Measurements of Particle Emissions and Size Distributions from a Modern Residential Pellet Stove under Laboratory Conditions

M. Obaidullah*, S. Bram and J. De Ruyck

Abstract—This paper presents experimental results of particle emissions obtained from a modern bottom feed pellet stove of 5 kW output in nominal heat and 2.5 kW in part load output using a state of the art instrument Electrical Low Pressure Impactor Plus (ELPI+) with the fourteen stages from 6 nm to 10 μm. The combustion experiments were conducted in a stove manufacturing plant in the southern part of Belgium. Two experiments (A and B) in part load and four experiments (C, D, E and F) in nominal load output were conducted for the emissions measurements. The stove was operated in different fan speeds, which regulate air flow into the combustion chamber. The particle emission results include of mass concentrations of two size fractions PM_1 and $PM_{2.5}$, number concentrations and their particle size distributions evaluated in this paper. The experimental results show that the PM_1, $PM_{2.5}$ and particle number concentrations vary from one experiments to another due to the difference of fuel consumption, different fan speed settings of the screw, which regulate air flow into the combustion chamber. Particle mass size distributions analysis show that all the experiments have maximum particle concentrations in the fine mode mainly at the particle size about 320 nm for the startup and combustion phase and 300 nm for the burnout phase. Particle number size distributions analysis show that the peak particle concentration was observed for all the experiments between 25 nm to 70 nm for startup phase, 70 nm to 100 nm for the combustion phase and 20 nm to 80 nm for the burnout phase.

***Keywords*—**particulate matter, residential pellet combustion, mass concentration, number concentration, size distributions.

I. Introduction

Biomass energy is a sustainable source of heat generation and could reduce the production of greenhouse gasses into the atmosphere and decrease the dependence on the usage of fossil fuels. Biomass sources is one of the main renewable energy for small scale and residential heating purposes in Europe [1]. Small scale and residential combustion sources including wood and solid mineral fuel heating appliances produce a significant contribution to emissions of several pollutants in Europe especially particulate matter (PM) [2], which is a dynamic mixture of particles in the flue gas released directly from the combustion appliances. The PM exists in different sizes and can be grouped accordingly into PM_1, $PM_{2.5}$ and PM_{10}. The particles have an aerodynamic diameter smaller than 1 μm, 2.5 μm, and 10 μm respectively.

Biomass combustion is one of the major contributors of fine particles to the atmosphere during winter times over large parts of Europe and small-scale combustion systems in particular play an important role [3-6]. Concerning PM emissions, epidemiological and experimental studies evidence a correlation between biomass combustion particles and health impacts like decreased lung function, reduced resistance to infections and increased incidences of acute asthma [7, 8]. Exposure to biomass smoke could also induce cardiovascular effects [7, 8].

Wood pellets in particular have become an important wood fuel source in recent years. They are mainly used for domestic heat production in Europe. Using wood pellets as biomass fuel is gradually increasing due to their high energy density, easy transportability and the lower amount of 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. For example, Johansson et al. [9] reported 180 times higher particle mass emissions observed for an old boiler compared to a modern appliance using wood pellets.

Sippula et al. [10] investigated the effect of wood pellet combustion on the particle emissions from a top feed pellet stove with a heat output of 8 kW using an ELPI. Their results show that particle number emissions varied from 1.3×10^7 particles/cm^3 to 4.4×10^7 particles/cm^3 and the particle mass (PM_1) varied from 69 mg/Nm^3 to 343 mg/Nm^3. Gaegauf et al. [11] investigated particle emissions by using an SMPS on a pellet boiler with a capacity of 17 kW. They observed that the major part of the particle emissions were in the range between 30 nm to 300 nm.

Bari et al. [12] studied particle mass and number emissions from a pellet stove with a nominal output of 5 kW. The measurements were conducted from the stack using a BLPI

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and an SMPS for mass concentrations and number size distributions respectively. The results show that the particle mass concentrations were between 31 mg/Nm^3 to 201 mg/Nm^3, while number concentrations varied between 1.5×10^7 particles/cm^3 to 5.4×10^7 particles/cm^3. They observed that the particle mass size distribution was unimodal with a maximum concentrations in the fine fraction.

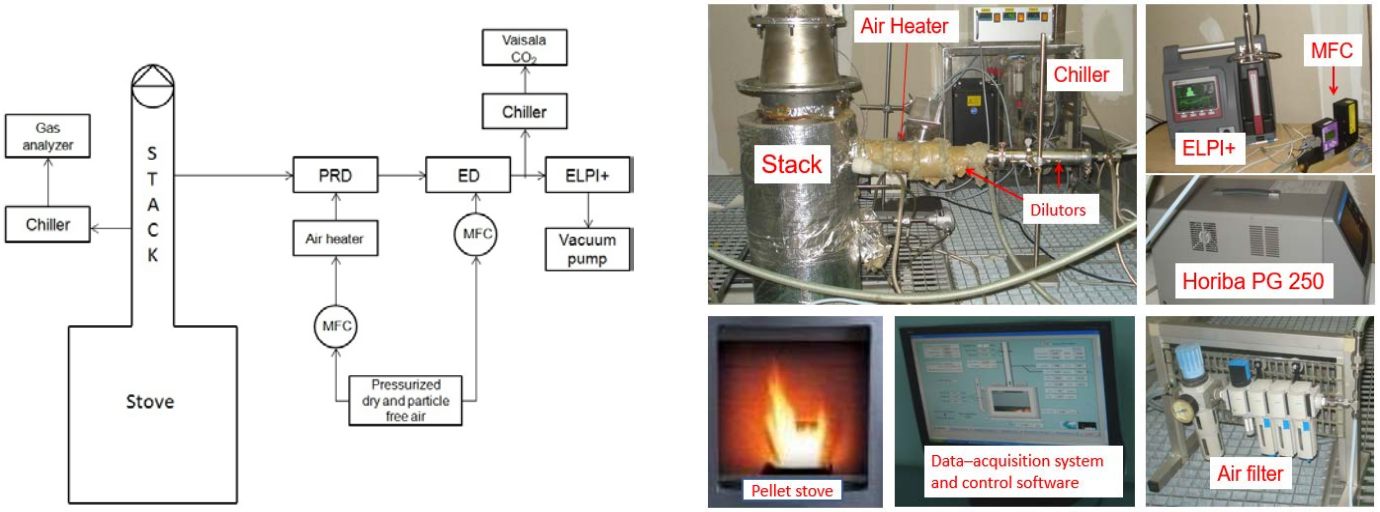
Several studies have been conducted to investigate the PM emissions from the small scale heating appliances at nominal load operations [10, 13-15]. Particle emissions from residential heating devices are documented mainly for stationary operation, however a considerable part of unburnt fuels are emitted during the startup and burnout phases. PM Emission characteristics at each phase of pellet stove operations are therefore important to be able to reduce the annual emissions from residential pellet combustion. The aim of this study was to investigate particle emissions from a modern bottom feed pellet stove operated with nominal load (5 kW) and part load (2.5 kW) output. The particle emission measurements include mass concentrations of two size fractions of PM_1, $PM_{2.5}$, number concentrations and their particle size distributions measured continuously using a partial flow dilution tunnel together with 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. The combustion experiments were conducted in a laboratory of stove manufacturing plant in Namur, Belgium.

II. Materials and Methods

This section briefly highlights the experimental setup, fuel characteristics, combustion appliance and instruments used in the particle emission measurements.

A. Experimental Setup

The particle emissions measurements were conducted according to the European standard EN 14785 for residential space heating appliances fired by wood pellets [16]. The schematic of the experimental setup for the emission measurements is shown in Figure 1.



(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

Two experiments (A and B) in part load and four experiments (C, D, E and F) in nominal load output were conducted for the emissions measurements from a modern bottom feed pellet stove. The stove was operated in different fan speeds, which regulate air flow into the combustion chamber. Experiments A and B were operated with low speed fan at 900 rpm, C and D with medium speed fan at 1250 rpm, E and F with high speed fan at 1400 rpm. The fan speed settings of each experiment are presented in Table 1. The wood 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 1.6 sec/6 sec for the part load measurements, while 3.2 sec/6 sec for the nominal load experiments. Screw-2 connected to the burner cup was operated at 2 rpm for all the experiments. The heat output of the stove was modified by controlling the rotation of screw-1, which controls the fuel supply.

The particle missions from each combustion experiments were evaluated at three combustion phases: startup, combustion and burnout phase. The startup phase is the time period commencing after the ignition and lasts until the emission concentrations reaches the same level as in stationary operation. This phase usually takes about 20-25 minutes to complete. The combustion phase is next to the startup, when the combustion is stable. This phase usually operates several hours. The burnout phase starts with an abrupt rise of CO emissions followed by a slow decrease and continues until the

combustion is completed. This phase takes about 30-50 minutes to complete.

Table 1. Fan speed settings for the different experiments

Experiments	Stove load	Fan speed (rpm)
A	Part Load	Low, 900
B	Part load	Low, 900
C	Nominal load	Medium, 1250
D	Nominal Load	Medium, 1250
E	Nominal load	High, 1400
F	Nominal Load	High, 1400

The burnout phase was started in this study, after 4-5 hrs stable operation of the main combustion phase. Firstly, the rotation of screw-1 was stopped to discontinue fuel supply from the pellet storage hopper and to avoid back combustion. Then, fuels remaining in the tube of screw-2 were transported to the burner cup. Finally, screw-2 was stopped, after finishing the combustion of those fuels. Operation of both screws was performed through an electronic control unit.

B. Fuel Characteristics

The elemental composition, moisture content and lower heating value (LHV), physical properties of the commercial pellets used in the combustion experiments are presented in Table 2. The pellets are made from soft wood, certified by DINPlus standard and available in the European market.

Table 2. Chemical properties of the pellet used in the combustion experiments

Parameter	Commercial pellets	DINplus
C (wt %)	49.1	-
H (wt %)	5.8	-
O (wt %)	44.8	-
Moisture (%)	8.6	10
Ash (wt %)	0.3	0.7
LHV (MJ/kg)	18.7	> 16.9
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

C. 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 was setup on a balance to monitor the fuel consumption. The pellet stove is equipped with an internal pellet storage, where the pellets are supplied through two screws into the burner cup. 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 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, removing 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. Before starting each combustion experiment, the grid was cleaned.

D. Particle Emission Measurements

A partial flow from the stack at about 2 m height from the pellet stove was withdrawn through an externally insulated bent tube steel probe of 12 mm dia. 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. 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. This current is proportional to particle numbers via mathematical algorithms [17]. Aluminum foils, greased with a mixture of acetone and Apiezon-L were placed on each of the impactor stages to prevent particle bouncing effects. 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 dilution tunnel consists of a porous tube diluter (PRD), an ejector diluter (ED) and an air heater. The first stage dilution air injected (17.5 lpm) into the PRD was heated to match the raw sample temperature to reduce the risk of condensation. The second stage dilution air injected (49 lpm) into the ED, which was operated at ambient temperature to further dilute the sample and to reduce the sample temperature to the ambient condition. Dilution air is taken from outside the building to simulate the field conditions.

The CO_2 and O_2 concentration from the undiluted flue gas were analyzed continuously by a Horiba PG250 gas analyzer. CO_2 concentration was also measured continuously from the diluted sample by a Vaisala Carbocap analyzer to calculate the dilution ratio (DR). The details of the DR measurement were presented other works [5, 6, 18, 19]. 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.

E. Representative Total Average Emissions Overtime

The total PM emissions depend on the relative duration of startup, combustion and burnout phases, where a combustion phase usually takes several hours. If the combustion phase is longer, the PM emission is smaller and vise versa. Since these

times for each phase are not identical in all the experiments, the representative average will be based on typical times. Representative times are set for three phases to 20, 240 and 30 minutes respectively. The representative total average particle mass and number concentrations over time for a complete combustion cycle are calculated by the following formula [20].

$$Total\ emissions = \frac{t_{SP}}{t_{TC}} \cdot E_{SP} + \frac{t_{CP}}{t_{TC}} \cdot E_{CP} + \frac{t_{BP}}{t_{TC}} \cdot E_{BP} \quad (1)$$

where:

t_{SP} is the duration of the startup phase
t_{CP} is the duration of the combustion phase
t_{BP} is the duration of the burnout phase
t_{TC} is the duration of the total cycle
E_{SP} is the emissions from the startup phase
E_{CP} is the emissions from the combustion phase
E_{BP} is the emissions from the burnout phase

F. Standard Uncertainty Analysis

The standard uncertainties were calculated from the mean values of each measurement taken over a period of time. Uncertainty for each relevant component to the experiments was calculated using the formulas as follows [21-23].

$$\text{Uncertainty} = \sqrt{(\text{Instrumental error})^2 + \sigma_M{}^2} \quad (2)$$

$$\sigma_M = \frac{2*\sigma}{\sqrt{N}} \quad (3)$$

$$\sigma = \sqrt{\frac{\Sigma (x-\bar{x})^2}{(N-1)}} \quad (4)$$

where:

σ_M is the standard error of mean
σ is the standard deviation of the repeated measurements
N is the total number of measurements taken
x is the measurement value under consideration.
$\bar{x}$ is the average of all the measurement values

III. Results and Discussions

A total of six combustion experiments on particle emissions from a modern bottom feed pellet stove were conducted. Experiments A and B were conducted with part load heat output of 2.5 kW, while four experiments C, D, E and F were in the nominal load output at 5 kW. The objectives of this study were to evaluate the particle emissions from different combustion phases of each experiment.

Table 3. Particle number and mass concentrations measured by an ELPI+ from a bottom feed pellet stove

Experiments	Phase	PM_1 (mg/Nm^3)	$PM_{2.5}$ (mg/Nm^3)	Number concentrations (particles/cm^3)	DR	O_2 conc. in flue gas (vol. %)	Excess air (λ)	Duration (hr:min)
A	SP	38.4±12.4	57.8±20.3	$1.9\times10^7\pm2.3\times10^6$	30.7±1.1	19.7±0.2	16.9	0:20
	CP	20.4±6.8	34.4±11.3	$9.5\times10^6\pm1.8\times10^6$	41.5±1.2	16.5±0.2	4.7	4:15
	BP	9.3±1.8	17.4±3.8	$8.2\times10^6\pm8.9\times10^5$	33±1.0	19.3±0.1	12.7	0:29
	Total	20.5±6.6	34.2±11.1	$1.0\times10^7\pm1.7\times10^6$	42.2±1.1	16.8±0.2	5.18	5:34
B	SP	26.1±5.3	45.3±10.2	$2.9\times10^7\pm8.9\times10^6$	31.5±3.5	19.2±0.2	12.1	0:20
	CP	29.8±14.6	48.0±21.3	$1.2\times10^7\pm3.1\times10^6$	37±2.7	15.8±0.3	4.2	5:35
	BP	10.2±2.3	17.9±4.9	$8.0\times10^6\pm7.8\times10^5$	32±1.4	19.5±0.2	14.5	0:29
	Total	27.6±12.7	44.7±18.8	$1.3\times10^7\pm3.3\times10^6$	36.3±2.6	16.0±0.3	4.2	6:24
C	SP	22.2±2.5	61.5±11.4	$4.6\times10^7\pm4.1\times10^6$	25.8±1.6	19.7±0.2	16.9	0:19
	CP	215.2±57.8	331.9±97.8	$8.4\times10^7\pm1.2\times10^7$	34.9±2.5	13.2±0.6	2.7	4:30
	BP	4.7±1.1	10.3±2.1	$3.4\times10^6\pm4.2\times10^5$	25.9±1.5	19.8±0.2	18.7	0:30
	Total	180.1±48.1	279.9±81.9	$7.4\times10^7\pm9.9\times10^6$	33.7±2.3	14.1±0.4	3.1	5:19
D	SP	92.7±4.7	136.9±10.1	$2.9\times10^7\pm4.5\times10^6$	37.7±4.4	18.6±0.4	9.1	0:20
	CP	276.1±50.9	435.9±94.4	$8.8\times10^7\pm1.1\times10^7$	39.5±4.3	13.8±0.5	2.9	3:50
	BP	12.0±1.5	26.3±4.2	$7.3\times10^6\pm2.0\times10^6$	32.3±2.2	20.1±0.1	24.0	0:28
	Total	236.1±42.6	372.9±79.2	$7.6\times10^7\pm9.6\times10^6$	38.3±3.8	14.9±0.4	3.5	4:38
E	SP	70.4±2.1	79.2±14.7	$7.2\times10^7\pm7.1\times10^6$	23.6±1.8	17.7±0.5	6.5	0:18
	CP	75.7±46.8	109.1±63.8	$2.4\times10^7\pm1.0\times10^7$	37.4±1.2	11.0±1.0	2.1	5:45
	BP	4.7±2.2	25±7.1	$8.1\times10^6\pm1.0\times10^6$	26.4±1.3	18.4±0.6	8.5	0:50
	Total	68.1±39.3	98.3±54.5	$2.6\times10^7\pm3.0\times10^6$	36.2±1.4	12.1±0.7	2.4	6:53
F	SP	105.6±26.1	137.8±34.1	$2.3\times10^7\pm3.0\times10^6$	22.7±2.3	17.9±0.3	6.9	0:17
	CP	43.3±20.1	66±28.5	$1.4\times10^7\pm3.2\times10^6$	33±1.3	11.4±0.7	2.2	4:40
	BP	7.6±1.7	14.6±4.2	$8.1\times10^6\pm1.0\times10^6$	23.4±2.1	18.7±0.7	9.4	0:52
	Total	43.8±18.6	65.7±26.3	$1.4\times10^7\pm1.8\times10^6$	32.1±1.8	12.6±0.6	2.5	5:49

SP = startup phase, CP = combustion phase, BP = burnout phase, DR = dilution ratio, Total mass and number concentrations were calculated based on equation 1.

Particle measurements in this study were sampled using an ELPI+ from a partial flow dilution tunnel, where sample flow extracted from the stack was diluted with filtered air. Particle mass concentrations of two fractions PM_1, $PM_{2.5}$, particle number concentrations measured from three phases and the complete combustion cycle are presented in Table 3.

The particle emission results for each experiment measured from the partial flow dilution tunnel were corrected by multiplying the corresponding dilution ratio (DR). The flue gas velocities in the stack and the nozzle were 0.45 m/s and 0.29 m/s respectively. This means that our PM measurements are under-isokinetic sampling and therefore PM_{10} fractions are not included.

The air excess (λ) obtained from all the combustion experiments in the combustion phase of the nominal load output experiments C, D, E, and F varied between 2.1 to 2.9, which is much lower than in the part load combustion experiments A and B. Since the combustion process varies over time, the presented standard deviation (±) also describes the variation of the process. The DR values were found quite stable during the measurements.

A. Particle Mass Concentrations

Time series of particle mass concentrations obtained from Experiment C at the nominal load output are presented in Figure 2. The vertical black dash lines indicate the time for ash removal by increasing air supply for about every 30 minutes interval. It can be seen from the figure how particle mass concentrations fluctuate over time during the different combustion phases. The particle mass concentrations in the main combustion phase experienced stronger fluctuations than in the other two phases.

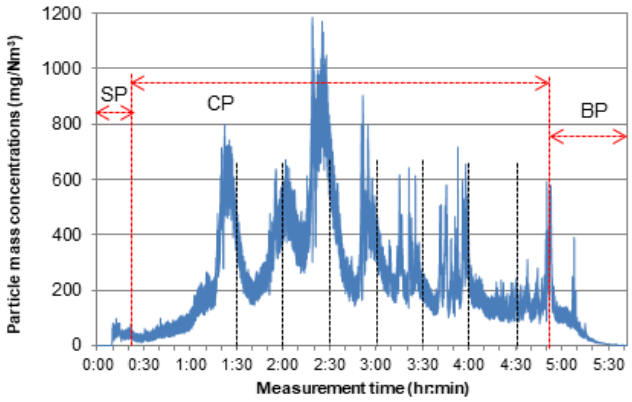


Fig. 2: Time series of particle mass, $PM_{2.5}$ concentrations obtained from combustion Experiment C, SP = startup phase, CP = combustion phase, BP = burnout phase.

Figures 3 and 4 present the comparison of particle mass concentrations of PM_1 and $PM_{2.5}$ obtained from the three startup, combustion, burnout phase and total cycle of all the combustion experiments. The error bars present the uncertainty of the measurements according to equation 2.

Figure 3 shows PM_1 concentrations obtained from the startup phase of the part load heat output Experiments A to B varied from 26.1 mg/Nm^3 to 38.4 mg/Nm^3 for the startup phase, 20.4 mg/Nm^3 to 29.8 mg/Nm^3 for the combustion phase, 9.3 mg/Nm^3 to 10.2 mg/Nm^3 for the burnout phase and 20.5 mg/Nm^3 to 27.6 mg/Nm^3 for the total cycle, while in the nominal load heat output Experiments C to D varied from 22 mg/Nm^3 to 106 mg/Nm^3 for the startup phase, 43.3 mg/Nm^3 to 276 mg/Nm^3 for the combustion phase, 4.7 mg/Nm^3 to 12 mg/Nm^3 for the burnout phase and 44 mg/Nm^3 to 236 mg/Nm^3 for the total cycle.

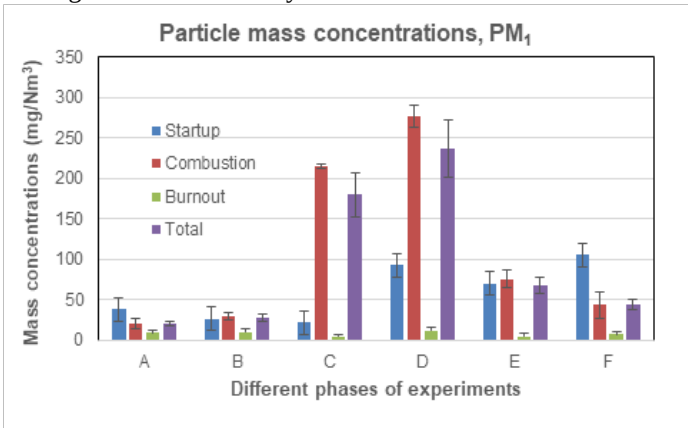


Fig. 3: Comparison of PM_1 concentrations obtained from all the combustion experiments

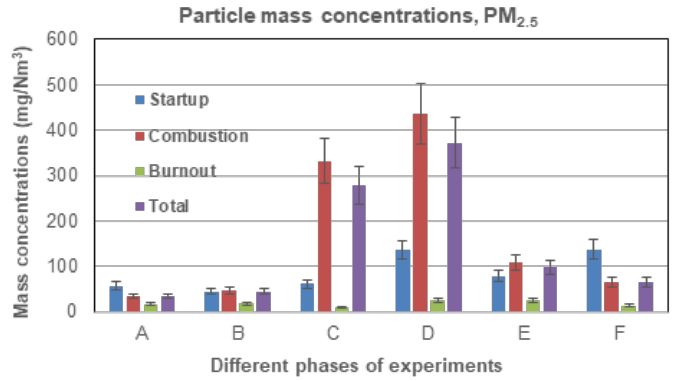


Fig. 4: Comparison of $PM_{2.5}$ concentrations obtained from all the combustion experiments

The PM_1 results obtained from the combustion phase in nominal load output of Experiments C and D are significantly higher than those from the other experiments. In the part load heat output measurements, the startup phase of Experiment A gave the highest PM_1 emissions. The variation of particle mass concentrations among all the experiments is due to the configuration of the burner operated with the different fan speeds.

The particle emissions reported by Sippula et al. [10], Johansson et al. [9] were also measured in a partial flow dilution tunnel. It should be mentioned that some conditions in the sampling line such as the dilution ratio, temperature and the measurement equipments were different. Therefore, it is difficult to formulate a direct comparison of the particle emissions results. Our particle mass concentration results for the PM_1 fraction obtained from the combustion phase in nominal load heat output can be compared with results from another study. For example, Sippula et al. [10] investigated

particle mass emissions from a top feed pellet stove with a heat capacity of 8 kW using filter samples. Average mass concentrations of PM_1 in their study varied between 69 mg/Nm^3 and 343 mg/Nm^3 which are slightly higher values than in our study.

Figure 4 shows the comparison of $PM_{2.5}$ concentrations obtained from different experiments at nominal load and part load heat output. In part load experiments, $PM_{2.5}$ concentrations varied from 45.3 mg/Nm^3 to 57.8 mg/Nm^3 for the startup phase, 34.4 mg/Nm^3 to 48 mg/Nm^3 for the combustion phase, 17 mg/Nm^3 to 18 mg/Nm^3 for the burnout phase and 34.2 mg/Nm^3 to 45 mg/Nm^3 for the total cycle, while in the nominal load experiments, varied from 61.5 mg/Nm^3 to 138 mg/Nm^3 for the startup phase, 66 mg/Nm^3 to 436 mg/Nm^3 for the combustion phase, 10.3 mg/Nm^3 to 26.3 mg/Nm^3 for the burnout phase and 65.7 mg/Nm^3 to 373 mg/Nm^3 for the total cycle.

It is observed that the particle mass fractions of PM_1 and $PM_{2.5}$ concentrations from the experiments operated with medium fan speed are about 4-folds higher than the high speed fan experiments. This might be due to the lower air excess factor λ=2.8 for the medium speed fan experiments, while λ=2.4 for the high speed fan experiments, which gives higher combustion temperature and creates favorable combustion condition.

In nominal load experiments C, D and E, particle mass fractions of PM_1 and $PM_{2.5}$ obtained from the combustion phase is significantly higher than in the other two phases of startup and burnout. The PM_1 and $PM_{2.5}$ concentration levels can also vary from one experiment to another which are typical for the biomass combustion. The PM_1 concentrations of all the nominal load experiments accounted for 61 %, 68 % and 50 % of the $PM_{2.5}$ concentrations for the startup, combustion and burnout phase respectively, while 62 %, 61 % and 55 % for the part load experiments, which are lower than the values found in literature [24]. These analysis from both nominal and part load het output experiments clearly shows that more that 50% of particle mass concentrations is the fine fractions of PM_1.

It is reported in the literature that the fine particle mass fractions (PM_1 and $PM_{2.5}$) are generally formed from easily volatile inorganic species (K, S, Na and Cl) and heavy metal elements (Zn and Pb) that have vaporized during combustion, which later saturate and form fine particles by nucleation. The nucleated particles grow further by coagulation, agglomeration, condensation and surface reactions. In the gas phase, these species undergo reactions resulting in the formation of alkaline metal sulphates, chlorides and carbonates as well as heavy metal oxides. Organic species represent the fraction of fine particle emissions. These particles are mainly due to incomplete combustion and to the condensation of the unburned hydrocarbon during the cooling phase of the flue gas [4, 10, 25-27].

B. Particle Mass Size Distributions

Figures 5 to 7 present the particle mass size distribution graphs obtained from the startup, combustion and burnout phases of all the experiments respectively. The abscissa represents the particle aerodynamic diameter against the ordinate which shows the ratio of particle mass concentration *dM* to the logarithm of the channel width *d*log*(Dp)*, where *Dp* is the aerodynamic diameter.

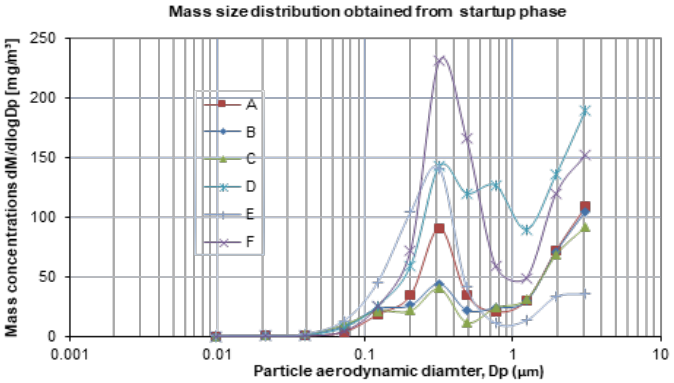


Fig. 5: Particle mass size distributions obtained from the startup phase of all the experiments

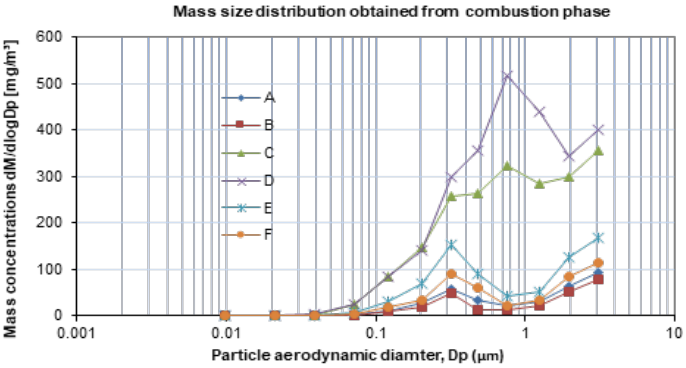


Fig. 6: Particle mass size distributions obtained from the combustion phase of all the experiments

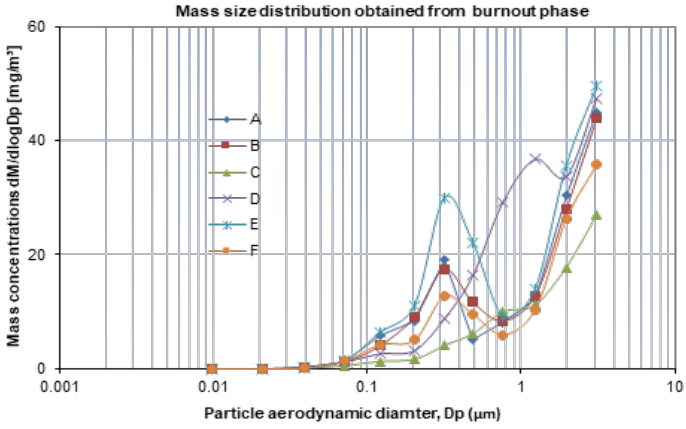


Fig. 7: Particle mass size distributions obtained from the burnout phase of all the experiments

Figure 5 shows that maximum particle concentrations obtained for all the experiments in the fine mode are at the particle size of 320 nm. Particle size between 10 nm and 80 nm contains very small amounts of mass and are probably soot particles, therefore these particles are not seen in the mass size distribution graphs. Figure 6 shows that Experiments A, B, E and F had quite similar mass size distributions, with

maximum particle concentrations in the fine mode at the particle size of 320 nm, while Experiments C and D had the peak particle emissions at the particle size of 750 nm

In Figure 6, it can be seen that particle mass size distributions of all the experiments (except Experiments C and D) from the burnout phase are quite similar with a maximum particle concentration at the particle size of 320 nm. The mass size distributions graphs showed that all the experiments had a fraction of particles appearing in the coarse mode.

C. Particle Number Concentrations

The particle number emission is one of the most important issues related to small scale biomass combustion systems. Because, the particle number concentrations affect the air quality more than the particle mass concentrations. Figure 8 shows the typical time series of the particle number concentrations obtained from Experiment C during nominal load output. It can be seen from the figure how particle number concentrations fluctuate during the different combustion phases.

Figure 9 shows the comparison of particle number concentrations obtained from the startup, combustion, burnout and total cycle of all the experiments. Particle number concentrations obtained from the part load Experiments A and B varied from 9.5×10^6 to 1.2×10^7 particles/cm^3 for the main combustion phase and 1.0×10^7 to 1.3×10^7 particles/cm^3 for the total cycle, while in the nominal load heat output Experiments C, D, E and F varied from 1.4×10^7 to 8.8×10^7 particles/cm^3 for the combustion phase and 1.4×10^7 to 7.6×10^7 particles/cm^3 for the total cycle. Particle number emissions from the startup and burnout phase has the less impact on the total particle number emissions.

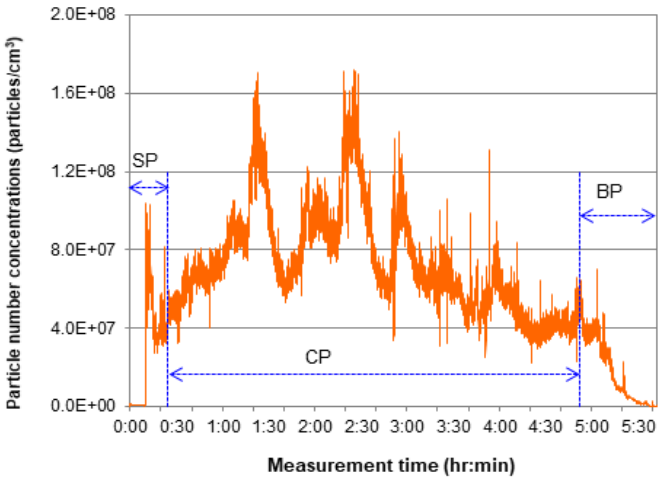


Fig. 8: Time series of particle number concentrations obtained from Experiment C during nominal load output, SP = startup phase, CP = combustion phase, BP = burnout phase

The duration of the main combustion phase varied from 3hr 50 min to 5 hr 45 min for all the measurements. In the nominal load output for the combustion Experiments C and D of the pellet stove, it can be seen from Figure 9 that the combustion phase had the highest particle number concentrations, followed by the startup phase and the burnout phase, while for the combustion Experiments E and F and Part load Experiments A and B, the highest particle number concentrations occurred in startup phase followed by the combustion phase and the burnout phase. This is because the configuration of the burner operated with the different fan speed used in the experiments.

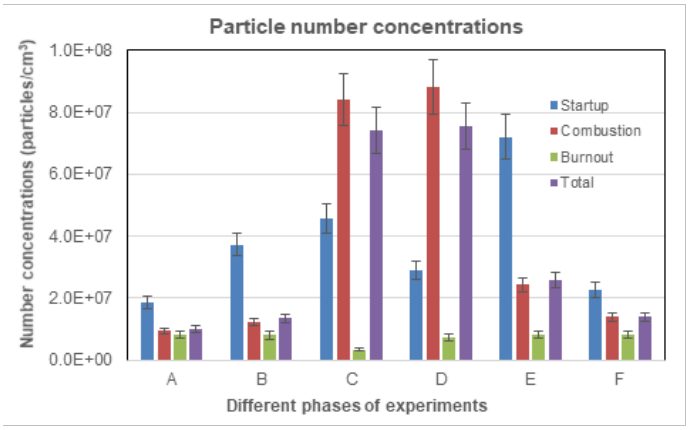


Fig. 9: Comparison of particle number concentrations

Experiments operated with nominal load heat output, much lower particle number emissions obtained from the stove operated with high speed fan Experiments E and F than the medium speed fan Experiments C and D. This could be explained lower air excess factor λ=2.8 for the medium speed fan experiments, while λ=2.4 for the high speed fan experiments. Besides, the average flue gas temperature was 85^{o}C for the medium speed experiments and 101 ^{o}C for the high speed fan experiments. The number concentrations from the main combustion of the part load experiments is much lower than nominal load experiments. This may be due to the difference of fuel consumption, fan speed of the screw, which regulate air flow into the combustion chamber and heat output. The average fuel consumption for part load experiments is about one-half lower than the nominal load experiments, which might impact on particle emissions.

The particle number concentrations obtained in this study can be compared with other studies. For example, Sippula et al. [10] 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. Their results show that particle number emissions varied from 1.3×10^7 to 4.4×10^7 particles/cm^3, which is a little lower than the values obtained in our measurements in the combustion phase at nominal heat output. In another study, Bari et al. [12] studied particle number concentrations using an SMPS with a 5 kW pellet. Their results show that particle number concentrations varied between 1.5×10^7 to 5.4×10^7 particles/cm^3, which is also little lower than the values obtained in our study. Since the fine particles are believed to be more harmful, more attention should be given to fine particle regulation. The EU standards describe the particle emissions in terms of mass concentration [28, 29], however, current research demonstrates that particle number emissions and particle size distributions are very important when considering particle impacts on air quality,

climate, environment and human health [2, 7]. The emissions of particle concentration are strongly dependent on combustion conditions, fuel properties, combustion appliances, excess air, heat output of the combustion technology, etc. Small scale biomass combustion is generally considered as an important source of fine particles due to the lack of cleaning systems.

D. Number Size Distributions

Typical particle number size distributions obtained from the startup, combustion and burnout phases of all the combustion experiments are presented in Figures 10 to 12.

Figure 10 shows that the peak in particle number concentrations was observed at the particle size between 25 nm to 70 nm for the startup phases of all the combustion experiments. A uni-modal peak can be seen in the Experiments C and D, while bimodal size distributions were appeared in the other combustion experiments.

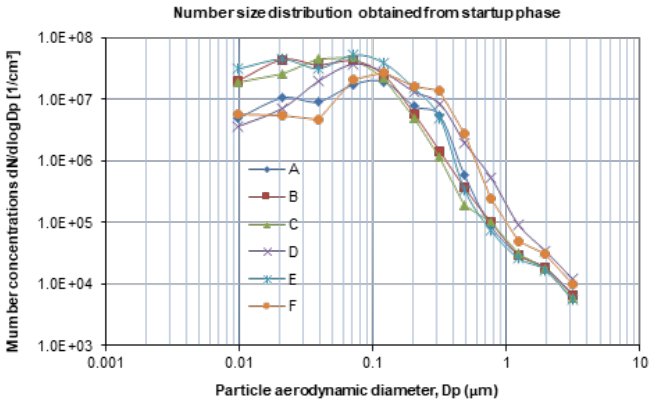


Fig. 10: Particle number size from distributions obtained from the startup phase of all the experiments

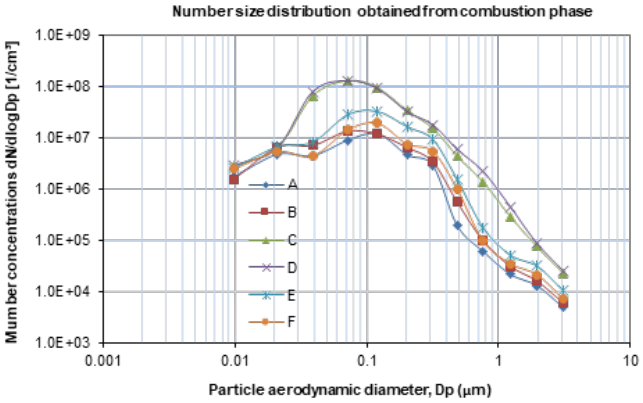


Fig. 11: Particle number size from distributions obtained from the combustion phase of all the experiments

Similar particle number size distributions were observed in other studies. For example, Bari et al. [12] investigated particle number size distributions from a pellet stove of 5 kW nominal output using an SMPS. Their results show that the maximum number particle concentrations were found at the particle size within the diameter range of 55 nm to 90 nm. Boman et al. [30] investigated particle number size distributions from a pellet stove of capacity 5 kW using an SMPS and their results show that maximum particle at the particle size was about 70 nm to 80 nm.

Figure 11 presents the particle number size distributions graphs for the combustion phase and it can be seen that the emitted particles for all the experiments were very similar with the startup phase and peak particle number concentrations were at the particle size around 70 nm to 100 nm. In contrast to the startup phase, the maximum particle concentrations shifted to larger particle sizes. The measured particle number concentrations for combustion Experiments C and D were significantly higher operated with medium fan speed than that high speed fan experiments followed by the low speed fan experiments.

Figure 12 presents the particle number size distributions for the burnout phase, where the maximum particle number concentrations were observed between 20 nm to 80 nm. The combustion Experiments C and D had uni-modal size distributions, while the remaining experiments had bi-modal size distributions. The fine particles (<1 µm) are formed from the easily volatile inorganic elements, released from the biomass fuels to the gas phase during combustion. Potassium, sulphur and chlorine are the most relevant element during the combustion of biomass fuels. These small size particles are considered very harmful for human health as they penetrate lower the alveolar region of the lung. Particles with diameter below 100 nm are the most important when considering the number distributions, but it contributes on only a very small fraction of the total mass. Fine particles originated from small scale biomass combustion mainly consist of ash, elemental carbon and organic material [25, 31]. Particle emissions are dominated by ash particles when the combustion quality is good, for example as in pellet combustion.

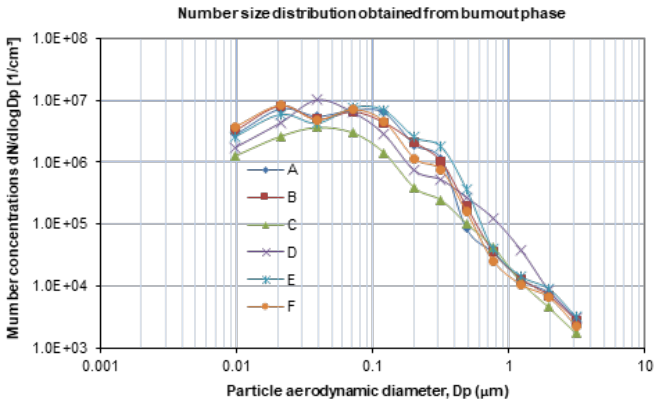


Fig. 12: Particle number size distributions obtained from burnout phase of all the experiments

V.CONCLUSIONS

A total of six combustion experiments on gaseous and particle emissions from a modern bottom feed pellet stove were conducted at the combustion laboratory of stove manufacturing plant. Experiments A and B were conducted with part load heat output of 2.5 kW, while four experiments C, D, E and F were in the nominal load output at 5 kW. Following conclusions can be drawn from this review.

- For the nominal load experiments, the particle mass fractions of PM_1 and $PM_{2.5}$ obtained from the combustion phase are significantly higher than those in the other two phases (startup and burnout phase). But, in the part load experiments, PM_1 emissions in the startup phase were relative higher than in the other phases.
- Particle mass size distributions analysis showed that all the experiments have maximum particle concentrations in the fine mode mainly at the particle size about 320 nm for the startup and combustion phase and at 300 nm for the burnout phase.
- Experiments operated with nominal load heat output, much lower particle number emissions obtained from the stove operated with high speed fan Experiments E and F than the medium speed fan Experiments C and D. The number concentrations from the main combustion of the part load experiments is much lower than nominal load experiments. This may be due to the difference of fuel consumption, fan speed of the screw, which regulate air flow into the combustion chamber and heat output.
- Particle number size distributions analysis showed that the peak particle concentration was observed for all the experiments between 25 nm to 70 nm for startup phase, 70 nm to 100 nm for the combustion phase and 20 nm to 80 nm for the burnout phase. These small size particles are considered very harmful for human health as they penetrate lower the alveolar region of the lung.
- The present study was performed under controlled laboratory conditions. Therefore, the further is to conduct field measurements, which will reveal the effects of daily life operational practices of the pellet stove.

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