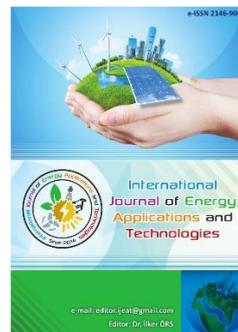




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Original Research Article

Particle mass and gaseous emissions from small scale modern wood stoves

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ABSTRACT

The objectives of the paper were to evaluate particle mass concentrations of PM₁ (size <1 μm) and PM_{2.5} (size <2.5 μm), mass size distributions and CO emissions under standard laboratory conditions obtained from two commercially available modern residential wood stoves with capacity 10 kW and 20 kW. Four combustion batches with minor modification of primary air flows into the combustion chamber for each stove were conducted to evaluate the emission results. Particle mass concentrations and size distributions were measured in real time using an Electrical Low Pressure Impactor Plus (ELPI+) instrument, which measures particles with a fast response time in a wide particle size range from 6 nm to 10 μm aerodynamic diameter. Gaseous concentrations of O₂ and CO₂ were measured continuously using a Horiba PG-250 analyzer and CO emissions were measured using a Siemens Ultramat 6 gas analyzer. The measurement protocols of each combustion test were conducted according to the European standard EN 13229. The combustion experiments were conducted in a laboratory of a stove manufacturing plant in Belgium. The results showed that PM₁ and PM_{2.5} concentrations of all the batches of both stoves varied from 116 to 327 mg/Nm³ and 139 to 413 mg/Nm³, respectively in the combustion cycle. Particle mass size distribution for all batches from both stoves is very similar showing a maximum in the fine mode at a particle size of around 330 nm to 500 nm. The CO emissions from all the batches varied from 447 to 1184 mg/Nm³ for the 10 kW stove and 958 to 1545 mg/Nm³ for the 20 kW stove. The experimental results of PM₁, PM_{2.5} concentrations and CO emissions from combustion measurements could be useful for the improvement of the combustion process as well as the reduction of gaseous and particle mass emissions from these residential biomass combustion appliances.

Keywords: particle mass concentrations; PM₁; PM_{2.5}; mass size distributions; CO emissions

1. Introduction

Biomass fuels are widely available across the globe and provide a major share of renewable energy in most countries. The combustion of biomass fuels can result in a broad range of potential pollutants. Emissions from biomass combustion can be classified into two groups, which are gaseous emissions and particle emissions [1-4]. The gaseous emissions are the main gas compounds (CO₂, H₂O and O₂), carbon monoxide (CO), partially combusted hydrocarbons (C_xH_y or OGC), sulphur dioxide (SO₂), nitrogen oxides

(NO_x), etc [2, 5]. Besides gaseous emissions, particulate matter (PM) emissions are always observed during biomass combustion. Particles can be divided into two groups according to their size [2, 6, 7]. These are fine particles and coarse particles. Particles smaller than 1 μm (micro meter) in diameter are often called fine particles. These fine particles are generally formed from elements that are vaporized during combustion, which later saturate and form fine particles by nucleation. The nucleated particles grow further by coagulation, agglomeration, condensation and surface reaction. Particles larger than 1 μm in diameter are often

called coarse particles, forming mainly from char or ash species with low vapour pressures which do not vaporize during combustion [2, 4, 7].

There is lack of information regarding the characterization of particulate and gaseous emissions from small scale biomass combustion appliances. Several studies on particle emissions from biomass stoves were carried out in EU countries. For example, Boman et al. [8] investigated six types of different pellet fuels in three different commercial pellet burners (10–15 kW) and observed that fine particles ($< 1 \mu\text{m}$) were found a significant amount of the total PM emissions. Bäfver et al. [9] experimentally studied particle mass 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 distributions. Modern pellets stoves showed lower mass concentrations of particles as well as lower CO concentrations than the old type wood stoves. Qie et al. [10] 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 concentrations results showed that wood pellets as biomass fuel are better than Miscanthus and straw pellets. However, limited information regarding particle mass concentrations and gaseous emissions from small scale biomass combustion appliances is available in the literature.

There is a need for more scientific information of particulate matter concentrations and gaseous emissions from small scale application of wood stoves. The objectives of this paper were to evaluate experimentally particle mass concentrations, particle mass size distributions and gaseous emissions from two commercially available modern wood stoves with a capacity 10 kW and 20 kW, respectively. The work includes particle mass concentrations of PM_{10} , $\text{PM}_{2.5}$ and CO emissions from the combustion cycle as well as comparison with previously reported data.

2. Materials and Methods

2.1 Fuel characteristics

The dimension of the wood log fuel was about 33 cm in length and 10 cm in diameter and the mass of each wood logs was about 1.15 kg. The wood log was Beech species available in the Belgian forest. The chemical composition of the fuels was tested in the laboratory of SGS Environmental Services, Arnhem, the Netherlands. The elemental composition of the wood log fuel used in the combustion experiments was 43.8% carbon, 4.8% hydrogen, 38.3% oxygen, moisture 13% and the lower heating value was 16.2 MJ/kg.

2.2. Combustion wood stoves

The combustion appliances used in the experiments were two different commercially available Belgian made modern wood stoves of 10 kW and 20 kW heat output, respectively. The volume of the combustion chamber is 0.090 m^3 for the 10 kW stove and 0.175 m^3 for the 20 kW stove. The flame is directed upwards and can be seen from the outside of the stoves, since the front side of the stoves has a transparent glass window. The top surface of the combustion chamber is equipped with a baffle plate made of vermiculite having high temperature insulation material. The other sides of the combustion chamber are insulated with refractory ceramic bricks made of calcium silicate. Both stoves have the advantages of two staged combustion with supplying of primary and secondary air. Figure 1 shows a photo of the both stoves together with the combustion chamber configuration.

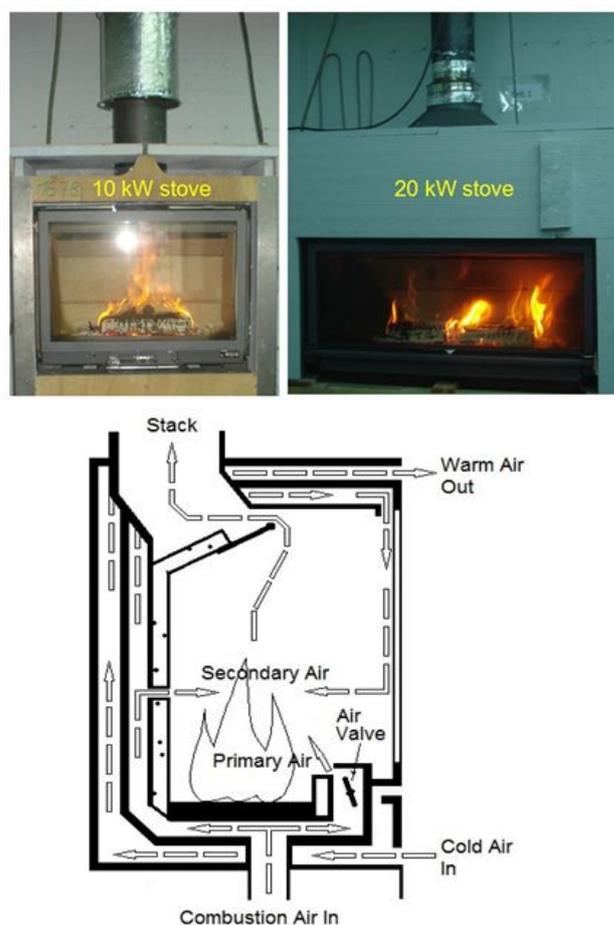
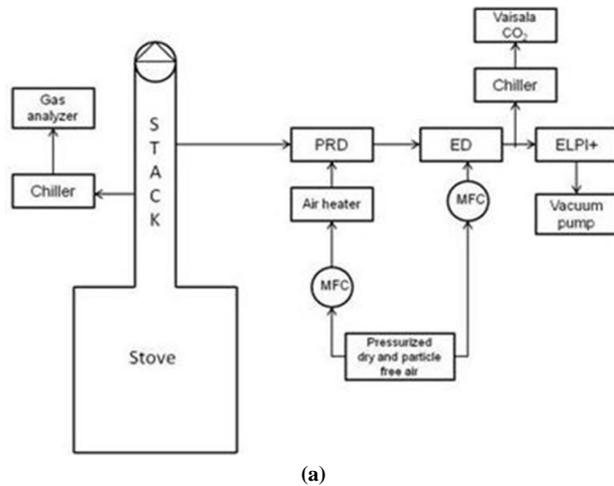


Fig. 1. Photo of 10 kW stove (top left), 20 kW stove (top right) and combustion chamber configuration with air flow pattern (bottom) used in the experiments [11]

2.3. Experimental setup

The experimental setup for the particle mass and gaseous emission measurements is shown in Figure 2. The measurement protocols of each combustion test were conducted according to the European standard EN 13229

[12]. For each stove, measurements were repeated for several batches with minor modification of primary air flows into the combustion chamber to evaluate the emissions results.



(a)



(b)

Fig. 2. Experim. setup for emission measurements from wood stoves (a) schematic of the setup, PRD = Porous tube diluter, ED = Ejector diluter, MFC = Mass flow controller, ELPI+ = Electrical Low Pressure Impactor Plus, (b) some photos of the measurements

2.4. Particle emissions measurements

Particle mass concentrations were measured in real time using an Electrical Low Pressure Impactor Plus (ELPI+) from Dekati Ltd., Finland. It measures particles with a fast response time in a wide particle size range from 6 nm to 10 μm aerodynamic diameter. A partial flow from the stack about 1.8 m above the wood stoves was led through an externally insulated bent tube probe which was made of 12 mm (diameter) stainless steel. The flue gases were passed through a partial flow dilution tunnel before reaching the particle measuring instrument, the ELPI+. The dilution tunnel consists of a porous tube diluter (PRD), an ejector diluter (ED) and an air heater. The working principle of the ELPI+, the measurement procedures of dilution air flows and the calculation of dilution ratio (DR) are discussed in the work [1, 6, 13, 14].

2.5. Gaseous emissions measurements

Gaseous concentrations of O_2 and CO_2 were measured continuously using a Horiba PG-250 analyzer and CO emissions were measured using a Siemens Ultramat 6 gas analyzer. The measurement principles of the gas analysers were galvanic analyzer for O_2 and non-dispersive infrared for CO and CO_2 . The raw flue gases were sampled by the steel probes from the stack at about 1.8 m above the stoves.

3. Results and Discussions

Emissions from residential biomass combustion are considered as a major contributor to ambient air pollution. The combustion experiments were performed from two commercially available modern wood stoves with a capacity 10 kW and 20 kW, respectively at the combustion laboratory of a stove manufacturing plant in Belgium. Particle mass concentrations, mass size distributions and gaseous emission measurements were conducted for four combustion batches for each wood stove under standard laboratory condition. The particle mass concentrations and CO emissions in this paper is defined as the amount of particle mass and CO emissions from the startup and combustion phases. The particle mass PM_{10} , $\text{PM}_{2.5}$ concentrations and gaseous emissions are presented in Table 1. Since the combustion process varies significantly over time in the batch fired heating appliances, the presented standard deviation (\pm) also describes the variation of the process.

3.1. Particle mass concentrations

The flue gas velocities in the stack of the 10 kW and 20 kW wood stoves were 0.47 m/s and 0.65 m/s, respectively. The flue gas velocity in the nozzle was about 0.29 m/s. This means that the PM measurements are sub-isokinetic and therefore PM_{10} concentrations are not included in this paper as the present work puts emphasizing on the very small particles.

Particles collected on the aluminum substrates of the impactor stages of the ELPI+ range from 6 nm to 10 μm aerodynamic diameter are shown in Figure 3. It can be seen from the figure that the black particles on the impactor stages are the fine particle deposition obtained from the Batch 2 of 10 kW wood stove. These particles are mostly fine particles formed from elements that are vaporized during combustion, which later saturate and form fine particles by nucleation. The nucleated particles grow further by coagulation, agglomeration, condensation and surface reaction. The fine particles are mainly formed of potassium salts such as K_2SO_4 (potassium sulphate), KCl (potassium chloride), K_2CO_3 (potassium carbonate) and smaller amounts of zinc, sodium and organic material [2, 5, 8].

Table 1. Average O₂, CO₂, and CO emissions measured by the gas analyzers, PM₁ and PM_{2.5} concentrations measured by the ELPI+ obtained from the 10 kW and 20 kW wood stoves

Particulars	10 kW stove				10 kW stove			
	Batch 1	Batch 2	Batch 3	Batch 4	Batch 1	Batch 2	Batch 3	Batch 4
Duration (min:sec)	45:30	41:45	40:15	47:15	51:00	48:15	43:00	51:30
O ₂ (vol. %)	9.7±0.8	8.1±0.7	8.3±0.7	9.7±0.6	11.0±0.5	10.7±0.6	9.9±0.6	10.8±0.5
CO ₂ (vol. %)	10.6±0.8	12.0±0.7	12.3±0.7	10.7±0.7	9.2±0.6	9.4±0.6	10.3±0.7	9.5±0.5
Stack Temp (°C)	288±15	301±11	305±7	292±4	289±11	294±12	319±7	279±4
Excess air (λ)	1.86	1.64	1.66	1.87	2.12	2.06	1.99	2.12
CO in 13% O ₂ (mg/Nm ³)	1095±217	1184±251	447±123	508±131	1545±205	1338±180	958±157	1255±152
Dilution ratio	35.5±3.4	37.8±2.8	40.9±2.2	34.3±1.5	36.9±1.7	37.6±1.9	37.9±1.0	31.0±0.7
PM ₁ (mg/Nm ³)	209±35.7	295±37.7	327±42.1	166±25.9	116±21.1	135±24.1	195±29.1	149±21.2
PM _{2.5} (mg/Nm ³)	265±57.6	371±58.5	413±65.3	225±38.1	139±37.7	161±40.1	279±51.9	229±35.3



Fig. 3. Particle deposition on the aluminium substrates of the impactor stages of the ELPI+

Figure 4 compares the particle mass concentrations of PM₁ and PM_{2.5} concentrations obtained from different combustion batches of the 10 kW stove and 20 kW stove, respectively. The error bars present the uncertainty of the measurements. It is observed from the figures that PM₁ concentrations of all the batches of both stoves varied from 116 to 327 mg/Nm³ while and PM_{2.5} concentrations varied between 139-413 mg/Nm³. Batch 4 for the 10 kW stove and Batch 1 for the 20 kW stove emitted the lowest PM emissions in the both PM₁ and PM_{2.5} concentrations. The mass concentrations results obtained from the combustion experiments are little high when compared to the literature [8, 10], which may be due to the difference of the combustion technologies, the measurement protocols and the instruments used.

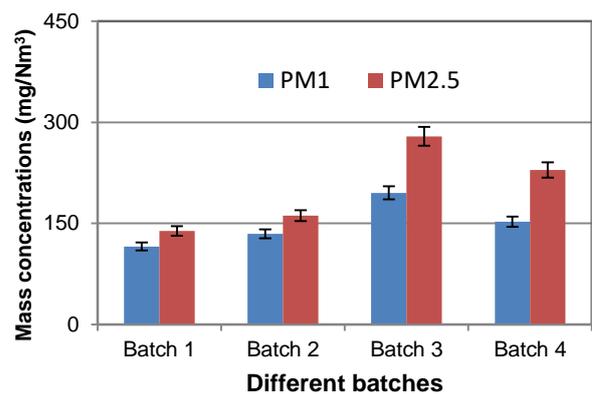
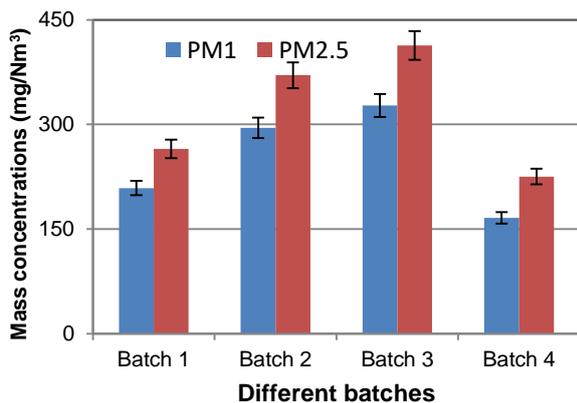


Fig. 4. PM₁ and PM_{2.5} emissions from different batches, (a) for the 10 kW stove, (b) for the 20 kW stove

The obtained results demonstrate quite some variation in the measured PM₁ and PM_{2.5} values over time for the different batches, which is typical for the combustion of wood log stoves. PM₁ concentrations of all the batches of the 10 kW stove accounted for 76.8 % of the PM_{2.5} concentrations,

while 75.6% of the 20 kW stove, which are little lower values than the literature [8]. The PM₁ and PM_{2.5} emissions from the 20 kW stove are much lower than the 10 kW stove. The average fuel consumption for each batch of the 10 kW stove is about one-half lower than the 20 kW stove, which might

impact on particle mass emissions. Several studies reported that increased particle concentrations from the combustion devices in the ambient air correlate with adverse health effects in the exposed population, including respiratory and cardiovascular illnesses as well as increased mortality [15-17]. Further, it has been reported in the literature that in the case of combustion related particles, the fine particle fraction is especially harmful to human health [18-20].

3.2. Particle mass size distribution

Figure 5 shows the particle mass size distributions obtained from the combustion experiments of the 10 kW and 20 kW stove, respectively. The abscissa represents the particle aerodynamic diameter against the ordinate which shows the ratio of particle mass concentrations dM to the logarithm of the channel width $d\log(Dp)$, where Dp is the aerodynamic diameter. It is observed from the figures that the emitted particle mass size distributions for all batches is very similar showing a maximum in the fine mode at a particle size of around 330 nm to 500 nm. Particles between 10 nm and 100 nm represent a very small amount of mass, probably soot

particles, therefore these particles are not seen in the mass size distribution graphs. These small size particles are considered very harmful for human health as they penetrate lower the alveolar region of the lung [16, 21].

Mass size distributions obtained in our measurements can be compared with other work. For example, Bäfver et al. [9] investigated particle mass size distributions in a wood stove using a DLPI. They found that maximum particle mass concentrations were at the particle size of 400 nm. Sippula et al. [4, 22] presented particle formation pathways from wood combustion where there are two types of particles. One is the fine mode, where the particles form through nucleation and condensation from the inorganic vapours. The other is the coarse mode which mainly consists of non-volatilized ash residuals and fly ash particles. Obaidullah et al. [23] investigated particle mass size distribution from a pellet stove with capacity of 5 kW using ELPI+ and the results show that the maximum particle concentrations in the fine mode mainly at the particle size about 320 nm for the start-up and combustion phase and at 300 nm for the burnout phase.

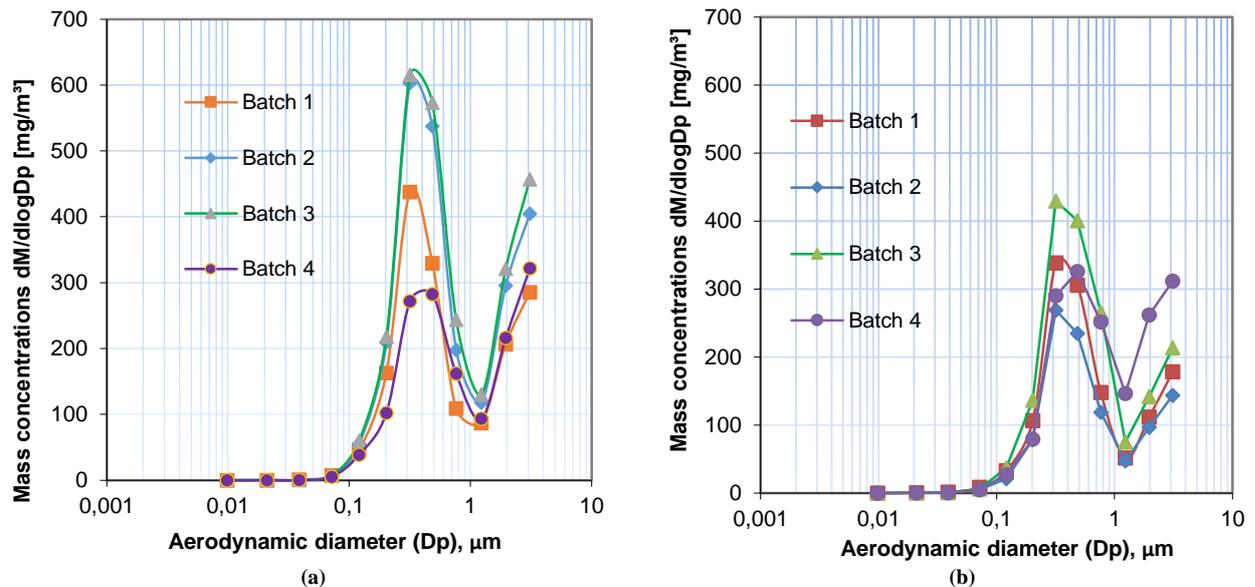


Fig. 5. Particle mass size distribution from different batches, (a) for the 10 kW stove, (b) for the 20 kW stove

3.3. Gaseous emissions

Generally, gaseous emissions from manually batch fired stoves are highly variable. Combustion behaviour is affected by different factors such as fuel properties, appliance type and operational practice, etc. Concentrations of O_2 , CO_2 and CO were measured continuously were measured by the gas analyzers. The NO_x emissions were not performed from the stoves because these emissions were measured by the manufacturer once during the formal pass-test. The following values were obtained 88 mg/Nm^3 for the 10 kW stove and 105 mg/Nm^3 for the 20 kW stove, which satisfy the European norms (240 mg/Nm^3). Besides, the NO_x cell of the Horiba

PG 250 analyzer was not operational. For those reasons, NO_x emission measurements were not performed.

3.4. Time series of CO_2 , CO and O_2 concentrations

Figure 6 shows the variations of the concentration of CO , CO_2 , O_2 and temperature of the flue gases over the measurement time during the combustion cycles of the 20 kW stove. The time for supplying a new batch of logwood was defined from the moment when no visible flames were observed and CO_2 concentration reached about 5%. Then, a batch of wood logs was supplied on the glow bed of the previous fire

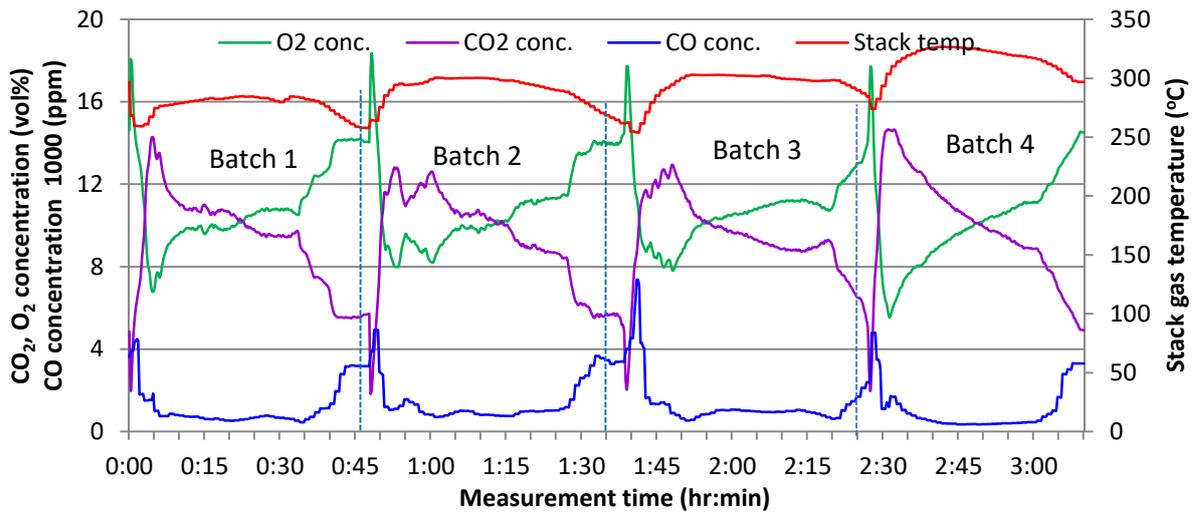


Fig. 6. Variation of gas concentrations of CO, CO₂, O₂ and stack temperature measured for the 20 kW stove

It can be seen from the figure that at the start-up phase, the highest concentrations of CO and significant variations of temperature of the flue gas occur. During the combustion phase, the CO concentrations are sufficiently lower and the stack temperature is higher. In figure 6, it is also observed that O₂ concentrations increase and CO₂ concentrations decrease during the combustion phases. This might be explained by the combustion of volatiles at the start of the combustion phase followed by a combustion slowdown as the fuel amount decreases.

3.5. CO emissions

CO emissions are observed in the combustion of all carbonaceous fuels, as an intermediate product of the combustion process. It is the most important intermediate product of fuel conversion to CO₂. It is oxidized to CO₂ under appropriate temperature and oxygen availability and sufficient presence of OH radicals. Figure 7 shows the comparison of CO emissions obtained from all the measurements from both stoves with the required limit value of standard NBN EN 13229 [24].

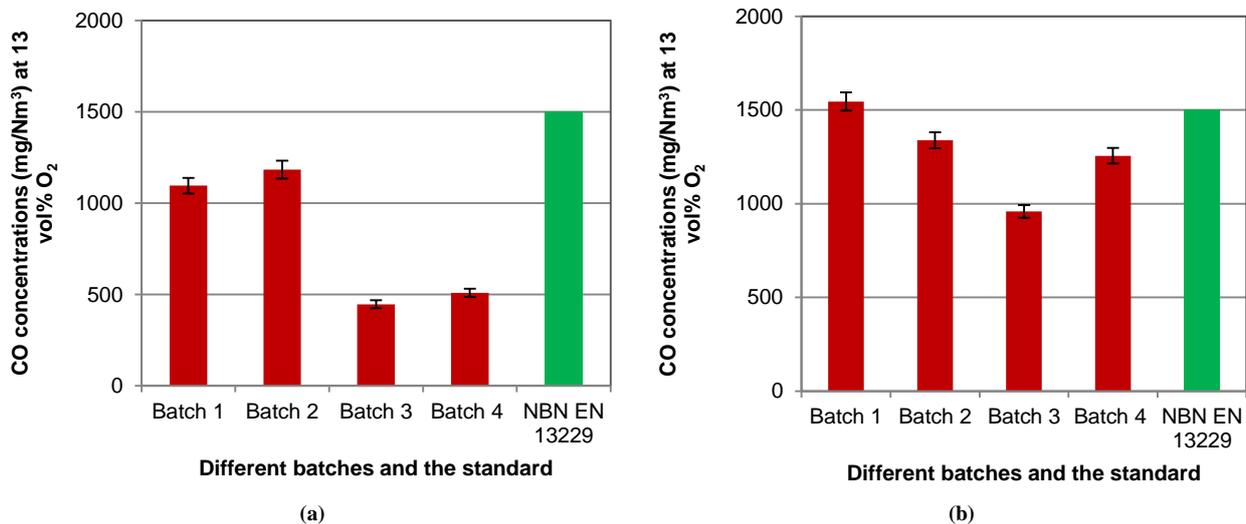


Fig. 7. Comparison of CO emissions with the Standard, (a) for the 10 kW stove, (b) for the 20 kW stove

The CO emission values presented in this paper are normalized to 13 vol % dry oxygen content. The error bars present the uncertainties of measurements calculated as the square root of the sum of the square of the standard error of mean (SEM) and the instruments' error. Both stoves (except

batch 1 of the 20 kW stove) satisfied the required limit value of the standard. The results show that the CO emissions from all the batches varied from 447 to 1184 mg/Nm³ for the 10 kW stove and 958 to 1545 mg/Nm³ for the 20 kW stove. It is observed that the CO emissions with the 20 kW stove were

higher than the 10 kW stove due to the differences in combustion chamber volume, fuel consumption and heat output. The average fuel load for each batch of the 20 kW stove (4.37 kg/batch) was about 2 times higher than the 10 kW stove (2.19 kg/batch). This can also be discussed in other ways. The higher air excess factor ($\lambda=2.1$) obtained in the 20 kW stove might have caused lower combustion temperature, leading to high CO emissions. On the other hand, a correctly matched air excess factor ($\lambda=1.8$) for the 10 kW stove created favorable combustion conditions leading to less CO emissions. No correlation was observed between CO emissions and minor modification of primary air flows into the combustion chamber. The higher CO emissions indicate poorer combustion conditions since these are related with incomplete combustion. Present results of the CO emission are close to those reported in another study of a residential modern wood stove [25, 26], while quite lower than those reported in other studies of wood modern stoves [9, 27-29]. CO emissions from residential biomass combustion 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. Hukkanen et al. [30] 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.

4. Conclusion

This study presents particle mass concentrations, particle mass size distributions and CO emissions obtained from several combustion batches of two commercially available modern wood stoves with a capacity 10 kW and 20 kW, respectively. The combustion experiments were performed at the combustion laboratory of a stove manufacturing plant in Belgium. The following conclusions can be made from this study.

- The obtained particle mass concentrations results of PM_1 and $PM_{2.5}$ demonstrate quite variation in the measured values over time for the different batches, which is typical for the combustion of wood log stoves.
- The particle mass size distributions obtained from the both wood stoves shows that maximum particle concentrations varied between 330 nm and 500 nm. It seems that the particle mass size distributions of both stoves are quite similar. These ultrafine particles are very harmful for human health as they penetrate the alveolar region of the lung.
- The CO emissions from all batches of both stoves (with exception for the Batch 1 of 20 kW) satisfied the required limit value of the standard. The results of CO

emissions from the wood stoves demonstrate the detailing characterization of certain parameters could be useful for the improvement of the entire combustion process.

- CO emissions from small scale biomass combustion appliances can be reduced using flue gas cleaning technologies such as catalytic combustors.
- The experimental results of PM_1 , $PM_{2.5}$ concentrations and CO emissions from combustion measurements could be useful for the improvement of the combustion process as well as the reduction of gaseous and particle mass emissions from these residential biomass combustion appliances.

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