Effect of Dilution Sampling on Particle Emissions and Size Distributions from a Modern Pellet Stove

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Abstract

A two stage partial flow dilution tunnel with the combination of a porous tube diluter (PRD) and an ejector diluter (ED) was used to examine the effect of dilution sampling on fine particle emissions and size distributions from an automatically fired small scale modern bottom feed pellet stove with a capacity of 5 kW. The combustion experiments were conducted using a state of the art instrument Electrical Low Pressure Impactor Plus (ELPI+), which measures fine particles in real time with a fast response time in a wide particle size range from 0.006 to 10 μm (micrometre) aerodynamic diameter. The particulate matter (PM) measurements were conducted according to the European standard EN 14785 for residential space heating appliances fired by wood pellets. Isokinetic sampling technique was not applied as the present study was emphasized on the very small particles, and results were limited to maximum $PM_{2.5}$. Five combustion experiments (A, B, C, D and E) with different dilution ratios varied between 32.1 to 53.8 were conducted at a stove manufacturing plant in the southern part of Belgium. Measurements include the particle number emissions, particle mass of PM_1 (size <1 μm) and $PM_{2.5}$ (size <2.5 μm) emissions and particle size distributions. The experimental results showed that both particle number and mass emissions decreased with increasing dilution sampling. Both particle mass and number size distributions did not vary with increasing dilution sampling, but the maximum number of concentrations appeared at the particle size of about 125 nm (nanometre), while the maximum mass concentrations showed in the fine mode at the particle size of around 330 nm. The results obtained from this study provide new insights into the effects of dilution sampling on the measurements of fine particle emissions, providing important data for the ongoing research to define a standardized dilution sampling methodology for characterizing emissions from stationary combustion sources for fine particle emissions.

Keywords:

Dilution sampling, pellet stove, PM_1 concentrations, $PM_{2.5}$ concentrations, number concentrations, particle size distributions

1. Introduction

Biomass is seen as one of the options to substitute fossil fuels and mitigate greenhouse gas emissions. Despite being considered renewable and CO_2 neutral, biomass combustion is recognized as a major source of fine particle emissions, and small scale combustion technologies especially play an important role in this [1, 2]. High particulate emissions from incomplete combustion in small scale appliances like woodstoves and fireplaces have been reported in several studies [3-5]. However, other technologies are available for domestic heating purposes with advantages from the emission point of view. Wood pellets particularly have become an important source of fuel in recent years. Using wood pellets as biomass fuel is gradually increasing due to their high energy density, easy transportability and the lower amount of greenhouse gas emissions from its production and transportation comparing to oil, coal and natural gas. Nowadays, combustion of wood pellets in small scale heating appliances is efficient and produces significantly lower emissions than the old wood log combustion appliances.

Traditionally, particle emission measurements from the small-scale biomass combustion technologies are performed in undiluted hot flue gases at temperatures of about 120-280 °C. However, sampling in raw hot flue gases may suffer from transient conditions with varying flue gas flows, or from the condensable nature of many of the semi-volatile organic compounds. This may lead to erroneous results and incorrect conclusions. In the case of particulate matter (PM) in particular, interactions between particles and walls must be limited, and appropriate quenching should be done in order to preserve particle size distributions. Dilution of the exhaust gas decreases the temperature and partial vapour pressures. This causes some of the semi-volatile compounds to condense on the particles. If particles are sampled from a hot and undiluted exhaust, many organic species remain in the gas phase, whereas a fraction of the organics condenses and is collected by using dilution [6-8]. Therefore, sampling at lower temperature is desirable and dilution of the hot exhaust gases is a suitable alternative method. Characterizing fine particle emissions from small scale heating systems is difficult because of the high temperatures and moisture content of exhaust gases released from the combustion. Upon exiting the stack the combustion products are rapidly cooled and diluted with ambient air, during which time processes such as coagulation, condensation, and nucleation change the size and composition of the fine particle emissions. Dilution sampling is a technique that has been developed to examine the influence of rapid cooling and dilution on fine particle emissions from combustion systems [9]. A dilution sampler rapidly mixes hot exhaust gases with a specified amount of conditioned air and allows for processes such as nucleation, condensation, and coagulation to occur.

Several researches regarding the effect of dilution sampling on fine particle emission were found in the literature. For example, Lipsky et al. [10] examined the effect of dilution sampling on fine particle mass concentrations from pulverized coal combustion. The fuel was combusted in a commercial coal boiler with capacity of 150 kW. Particle mass concentrations were measured using a Scanning Mobility Particle Sizer (SMPS). The results show that particle mass concentrations did not vary with the dilution ratio. Smits et al. [11] conducted the effect of sampling conditions on the exhaust gas emission of small-scale power generators. A DustTrak Model 8530 was used to measure particle mass concentration from a 6 kW diesel generator. The authors mentioned that higher dilution had the lower PM concentrations. Lipsky et al. [12] evaluated effect of dilution on fine particle mass emissions from a diesel generator 4.5 kW and a wood stove. The Teflon filter was used for quantifying $PM_{2.5}$ mass concentrations. The experimental results indicate that $PM_{2.5}$ mass concentrations decrease with increasing dilution ratio. These works discuss mainly particle mass concentrations emissions from the commercial coal boiler, diesel generators and wood stove. However, not enough information on the effect of particle mass concentrations, number concentrations and their size distributions, from the residential biomass pellet combustion, can be found in the literature. There is a need for much knowledge on the effect of dilution sampling on particle emissions and size distributions from residential pellet combustion.

This study presents experimental investigation on the influence of dilution sampling on fine particle emissions from an automatically fired small scale modern bottom feed pellet stove with a capacity of 5 kW. A two stage partial flow dilution tunnel with a combination of a porous tube diluter and an ejector diluter was used to characterize dilution effect on fine particle emissions. Particle number emissions, particle mass of PM_1 and $PM_{2.5}$ emissions and particle size distributions were investigated by increasing dilution sampling.

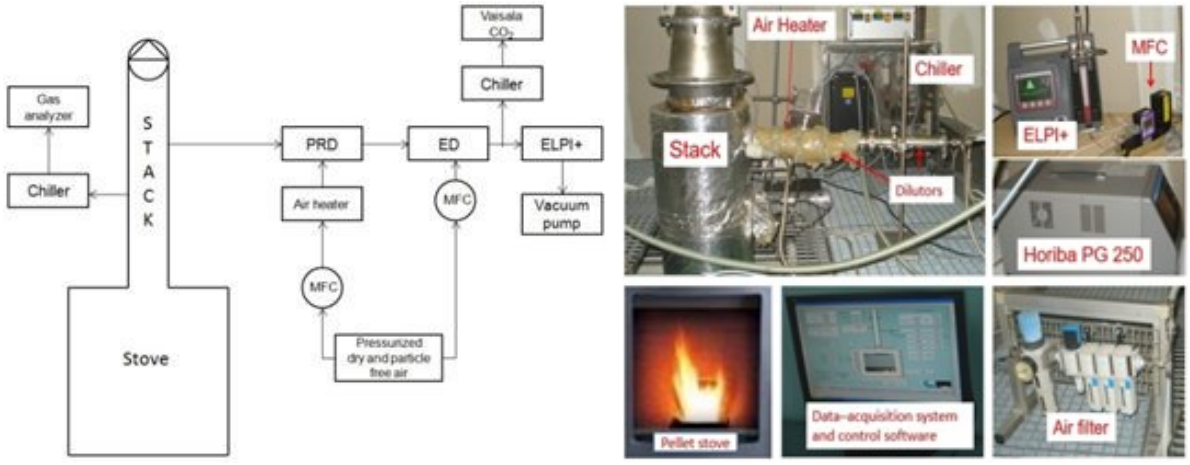
2. Materials and Methods

The following sub-sections briefly illustrate the experimental setup, fuel characteristics, combustion appliance, dilution sampler and instruments used in the particle emission measurements.

2.1. Experimental setup

The measurements were conducted according to the European standard EN 14785 for residential space heating appliances fired by wood pellets [13]. The schematic of the experimental setup for the fine particle emission measurements is shown in Fig. 1. Five experiments A, B, C, D and E were

conducted for the emissions measurements from a bottom feed pellet stove. Emissions from each combustion experiments were investigated at the main combustion phase, when the combustion was stable. Isokinetic sampling technique was not applied as the present study was emphasized on the very small particles, and results were limited to maximum $PM_{2.5}$.



(a) Schematic of the experimental setup (b) Some photos of the experimental set up

Fig. 1 Schematic of the experimental setup for the PM emission measurements, PRD = Porous tube diluter, ED =Ejector diluter, MFC = Mass flow controller.

2.2. Fuel characteristics

The elemental composition, moisture content and lower heating value (LHV) of the commercial pellets used in the combustion experiments are presented in Table 1. The pellets were made from soft wood, certified by DIN-Plus standard and were available in the European market.

Table 1 Chemical properties of the pellet used in the combustion experiments.

Parameter	Commercial pellets	DINplus
Length (mm)	<45	<45
Diameter (mm)	6.06±0.1	6±0.5
Durability (%)	98.9	>97.7
Fine content (%)	0.13	<1
Volumetric mass (kg/m^3)	675	>650
LHV (MJ/kg)	18.7	> 16.9
Moisture (%)	8.6	10
Ash (wt %)	0.3	0.7
C (wt %)	49.1	-
H (wt %)	5.8	-
O (wt %)	44.8	-

2.3. Combustion appliance

The combustion appliance used in the experiments was a modern bottom feed pellet stove with a nominal heat output of 5 kW. The pellet stove is shown in the schematic diagram of the Fig. 1. The inlet sampling port of the dilution tunnel and the chiller was connected to the stack of the stove. The ELPI+ was installed to the downstream of the dilution tunnel, while the gas analyzers (Horiba PG250 and Vaisala Carbocap) to the downstream of the chiller. The pellet stove was setup on a balance to monitor the fuel consumption. The pellet stove is equipped with an internal pellet storage, where the pellets are transported through two screws from the pellet storage hopper to the burner cup. The rotation of screw-1 connected to the pellet storage hopper was 3.2 sec/6 sec. Screw-2 connected to the burner cup was operated at 2 rpm. The combustion takes place in the burner cup. A step motor is used to supply the pellet into the combustion chamber. The combustion air consisting of primary and secondary air is supplied through the holes under the grid of the burner cup. The stove was operated in high fan speed at 1400 rpm, which regulate air flow into the combustion chamber. The air supply is fan assisted and depends upon the selected thermal output. A short cleaning period is set to occur every 30 minutes in the stove. During cleaning, the fuel supply decreases and the air supply increases for 1 minute to remove the ash gathered on the grid. The flame of the stove is upwards and can be seen from the front side of the stove, which is covered with a high temperature transparent glass window. The top of the combustion chamber is equipped with the baffle plate made of vermiculite materials and the sides of refractory ceramic bricks made of calcium silicate. The flue gases are drawn out by an exhaust fan.

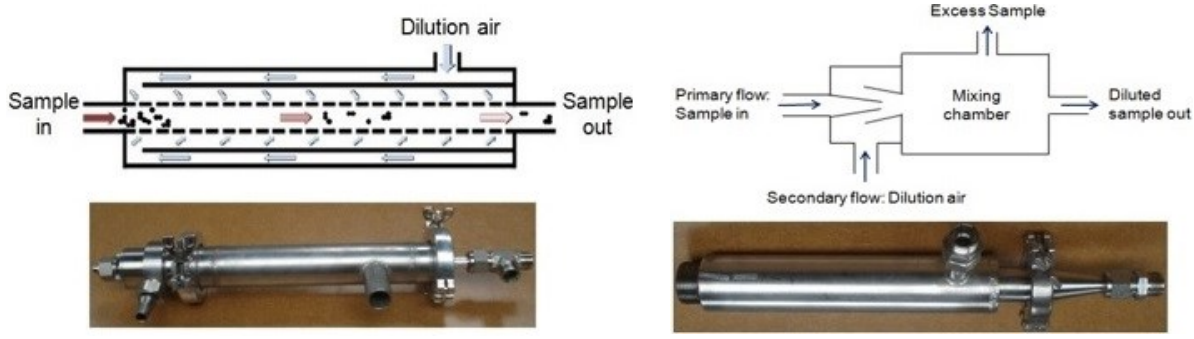
2.4. Partial flow dilution tunnel

Dilution tunnels using in particle sampling are generally two types: full flow dilution and partial flow dilution tunnel. In the full flow dilution tunnel, all the exhaust gases from the combustion appliances are drawn by a constant volume pump through a collection hood and are mixed with ambient dilution air. Next, the diluted exhaust gas sample passes through the filters and measuring instruments to prepare for PM sampling. With this sampling method, the size of the dilution tunnel is dependent on the volume flow of the exhaust gas. In the partial flow system, only a small part of the exhaust gas from the combustion appliance is drawn to a dilution tunnel and is mixed with dilution air. The diluted sample passes through the analyzer for particle analysis. A number of partial flow dilution tunnels are available, including a combination of porous tube diluter (PRD) and ejector diluter (ED), ejector diluter only, two stage of ejector diluters.

A two stage dilution sampler with the combination of a PRD and an ED was chosen for this study in conducting the combustion experiments, because this combination is believed to be the best in preserving the particle distribution. This combination moreover yields very stable conditions, which allows for the possibility to add or remove objects downstream without affecting the dilution ratio. The advantages of this system are; it is well controllable and can also be used to carry out measurements in both field and laboratory condition. After the porous tube diluter, the sample is mixed efficiently in the ejector diluter. Higher dilution ratios are possible due to additional dilution by the ejector diluter.

In the PRD, the sample is drawn through a porous tube, while the dilution gas is introduced through the pores of the porous tube wall to prevent thermophoresis particle losses and vapor condensation on walls as shown in Fig. 2 (a). The PRD is 250 mm (millimetre) long and the inner diameter of the porous tube is 12 mm and the dilution zone length is 200 mm. The balancing of the dilution flow and suction in the diluter outlet is used to get the desired sample flow into the diluter. This allows a wide range of dilution ratios. The ED is a secondary diluter installed downstream of the porous tube diluter as shown in Fig. 2 (b). The advantage of the ejector diluter is that it stabilizes the flow of the diluted sample. Secondly, the ejector has a relatively stable dilution ratio and due to the high speed at the ejector nozzle. It also provides a good mixing which is essential before sampling for particle analysis. Stabilization of the ED gives the possibility to add or remove instruments after ED without affecting the dilution ratio. The ED is 360 mm long and the sample inlet diameter of the ED is 12 mm. The combination of the

PRD and ED also allows for a wider range in dilution ratio. The pressurized dilution air flows into the porous tube diluter and the ejector diluter were controlled separately by the two mass flow controllers (brand Aalborg, Germany) of 20 lpm (liter per minute) and 200 lpm respectively.



(a) Porous tube diluter (PRD) (b) Ejector diluter (ED)

Fig. 2 Schematic of the partial flow dilution system.

2.5. Instruments used in particle emission measurements

A partial flow from the stack at about 2 m (metre) height from the pellet stove was withdrawn through an externally insulated bent tube steel probe of 12 mm diameter. The opening of the probe was positioned towards the flow of the stack. Particle emissions were measured continuously from a partial flow dilution tunnel using an Electrical Low Pressure Impactor Plus (ELPI+) with a flow rate 10 lpm and cut-off size of the fourteen stages from 6 nm to 10 μm. Fig. 3 shows the working principle of the ELPI+ instrument. Sample particles entering the ELPI+ are first charged in the charger. The charged particles collected in each impactor stage produce an electrical current which is recorded by the respective electrometer channel. After being charged, the particles are introduced in the cascade impactor in order to be separated on the basis of their inertia and their aerodynamic diameter. This current is proportional to particle numbers via mathematical algorithms [14, 15]. Aluminum foils, greased with a mixture of acetone and Apiezon-L were placed on each of the impactor stages to prevent particle bouncing effect. The flue gases were diluted through a two steps partial flow dilution tunnel with pre-filtered dilution air before reaching the particle measuring instrument, ELPI+.

The CO_2 concentration from the undiluted flue gas from the stack and diluted sample were analyzed continuously by a Horiba PG250 gas analyzer and a Vaisala Carbocap analyzer to calculate the dilution ratio (DR). Both gas analyzers cannot withstand the hot and humid flue gases for direct analysis. Before the analyzers, the flue gas samples passed through the chillers to remove moisture and to cool down the gas. Each gas analyser was calibrated with an appropriate gas mixture, before and after each combustion experiment.The analyzers have the measurement error of ±2 % full scale in linearity and ±0.5 % full scale in repeatability. The dilution ratio (DR) was calculated based on concentration of CO_2 in the raw sample and the diluted gas sample using the following equation [2, 15-18].

$$DR = \frac{CO_{2,RG} - CO_{2,BG}}{CO_{2,S} - CO_{2,BG}} \quad (1)$$

where, $CO_{2,RG}$ is the concentration in the raw gas, $CO_{2,BG}$ is the background dilution air and $CO_{2,S}$ is the diluted sample.

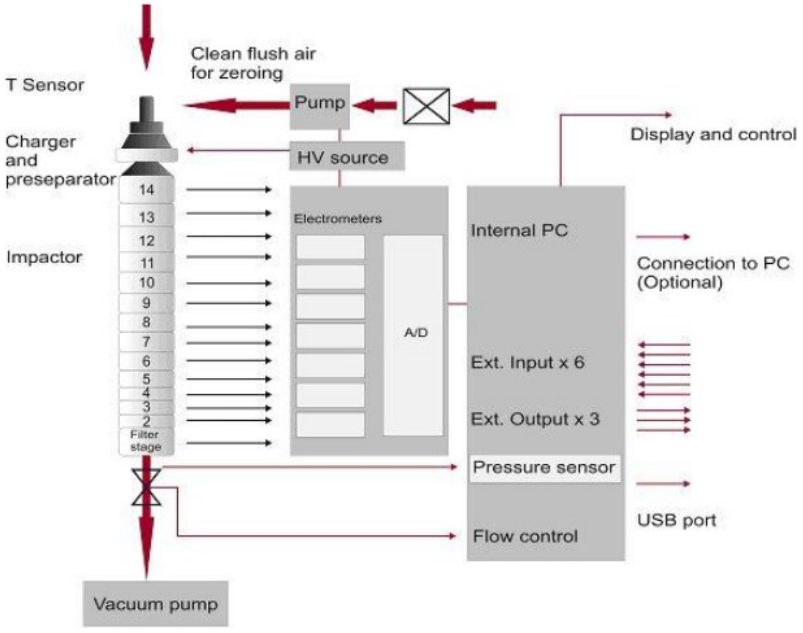


Fig. 3 Working principle of the ELPI+ instrument [14, 15].

3. Results and Discussions

Five combustion experiments (A, B, C, D and E) with different dilution ratios were conducted from a bottom feed modern pellet stove. Particle mass concentrations PM_1 and $PM_{2.5}$, number concretions and their particle size distributions were investigated by increasing dilution sampling. DR range between 32.1 to 53.8 was applied in the present study because the sample flow from the stack into the dilution tunnel was quite stable within this range. The particle emission results measured at the downstream of the ED were corrected by multiplying the corresponding dilution ratio (DR). Isokinetic sampling technique was not applied as the present work was emphasized on the very small particles, and results were limited to maximum $PM_{2.5}$. Summary of the PM_1, $PM_{2.5}$ and number concentration results obtained from the combustion experiments is presented in Table 2.

Table 2 Summary of the results obtained from the combustion experiments.

Combustion Experiments	DR	Number (particles/cm^3)	PM_1 (mg/Nm^3)	$PM_{2.5}$ (mg/Nm^3)
A	32.1±0.8	$1.51\times10^7\pm2.1\times10^6$	51.5±15.3	77.1±26.9
B	36.3±0.8	$1.43\times10^7\pm3.8\times10^6$	49.7±16.9	75.3±23.2
C	40.6±0.6	$1.61\times10^7\pm1.3\times10^6$	48.6±18.7	74.9±25.1
D	43.2±0.9	$1.44\times10^7\pm4.1\times10^6$	45.8±15.2	71.8±24.6
E	53.8±0.7	$1.32\times10^7\pm5.7\times10^6$	39.6±14.5	62.3±20.4

3.1. Particle number concentrations and number size distributions

The particle number emissions obtained from the combustion experiments are compared in Fig. 4. The error bars present the uncertainty of the measurements which is the square root of the sum of the square of the standard error of mean and the instrument's error. For all the experiments, particle number concentrations varied from 1.4 x 10^7 to 1.6 x 10^7 particles/cm^3. Experiment E had the lowest

concentration followed by the Experiments B, D, A and C. The results show that particle number concentrations decreased except the Experiment C with increasing the dilution ratio from 32.1 to 53.8.

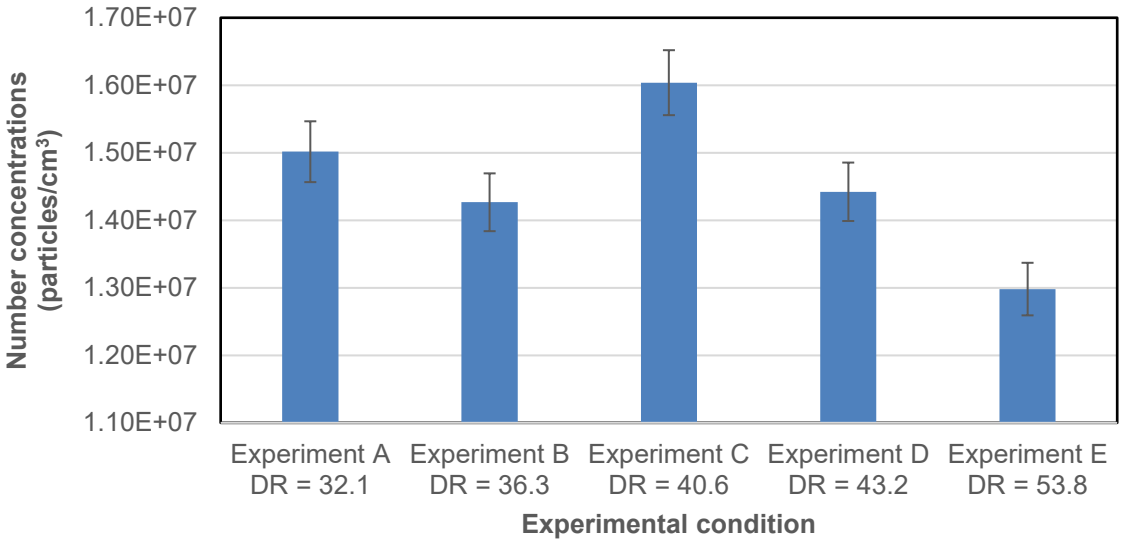


Fig. 4 Comparison of particle number concentration with variation of dilution sampling.

The particle number concentrations obtained in this study can be compared with other studies. For example, Sippula et al. [19] investigated the effect on particle number concentrations from a top feed pellet stove with a capacity of 8 kW in nominal load output using an ELPI. A dilution tunnel was used in the experiments and DR was set around 80. Their results show that particle number emissions varied from 1.3×10^7 to 4.4×10^7 particles/cm^3, which is higher the concentrations obtained in our measurements in the combustion phase at nominal heat output. In another study, Bari et al. [20] studied particle number emissions using an SMPS from a 5 kW pellet stove. Their results show that particle number concentrations varied between 1.5×10^7 to 5.4×10^7 particles/cm^3, which is also higher than the values obtained in our study. Particle number emissions obtained in our study were relatively lower comparing with other studies [19, 20] probably due to the different combustion technologies, heat output, fuel consumption, air fuel ratio, and instruments used in the PM measurements.

Fig. 5 presents the particle number size distributions obtained from all the experiments. It can be seen that all the experiments have particle size distributions with the maximum number concentration appearing at particle size of about 125 nm. These small size particles are the most important when considering the number size distributions, but it contributes only a very small fraction of the total mass of particles, which is discussed in the Section 3.2 below. In the figure, particles from 1 to 10 nm are not seen in the distribution graphs as the ELPI+ instrument has cut-off size of the fourteen stages from 6 nm to 10 µm. Particles between 1 and 10 µm are of very small quantity of number and are probably fly ash particles, therefore, these particles are not seen in the distribution graphs. It is observed from the figure that with increased dilution sampling, particle sizes are almost unchanged, but the number concentrations varied among the combustion experiments.

The number concentration of particles appearing in the distribution graphs are very smaller in size and these particles are probably soot particles, which are formed mainly inside the flame in the fuel rich area through complex mechanisms. Soot formation starts during devolatilization and combustion of volatiles when hydrocarbon fragments leave from the fuel particles. These fragments then crack into smaller pieces and react with one another and with the surrounding gases to form aromatic rings. These aromatic rings then start to form polycyclic aromatic hydrocarbon (PAH). Further growth of PAH leads to form soot. Generally, two pathways for the formation of soot nuclei can be discussed. First, at lower

temperatures, aromatic hydrocarbons produce soot directly by growing into graphite-like structure. Second, at higher temperatures, both aliphatic and aromatic hydrocarbons first fragment, which are then followed by polymerization of the fragments to larger molecules, forming soot. Thereafter, the particles grow larger by surface reactions, coagulation and agglomeration [1, 2, 21-24].

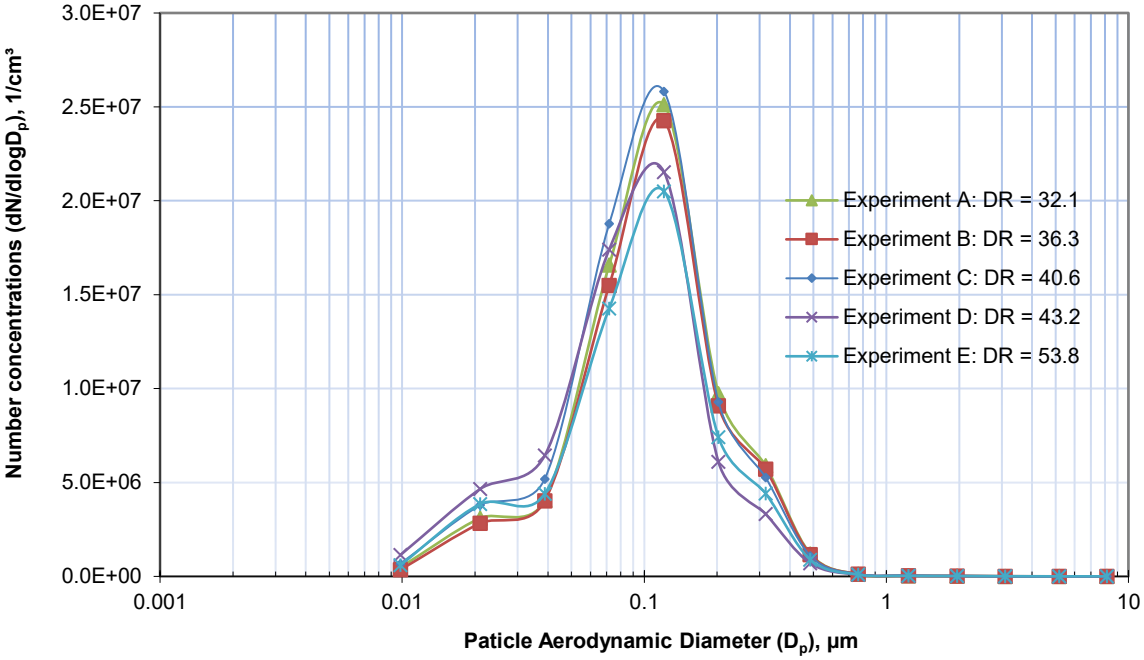


Fig. 5 Effect of dilution sampling on particle number size distributions.

3.2. Particle mass concentrations and mass size distributions

Fig. 6 presents the comparison of particle mass concentrations of PM_1 and $PM_{2.5}$ obtained from the combustion experiments. The error bars present the uncertainty of the measurements as explained before in Section 3.1. The PM_1 concentrations obtained from the measurements varied from 40 mg/Nm^3 to 51 mg/Nm^3, while 62 mg/Nm^3 to 77 mg/Nm^3 for the $PM_{2.5}$ concentrations. It can be observed from the experimental results that particle mass of both PM_1 and $PM_{2.5}$ concentrations decreases gradually with increasing the dilution ratio from 32.1 to 53.8. The results show higher dilution sampling gives the lower particle mass concentrations. This can be explained by the fact that dilution lowers the saturation ratio of the PM precursors, which results in less nucleation and accumulation processes and therefore in less PM concentrations [25].

Our results of the particle mass concentrations obtained from the dilution sampling can be compared with the undiluted mass concentrations. For example, Obaidullah et al. [4] conducted simultaneously two measurements for particle mass concentrations from the raw gas sample of the 5 kW pellet stove by a WÖHLER-Staubmessgerät SM 96 instrument using the DINplus sampling technique. For each measurement, particles were sampled for a period of 30 minutes to allow a flue gas volume of 270±27 litres. In the DINplus sampling device, the filter catches all the particles larger than 0.3 µm. Particle mass concentrations were obtained between 10 mg/Nm^3 and 15 mg/Nm^3 for the measurements. The filterable particles consist of inorganic, soot and organic particles. The inorganic particles are constituted of a large fraction of alkaline salts (K_2SO_4 and KCl), depending on the fuel composition and favourable combustion conditions, while soot and organic particles are also emitted as

solid particles if the combustion conditions are poor. In the DINplus sampling device, the filter catches all the particles larger than 0.3 µm. In the ELPI+ measurements, average $PM_{0.3}$ (diameter <0.3 µm) concentrations for the dilution sampling experiments (A, B, C, D and E) were found to be 42 mg/Nm^3 respectively. Therefore, the average particle mass concentrations in the ELPI+ measurements between 0.3 µm and 2.5 µm for those dilution sampling experiments are about 30 mg/Nm^3, which are much higher than the undiluted sampling measurements with the DINplus sampling technique. The different measurement techniques lead to different results.

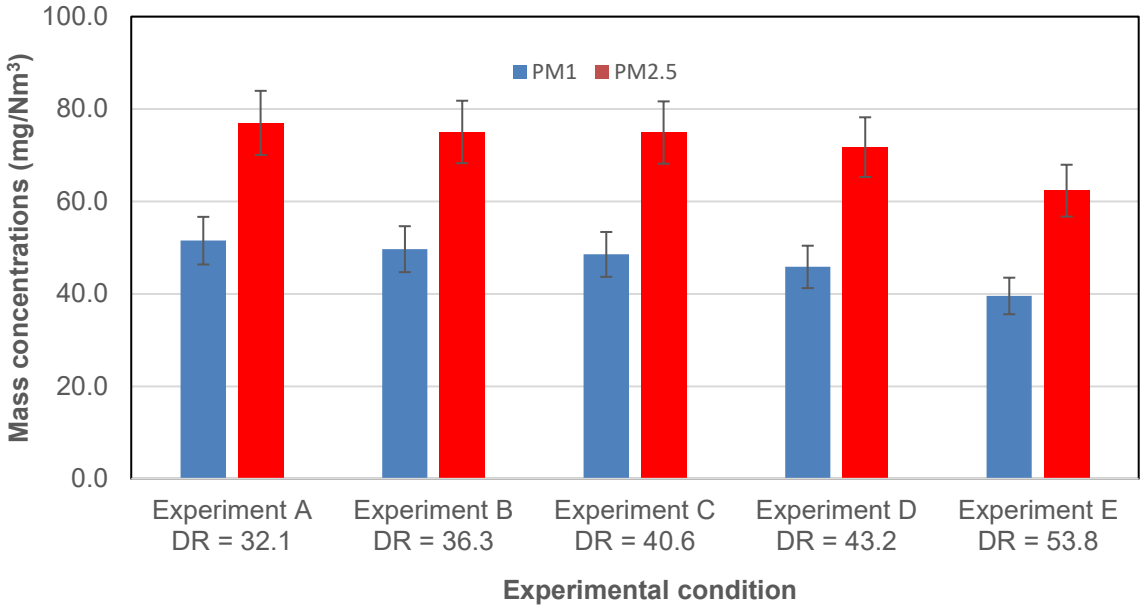


Fig. 6 Comparison of PM_1 and $PM_{2.5}$ concentrations with variation of dilution sampling.

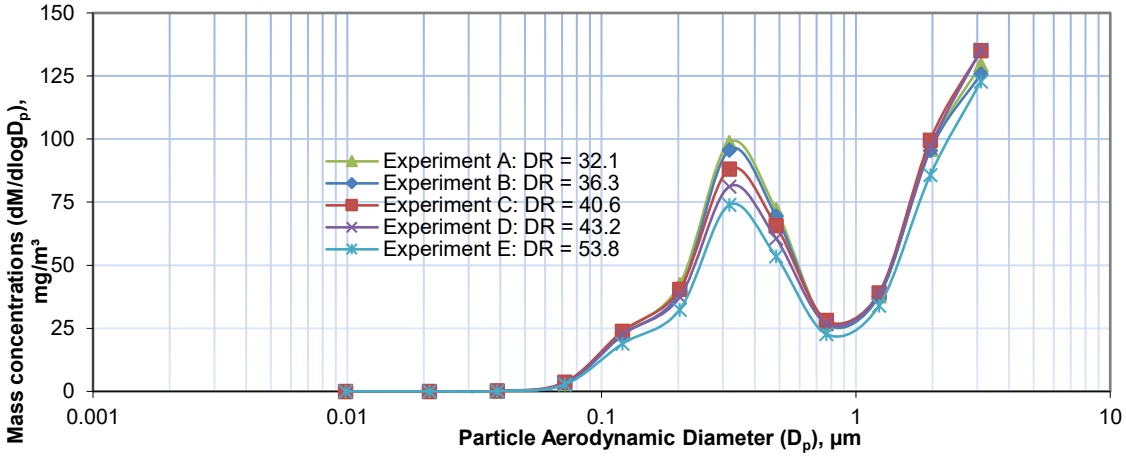


Fig. 7 Effect of dilution sampling on particle mass size distributions.

Fig. 7 shows particle mass size distributions obtained from all the experiments. The distribution graph shows that the combustion experiments have quite similar distribution shape. Particles between 10 to 100 nm represent a very small amount of mass, probably soot particles, therefore these particles are not seen in the mass size distribution graphs. Increasing dilution sampling, the particle sizes remain unchanged except the little variation of mass concentrations. Particle mass concentrations between 3 and 10 μm are not seen in the distribution graphs, as the PM measurements were not conducted with isokinetic sampling technique and therefore PM_{10} concentrations were not included.

It can be seen in the figure that the emitted particle mass size distributions showing the maximum concentration in the fine mode is at a particle size of around 330 nm. Particle mass size distributions obtained in our measurements are slightly higher than the results obtained in other studies.

For example, mass size distributions of 150 nm measured by a DLPI in a residential wood stove have been reported by Bäfver et al. [26]. These fine particles were generally formed easily from volatile inorganic species and heavy metal elements of the biomass fuel that have vaporized during combustion, and which later saturated and formed fine particles by nucleation. The nucleated particles grew further by coagulation, agglomeration, condensation and surface reactions. In the gas phase, these species underwent reactions resulting in the formation of alkaline metal sulphates, chlorides and carbonates as well as heavy metal oxides [1, 2, 19, 21, 27- 29].

Lipsky et al. [10] investigated the effect of dilution ratio on size distribution in a pilot scale pulverized coal combustor (150 kW) using an SMPS. The dilution tunnel was much bigger (sample flow: about 10-30 lpm, dilution air flow: about 350-1400 lpm) than that used in the present study. Their results showed that increasing dilution ratio of particle mass size distribution (from 15 to 75 and 150) shifted to smaller sizes.

In our measurements, the dilution sampler was smaller in size and residence time of the diluted sample was shorter with a difference of the maximum and minimum dilution ratios of about 20. Therefore, particle formation processes such as nucleation, condensation, accumulation, and coagulation probably occured less. Therefore, the effect of dilution sampling on particle emissions and size distributions in our investigation had less impact. DR range from 32.1 to 53.8 was applied in the present study because the sample flow from the stack into the dilution tunnel was quite stable within this range.

Particle formation and emissions depend on various aspects such as combustion conditions, combustion appliances, fuel properties, air fuel ratio, etc. Particularly, biomass fuels contain large amounts of ashes and these ashes contain different elements in varying concentrations. Various studies reported that increased particle emissions from the combustion appliances in ambient air conditions has adversed health effects on the exposed population. Effects include respiratory and cardiovascular illnesses as well as increased mortality [30-33]. In the case of combustion related particles it has been further, reported in the literature that, fine particle fraction is especially harmful to human health and the environment [34-37].

4. Conclusions

Investigations on the influence of dilution processes on fine particle emissions and size distributions were carried out from an automatically fired small scale modern bottom 5 kW feed pellet stove. Five experiments, using different dilution ratios, were conducted. Particle mass concentrations PM_1 and $PM_{2.5}$, number concretions and their particle size distributions were investigated. The following conclusions can be drawn from this study.

- The results show that variations of the dilution ratio have less impact on the total number concentrations and mass fractions of PM_1 and $PM_{2.5}$. It is observed that higher dilution ratios give slightly lower mass and number concentrations.
- Increasing dilution sampling particle number size distributions did not vary but maximum number concentration appeared at the particle size of about 125 nm.

- The particle mass size distribution graph shows that all the combustion experiments have quite similar distribution shape with increasing dilution sampling with the maximum mass concentration in the fine mode at the particle size of around 330 nm.
- In our measurements, the dilution sampler was smaller in size and residence time of the diluted sample was shorter with a difference of the maximum and minimum dilution ratios of about 20. Particle formation processes such as nucleation, condensation, accumulation, and coagulation probably occurred less. Therefore, the effect of dilution sampling on particle mass concentrations, number concentrations and number size distributions in our investigation were less observed.
- The results obtained from this study deliver new insight into the effect of dilution sampling on measurements of fine particle emissions, providing important data for the ongoing research on fine particle emission in defining standardized dilution sampling methodology for characterizing emissions from stationary combustion sources.

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