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Flame confinement in biomass combustion systems for particles abatement

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ABSTRACT

This work explores the use of open-pore, inert ceramic foams with different pore sizes as particle abatement systems in small biomass combustion systems. Porous foams made of silicon carbide with pore sizes 10 to 60 pores-per-inch were installed in an in-house designed combustion unit operated with wood pellets. Their effects on the temperature distribution inside the chamber, particulate and gases emissions were studied using different airflow rates in the reaction-limited regime (low equivalence ratio) to minimise stoichiometric factors. The influence of pore size, foam position with respect to the flame and space velocity were assessed. The confinement of the flame with inert foams was found to substantially modify the temperature distribution in the combustion chamber, improve the air-fuel mixture, and favour the thermal decomposition of the pellet, leading to a reduction in particulate emissions when compared to free-flame combustion at the same experimental conditions. In general, the amount of particulate matter was found to decrease by up to one order of magnitude as the pore size of the foam was reduced, while the temperature gradient in the combustion chamber was increased. Nitrogen oxides and carbon dioxide emissions were essentially unchanged, irrespectively of the pore size of the foam. It is expected that these values will be improved with longer residence times, as happens in operations with reduced excess air ratios. These results suggest that it is possible to control pollutants derived from domestic heating within the most restrictive current regulations on particulate emissions by integrating flame confinement designs with better operating practices and efficient abatement systems.

1. Introduction

Encouraged by the most recent climate and energy policies [1], biomass is playing an increasingly leading role in the energy landscape [2], with an increasingly higher share in the renewable mix [3]. While providing other benefits, domestic biomass boilers are one of the main sources of particulate emissions (PM emissions) worldwide [4], and they are responsible for millions of premature deaths [5]. They are especially relevant in rural areas [18]. For this reason, current regulations impose severe PM emission limits on biomass combustion facilities [6]. For instance, the eco-design requirements presented in the Commission Regulation 2015/1189 set PM emission limits of 40 mg/m^3 for automatically stoked boilers and 60 mg/m^3 for manually stoked boilers [7].

PM emissions from pellet-fuelled stoves are lower than those of wood-fired stoves [8]. Upgraded biomass fuels provide a higher control and allow optimised combustion, reducing emissions of products of incomplete combustion. However, fine PM emissions from a pellet-fired biomass boiler may range from 0.4 g/kg of pellets to 2.91 g/kg of pellets [9].

PM emissions may be reduced with pre-combustion and post-combustion systems. Preventive measures (pre-combustion) to reduce PM emissions include improving fuel quality, modifying appliance design, reducing energy demand, or using better operating practices [10]. For medium and large combustion plants, there are several post-combustion PM control systems (baghouses, electrostatic precipitators, wet scrubbers) that provide high filtration efficiency (greater than 95%) with reasonable costs [11]. However, these large systems become too expensive when the combustion facility is relatively small (less than 1 MW_{th}) [10]. For small combustion facilities, few affordable end-of-pipe (post-combustion) PM abatement systems have been proposed [12].

Catalytic wall-flow particulate filters [13], widely spread in the automotive industry, can achieve high filtration efficiencies (~92%).

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However, they present challenges for their effective application in small biomass combustion systems. They introduce high backpressures in the system, difficulting the combustion stability and requiring frequent regeneration cycles [14]. To overcome these drawbacks, some researchers propose using ceramic filter foams with high porosity [15]. Meloni et al. [16] showed that open-pore ceramic foams could reduce PM emissions by up to 60%, depending on the pore size.

Ceramic foams can be placed either in the exhaust pipe (far from the combustion region), where they act as mere particle filters [17] or inside the combustion chamber (near the combustion region), where they can also interact with the flame [18]. Depending on the size of the pores and their position relative to the flame, a ceramic filter foam can help capture airborne particles while controlling and homogenizing the thermal field in the combustion chamber [19]. The presence of local temperature peaks in the combustion region affects the production of particles and the emission of other pollutants such as Nitrogen Oxides, NO_x [20]. Their values will depend on the scale. In MW-scale boilers, maximum temperatures reach values above 1300 K at the combustion zone but with large sections at temperatures below 400 K [21]. Small combustion systems are colder with lower temperature peaks and mean temperatures [22]. NO_x control is a relevant design challenge in large boilers [23]. In small domestic systems, the challenge is the control of PM and CO emissions, maintaining high efficiencies in the global system. The distribution of temperatures affects the development of the combustion and formation of PM and CO. Combustion will be controlled by air in excess ratio, the physics of the combustion region [24 25], and the chemical characteristics of the fuel [26].

The flame confinement with porous foams in biomass pellet-fired combustors is being recently explored as a way to reduce PM emissions. It modifies the framework of the combustion, the physics and the distribution of the temperatures in the combustion region. It constrains the free flame development and, in the pathway of the gases and volatiles, it confines them in small volumes limiting the possible evolution of the combustion. It can be a relatively simple approach to integrate into biomass combustion systems designs to control PM emissions. The flame confinement is being mainly studied from a macroscopic physical point of view. This work analyses the impact of inert ceramic foam on the combustion process and PM production mechanisms. It makes a first approach to the effects of porous confined combustion development. The study is performed in an in-house designed small solid biomass combustion test bench developed to study biomass microporous combustion. The combustion tests were performed with a constant fuel feed rate of 6 pellets/minute (0.29 kg/h) and two airflow rates: 90 m^3/h and 110 m^3/h.

This pilot combustion unit was designed to continuously burn biomass pellets at a constant feed rate, maintaining stable combustion with ceramic foams with pore sizes of 10, 30 and 60 PPI (pores-per-inch) and characteristics. They were tested as filter/container elements under different operation conditions. First, a thorough characterisation of the biomass fuel and the ceramic foams was made. Then, the temperature profiles and the gas emissions under different operating conditions and different combustion chamber configurations were measured, paying particular attention to the elemental composition of the agents involved in the process and the particle size distribution of the soot at different sampling points. A critical analysis of the data was then performed to combine all the results to construct a justified theoretical explanation of the observed phenomena.

2. Materials and methods

Tests were designed to evaluate the impact of the inert porous foams on the combustion process and the changes in the PM emission mechanisms under different operating conditions in small solid biomass combustion systems. Commercial pellets were used for fueling the test bench. Particular emphasis was put on keeping identical fuel-to-air ratios in all the experiments. In this way, the thermal effects could be analysed independently, requiring a constant solid fuel feed rate and additional control for the pressure drop introduced by the finer-pore foams. This section provides a detailed description of the combustion facility and the characterization techniques.

2.1. Fuel

This work used high-quality commercial pinewood pellets (ENplus® A1, GreenEnergy) as fuel (diameter = 6 mm). Fig. 1 shows a photo of the pellets. According to the manufacturer, this biomass fuel contains 6.19% moisture and 0.45% ash on average. Its heating value is $LHV = 5647 Kcal/Kg$. An exhaustive characterisation of this fuel was performed in a previous publication [19]. Its composition is presented in Table 1 and is similar to that of other biomass fuels reported in previous works [27-29]. Pellets were classified based on their length to facilitate a constant feed rate into the combustion chamber, and only those 15–20 mm long were used.

2.2. Foam filters

Commercial ceramic foams (VUKOPOR S® from LANIK s.r.o) made of silicon carbide (SiC) with alumina (Al_2O_3) and silica (SiO_2) as sintering additives [30] were used in the present study. Foams of 10, 30 and 60 PPI were selected to study the effect of pore size while maintaining total porosity fixed (Fig. 2). The pore sizes for the tests were chosen based on two criteria: (i) the estimated critical pore size capable of sustaining porous combustion (Section 3.1.2) and (ii) evidence of optimum temperature profiles found in a previous study [31]. For integration in the combustion test bench, foams dimensions were 100 × 100 × 20 mm.

2.3. Combustion facility

The combustion test bench unit was described in [19]. It consists of a well-insulated combustion chamber with a height-adjustable grill and a perimeter support bracket (Fig. 3**b and 3c**). The grill accommodates the pellet combustion bed and adjusts the combustion chamber configuration. The support bracket is designed to hold the ceramic foams. Ten N-type thermocouples measured the temperature distribution through the chamber. Two additional thermocouples measured the temperature in

Fig. 1. Pinewood pellets for the tests (ENplus® A1, GreenEnergy).

Table 1
Ultimate composition analysis of pinewood pellets (wt.%).

Elemental analysis	C	H	O	N	S
% Weight, dry basis	44.484	5.498	~43*	0.0690	≤ 0.186
Proximate analysis		**Moisture**	**Volatiles**	**Fixed carbon**	**Ash**
% Weight, as received		6.82	74.12	18.83	0.23

* Calculated as the remaining up to 100%.

the ashtray module and in the chimney. They are mineral insulated thermocouples with nickel–chromium alloy sheaths to avoid possible deviations due to radiation in the temperature measurements. The in-house combustion test bench was developed focused on the tests for testing the effect of the confined flame compared to the free flame tests. It is not a heating conceived element, and it works with high air in excess ratios to assure stable and repeatable operations.

Two measuring probes for an optical particle sizer (OPS 3330, TSI) and another for a gas emission analyzer (Testo 350) were attached to the upper part of the combustion chamber. A frequency controller acting on a Sunon CY 201 fan installed on top of the chimney established an adjustable constant airflow rate, measured using a CFM/CMM

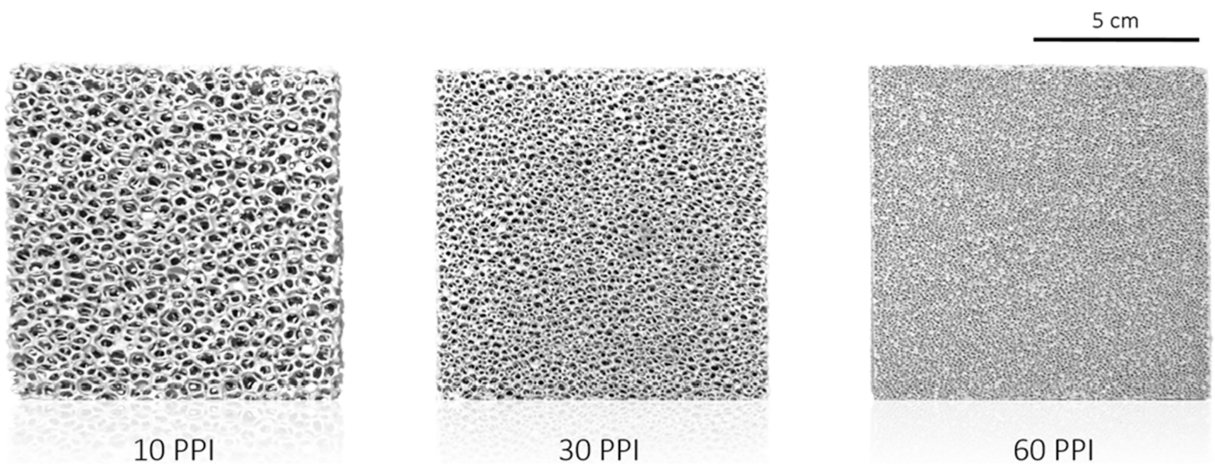

Fig. 2. Ceramic foams with different cell densities were used in the combustion experiments.

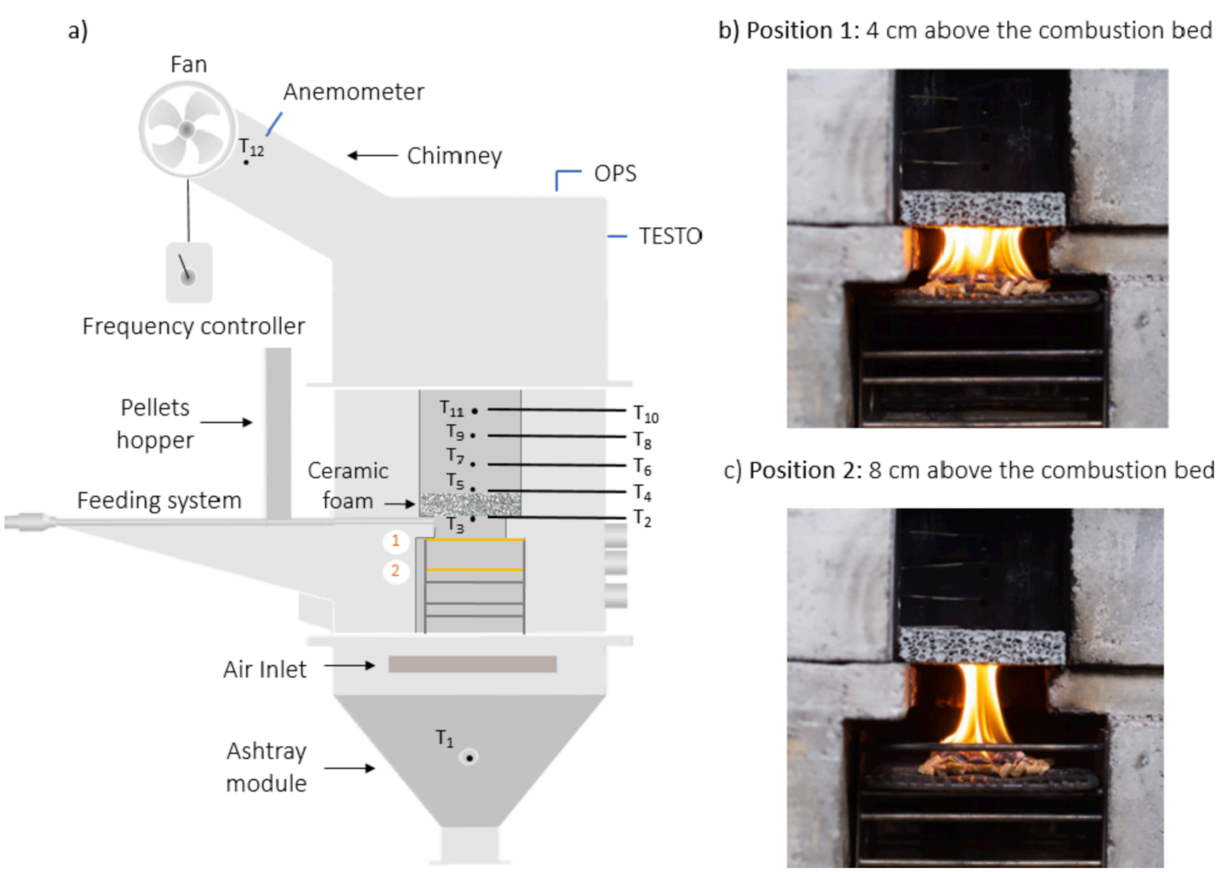

Fig. 3. (a) Schematic of the facility; tested positions of the biomass fuel grill: (b) 4 cm (position 1) and (c) 8 cm (position 2) above the combustion bed.

thermoanemometer (Extech Instruments). Fig. 3a shows the schematic layout of the experimental facility. The optical particle sizer provides the distribution of particles. PM mass was estimated using the optical diameter as presented in [32].

2.4. Combustion experiments

Each test started by firing a pile of 40 g of pellets on the grill, followed by a 15 min interval for thermal stabilization. Then a constant feed rate of 6 pellets/minute (0.29 kg/h) was supplied to the combustion unit. For the final composition presented in Table 1, the stoichiometric air supply is around 1.2 Nm^3/h [33].

The influence of air flow rate on the temperature distribution of the combustion chamber and exhaust gas composition is analysed using two different flow rates: 90 m^3/h and 110 m^3/h, corresponding to space velocities of 124 s^{-1} and 155 s^{-1}, respectively. Space velocity (SV) was calculated as the ratio of volumetric gas flow rate Q to the bulk volume of the porous foam V_{foam}.:

$$SV = \frac{Q}{V_{foam}}\left[s^{-1}\right] \tag{1}$$

The volume of the pieces of porous foam is fixed and determined by their geometric dimensions. The airflow can affect the combustion process in two ways [34]: on the one hand, it can influence the chemistry of the process depending on the stoichiometric proportions (air to fuel ratio); on the other hand, it affects the heat transfer process due to its convective effects. In this work, the chemical effects of the airflow rate have been minimised by maintaining a low equivalence ratio and forcing the process to be in a reaction-limited regime [35]. Reducing the air excess ratio allows (i) to analyse the effect of the flow rate on the combustion temperatures and the PM production without (or at least minimising) the chemical factors intrinsic to the specific fuel; ii) to maintain a stable and fully repeatable combustion pattern in the combustion test bench. In commercial biomass boilers with lower air to fuel ratios, longer residence times, and higher temperatures, the impact of the flame confinement on particle abatement efficiency is expected to be higher. Under the assumptions presented, the porous combustion characteristics will be maintained, but designs will consider the additional pressure losses. Table 2 summarises the cases studied in this work:

3. Results

A set of tests was performed under different combustion chamber configurations and operating conditions (Table 2), identifying the effect of different experimental conditions on PM emissions of solid biomass combustion systems in terms of concentration and size distribution. Most of the PM formation mechanisms were observed to depend on temperature and, more specifically, on its spatial distribution and the presence of high-temperature regions.

Table 2
Case studies considered in this work.

Case study no.	Position of the biomass fuel grill to the foam (cm)	Space velocity (s^{-1})	Foam cell density (PPI)
#1	4	124	10
#2	4	124	30
#3	4	124	60
#4	4	155	10
#5	4	155	30
#6	4	155	60
#7	8	124	10
#8	8	124	30
#9	8	124	60
#10	8	155	10
#11	8	155	30
#12	8	155	60

3.1. Temperature distribution

The influence of two factors on the temperature distribution was studied: the airflow rate and the combustion chamber configuration, modifying ceramic foam position over the grill.

3.1.1. Effects of the flow rate on the temperature

This study addresses the physical influence of airflow rate on the combustion process as a result of diffusive or advective heat transfer mechanisms.

- Advection refers to the heat transport by bulk motion of the gas. Advection transfers the heat downstream the exhaust gas pipe.
- Diffusion refers to the standard heat transfer mechanisms: conduction, convection and radiation.

Fig. 4 presents the temperature distribution in the chamber as a function of the position for different flow rates. In general, the results indicate that an increase in flow rate causes a slight reduction in temperature.

The temperature gradients through the foam are in the range of 50 °C to 480 °C. In the most extreme cases (60 PPI), the high temperatures under the foam are due to the fact that they are being measured very close to the flame.

In free-flame tests (without foam), reducing the air flow rate increases the temperature levels at all heights, widening the combustion influence section. In these tests, the stoichiometric effects are considered minor since the combustion takes place in a reaction-limited regime with a low equivalence ratio. A higher flow rate may favour heat transfer because of diffusion effects if the flow is turbulent. Even for free-flame tests, both flow rates result in a turbulent flow. The Reynolds number has been estimated at 9070 and 11250 for low and high flow rates, respectively. However, increasing the airflow rate also favours heat transfer as a result of advective effects. This turns out to be the dominant factor in the heat transfer process. Consequently, when the airflow rate is increased, the combustion heat is dissipated faster, and the temperature levels decrease throughout the height of the chamber.

The last thermocouple (T_{12}) was placed at the end of the non-isolated exhaust pipe where, due to heat losses, the exhaust gases arrived much colder. Consequently, variations in T_{12} are of a smaller order and cannot be identified in the scale of Fig. 4. This trend may also be observed below in Fig. 5.

Airflow rate has a smaller effect when a high-density confining foam

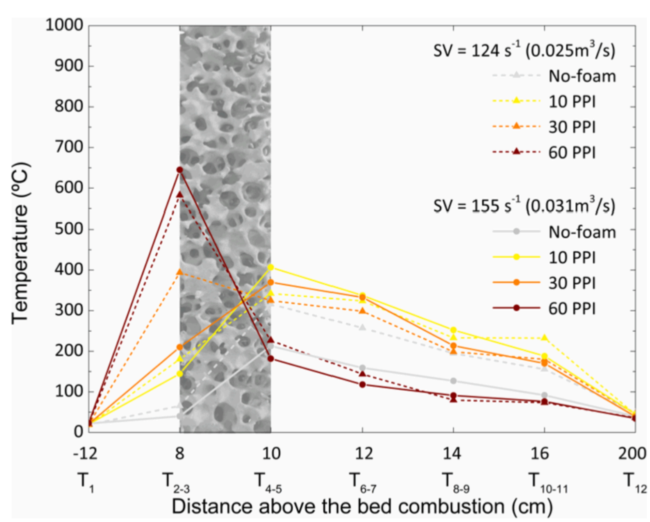

Fig. 4. Temperature distribution in the combustion chamber for the free flame and the confined flame tests (10, 30 and 60 PPI). Comparison for two different space velocities: 124 s^{-1} (triangle) and 155 s^{-1} (circles).

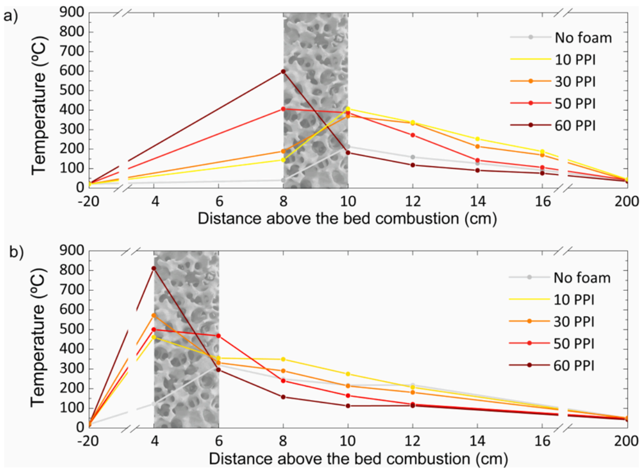

Fig. 5. Temperature distribution in the chamber above the combustion bed for different positions of the ceramic foams for the free-flame and confined-flame tests at 0.031 m^3s^{-1}. Data for experimental tests of 50 PPI are also shown.

(60 PPI) is used. In this case, the placement of the foam is likely to create more turbulence in the air, favouring the mixture with a volatile fraction of the fuel. The combustion reaction takes place mainly under the foam, and most of the energy is released there. A high-temperature gas "cloud" is observed between the fuel grate and the foam. This phenomenon overshadows advective effects, and the temperature levels along the chamber are similar for both flow rates.

It is interesting to note the particular influence that the modification in the flow rate has on the temperature field for the medium density 30 PPI foam. In this case, a slight variation in the flow rate (~24%) turns out to determine the preferential combustion area below or above the foam:

- When the flow rate is higher, the residence time of the volatiles under the foam is shorter. The reaction begins on the combustion bed but extends upward, surpassing, in some cases, the upper surface of the foam. In those cases, the flame is not totally confined. A relevant amount of heat is released above the foam, which raises the gas temperature in that region of the chamber.
- In contrast, when the flow rate is lower, a longer residence time (favoured by a slightly higher equivalence ratio) enables the earlier start of the combustion reaction, which concentrates more in the confining region between the grate and the foam.

This observation suggests that for each foam density or even for each chamber design (distance from the combustion bed to the foam), the airflow rate could be adjusted to set the preferential combustion area. At a certain optimum point, the course of the combustion reaction might take place under superadiabatic conditions. This phenomenon has been described extensively in the literature [36]: When a combustion reaction takes place within a porous medium, the heat released downstream by the exothermic reaction may be absorbed by the solid phase and transferred upstream by a conduction mechanism. The combustion reactants, which get into the porous medium at a lower temperature, may in turn absorb this heat and be burnt in superadiabatic conditions. This creates a thermal energy loop or a "heat recirculation" within the porous medium. The positive effects of the porous combustion on the PM reduction will be increased when the residence times are higher, with lower air excess ratios as happens in commercial biomass combustion systems.

3.1.2. *Effects of the location of the filter foam on the temperature*

The position of the porous ceramic foam and its distance from the flame affected substantially to the temperature distribution. Furthermore, it showed a strong dependency on the pore size of the foam under different operating conditions. Fig. 5 shows the temperature distribution through the combustion chamber for the different locations of the ceramic foams (Fig. 3**a and 3b**). Data from experimental tests of 50 PPI are also shown for comparison. In all cases, reducing the distance between the combustion bed and the foam caused a significant increase in temperature. The general trend is shown in Fig. 5**a,** where the foam was placed 8 cm above the combustion bed: a denser foam was correlated with a higher temperature in the combustion area. However, this trend was not followed when the foam was located closer to the combustion bed (Fig. 5**b**).

When 60 PPI and 50 PPI foams were used, the temperature level increased by 210 °C and 95 °C, respectively, due to the reduction of the distance between the combustion bed and the foam. However, for the 30 and 10 PPI foams, it is interesting to note the strong influence that the variation of the heights of the filter element has on the temperature field, reaching a temperature increase of 370 °C and 310 °C respectively. This sharp increase in temperature in the combustion region when low- and medium-pore density foams are used could be associated with the heat recirculation provided by the porous medium. When an exothermic combustion reaction takes place within a porous medium, the presence of the solid foam may promote the recirculation of the heat from the reaction zone towards the unburned reactants entry area (upstream) by conduction [37]. This extra energy provided by the porous solid creates an enthalpy excess which helps the mixture to react in superadiabatic conditions [38]. This phenomenon is characteristic of a porous microcombustion and may be responsible for the sudden increase in temperature in the combustion region.

An estimation of the critical pore diameter required for the flame to spread within the porous medium was made to support the evidence of porous combustion [39]. This pore diameter is correlated with the critical Peclet number by the following equation (Eq. (2)):

$$Pe_{cr} = \frac{S_L \hat{A}\cdot d_{cr}}{\alpha} \tag{2}$$

where S_L is the laminar flame speed, d_{cr} the critical pore diameter, and α the thermal diffusivity of the unburned gas. Flame quenching has been proven to occur in porous ceramics for values of the Peclet number values below $Pe_{cr} = 18$ [40]. Several assumptions were made to evaluate d_{cr} since there was no insight into the reacting volatile gas or its local combustion conditions. The volatile fuel gas was characterised as gasified biomass gas [41] or syngas [42,43]: $2.00\hat{A}\cdot 10^{-5} m^2 s^{-1} < \alpha < 2.65\hat{A}\cdot 10^{-5} m^2 s^{-1}$. The speed of the laminar flame was taken from the lowest equivalence ratio in each bibliographic reference: $\phi = 0.5$ in [42,43]; $\phi = 0.8$ in [41], resulting in values from $5cm/s < S_L < 22cm/s$. Based on these considerations, the critical pore diameter was estimated to range between $2.0mm < d_p < 7.2mm$.

Fig. 6 shows representative SEM micrographs of ceramic foams. The foams have an open 3D structure made up of windows-connected pores, distributed in turn over the pore wall (Fig. 6**a**). The pore window determines the dimension of the flow path. The microstructural characterisation of the different foams reveals that the pore size varies between 5.1 and 0.7 mm. For the densest foams, a pore diameter in the range of 0.7–1.3 mm was found (Fig. 6**b**). The 30 PPI foams exhibited a pore size between 1.8 and 2.3 mm with a channel diameter of 0.9 – 1.5 mm (Fig. 6**c**). Foams with 10 PPI had the highest pore diameter and window size, 3.9 – 5.1 mm and 2.2 – 2.8 mm, respectively (Fig. 6**d**). These values are in good agreement with the data in the literature on the pore size of porous ceramic foams [40,44]. This result shows that foams with higher pore density (60 PPI) will not allow the flame to propagate through, as their pores are much smaller than the critical size. Porous combustion would be only possible with the 10 and 30 PPI foams. The porous microcombustion process occurs randomly within the foam within a certain range of pore sizes, and the probability of success is greater as the pores and channel windows are coarser. This supports the assumption

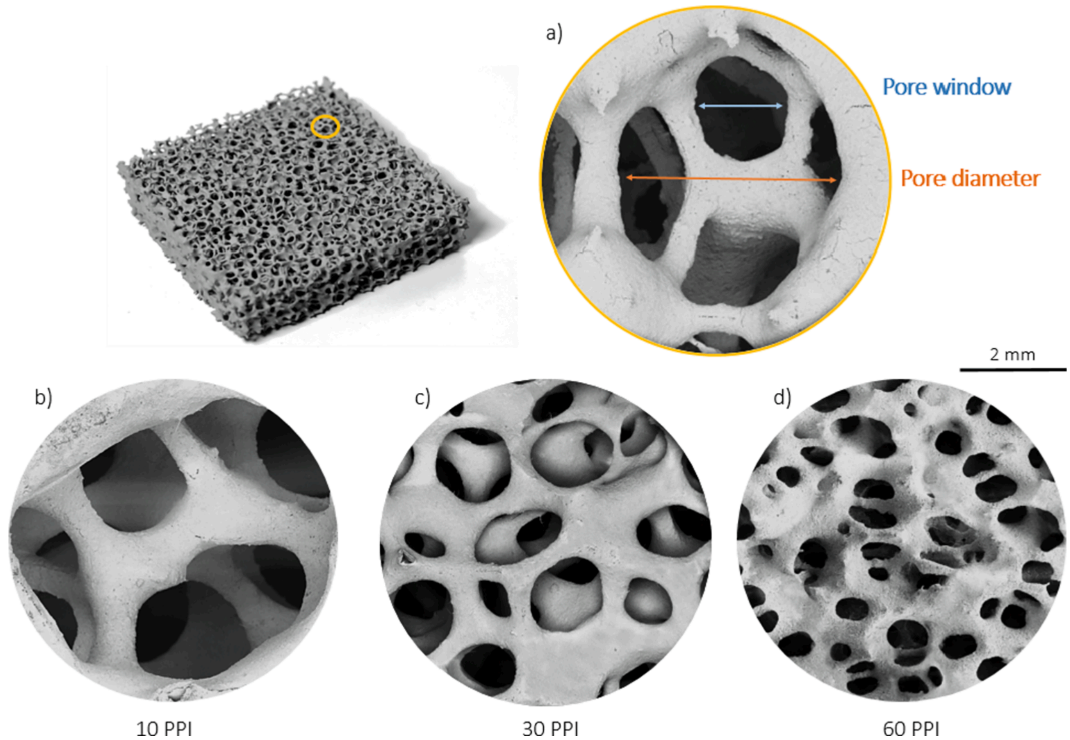

Fig. 6. SEM micrographs of ceramic foams.

mentioned above to explain the unexpected temperature rise in the 10 and 30 PPI experiments due to the heat recirculation caused by the porous micro-combustion.

3.2. Particulate emissions

The carbonaceous fraction (soot and organic matter) of PM emissions in pellet combustion devices results from inefficient or incomplete combustion [45]. Although some other factors (residence time, stoichiometry, fuel composition) may have some influence, the combustion temperature is determinant in the completeness of the reaction and, thus, in particle production [46]. In a previous study by the authors [19], the influence of temperature on the PM emissions of the combustion unit was analyzed for free flame and confined flame tests with different foams. It was observed that the concentration of PM was inversely proportional to the average temperature reached in the combustion region. The placement of a porous foam that confines the flame creates a homogeneous high-temperature region that promotes the complete oxidation of organic compounds. A similar trend was observed in this study for both air flow rates (Fig. 7). However, varying the airflow rate has different effects on the measured net number of particles depending on the confining element for similar temperature levels. In free-flame tests, increasing the airflow rate reduces the net particle record (63%), while in the tests with the 10 PPI foam, it causes a larger net particle measurement. The production of particles is generally lower with a higher flow rate. A fraction of the particle reduction is directly associated with the additional dilution that a higher airflow rate introduces. This effect represents a 20% reduction in any case. Considering that stoichiometric factors are negligible, the rest must be associated either with the track of the particle flows through the chamber (and its interaction with the particle probe) or with the gathering/dispersing effect of the air flow.

This work was performed at a laboratory scale with an in-house designed and constructed combustion unit. The OPS measured the number concentration of particles as a function of their optical diameter, and the Testo 350 unit measured gases emissions in vol.% ppm. PM

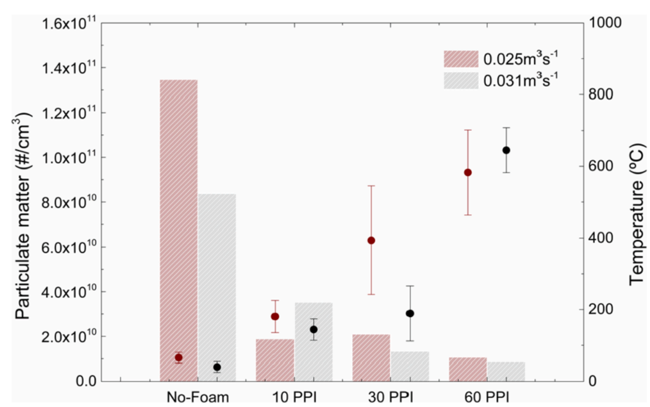

Fig. 7. Particulate matter emissions (bars) and the average temperature reached in the combustion chamber (dots) for two different space velocities: 0.025 m^3s^{-1} (124 s^{-1}) and 0.031 m^3s^{-1} (155 s^{-1}). The symbol “#” indicates the raw number of particles.

emissions mass concentrations were estimated based on an effective density [32]. In all experiments, the estimated PM emissions values were below 10 mg/Nm^3. The comparison between the confined and the free flame tests clearly shows the impact of the confinement with ceramic foams on PM emissions.

Fig. 8 shows the PM concentration in the exhaust gas stream of each confined flame test compared to that under free flame conditions. A reduction of more than 60% was reached by placing the ceramic foam just above the combustion region. When the distance between the foam and the combustion bed is greater (8 cm; light grey bars), denser foams result in a higher temperature in the combustion region and lower PM emissions. These results correlate well with data found in the literature. For example, Meloni et al. [16] reported that the filtration efficiency of open-pore ceramic foams strongly depends on their pore size. Under similar test conditions, a 65 PPI foam was 50% more efficient at capturing particles than a 10 PPI foam. However, this trend seems to

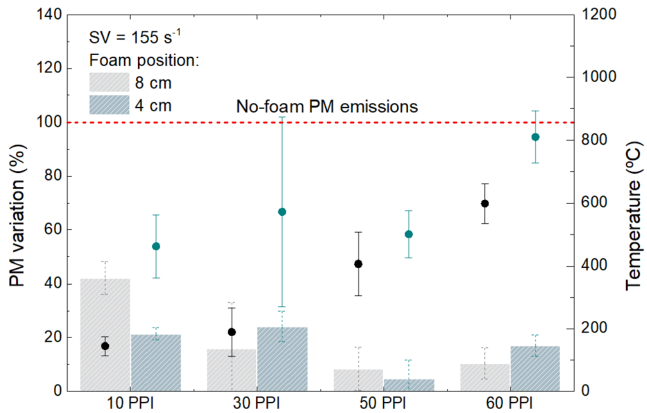

Fig. 8. Relative variation in PM emissions (referred to the number of particles) for confined flame experiments as a function of foam cell porosity and their distance from the combustion bed (bars) and the average temperature reached in the combustion chamber (dots) for space velocities of 0.031 m^3s^{-1} (155 s^{-1}). The dashed line shows the emission of particulate matter under free-flame conditions.

deviate when the porous medium is positioned closer to the grill where the pellets burn (4 cm; bars are blue-grey). When 60 or 50 PPI foams are used, reducing the distance between the foam and the combustion bed induces a slight increase in temperature levels. This modification does not appear to affect PM production (considering the standard deviation of the measurement) in any case. These results may indicate that, in the case of high-pore-density foams, their filtration performance would not be strongly affected by the position of the foam or by the different flow rates.

For 30 PPI, it is interesting to note the wide temperature deviation observed and its influence on PM emissions. As mentioned in **Section 3.1.2.** porous combustion has a random character, and its probability of success depends on the pore and window size of the foam for a certain operating condition. The mean pore diameter of 30 PPI foams appears to meet the critical value; however, the channel diameter may be insufficient in some cases, inducing quenching when the flame spreads through the pore window. The differences in heat recirculation due to this behaviour could be responsible for the wide temperature deviation in the combustion region and the variation in PM emissions. Further research will be needed to evaluate this hypothesis.

Finally, as can be observed in Fig. 8, the concentration of particulate matter measured for the 10 PPI tests turned out to be comparable to that obtained for 60 PPI and 30 PPI. Additional evidence of porous combustion was found in these conditions with the 10 PPI foam. As shown in Figs. 4 and 7, when the 10 PPI foam is placed 4 cm above the combustion bed and the airflow rate is set at 0.031 m^3s^{-1} (SV = 155 s^{-1}), the temperature profile shifts towards the bottom surface of the foam, and the PM production is lower.

The 30 PPI case is an exception, where temperature levels and PM production seem decoupled. This behaviour requires additional study to understand the specific mechanisms involved. In general, as a rule of thumb, the use of ceramic foams confining the flame always seems a satisfactory solution to reduce PM emissions. The temperature rise associated with the porous combustion normally reduces PM emissions. This effect is expected to be higher with lower airflow excess ratios and longer residence times. The porous medium can perform two distinct functions depending on its location and pore density. Placing the foam in the exhaust duct helps to capture airborne particles. The influence of foam porosity on its filtration efficiency has already been mentioned, but setting the foam just above the combustion region may simultaneously contribute to controlling and homogenising the thermal field, improving the combustion. In the latter case, porous microcombustion would play an important role, as heat recirculation is characterised by increasing the speed of the flame and reducing emissions [36]. Considering that porous combustion is preferred for foams with the coarsest pores due to the critical pore size, the significant reduction in PM emission for 10 PPI experiments could be associated with the higher reaction rates and efficiencies achieved under these conditions. Wiinika et al. [47] reported a direct link between the amount of soot and organic compounds and incomplete combustion. In this sense, using foams with low-density pores just above the combustion bed may help improve the reactions that occur in the combustion process, reducing the products of incomplete combustion [48].

Considering that the lowest PM production is yielded with the 60 PPI foam, it is worth considering whether using a foam with higher cell density would further improve this effect. While an extension of this study is addressed, one might foresee that using a foam with a smaller pore size (higher cell density; i.e. 80 PPI) would accentuate the "high-temperature cloud of gas" under the foam. It might increase the mean temperature levels in the chamber and reduce PM emissions. This effect would not be so straightforward, though. A very small pore diameter might also be detrimental to the combustion: it might hinder the diffusion of reactants, lead to an early flame quenching, or even create such high backpressure penalising the stability of the combustion.

To better understand the influence of the location of the foam and its distance from the flame in the porous microcombustion process, the concentration of the main chemical species in the flue gas was monitored: oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2) and nitrogen oxides (NO_x).

NO_x emissions depend on different factors, including fuel composition (fuel NO_x) and high temperatures (thermal NO_x). However, since the temperatures reached in solid biomass combustion are usually much lower than 1600 °C, thermal NO_x is neglected [49]. Furthermore, due to the low presence of nitrogen in the fuel (Table 1), NO_x concentration remained in all tests below 6 ppm.

The volume concentrations of CO and CO_2 measured in the exhaust gases using the different ceramic foams are shown in Fig. 9Higher CO concentrations may be associated with incomplete combustion, carbon monoxide being an intermediate species in the oxidation process of hydrocarbon fuel to CO_2 and H_2O [50]. Therefore, higher CO_2 concentrations may be related to more developed combustion. CO emissions increase with decreasing pore size of the foam. Based on the calculations on the critical Peclet number (Section 3.1.2), it was concluded that foams with higher pore density (50 PPI, 60 PPI or more) do not allow the flame to propagate through. These foams block the flame, expand it horizontally, and force it to develop in a limited space. The temperatures measured under these foams are much higher because: (i) the convective heat flow upward is blocked, and (ii) the flame occupies almost all the space, and the thermocouples are immersed in it. Despite this, the CO concentration is observed to rise in these cases, proving that the combustion reaction is not complete. The foam is not providing to the

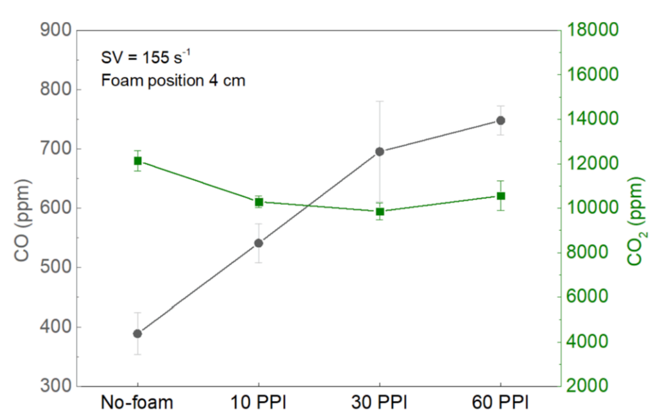

Fig. 9. Mean volume concentration of CO and CO_2 in the exhaust gases for the free-flame and confined-flame tests at space velocities: 155 s^{-1}. The foams were placed 4 cm above the combustion bed.

reaction enough space or a path long enough to fully develop. On the contrary, the pores of the 10 PPI and the 30 PPI foams exceed the critical pore diameter. Despite inducing a fainter thermal cloud with more moderate temperatures, these foams produce lower CO concentrations with more completed combustion. If the space under the foam is not enough to allow the reaction development, the reaction will also evolve through the foam or maybe even after it, obtaining porous combustion.

Fig. 10 shows the concentration of the main gas species in the exhaust gases for the free flame and confined flame tests comparing the two airflow rates used: 0.025 m^3/s and 0.031 m^3/s. When the air flow rate is modified, the concentration of species is affected. Considering that one of the flow rates is 24% higher than the other, a similar dilution factor should be considered. This could explain the lower concentration of CO_2 in the tests with a higher flow rate. Both concentrations are similar when the results are normalized through the flow rate. CO production was also influenced by the flow rate and the presence of foam, and its density. According to Shakiba *et al.* [54], increasing air excess improves the efficiency of porous burners and reduces CO emissions, particularly when coarse-pore foams are used. Although finer pore foams provide more stable combustion, in general, the pore size of 30 PPI foams is, in some samples, too small to allow the mixture to ignite [48].

The 2015/1189 eco-design regulation for biomass boilers requires compliance with maximum values for PM, carbon monoxide, and nitrogen oxide emissions for small solid fuel boilers (less than 500 kW) powered by solid fuels. In this context, the most restrictive limit for particulate emissions is established at 40 mg/Nm^3, and all conditions implemented in this work comply fully with these restrictions, obtaining values below 10 mg/Nm^3 in all experiments. Regarding CO emissions, automatic stoked boilers should be below 500 mg/Nm^3, and manually stoked boilers should be less than 700 mg/Nm^3, while NO_x should be less than 200 mg/m^3. The use of confined combustion and microporous combustion can be an effective approach for designing boilers and biomass combustion systems below these limits. The results obtained in a non-commercial test bench show how the reduction of excess air causes a significant increase in CO emissions, especially when fine-pore foams are used. In contrast, the CO concentrations measured that increase the excess air for coarse-pore foams would be below the limits imposed by compliance with this regulation. Regarding NO_x emissions, the NO_x concentration remained in all tests below 6 ppm, according to European regulations for gaseous emissions. Current commercial systems operate with small air in excess ratios to obtain high efficiencies of the global system reducing thermal losses. However, this strategy reduces oxygen availability, and it is challenging at the same time to control CO and PM emissions. The integration of porous foams promoting microporous combustion will increase temperatures and residence times at these temperatures. It is expected that its integration

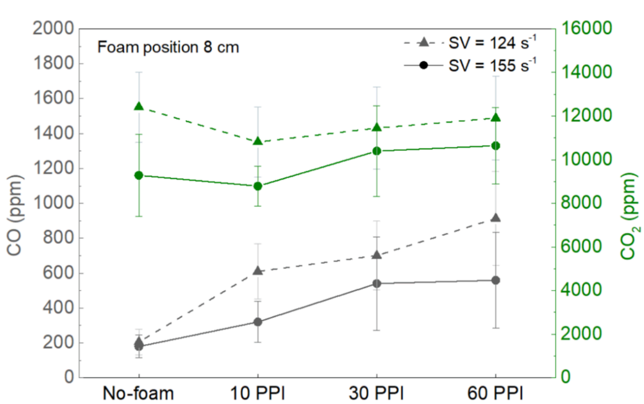

Fig. 10. CO and CO_2 volume in the exhaust gases for the free-flame and confined-flame tests. Comparison of two space velocities: 124 s^{-1} (triangles) and 155 s^{-1} (squares). The foams were placed 8 cm above the combustion bed.

within appropriate novel designs, taking into account the pressure drop in the foam and taking advantage of the temperature distribution and longer residence times, can reduce PM and CO formation and evolution.

This work shows how inert porous foams affect the combustion process and alter PM emissions under different operating conditions in small solid biomass combustion systems. The placement of an inert porous medium results in a higher and more homogeneous temperature field between the fuel grate and the foam. On the one hand, the higher the cell density, the stronger the "high-temperature thermal cloud" underneath the foam and the higher its filtration efficiency; on the other hand, the lower the cell density, the higher the probability of porous micro-combustion. Evidence of porous combustion is identified by placing a coarse pore foam just above the combustion region. The porous micro-combustion has a strong influence on the thermal field, improving combustion, and reducing emissions.

Furthermore, the increase in flow rate also led to a reduction in emissions. These effects have been shown to drastically modify the heat and mass transport phenomena in the combustion chamber, favouring the fuel–air mixture and thus significantly improving the reactions in the combustion process leading to reduced PM emissions. However, under non-optimal conditions, CO emissions may increase. It is expected that in commercial boilers or stoves with low air in excess, with higher residence times and temperatures, the effect of confined combustion on PM abatement will be higher. The optimal distances over the flame will vary, being shorter, and the effect of porosity will be very similar to the presented in this paper, but the designs of the whole system will have to consider the additional pressure drop.

4. Conclusions

This work has experimentally studied the impact of flame confinement for small solid biomass combustion systems in an in-house combustion test bench. The following main conclusions are derived from this study:

- The confinement of the flame with inert foams substantially modified the temperature distribution in the combustion chamber, improving the air–fuel mixture and reducing particulate emissions above 60%.
- The airflow rate significantly impacted the combustion process as it changed the ratio of diffusive to advective heat transfer mechanisms.
- A different behaviour has been identified for a specific case. With medium pore density foam (30 PPI), the airflow rate may determine whether the preferential combustion area is placed, below or above the foam.
- The reduction in the distance between the combustion bed and the foam caused a significant temperature rise, especially for the 30 and 10 PPI foams, where the temperatures increased by more than 200% (in Celsius) when compared with free-flame (no-foam) conditions.
- When the mean pore size of both foams is taken into account, this sharp temperature rise in the combustion region was associated with the heat recirculation provided by the porous microcombustion.
- Despite the limited thickness of the tested foams, porous combustion conditions have increased combustion efficiency while reducing emission levels.
- In general, as a rule of thumb, the use of ceramic foams confining the flame always seems a satisfactory solution to reduce PM emissions. The temperature rise associated with the porous combustion normally contributes to reducing PM emissions. This effect is expected to be higher with lower airflow excess ratios and higher residence times.
- Gases emissions were essentially unaffected by the pore size or position of the ceramic foams for the case of CO_2 and NO_x, while a three-fold increase in CO emissions was found when comparing the effect of the highest pore density foam (60 PPI) with the open flame experiments, probably due to reduced heat recirculation.

These results suggest that, by confining the flame using suitable ceramic foams and inducing porous combustion, it is possible to mitigate pollutants derived from domestic heating to comply with recent and restrictive European regulations on particulate emissions.

CRediT authorship contribution statement

D. Ciria: Methodology, Investigation, Data curation. **M.P. Orihuela:** Methodology, Investigation. **P. Moreno-Naranjo:** Investigation, Data curation. **R. Chacartegui:** Conceptualization, Methodology, Supervision, Resources, Writing – review & editing. **J. Ramírez-Rico:** Conceptualization, Writing – review & editing, Investigation. **J.A. Becerra:** Conceptualization, Methodology, Supervision, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] European Commission. 2030 climate & energy framework. EU Action Clim Strateg Targets 2014.
[2] International Energy Agency I. Key World Energy Statistics 2020 2020.
[3] Scarlat N, Dallemand J, Taylor N, Banja M. Brief on biomass for energy in the European Union. Publ Off Eur Union 2019. https://doi.org/10.2760/546943.
[4] Vicente ED, Alves CA. An overview of particulate emissions from residential biomass combustion. Atmos Res 2018;199:159–85. https://doi.org/10.1016/j.atmosres.2017.08.027.
[5] Hopke PK, Dai Q, Li L, Feng Y. Global review of recent source apportionments for airborne particulate matter. Sci Total Environ 2020;740:140091. https://doi.org/10.1016/j.scitotenv.2020.140091.
[6] Environmental Protection Agency. Subpart DDDDD — National Emission Standards for Hazardous Air Pollutants for Industrial, Commercial and Institutional Boilers and Process Heaters. 76 FR 15664 2015;40 CFR:1–86.
[7] European Commission. Commission Regulation (EU) 2015/1189. Off J Eur Union 2015:100–14.
[8] Boman C. Particulate and gaseous emissions from residential biomass combustion. Energy Technology and Thermal Process Chemistry. Umea University; 2005.
[9] Hays MD, Kinsey J, George I, Preston W, Singer C, Patel B. Carbonaceous particulate matter emitted from a pellet-fired biomass boiler. Atmosphere (Basel) 2019;10:1–14. https://doi.org/10.3390/atmos10090536.
[10] Pye S, Thistlethwaite G, Adams M, Woodfield M, Goodwin J, Forster D, et al. Costs and environmental effectiveness of options for reducing air pollution from small-scale combustion installations. Harwell 2004.
[11] Miller B. Particulate formation and control technologies. Foss Fuel Emiss Control Technol 2015:145–96. https://doi.org/10.1016/b978-0-12-801566-7.00003-8.
[12] Amann M, Cofala J, Klimont Z, Nagl C, Schieder W. Measures To Address Air Pollution From Small Combustion. Austria 2018.
[13] Stoppiello G, Palma V, Hugony F, Meloni E, Gualtieri M. Catalytic wall flow filters for the reduction of biomass boilers emissions. Chem Eng Trans 2014;37:19–24. https://doi.org/10.3303/CET1437004.
[14] Palma V, Meloni E, Caldera M, Lipari D, Pignatelli V, Gerardi V. Catalytic wall flow filters for soot abatement from biomass boilers. Chem Eng Trans 2016;50:253–8. https://doi.org/10.3303/CET1650043.
[15] Meloni E, Caldera M, Palma V, Pignatelli V, Gerardi V. Open cell foams filters for soot abatement from biomass boilers. Chem Eng Trans 2018;65:799–804. https://doi.org/10.3303/CET1865134.
[16] Meloni E, Caldera M, Palma V, Pignatelli V, Gerardi V. Soot abatement from biomass boilers by means of open-cell foams filters. Renew Energy 2019;131:745–54. https://doi.org/10.1016/j.renene.2018.07.098.
[17] Jesús Rico J, Patiño D, Cid N, Pérez-Orozco R. PM reduction and flame confinement in biomass combustion using a porous inert material. Fuel 2020;280:118496.
[18] Llamas Mesa A, Orihuela MP, Palomo-Guerrero F, Becerra-Villanueva JA, Chacartegui R, Llamas-Mesa A, et al. Study of the effect of flame top confinement with porous ceramic foams on the emissions of a domestic pellet boiler. 13th Conf. Sustain. Dev. Energy, Water Environ. Syst., Palermo (Italy): 2018.
[19] Ciria D, Orihuela MP, Becerra JA, Chacartegui R, Ramírez-Rico J. Impact of flame confinement on the particulate emissions of domestic heating. Fuel 2021.
[20] Glarborg P, Jensen AD, Johnsson JE. Fuel nitrogen conversion in solid fuel fired systems. Prog Energy Combust Sci 2003;29:89–113. https://doi.org/10.1016/S0360-1285(02)00031-X.
[21] Karim MR, Naser J. CFD modelling of combustion and associated emission of wet woody biomass in a 4 MW moving grate boiler. Fuel 2018;222:656–74. https://doi.org/10.1016/J.FUEL.2018.02.195.
[22] Chaney J, Liu H, Li J. An overview of CFD modelling of small-scale fixed-bed biomass pellet boilers with preliminary results from a simplified approach. Energy Convers Manag 2012;63:149–56. https://doi.org/10.1016/J.ENCONMAN.2012.01.036.
[23] Gómez MA, Martín R, Chapela S, Porteiro J. Steady CFD combustion modeling for biomass boilers: An application to the study of the exhaust gas recirculation performance. Energy Convers Manag 2019;179:91–103. https://doi.org/10.1016/J.ENCONMAN.2018.10.052.
[24] Farokhi M, Birouk M, Tabet F. A computational study of a small-scale biomass burner: The influence of chemistry, turbulence and combustion sub-models. Energy Convers Manag 2017;143:203–17. https://doi.org/10.1016/J.ENCONMAN.2017.03.086.
[25] Karim MR, Naser J. Numerical study of the ignition front propagation of different pelletised biomass in a packed bed furnace. Appl Therm Eng 2018;128:772–84. https://doi.org/10.1016/J.APPLTHERMALENG.2017.09.061.
[26] Forbes EGA, Easson DL, Lyons GA, McRoberts WC. Physico-chemical characteristics of eight different biomass fuels and comparison of combustion and emission results in a small scale multi-fuel boiler. Energy Convers Manag 2014;87:1162–9. https://doi.org/10.1016/J.ENCONMAN.2014.06.063.
[27] Dhaundiyal A, Bercesi G, Atsu D, Toth L. Development of a small-scale reactor for upgraded biofuel pellets. Renew Energy 2021;170:1197–214. https://doi.org/10.1016/j.renene.2021.02.057.
[28] Malaťák J, Gendek A, Aniszewska M, Velebil J. Emissions from combustion of renewable solid biofuels from coniferous tree cones. Fuel 2020;276:1–7. https://doi.org/10.1016/j.fuel.2020.118001.
[29] Schmid M, Beirow M, Schweitzer D, Waizmann G, Spörl R, Sche G. Product gas composition for steam-oxygen fluidized bed gasification of dried sewage sludge, straw pellets and wood pellets and the influence of limestone as bed material. Biomass Bioenergy 2018;117:71–7. https://doi.org/10.1016/j.biombioe.2018.07.011.
[30] Lanik n.d. www.lanik.eu.
[31] Ciria D, Orihuela MP, Becerra JA, Chacartegui R, Ramírez-Rico J. Impact of flame confinement with inert ceramic foams on the particulate emissions of domestic heating systems. Fuel 2021;304:121264.
[32] Orihuela MP, Gómez-Martín A, Becerra-Villanueva JA, Chacartegui R, Ramírez-Rico J. Performance of biomorphic silicon carbide as particulate filter in diesel boilers. J Environ Manage 2017;203:907–19. https://doi.org/10.1016/j.jenvman.2017.05.003.
[33] Paraschiv LS, Serban A, Paraschiv S. Calculation of combustion air required for burning solid fuels (coal/biomass/solid waste) and analysis of flue gas composition. Energy Rep 2020;6:36–45. https://doi.org/10.1016/j.egyr.2019.10.016.
[34] Ryu C, Bin YY, Khor A, Yates NE, Sharifi VN, Swithenbank J. Effect of fuel properties on biomass combustion: Part I. Experiments - Fuel type, equivalence ratio and particle size. Fuel 2006;85:1039–46. https://doi.org/10.1016/j.fuel.2005.09.019.
[35] Porteiro J, Patiño D, Collazo J, Granada E, Moran J, Miguez JL. Experimental analysis of the ignition front propagation of several biomass fuels in a fixed-bed combustor. Fuel 2010;89:26–35. https://doi.org/10.1016/j.fuel.2009.01.024.
[36] Wood S, Harris ATT. Porous burners for lean-burn applications. Prog Energy Combust Sci 2008;34:667–84. https://doi.org/10.1016/j.pecs.2008.04.003.
[37] Barra AJ, Ellzey JL. Heat recirculation and heat transfer in porous burners. Combust Flame 2004;137:230–41. https://doi.org/10.1016/j.combustflame.2004.02.007.
[38] Pisarello ML, Milt V, Peralta MA, Querini CA, Miró EE. Simultaneous removal of soot and nitrogen oxides from diesel engine exhausts. Catal Today 2002;75(1-4):465–70.
[39] Shafiey Dehaj M, Ebrahimi R, Shams M, Farzaneh M. Experimental analysis of natural gas combustion in a porous burner. Exp Therm Fluid Sci 2017;84:134–43. https://doi.org/10.1016/j.expthermflusci.2017.01.023.
[40] Joo HI, Duncan K, Ciccarelli G. Flame-quenching performance of ceramic foam. Combust Sci Technol 2006;178(10-11):1755–69.
[41] Munajat NF, Erlich C, Fakhrai R, Fransson TH. Influence of water vapour and tar compound on laminar flame speed of gasified biomass gas. Appl Energy 2012;98:114–21. https://doi.org/10.1016/j.apenergy.2012.03.010.
[42] Ouimette P, Seers P. Numerical comparison of premixed laminar flame velocity of methane and wood syngas. Fuel 2009;88:528–33. https://doi.org/10.1016/j.fuel.2008.10.008.
[43] Hu E, Fu J, Pan L, Jiang X, Huang Z, Zhang Y. Experimental and numerical study on the effect of composition on laminar burning velocities of H2/CO/N2/CO2 air mixtures. Int J Hydrogen Energy 2012;37:18509–19. https://doi.org/10.1016/j.ijhydene.2012.09.053.
[44] Řehořek L, Dlouhý IVO, Chlup Z. Tensile behaviour of open cell ceramic foams. Ceramics 2009;53:237–41.

[45] Obaidullah M, Bram S, De Ruyck J. An Overview of PM Formation Mechanisms from Residential Biomass Combustion and Instruments Using in PM Measurements. Int J Energy Environ 2018;12:41–50.

[46] Williams A, Jones JM, Ma L, Pourkashanian M. Pollutants from the combustion of solid biomass fuels. Prog Energy Combust Sci 2012;38:113–37. https://doi.org/10.1016/j.pecs.2011.10.001.

[47] Wiinikka H, Gebart R. Critical parameters for particle emissions in small-scale fixed-bed combustion of wood pellets. Energy Fuels 2004;18(4):897–907.

[48] Shakiba SA, Ebrahimi R, Shams M, Yazdanfar Z. Effects of foam structure and material on the performance of premixed porous ceramic burner. Proc Inst Mech Eng Part A J Power Energy 2015;229(2):176–91.

[49] Sartor K, Restivo Y, Ngendakumana P, Dewallef P. Prediction of SOx and NOx emissions from a medium size biomass boiler. Biomass Bioenergy 2014;65:91–100. https://doi.org/10.1016/j.biombioe.2014.04.013.

[50] Flagan RC, Seinfeld JH. Fundamentals of air pollution engineering. Courier Corporation 2012.