. 2014, doi: 10.1016/S2213-2600(14)70168-7.
- [16] A. Addisu, T. Getahun, M. Deti, Y. Negesse, and B. Mekonnen, “Association of Acute Respiratory Infections with Indoor Air Pollution from Biomass Fuel Exposure among Under-Five Children in Jimma Town, Southwestern Ethiopia,” *J. Environ. Public Health*, vol. 2021, 2021, doi: 10.1155/2021/7112548.
- [17] K. R. Smith *et al.*, “Millions dead: How do we know and what does it mean? Methods used in the comparative risk assessment of household air pollution,” *Annu. Rev. Public Health*, vol. 35, no. Volume 35, 2014, pp. 185–206, Mar. 2014, doi: 10.1146/ANNUREV-PUBLHEALTH-032013-182356/1.
- [18] “T. B. Mathers C Ma Fat D., ‘The global burden of disease 2004,’ *Updat. World Heal. Organ.*, p. 146, 2004.” <https://www.sciepub.com/reference/449939> (accessed Jan. 26, 2026).
- [19] “Household air pollution.” <https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health> (accessed Jan. 26, 2026).
- [20] R. Suresh, V. K. Singh, J. K. Malik, A. Datta, and R. C. Pal, “Evaluation of the performance of improved biomass cooking stoves with different solid biomass fuel types,” *Biomass and Bioenergy*, vol. 95, pp. 27–34, Dec. 2016, doi: 10.1016/J.BIOMBIOE.2016.08.002.
- [21] M. Tiwari, S. K. Sahu, and G. G. Pandit, “Probabilistic single box approach for modeling PAHs associated with combustion aerosols in a typical indoor environment,” *Biomass and Bioenergy*, vol. 86, pp. 172–179, Mar. 2016, doi: 10.1016/J.BIOMBIOE.2016.02.003.
- [22] J. B. Kandpal, R. C. Maheshwari, and T. C. Kandpal, “Particulate pollution from biomass combustion in three cookstoves,” *Int. J. Energy Res.*, vol. 19, no. 5, pp. 433–441, Jul. 1995, doi: 10.1002/ER.4440190508.
- [23] R. Rajkumar, S. Monika, K. G. Priya, P. A. Karthick, D. Thiyagarajan, and M. Menagadevi, “Comprehensive Analysis of the Toxic Emissions from Commercial Solid Fuels Combustion,” *8th Int. Conf. Adv. Comput. Commun. Syst. ICACCS 2022*, pp. 1951–1955, 2022, doi: 10.1109/ICACCS54159.2022.9785312.
- [24] G. J. Stewart *et al.*, “Emission estimates and inventories of non-methane volatile organic compounds from anthropogenic burning sources in India,” *Atmos. Environ. X*, vol. 11, p. 100115, Oct. 2021, doi: 10.1016/J.AEAOA.2021.100115.
- [25] G. J. Stewart *et al.*, “Emissions of intermediate-volatility and semi-volatile organic compounds from domestic fuels used in Delhi, India,” *Atmos. Chem. Phys.*, vol. 21, no. 4, pp. 2407–2426, Feb. 2021, doi: 10.5194/ACP-21-2407-2021.
- [26] G. J. Stewart *et al.*, “Comprehensive organic emission profiles, secondary organic aerosol production potential, and OH reactivity of domestic fuel combustion in Delhi, India,” *Environ. Sci. Atmos.*, vol. 1, no. 2, pp. 104–117, Feb. 2021, doi: 10.1039/D0EA00009D.
- [27] G. J. Stewart *et al.*, “Emissions of non-methane volatile organic compounds from combustion of domestic fuels in Delhi, India,” *Atmos. Chem. Phys.*, vol. 21, no. 4, pp. 2383–2406, Feb. 2021, doi: 10.5194/ACP-21-2383-2021.

- [28] A. Mondal *et al.*, “Non-methane volatile organic compounds emitted from domestic fuels in Delhi: Emission factors and total city-wide emissions,” *Atmos. Environ. X*, vol. 11, p. 100127, Oct. 2021, doi: 10.1016/J.AEAOA.2021.100127.
- [29] J. C. Domínguez, M. Oliet, M. V. Alonso, M. A. Gilarranz, and F. Rodríguez, “Thermal stability and pyrolysis kinetics of organosolv lignins obtained from *Eucalyptus globulus*,” *Ind. Crops Prod.*, vol. 27, no. 2, pp. 150–156, Mar. 2008, doi: 10.1016/J.INDCROP.2007.07.006.
- [30] C. Venkataraman and G. U. M. Rao, “Emission Factors of Carbon Monoxide and Size-Resolved Aerosols from Biofuel Combustion,” *Environ. Sci. Technol.*, vol. 35, no. 10, pp. 2100–2107, May 2001, doi: 10.1021/ES001603D.
- [31] S. K. Yadav, A. Khan, and P. Shukla, “Development of a high temperature facility for study of aerosol emission behavior of combustible materials,” *ElsevierSK Yadav, A Khan, P ShuklaMeasurement, 2019•Elsevier*, vol. 139, pp. 308–316, Jun. 2019, doi: 10.1016/J.MEASUREMENT.2019.02.067.
- [32] J. Liu, X. Jiang, L. Zhou, X. Han, and Z. Cui, “Pyrolysis treatment of oil sludge and model-free kinetics analysis,” *J. Hazard. Mater.*, vol. 161, no. 2–3, pp. 1208–1215, Jan. 2009, doi: 10.1016/J.JHAZMAT.2008.04.072.
- [33] S. K. Yadav, M. Joshi, P. Shukla, and A. Khan, “Aerosol generation from graphite at high temperature: Role of heating rate and air flow rate,” *Ann. Nucl. Energy*, vol. 167, Mar. 2022, doi: 10.1016/j.anucene.2021.108792.
- [34] B. Bharadwaj, P. Dhungana, and P. Ashworth, “Burning dung cake as a household fuel: A review,” *Next Energy*, vol. 9, p. 100410, Oct. 2025, doi: 10.1016/J.NXENER.2025.100410.
- [35] M. M. G. Hargrove *et al.*, “Smoldering and Flaming Biomass Wood Smoke Inhibit Respiratory Responses in Mice,” *Inhal. Toxicol.*, vol. 31, no. 6, p. 236, May 2019, doi: 10.1080/08958378.2019.1654046.
- [36] R. P. Pokhrel, J. Gordon, M. N. Fiddler, and S. Bililign, “Impact of combustion conditions on physical and morphological properties of biomass burning aerosol,” *Aerosol Sci. Technol.*, vol. 55, no. 1, pp. 80–91, 2021, doi: 10.1080/02786826.2020.1822512;JOURNAL:JOURNAL:UAST20;REQUESTEDJOURNAL:JOURNAL:UAST20;WGROU:STRING:PUBLICATION.
- [37] K. Słopiecka, P. Bartocci, and F. Fantozzi, “Thermogravimetric analysis and kinetic study of poplar wood pyrolysis,” *Appl. Energy*, vol. 97, pp. 491–497, Sep. 2012, doi: 10.1016/J.APENERGY.2011.12.056.
- [38] C. Jiang, Q. Lin, C. Wang, X. Jiang, H. Bi, and L. Bao, “Experimental study of the ignition and combustion characteristics of cattle manure under different environmental conditions,” *Energy*, vol. 197, p. 117143, Apr. 2020, doi: 10.1016/J.ENERGY.2020.117143.
- [39] R. Mehrabian, R. Scharler, and I. Obernberger, “Effects of pyrolysis conditions on the heating rate in biomass particles and applicability of TGA kinetic parameters in particle thermal conversion modelling,” *Fuel*, vol. 93, pp. 567–575, Mar. 2012, doi: 10.1016/J.FUEL.2011.09.054.
- [40] R. Hadeif, K. P. Geigle, W. Meier, and M. Aigner, “Soot characterization with laser-

induced incandescence applied to a laminar premixed ethylene–air flame,” *Int. J. Therm. Sci.*, vol. 49, no. 8, pp. 1457–1467, Aug. 2010, doi: 10.1016/J.IJTHERMALSCI.2010.02.014.

- [41] H. Wang, “Formation of nascent soot and other condensed-phase materials in flames,” *Proc. Combust. Inst.*, vol. 33, no. 1, pp. 41–67, Jan. 2011, doi: 10.1016/J.PROCI.2010.09.009.

Appendix-1

Calculation

following calculations were performed and flow rate was determined to synchronize real and experimental conditions.

Internal diameter of quartz tube (D_i) = 0.07 m

$$\begin{aligned}\text{Cross sectional area of tube} &= \frac{\pi}{4} \times D_i^2 \\ &= 0.785 \times 0.07^2 \\ &= 0.003846 \text{ m}^2\end{aligned}$$

$$\begin{aligned}\text{Volume flow rate inside tube (Q)} &= 20 \text{ lpm} \\ &= (20 \times 0.001) / 60 \\ &= 3.333 \times 10^{-4} \text{ m}^3/\text{s}\end{aligned}$$

$$\begin{aligned}\text{Velocity inside tube (V)} &= Q / \text{Area} \\ &= 3.333 \times 10^{-4} / 0.003846 \\ &= 0.0866 \text{ m/s}\end{aligned}$$

$$\text{Area at inlet } A_i = \frac{\pi}{4} \times d_i^2 = \frac{\pi}{4} \times 0.1778^2 = 0.0248 \text{ m}^2$$

Temperature at inlet $T_i = 300 \text{ K}$

$$\text{Area at outlet } A_o = \frac{\pi}{4} \times d_o^2 = \frac{\pi}{4} \times 0.0508^2 = 0.00203 \text{ m}^2$$

Temperature at outlet $T_o = 353 \text{ K}$

Pressure at inlet P_i = pressure at outlet $P_o = 1 \text{ atm} = 101.325 \text{ kPa}$

$$\text{Density of air at inlet } \rho_i = \frac{P_i}{RT_i} = \frac{101.325}{0.287 \times 300} = 1.176 \frac{\text{kg}}{\text{m}^3}$$

$$\text{Density of gases at outlet } \rho_o = \frac{P_o}{RT_o} = \frac{101.325}{0.287 \times 353} = 1.00 \frac{\text{kg}}{\text{m}^3}$$

According to conservation of mass:

$$\rho_i A_i V_i = \rho_o A_o V_o$$

$$1.176 \times 0.0248 \times V_i = 1.00 \times 0.00203 \times 1.2$$

$$V_i = 0.083 \text{ m/s}$$

Cross sectional area of quartz tube = 0.003846 m²

$$\begin{aligned}\text{Volume flow rate through tube (Q)} &= (\text{area of tube}) \times V_i \\ &= 0.003846 \times 0.083 \\ &= 3.2 \times 10^{-4} \text{ m}^3/\text{s}\end{aligned}$$

or

$$Q = 19.2 \text{ lpm}$$