Chapter

Performance, Gaseous and Particle Emissions from a Residential Pellet Stove

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Abstract

The objectives of this chapter are to present experimental results on performance, gaseous and particle emissions obtained from a modern bottom feed pellet stove of 2.5 kW output in part load heat and 5 kW output in nominal heat. Two experiments in part load and four experiments in nominal load output were conducted in a stove manufacturing plant in the southern part of Belgium. The particle emissions measurements are mass concentrations of PM_1 and $PM_{2.5}$, number concentrations and their particle size distributions. Particle emission measurements were conducted continuously from a partial flow dilution tunnel using an Electrical Low Pressure Impactor Plus (ELPI+). The CO emissions were analyzed continuously from the flue gas by a Siemens Ultramat 6 gas analyzer, CO_2 and O_2 concentrations were measured continuously using a Horiba PG-250 gas analyzer. A performance analysis in terms of combustion efficiency together with different losses of the pellet stove is also discussed. The results show that PM_1 and $PM_{2.5}$ concentrations obtained from the combustion phase of the nominal load experiments varied from 43.3 to 276 mg/Nm^3 and 66 to 36 mg/Nm^3 respectively, while the particle number concentrations varied from 1.4×10^7 to 8.8×10^7 particles/cm^3. The CO emissions obtained from the main combustion phase of the nominal load heat varied output from 50 to 145 mg/Nm^3.

Keywords: gaseous emissions, particulate matter, mass concentrations, number concentrations, size distributions, performance analysis

1. Introduction

Small scale combustion appliances are mainly used for the purpose of residential heating. Several studies show that combustion of biomass fuels in small scale heating appliances is a common source of both particulate matter (PM) and gaseous emissions such as fine particles, polycyclic aromatic hydrocarbons (PAH), volatile organic compounds (VOC) and carbon monoxide, carbon dioxide, nitrogen oxide, sulfur oxide, etc. [1–8]. PM is a dynamic mixture of particles in the flue gas released directly from the combustion devices. The aerodynamic diameter is generally used to indicate the particle size since the particles have different shapes and densities. It is defined as the diameter of a spherical particle with a mass density of 1000 kg/m^3 that has the same inertial properties in the flue gases [9–11]. Several particles size fractions of PM are defined in the literature: $PM_{0.1}$ (nano particles: <0.1 μm), PM_1 (ultrafine particles: <1 μm), $PM_{2.5}$ (fine particles: <2.5 μm), PM_{10} (coarse particles: <10 μm) [9, 10, 12].

In comparison to liquid and gaseous fuels, the emissions of particulate matter from biomass combustion are high [9, 13–17]. Majority of the particles is less than 1 μm (micrometer) in size and emitted straight away to the ambient air from the combustion appliances [18, 19]. Numerous studies have demonstrated that increased particle emissions in the ambient air correlate with severe health effects in the exposed population, including respiratory and cardiovascular illnesses as well as increased mortality [15, 20, 21]. Further, it has been mentioned that in the case of combustion related fine particle fraction is more dangerous to human health and environmental effects [2, 15, 20–22].

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 [23]. Nowadays, combustion of wood pellets in small scale heating appliances is efficient and produces significantly lower emissions than the old wood log combustion appliances [4].

Most of the heating appliances in the market claim an optimized combustion with low emissions of gaseous pollutants at nominal operational load. However, operation at full load is only required for a short peak winter period [4]. For the rest of the year, the combustion appliances may work at lower operational loads as far as continuous operation is considered. The emissions of these pollutants are significantly different if the heating appliance is operating at lower loads i.e. part load. Carbon monoxide (CO) emissions from residential pellet heating devices mainly report during stationary operation, however, a considerable part of un-burnt fuels is emitted during the startup and burnout phases [24, 25].

This chapter presents the experimental results regarding particle and gaseous emissions from a modern bottom feed pellet stove operated with nominal load (5 kW) and part load (2.5 kW) heat output. The particle emission measurements include mass concentrations of PM_1 and $PM_{2.5}$, 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 14 stages from 6 nm to 10 μm.

2. Materials and methods

This section briefly discusses the previous work on particle emissions, experimental setup, fuel characteristics and combustion appliance related to the emissions measurements.

2.1 Literature review

There is lack of information regarding the characterization of particulate emissions from small scale biomass combustion. Several studies on particle emission from biomass stoves were carried out in EU countries. For example, Boman et al. [26] investigated six types of different pellet fuels in three different commercial pellet burners (10–15 kW) and observed that fine particles (<1 μm) contain a significant part of the total PM emissions.

Sippula et al. [27] 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 to 4.4×10^7 particles/cm^3 and the PM_1 varied from 69 to 343 mg/Nm^3. Gaegauf et al. [28] 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 and 300 nm.

Bari et al. [29] 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 Berner Low Pressure impactor (BLPI) and a Scanning Mobility Particle Sizer (SMPS) for mass concentrations and number size distributions respectively. The results show that the PM_{10} concentrations were between 31 and 201 mg/Nm^3, while number concentrations varied between 1.5×10^7 and 5.4×10^7 particles/cm^3. They observed that the particle mass size distributions were unimodal with maximum concentrations in the fine fraction.

Bäfver et al. [30] experimentally studied particle and CO emissions from modern and old type residential stoves of various heat capacity fired with wood logs and wood pellets. Measurements were performed using a Dekati Low Pressure Impactor (DLPI) for mass size distribution while an ELPI was used for number size distributions. Modern pellets stoves showed lower mass concentration of particles as well as lower CO concentrations than the old type wood stoves. They found that in all cases, the particle mass emissions were dominated by fine particles and there was only small fraction of coarse particles.

Qie et al. [31] studied particle emissions in a small scale pellet boiler (50 kW) using a Dust Trak-II Handheld Aerosol Monitor from 100 nm to 10 μm. Three types of biomass pellets, i.e. wood pellets, Miscanthus pellets and straw pellets were combusted. PM_{10} concentrations of wood pellets, Miscanthus pellets and straw pellets were 72.7, 100 and 150 mg/Nm^3, respectively. PM concentration results show that wood pellets are better than Miscanthus and straw pellets.

Johansson et al. [32] investigated particle emissions from a domestic pellet stove with a capacity of 6 kW. The stove was fired with wood pellets. Particle characterizations were done with an Electrical Low Pressure Impactor (ELPI). PM_{10} mass concentration was 47 mg/Nm^3, number concentrations varied between 1.8×10^7 and 8.7×10^7 particles/cm^3.

The above review briefly illustrates that a number of studies on particulate matter concentrations related to the small scale heating appliances at nominal load operations [19, 27, 33, 34]. Particle emissions from residential heating devices are documented mainly for stationary operation, however a considerable part of un-burnt 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.

2.2 Experimental setup

The measurements were conducted according to the European standard EN 14785 for residential space heating appliances fired by wood pellets [35]. Two experiments (A and B) in part load and four experiments (C, D, E and F) in nominal load heat output were conducted for the emissions measurements from a bottom feed modern 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. 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 1.6/6 sec for the part load measurements, while 3.2/6 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.

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

Table 1.
Fan speed settings for the different experiments [7, 17].

2.3 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 2**. The pellets are made from soft wood, certified by DINPlus standard and available in the European market.

2.4 Combustion appliance

The combustion appliance used in the experiments was a 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 min in the stove. During cleaning, the fuel supply decreases and the air supply increases for 1 min, removing the ash gathered on the grid. The front side of the stove is covered with a high temperature transparent glass window. The top of the combustion chamber is equipped with the baffle plate made

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	—

Table 2.
Chemical properties of the pellet used in the combustion experiments [7, 17].

of vermiculite materials and the sides of refractory ceramic bricks made of calcium silicate. The flue gases are drawn out by an exhaust fan.

2.5 Gaseous emission measurements

A partial flow from the stack at about 2 m height from the pellet stove was withdrawn through an externally insulated steel probe of 12 mm diameter. The opening of the probe was positioned towards the flow of the stack. The CO emissions were analyzed continuously from the flue gas by a Siemens Ultramat 6 gas analyzer, CO_2 and O_2 concentrations were measured continuously using a Horiba PG-250 gas analyzer. Both gas analyzers cannot withstand the hot and humid flue gases for direct analysis. Before the analyzers, the flue gas samples passed through the chiller to remove moisture and to cool down the gas. The gas analyzers were calibrated with an appropriate gas mixture, before and after each combustion experiment. The measurement principles of the gas analyzers were galvanic analyzer for O_2 and non-dispersive infra-red for CO, CO_2. The analyzers have the measurement error of ±2% full scale in linearity and ± 0.5% full scale in repeatability. Temperature of the indoor air and flue gas in the stack were measured by the K-type thermocouples.

2.6 Particle emission measurements

Particle emissions were measured continuously from a partial flow dilution tunnel using an ELPI+ with a flow rate 10 lpm and cut-off size of the 14 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 [36]. 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 prefiltered dilution air before reaching the 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 [4, 5, 37, 38].

3. Results and discussions

A total of six combustion experiments on gaseous and particle emissions from a bottom feed pellet stove were conducted. As the objectives of this chapter were to evaluate the emissions from different combustion phases of each experiment, the emission results from each experiment are presented as the startup, the combustion and the burnout phases.

3.1 CO emissions

The CO emissions obtained from the startup, combustion, burnout phase of all the experiments are presented in **Figures 1–3** respectively. The error bars present the uncertainty of the measurements. The CO emission values presented here are normalized with 13% dry oxygen content. It is clearly observed from all the experiments that CO emissions in the burnout phase were significantly higher than that in the startup phase followed by the combustion phase. The air excess (λ) in the burnout phase for all the experiments was quite higher than that in the other two phases. High excess air in the burnout phase cools the combustion chamber, resulting in high CO emissions.

It can be seen from **Figure 1** that the CO emissions obtained from the startup phase of the part load heat output varied from 1710 to 2370 mg/Nm^3 for experiments A to B, while in the nominal load heat output varied from 908 to 2294 mg/Nm^3 for the experiments C to F. The duration of startup phase is about 20 min for all the experiments. The stove operated in the medium speed fan gives lower CO emission in the startup phase. However, CO emissions in the startup phase for the experiments E and F were higher than the measurements C to D. At the startup phase, the combustion temperature was not high enough to provide sufficient burnout condition. This might be a reason for increasing CO emissions during the startup phase.

Figure 2 shows the comparison of CO emissions obtained from the main combustion phase of all the experiments with the required limit value of the NBN EN 14785 standard and the literature [39]. CO emission in Y axis is presented in logarithm scale. The CO emissions from the medium and high speed fan stove operated with nominal load output satisfied the required limit value of the NBN EN 13229 standard and lower than other work [39]. CO emissions obtained from the low speed fan operated with part load heat output did not meet the required limit value of the standard.

It can also be seen from **Figure 2** that the CO emissions obtained from the main combustion phase of the part load heat output varied from 1215 to 1450 mg/Nm^3 for experiments A and B, while in the nominal load heat output varied from 50 to 145 mg/Nm^3 for the experiments C to F. The duration of the main combustion phase varied from 3 h 50 min to 5 h 45 min for all the measurements. The lower CO emissions obtained from the stove operated with high speed fan than the medium speed fan followed by the low speed fan. Higher CO emission in the part

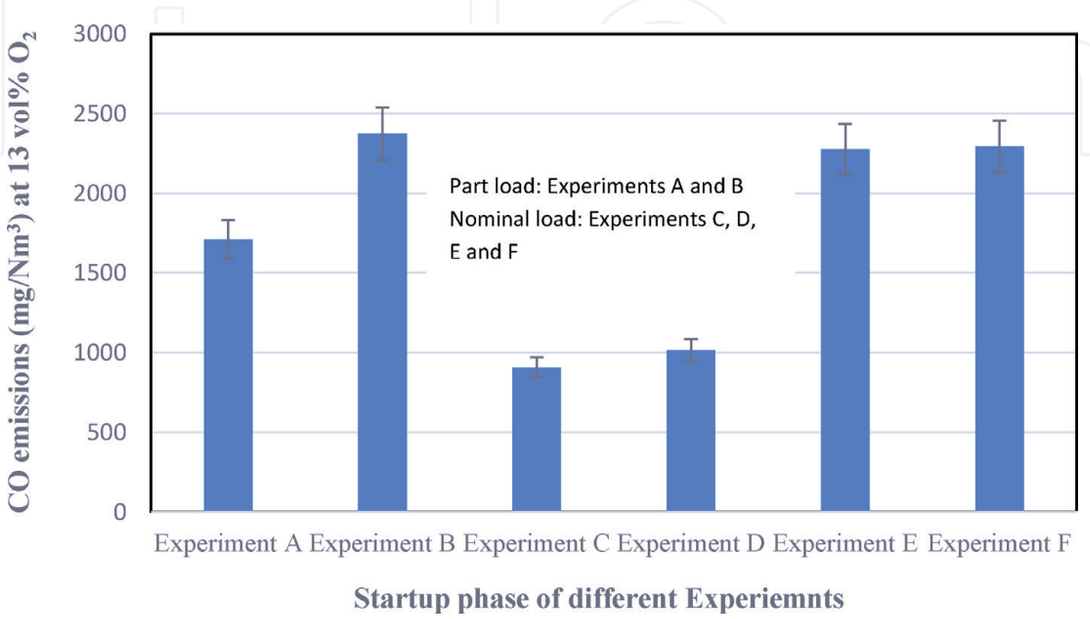

Figure 1.
CO emissions obtained from the startup phase of all the experiments [7].

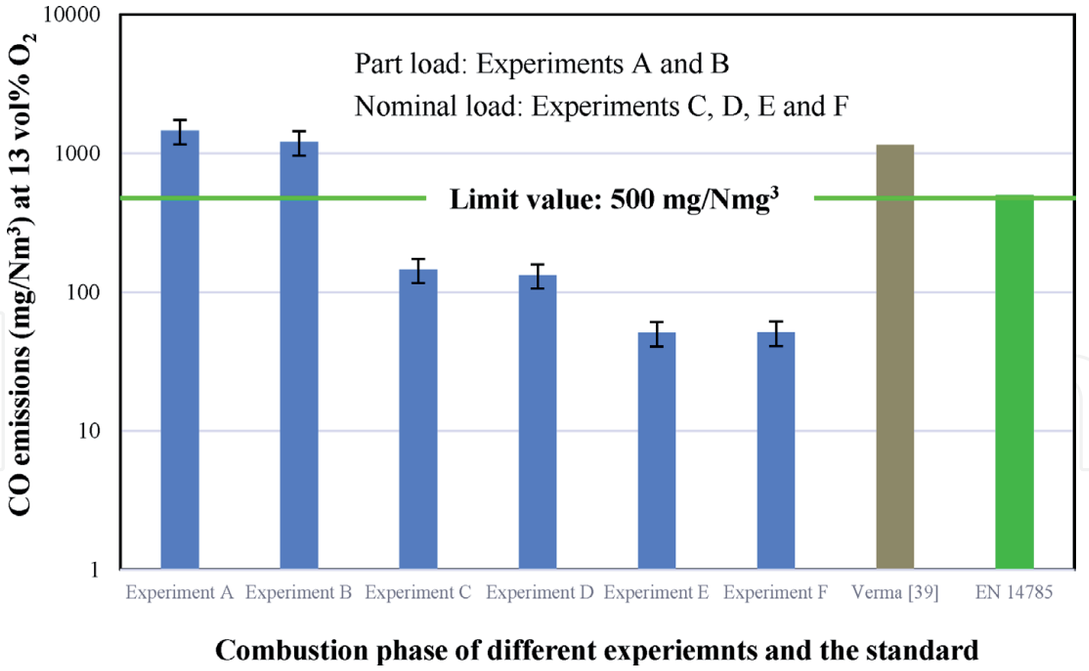

Figure 2.
Comparison of CO emissions obtained from the combustion phase of all experiments with the standard [7].

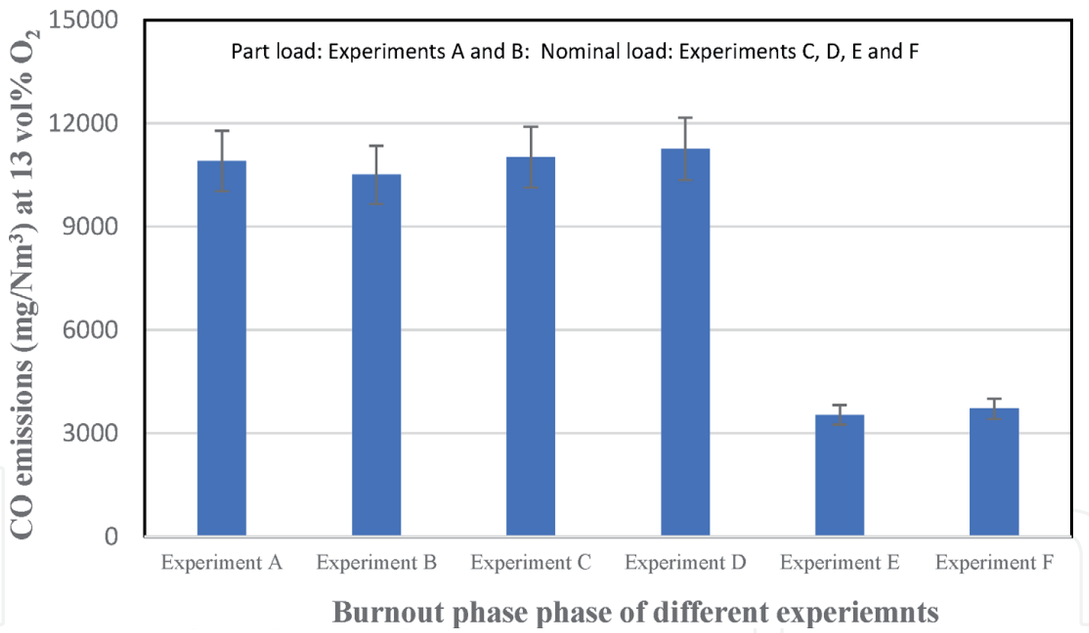

Figure 3.
CO emissions obtained from the burnout phase of all experiments [7].

load experiments was probably due to the higher air excess factor (about λ = 4.35) obtained in low speed fan, which gives lower combustion temperature, leading to high CO emissions. On the other hand, a correctly matched air excess factor (about λ = 2.5) for the medium and high speed fan operated experiments created favorable combustion conditions, leading to less CO emissions. Besides, the average flue gas temperature was much lower in the low speed fan (64°C) operated experiments than the medium speed (85°C) and high speed fan (101°C).

It can be seen from **Figure 3** that experiments E and F had the lower CO emissions in the burnout phase because of the different configuration of the fan speed from other measurements A, B, C and D. Also, the fan speeds for the experiments E and F were higher than the other experiments. This means that sufficient amounts

of combustion air were supplied to burn the combustible gases; as a result, CO emissions were lower. Experiments conducted in the high speed fan gives lower CO emission in the burnout phase.

The total CO emissions showing in **Figure 4** are relatively higher in part load combustion experiments compared to nominal load output. This was due to the lower combustion temperatures caused by high air excess at the part load combustion experiments. The total CO emissions obtained in the part load experiments can be compared with values found in other work. For example, Schmidl et al. [40] investigated gaseous emissions from a 3 kW pellet stove in part load power output. The CO emissions in their study were 751 mg/Nm^3 which is quite lower than that in our study. The total CO emissions obtained from the nominal load output experiments are higher than other studies. For example, the CO emissions results of Bäfver et al. [30] investigated from a pellet stove with 5 kW capacity range between 140 and 405 mg/Nm^3.

It is clearly observed that CO emissions in the burnout phase from all the experiments were significantly higher than that in the startup phase followed by the combustion phase. For example, CO emissions in the burnout phase for experiments C to D were about 12 fold higher than in the startup phase and 75 fold higher than in the combustion phase. The air excess (λ) in the burnout phase for all the experiments was quite higher than that in the other two phases. High excess air in the burnout phase cools the combustion chamber, resulting in high CO emissions. It can be mentioned from the experimental results that the impact of higher CO emissions in the startup and burnout phase has influence on the total CO emissions.

Several studies [34, 41, 42] mention that higher combustion temperature, better turbulence mixing fuel with necessary oxygen and sufficient residence time can play a major role in combustion optimization and consequently emissions reduction. The CO emissions from a combustion device might represent the incomplete combustion caused by low combustion temperature, insufficient oxygen, short residence time, poor fuel and air mixing or a combination of these factors [34, 43].

CO emissions from small scale biomass combustion appliances can be reduced using flue gas cleaning technologies such as catalytic combustors, which consist of a metal wire mesh covered with catalytic material, platinum and palladium. The catalytic combustors are attached to a steel frame which can be inserted compactly

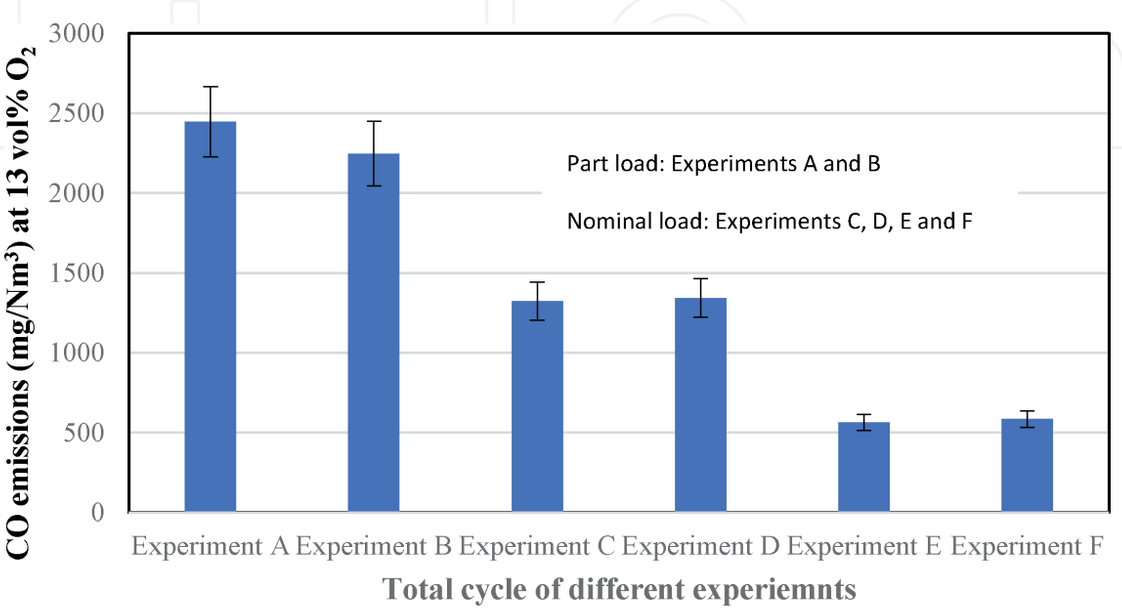

Figure 4.
Total CO emissions obtained from all the experiments [7].

inside the stack through an opening. Smoke gases pass through the catalytic element and ignite at a much lower temperature around 250°C. The result is that harmful substances are more completely burned. The fuel produces more heat through an extended clean burn. Hukkanen et al. [44] investigated reduction of gaseous emissions using a catalytic combustor from a 15 kW stove. Their results show that reductions of CO reached about 25% during the whole combustion cycle. Such gas cleaning systems are however quite expensive for small scale applications.

3.2 Particle mass concentrations

Figures 5 and **6** present the comparison of particle mass concentrations of PM_1 and $PM_{2.5}$ obtained from the startup, combustion, burnout phases and the total cycle of all the combustion experiments. **Figure 5** shows PM_1 concentrations obtained from the startup phase of the part load heat output. Experiments A to B varied from 26.1 to 38.4 mg/Nm^3 for the startup phase, 20.4 to 29.8 mg/Nm^3 for the combustion phase, 9.3 to 10.2 mg/Nm^3 for the burnout phase and 20.5 to 27.6 mg/Nm^3 for the total cycle, while in the nominal load heat output experiments C to F varied from 22 to 106 mg/Nm^3 for the startup phase, 43.3 to 276 mg/Nm^3 for the combustion phase, 4.7 to 12 mg/Nm^3 for the burnout phase and 44 to 236 mg/Nm^3 for the total cycle.

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, which operated with the different fan speeds.

The particle mass emissions reported by Sippula et al. [27], Johansson et al. [18] 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. [27] investigated particle mass emissions from a top

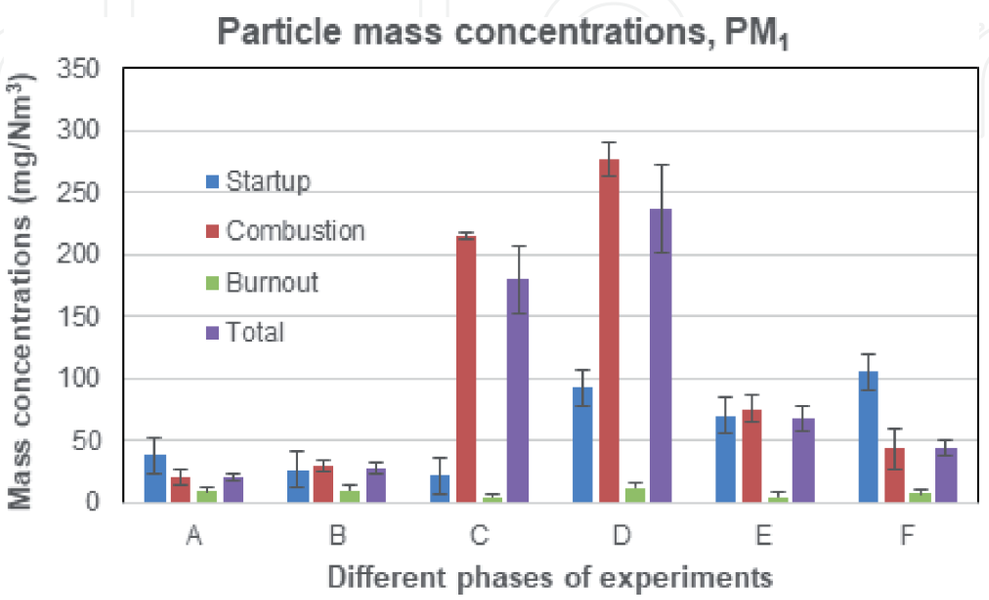

Figure 5.
Comparison of PM_1 concentrations obtained from all the combustion experiments [17].

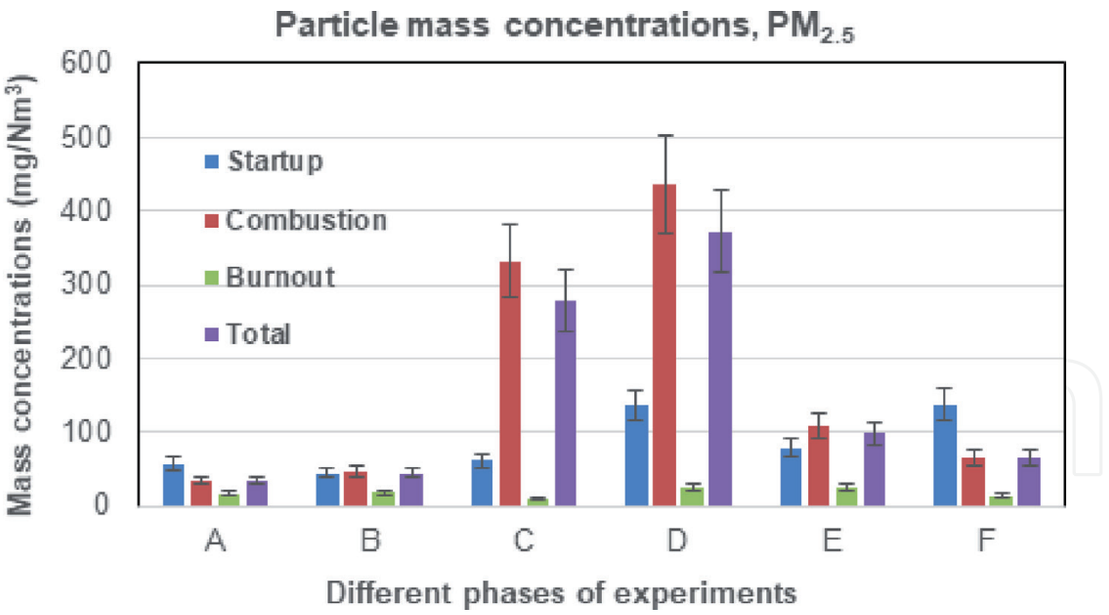

Figure 6.
Comparison of $PM_{2.5}$ concentrations obtained from all the combustion experiments [17].

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 and 343 mg/Nm^3 which are slightly higher values than in our study.

Figure 6 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 to 57.8 mg/Nm^3 for the startup phase, 34.4 to 48 mg/Nm^3 for the combustion phase, 17 to 18 mg/Nm^3 for the burnout phase and 34.2 to 45 mg/Nm^3 for the total cycle, while in the nominal load experiments, varied from 61.5 to 138 mg/Nm^3 for the startup phase, 66 to 436 mg/Nm^3 for the combustion phase, 10.3 to 26.3 mg/Nm^3 for the burnout phase and 65.7 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 are 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 [26]. This analysis from both nominal and part load het output experiments clearly shows that more than 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 [9, 10, 12, 27, 45].

3.3 Particle mass size distributions

Figures 7–9 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 dlog(Dp), where Dp is the aerodynamic diameter.

Figure 7 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 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 8** 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 9**, 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.

3.4 Particle number concentrations

Figure 10 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 have the less impact on the total particle number emissions.

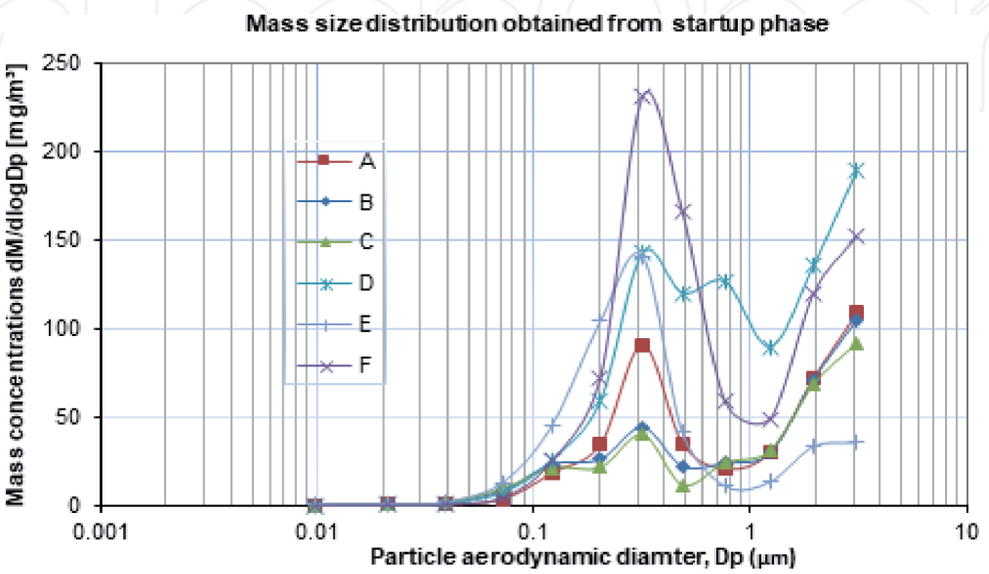

Figure 7.
Particle mass size distributions obtained from the startup phase of all the experiments [17].

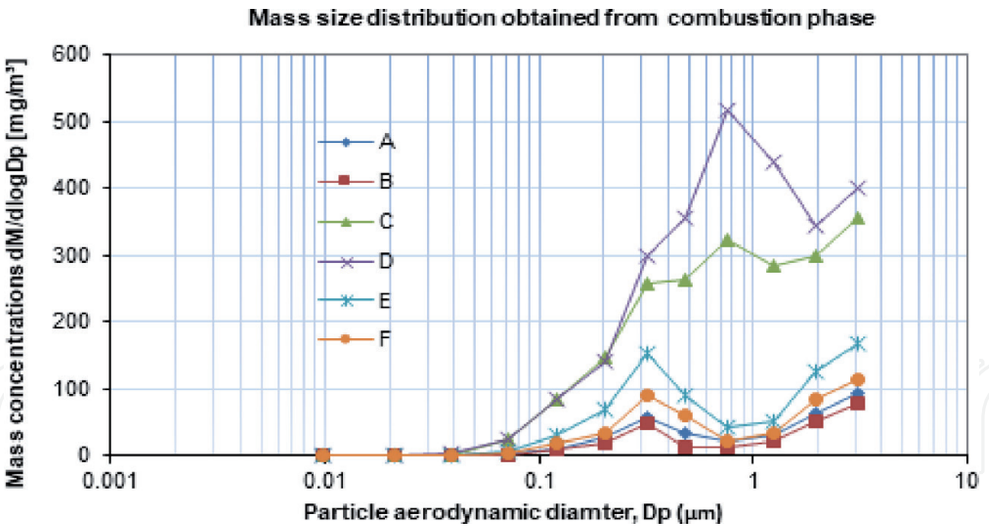

Figure 8.
Particle mass size distributions obtained from the combustion phase of all the experiments [17].

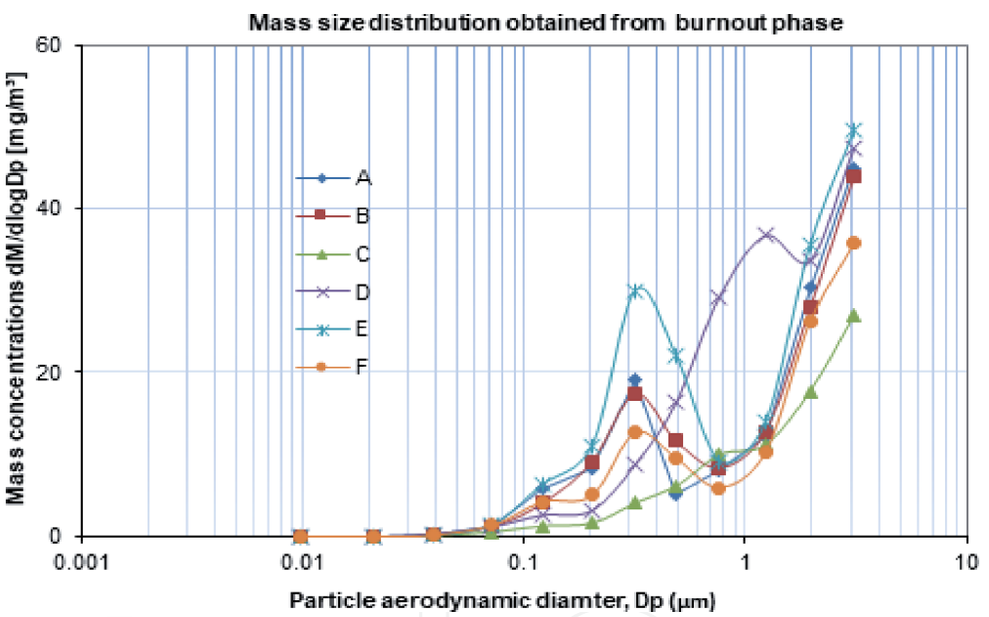

Figure 9.
Particle mass size distributions obtained from the burnout phase of all the experiments [17].

The duration of the main combustion phase varied from 3 h 50 min to 5 h 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 10** 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 had 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.

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 $\lambda = 2.8$ for the medium speed fan experiments, while $\lambda = 2.4$ for the high speed fan experiments. Besides, the average flue gas temperature was 85°C for the medium speed experiments and 101°C for the high

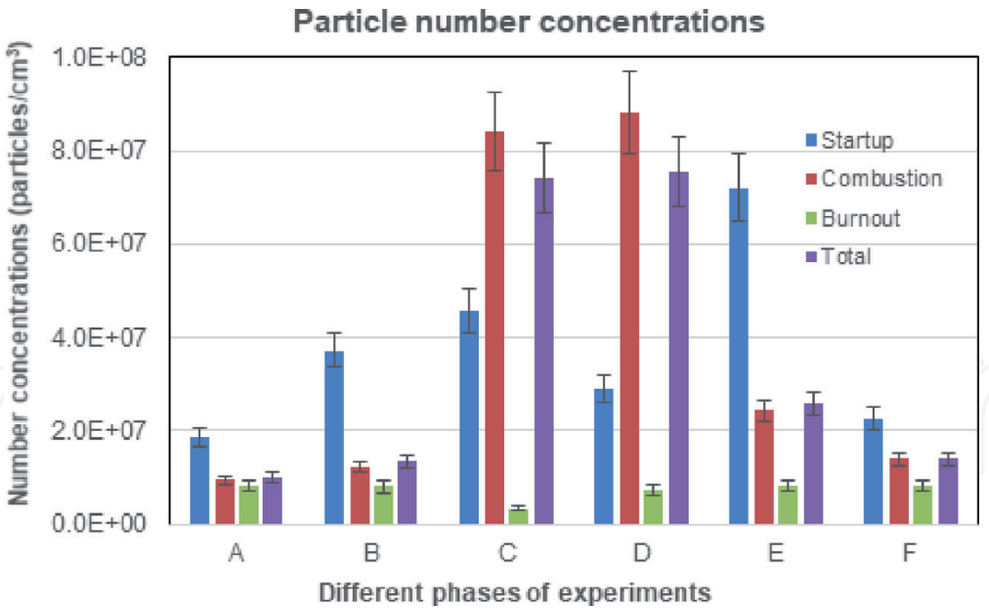

Figure 10.
Comparison of particle number concentrations [17].

speed fan experiments. The number concentrations from the main combustion of the part load experiments were much lower than nominal load experiments. This may be due to the difference of fuel consumption, fan speed of the screw, which regulates 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. [27] 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. [29] studied particle number concentrations from a 5 kW pellet using a SMPS instrument. Their results show that particle number concentrations varied between 1.5×10^7 and 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 [46, 47], 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 [21, 48]. 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.

3.5 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 11–13**. **Figure 11** shows that the peak in particle number concentrations was observed at the particle size from 25 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.

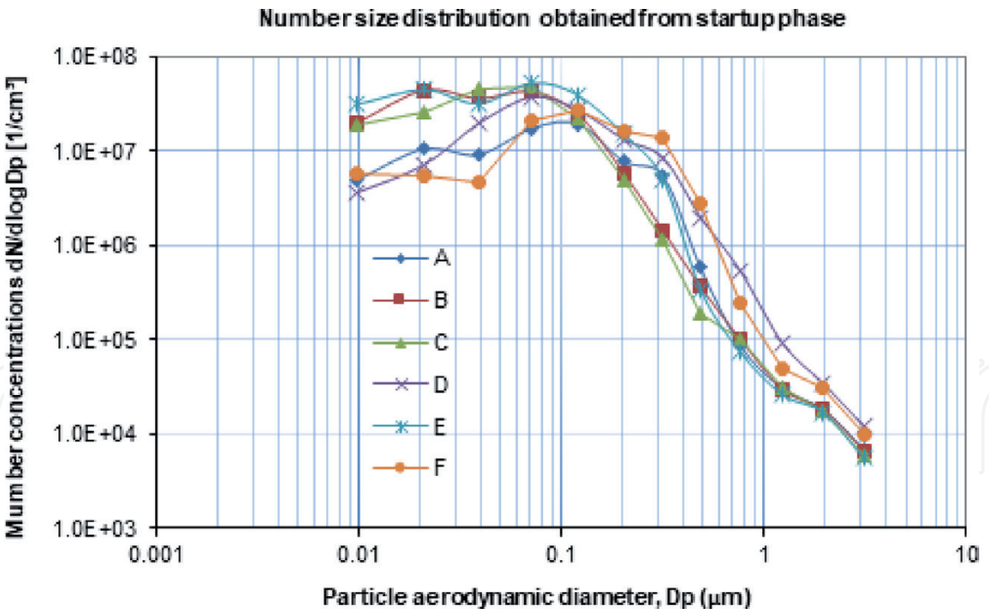

Figure 11.
Particle number size from distributions obtained from the startup phase of all the experiments [17].

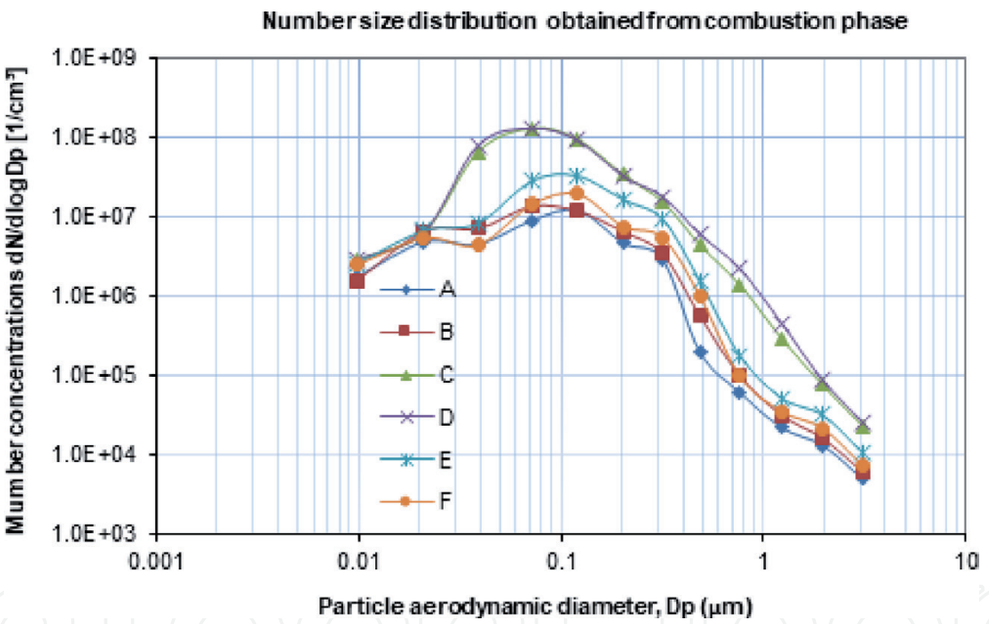

Figure 12.
Particle number size from distributions obtained from the combustion phase of all the experiments [17].

Similar particle number size distributions were observed in other studies. For example, Bari et al. [29] investigated particle number size distributions from a pellet stove of 5 kW nominal output using a SMPS. Their results show that the maximum number particle concentrations were found at the particle size within the diameter range from 55 to 90 nm. Boman et al. [49] investigated particle number size distributions from a pellet stove of capacity 5 kW using a SMPS and their results show that maximum particle at the particle size was about 70–80 nm.

Figure 12 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 70–100 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

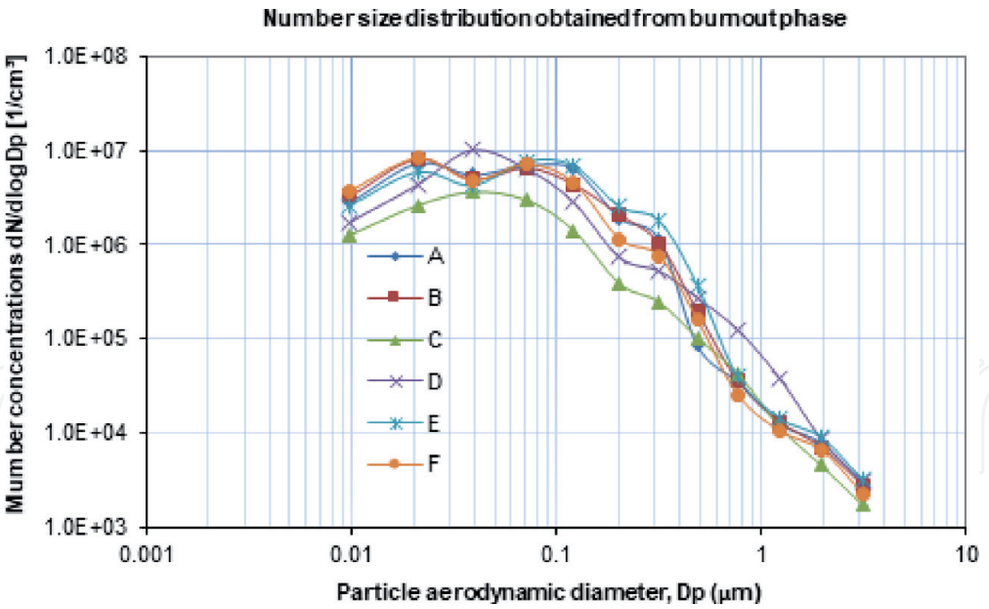

Figure 13.
Particle number size distributions obtained from burnout phase of all the experiments [17].

higher operated with medium fan speed than that high speed fan experiments followed by the low speed fan experiments.

Figure 13 presents the particle number size distributions for the burnout phase, where the maximum particle number concentrations were observed between 20 nm and 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 size less than 1 μm are formed from the easily volatile inorganic elements, released from the biomass fuels to the gas phase during combustion. Potassium, sulfur 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 [9, 14]. Particle emissions are dominated by ash particles when the combustion quality is good, for example as in pellet combustion.

3.6 Performance analysis

The performance analysis in terms of combustion efficiency of the pellet stove was determined using an indirect method according to the standard EN 14785 that takes the thermal, chemical and radiation heat losses into consideration [35]. Efficiency was determined according to the difference between energy input and the sum of the losses. The thermal heat loss was evaluated on the basis of the difference between the temperature of the flue gas and the room temperature and the specific heat of the flue gas. The chemical heat loss is calculated from the CO and CO_2 concentrations of the flue gas. The radiation heat loss is taken as 0.2% according to the standard EN 14785. The formulas used for the calculation of the combustion efficiency and the different losses were discussed in the works [4, 7].

The combustion efficiency of the pellet stove as a function of different operational loads is compared with the required limit value of the standard NBN EN 14785 and presented in **Figure 14**. It can be seen from the figure that all the measurements both from nominal heat and part load output meet the standard. All

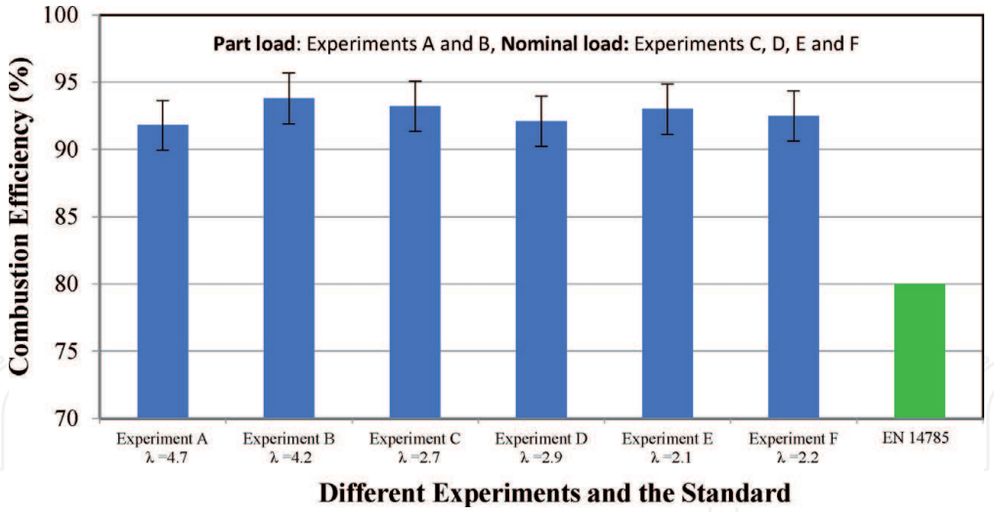

Figure 14.
Combustion efficiency compared with the standard [7].

the experiments have almost similar combustion efficiencies at both operational loads. The average combustion efficiency obtained from all the experiments for the low speed fan, medium speed fan and high speed fan was 92.8 ± 1.2, 92.4 ± 1.1 and 92.7 ± 1.2% respectively. The average thermal heat and chemical heat losses are estimated at 6.05 and 0.93% respectively for the low speed fan, 6.95 and 0.22% respectively for the medium speed fan and 6.95 and 0.14% respectively for the high speed fan, which influences the variations of the combustion efficiency as seen from **Figure 14**. Experiment B had the highest combustion efficiency from the part load operated with low speed fan, while experiments C and E had the higher efficiency from the nominal load output.

The combustion efficiency evaluated from the experiments in nominal load heat output can be compared with other works. For example, Sippula et al. [27] mentioned about 85% combustion efficiency from a 8 kW modern pellet stove in standard laboratory condition which is lower than this study.

4. Conclusions

A total of six combustion experiments on gaseous and particle emissions from a modern bottom feed pellet stove were conducted. Following conclusions can be drawn from this chapter.

- CO emissions in the burnout phase from all the experiments were significantly higher than that in the startup phase followed by the combustion phase. CO emissions in the burnout phase for experiments C to D were about 12 fold higher than in the startup phase and 75 fold higher than in the combustion phase. The air excess (λ) in the burnout phase for all the experiments was quite higher than that in the other two phases. The experimental results show that the impact of higher CO emissions in the startup and burnout phase has influence to increase the total CO emissions.

- The CO emissions obtained in the main combustion phase from the experiments conducted with high speed fan were lower than the medium speed fan followed by the low speed fan. Higher CO emission in the low speed fan was probably due to the higher air excess factor (about λ = 4.35), which gives lower combustion temperature, leading to high CO emissions.

- 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.

- The number concentrations from the main combustion of the part load experiments were 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.

- Analysis from the particle number size distributions showed that maximum particle emissions were found for all the experiments between 25 and 70 nm for startup phase, 70 and 100 nm for the combustion phase and 20 nm and 80 nm for the burnout phase.

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Conflict of interest

The author declares no conflict of interest.

Nomenclature

BLPI	Berner low pressure impactor
DLPI	Dekati low pressure impactor
ED	ejector diluter
EN	European norms
EU	European union
ELPI	electrical low pressure impactor
ELPI+	electrical low pressure impactor plus
Dp	particle diameter
DR	dilution ratio
Hr	hour
LHV	lower heating value
lpm	liter per minute
PAH	polycyclic aromatic hydrocarbons
PM	particulate matter
PRD	porous tube diluter

rpm	rotation per minute
SMPS	scanning mobility particle sizer
sec	second
VOC	volatile organic compounds
μm	micrometer
nm	nanometer
mg	milligram
min	minute
cm	centimeter
λ	air excess
°C	degree celsius

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