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Open Cell Foams Filters for Soot Abatement from Biomass Boilers

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The depletion of fossil fuels and the increasing environmental concerns related to their use, lead to the research of new solutions to limit the greenhouse gas effects. Among the available renewable energy sources for the mitigation of greenhouse gas emissions, biomass is the only carbon-based sustainable option; however its incomplete combustion can lead to the emission of hazardous and environmental pollutants, such as particulate matter (PM, or soot). Filtration devices for PM emissions are required in biomass combustion plants, if primary measures are not sufficient to respect the stricter emissions limits set by European Directives. Actually different filtration systems are available, and some have reached a technological maturity and wide diffusion, but they are quite expensive, e.g. electrostatic precipitators, sleeve filters and wet scrubbers. Therefore, a lot of research has focused on cheaper filtration solutions that can be applied both in new equipment and in retrofit of existing boilers, and may be easily scaled according to the boiler size, such as ceramic filters. In our previous works we studied the use of catalytic ceramic wall flow filters as soot emission control devices of biomass-fired boilers and stoves. Starting from those results, in this work we investigated the use of a different kind of filters, the open-cell ceramic foams, characterized by a different porosity if compared to wall flow filters. The filters were tested in a customised sampling line at the exhaust of a 30 kW pellets boiler, and regeneration was realised by means of a high-temperature electrical heater. During the tests, PM concentration in the flue gas was monitored by means of a real-time continuous detector and a cascade impactor. The tests evidenced that the higher average pores diameter of the foams, compared to ceramic wall-flow filters, resulted in two main consequences, (i) lower pressure drop, and (ii) lower filtration efficiency. In particular, the pressure drop never reached critical values for the actual operation of biomass boilers, and the filtration efficiency was higher than 50%. Therefore, open cells foam filters are an interesting solution for soot emissions control in biomass boilers and appliances. Further studies are currently carried out in order to investigate the effects of the deposition of a catalyst on the foams.

1. Introduction

Currently, fossil fuels cover approximately 80% of the global gross energy demand, but these energy sources will probably be depleted within the next decades, and increasing environmental concerns are related with their use, so the research focused on new solutions to limit the greenhouse gas effect (Saidur et al., 2011). Biomass is currently seen as the most promising carbon-based renewable energy source, in order to mitigate greenhouse gas emissions, even if its incomplete combustion can lead to the emission of environmental pollutants as well as substances which are hazardous to health, such as particulate matter (PM, or soot), polycyclic aromatic hydrocarbons (PAH), and several organic volatile and semi-volatile compounds (VOC) (Khan et al., 2009). The optimisation of combustion and the electronic control devices of modern biomass boilers and appliances are primary measures that must be taken into account to reduce emissions but, above all for small scale appliances, different factors limit their performance, and secondary measures may become necessary in order to respect stricter limits imposed by Authorities (Illerup et al, 2015). PM abatement techniques currently available are electrostatic precipitators (ESPs), fabric filters and wet scrubbers, which are standard solutions for big plants, but are still too expensive for small domestic appliances (Van Loo and Koppejan, 2008), even if some ESPs have been investigated also for small scale boilers (Migliavacca et al., 2014). In our previous works we studied the use of catalytic Silicon Carbide wall flow filters as soot emission control devices for biomass-fired boilers and stoves (Palma et al., 2016). These devices, even if characterized by filtration efficiency higher than 90%, typical of these devices used at the exhaust of Diesel engines (Meloni et al., 2017), showed excessive pressure drops for the specific application, so making them not suitable Starting from these results, the present work focused on the open-cell ceramic foams, characterized by a different porosity and by a different filtration mechanism with respect to wall flow filters. These filters are characterized by a sponge-like open structure with pore densities of typically 10-100 PPI (pores per inch), which creates an interconnecting porosity in the range of 75%-90% or even higher. Consequently, they have low aerodynamic drag, and generate considerable turbulence in the tortuous flow paths, which promote the deposition of the soot particles on the ceramic surface (Twigg and Richardson, 2007). This filtration mechanism is known as "deep bed filtration". In this work, we investigated the behaviour in terms of pressure drop, filtration efficiency and regeneability of filters prepared starting from two different porous open-cell ceramic foams, i.e. with 10 and 65 ppi, tested at the exhaust of a 30 kW pellets boiler present in ENEA laboratories.

2. Materials and methods

2.1 Open-cell foams

The tested filters were prepared starting from OBSIC foams, made in Silicon Carbide (SiC) and alumina, with two different porosity, i.e. with 10 and 65 ppi. The prepared filters, showed in Figure 1, were assembled in order to realize a radial flow of the exhaust gas, with the gas entering radially in the external walls and exiting from the central hole.

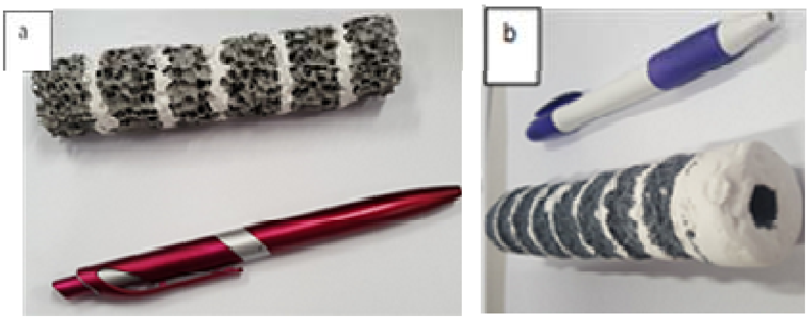

Figure 1: Open-cell foams investigated in this work: (a) 10 ppi OBSIC foam, (b) 65 ppi OBSIC foam.

The filters were properly shaped as cylinders, with nominal diameter 30 mm, length 125 mm and central hole diameter of 10 mm; the terminal part with the central hole was wrapped in a heat expanding intumescent ceramic-mat, i.e. Interam by 3M, in order to be enclosed in a filter housing placed in the sampling line at the exhaust of the biomass boiler.

2.2 Materials characterization

The prepared filters were characterized by Scanning Electron Microscopy (SEM mod. LEO 420 V2.04, ASSING), and Energy Dispersive Spectroscopy (EDX mod. INCA Energy 350, Oxford Instruments), before and after the tests. Preliminary activities also included the characterization in terms of solid compositions of the exhaust gases emitted by the biomass boiler.

2.3 Test facility and operating conditions

The tests were performed at the TH.EX.A.S. (THermal EXperimental Area of Saluggia) ENEA research facility. An overview of the test bench is reported in previous works (Stoppiello et al., 2014). The exhaust gases were produced by a pellets boiler KWB Multifire with a nominal power of 30 kW. The filter was located in a customised 1" ¼ stainless steel housing in the derivation column at the exhaust duct, from which gases were drawn by a Zambelli ZB1 volumetric pump. The derivation line and the filter housing were heated by two silicon heating bands with integrated temperature control, in order to keep the flue gas temperature close to 160°C and prevent condensation. Filters regeneration was achieved by a Watlow electric heater with a nominal power of 900 W and max temperature of 750 °C, wrapped around the filter holder and controlled by means of a PID Watlow model PM Express microprocessor. The electrical energy absorbed by the heater was monitored by a Vemer energy meter. The composition of the exhaust gas was monitored continuously upstream and downstream of the filter by means of specific analyzers. PM concentrations upstream the catalytic filter (at the exhaust of the boiler) were measured by means of Dekati cascade impactor, while downstream the filter fine PM was measured by Pegasor Particle Sensor, a continuous and real-time detector of the concentration of particles with an aerodynamic diameter up to 1 μm, in the range between 1 and 300 mg/m^3, based on the measurement of the electrical charge carried by particles. The forced draught in the exhaust duct and the pressure drop in the filter were measured by piezoelectric transducers, while temperatures of the flue gas and of the cooling water in the boiler were measured by K-type thermocouples. The water flow rate in the boiler was electronically controlled and measured by an electromagnetic induction flow meter. The main variables set for the hydraulic circuit were the volumetric flow rate (43 l/min), the maximum water flow temperature (70°C) and the minimum water return temperature (55°C). These quantities were recorded every second by means of a National Instruments DAQ system managed by a Labview® program ad hoc implemented. Tests were carried out at steady-state, nominal operation of the boiler, using EN A1 plus certificated fir pellets , whose composition is summarised in Table 1.

Table 1: Pellets composition

Element	Unit	Value
C	%wt db	50.85
H	%wt db	5.82
O	%wt db	43.20
S	%wt db	0.01
N	%wt db	0.10
Ashes	%wt db	0.24
Humidity	%wt av	6.50
LHV	kJ/kg av	17,44
Density	kg/m^3	690

The flue gas flowrate inside the filter, i.e. 14 NL/min, was calculated in order to approach in the filter the average flue gas velocity in the exhaust duct. Moreover, the suction nozzle was chosen in order to approach isokinetic conditions of the flue gas, drawn by a volumetric pump installed downstream the derivation column where the filter was located. During regeneration, the temperature of the external wall of the filter housing was increased from 160°C up to 600°C.

3. Results and discussion

3.1 Materials characterization

The PM emitted by the boiler was measured by a cascade impactor upstream the filter, which classifies airborne particles into four size fractions: up to 10 microns (stage 1), from 10 to 2.5 microns (stage 2), from 2.5 to 1.0 micron (stage 3), and smaller than 1 micron (absolute filter). The typical distribution of the particle fractions in the flue gas is depicted in Figure 2 (left). The gravimetric analysis of the aerosol particles gave the results collected in Figure 2 (right): on average PM1 and PM2.5 contributed to more than 94% and 98% of the total suspended particles (TSP), respectively. Furthermore, soot at the exhaust of the boiler was analysed by means of SEM technique (not shown here), which confirmed that the particles had the typical cluster structure with an average size of about 50 nm. The measured average total PM emitted by the boiler was about 100 mg/Nm^3 @10% O_2, even though significant cyclic fluctuations, typical of biomass appliances, were observed.

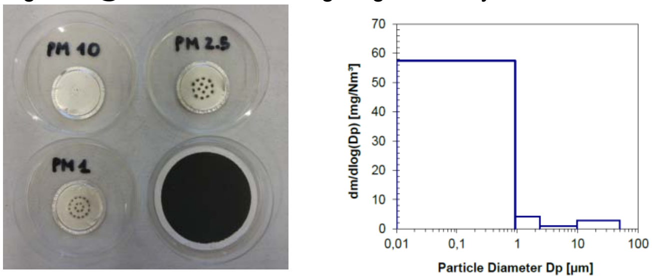

Figure 2: Particle distribution of soot emitted from the biomass boiler.

The two open-cell foams investigated in this work were characterized by means of SEM and SEM-EDX analysis. In particular, the different porosimetric characteristics of the two foams were characterised by an average pore diameter of about 2 mm for the 10 ppi OBSIC foam, and of about 200 μm for the 65 ppi OBSIC foam. The SEM-EDX images verified the species present on the OBSIC foams. The results relevant to the 65 ppi foam evidenced the presence of the main structural chemical elements of the OBSIC foam, i.e. C, O, Al and Si, confirming the structural characteristics declared by the supplier.

3.2 Preliminary soot deposition tests

The two different OBSIC foams were tested in terms of pressure drop and filtration efficiency. The filtration efficiency was calculated according to the following equation:

$$\eta_f = \frac{C_{before} - C_{after}}{C_{before}} \times 100 \qquad (1)$$

where C_{before} is the soot concentration in the exhaust stream upstream the filter, while C_{after} is the soot concentration downstream the filter. The pressure drop and the PM emissions downstream the filters for the 10 and 65 ppi OBSIC foams are reported versus time in Figure 3. The tests were performed for 15 and 13 hours, respectively.

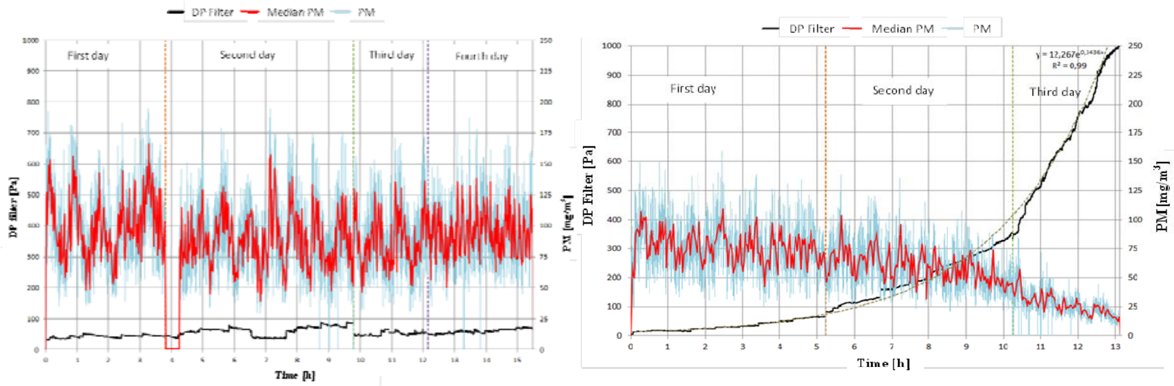

Figure 3: Pressure drop (black curve) and fine PM concentrations downstream the 10 ppi (left) and 65 ppi (right) OBSIC foam filters. The red line represents the PM value mediated every minute.

The results in Figure 3 showed a trend substantially flat of the DP curve (black line) and of the PM measured downstream the 10 ppi OBSIC foam during the deposition test, therefore, only a very little fraction of the soot emitted from the biomass boiler was trapped. In fact, the filtration efficiency was limited to 5%. This result demonstrated that the 10 ppi foam, even if characterized by very low pressure drop (about 50 Pa), had an average pore diameter too high for soot abatement in biomass boilers. The results relevant to the 65 ppi OBSIC foam evidenced a different behavior: indeed an increase of the DP curve (black line) and a contemporary decrease of the PM measured after the filter demonstrated that the soot filtration was more effective. In this case, the average filtration efficiency increased to about 60%. The results of these preliminary tests limited the next analysis to the 65 ppi OBSIC foams, since they showed the optimal compromise between pressure drop and filtration efficiency.

3.3 Soot deposition and regeneration tests

In the next phase, the 65 ppi foams were tested in several soot deposition and regeneration cycles, in order to investigate the repeatability of their performance and to verify any regeneration failures after the ashes deposition. In particular, the filter was submitted to seven consecutive soot deposition and regeneration cycles during a 38-hours test. The results shown in Figure 4 evidenced the good repeatability of the performance during different cycles; in fact, all the deposition and regeneration cycles showed (i) the contemporary increase of the DP (black line) and the decrease of the PM downstream the filter during the deposition phase, and (ii) the fast decrease of the DP during regeneration , which confirmed the complete filter regeneration. The regeneration efficiency was calculated with the following relation:

$$\eta_{reg} = \frac{\Delta p_1 - \Delta p_2}{\Delta p_1 - \Delta p_i} \qquad (2)$$

where Δpi is the initial pressure drop of the new filter, while Δp_1 and Δp_2 are the pressure drops in the filter at the beginning and at the end of regeneration, respectively.

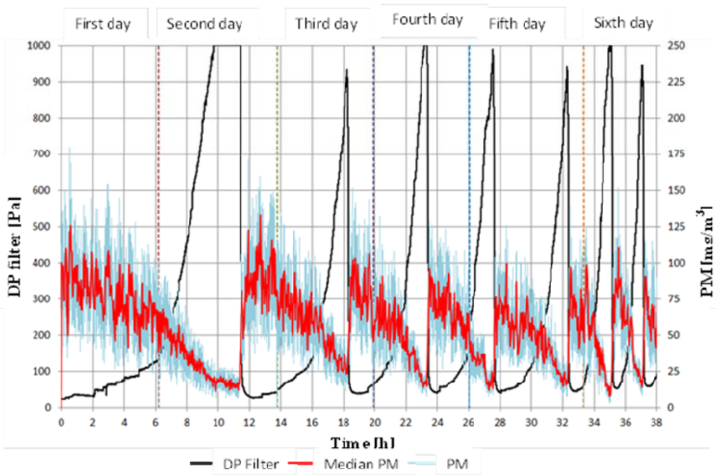

Figure 4: Pressure drop (black curve) and PM measured downstream the 65 ppi OBSIC foam during seven consecutive regeneration cycles. The red line represents the average PM every 2 minutes.

Regeneration efficiency decreases from 99.6% in the first cycle, up to 96.2% in the seventh cycle. This result confirmed the good regeneration performances, since the filter was completely regenerated after every cycle, but evidenced that an increasing layer of ashes probably deposited on its surface, so decreasing the regeneration efficiency and the cycle’s duration, since the ashes were difficult to remove by simple oxidation. This result was confirmed by comparing the pressure drop at the end of each regeneration cycle: the DP at the end of regeneration increased from 27 Pa (first cycle) up to 58 Pa (seventh cycle). However the 65 ppi OBSIC foam is more suitable than SiC wall flow filters (Palma et al., 2016) for PM abatement devices in biomass boiler, since the DP are compatible with their operation, even though foam filters are characterized by a lower filtration efficiency (about 60%, instead of about 98% typical of wall-flow filters).

3.4 SEM and SEM-EDX analysis on a 65 ppi OBSIC foam after a deposition test

The 65 ppi OBSIC foam after a deposition test was characterized by a SEM and SEM-EDX analysis, aimed at investigating the PM deposition and the soot composition. The images of the filter after a deposition test are shown in Figure 5: the image on the left shows that the external filter surface was covered by soot particles, while in the image on the right shows the soot particles collected inside the foam. Therefore, soot filtration effectively occurred also in the internal filter surface and not only on the external walls.

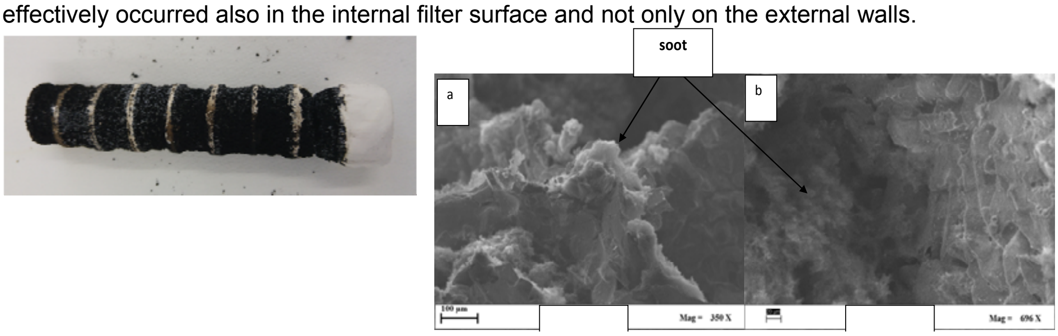

Figure 5: Images of the 65 ppi OBSIC foam after a deposition test: external surface (left), internal surface (right).

Furthermore the SEM-EDX analysis evidenced the presence on the foam surface not only of the main structural chemical elements of the OBSIC foam, i.e. C, O, Al and Si, but also of the soot main constituents, i.e. C, S, Cl and K. In particular, the presence of these elements (that depended on the pellet composition) confirmed the efficacy of the regeneration, since only C was removable by simple oxidation, while S, Cl and K were more difficult to remove and progressively deposited on the filter.

4. Conclusions

In our previous works we studied the use of catalytic SiC wall flow filters as soot emission control devices for biomass-fired boilers and stoves. Starting from those results, in this work we investigated the use of a different kind of filters, the open-cell ceramic foams, characterized by a different porosity and by a different filtration mechanism. In particular, we investigated the behaviour in terms of pressure drop, filtration efficiency and regenerability of two filters made of open-cell OBSIC (i.e. SiC and alumina) foams characterized by 10 and 65 ppi, installed in a derivation column at the exhaust of a 30 kW pellets boiler. The filters were characterized by means of SEM and SEM-EDX analysis, which showed an average pore diameter of about 2 mm for the 10 ppi OBSIC foam and of about 200 μm for the 65 ppi OBSIC foam, and the presence of the main structural chemical elements of the OBSIC foam, i.e. C, O, Al and Si. Preliminary deposition tests highlighted a filtration efficiency of about 5% and 60% for the 10 ppi and 65 ppi OBSIC foam, respectively. These results limited the following analysis to the 65 ppi OBSIC foams, which were tested in several soot deposition and regeneration cycles, in order to investigate the repeatability of their performance and to verify the occurrence of regeneration failures due to ashes deposition. The tests evidenced a good repeatability of the filter performance; in fact, in all the deposition and regeneration cycles, (i) the contemporary increase of the DP and the decrease of the PM measured downstream the filter during the deposition phase, and (ii) the fast decrease of the DP during regeneration at 600°C up to a minimum value, were observed. An important result was related to the regeneration efficiency, since it decreases from 99.6% in the first cycle up to 96.2% in the seventh cycle. Filters were completely regenerated after every cycle, but they evidenced an increasing layer of ashes deposited on their surface, which decreased the regeneration efficiency and the cycle duration. This result was confirmed by comparing the DP value at the end of each regeneration cycle: the DP at regeneration end increased from 27 Pa in the first cycle up to 58 Pa in the seventh cycle. The SEM-EDX analysis on a 65 ppi OBSIC foam after a deposition test evidenced the presence on the foam surface not only of the main structural chemical elements, i.e. C, O, Al and Si, but also of the soot main constituents, i.e. C, S, Cl and K. The presence of these elements (that depended essentially on the pellets composition) confirmed the results obtained in terms of regeneration efficiency, since only C was removable by simple oxidation, while S, Cl and K constitute the ashes that progressively deposited on the filter. Therefore, the 65 ppi OBSIC foam revealed a more suitable solution for PM abatement than SiC wall flow filters, since the DP are compatible with the actual operation of biomass boilers, even though foam filters are characterized by a lower filtration efficiency (about 60%, instead of about 98% typical of wall-flow filters). Further studies are currently carried out in order to investigate the effects of the deposition of a catalyst on 65 ppi OBSIC foams on the pressure drop, the filtration and the regeneration efficiencies, besides to verify the catalyst threshold temperature.

Acknowledgments

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Reference

Illerup J.B., Hansen B.B., Lin W., Nickelsen J., Dam-Johansen K. (2015) Intelligent heat system – High-energy efficient wood stoves with low emissions of gases and particles. *Proc. 23rd European Biomass Conference and Exhibition*, 448-451.

Khan A.A., De Jong W., Jansens P.J., Spliethoff H. (2009) Biomass combustion in fluidized bed boilers: Potential problems and remedies. *Fuel Processing Technology*, 90, 21 – 50.

Meloni E., Palma V. (2017) Optimized microwave susceptible catalytic diesel soot trap, *Fuel*, 205, 142 – 152.

Migliavacca G., Morreale C., Hugony F., Tombolato I., Pession G. (2014) Reduction of PM emissions from biomass combustion appliances: evaluation of efficiency of electrostatic precipitators. *Chemical Engineering Transactions*, 37, 25-30.

Palma V., Meloni E., Caldera M., Lipari D., Pignatelli V., Gerardi V. (2016) Catalytic wall flow filters for soot abatement from biomass boilers. *Chemical Engineering Transactions*, 50, 253 – 258.

Saidur R., Abdelaziz E.A., Demirbas A., Hossain M.S., Mekhilef S. (2011) A review on biomass as a fuel for boilers. *Renewable and Sustainable Energy Reviews*, 15, 2262–2289.

Stoppiello G., Palma V., Hugony F., Meloni E., Gualtieri M. (2014) Catalytic wall flow filters for the reduction of biomass boilers emissions. *Chemical Engineering Transactions*, 37, 19-24.

Twigg M. V. and Richardson J. T. (2007) Fundamentals and Applications of Structured Ceramic Foam Catalysts, *Ind. Eng. Chem. Res.* 46, 4166-4177.

Van Loo S., Koppejan J. (2008) The handbook of biomass combustion and co-firing, Earthscan Ed., Ch. 9, 318-333.