Experimental study of PM emissions from wood pellet stoves with an innovative burning pot

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Abstract.
In this study, results of an extensive set of experiments on a wood pellet stove model equipped with innovative burning pots are presented. Tests have been performed to investigate the relations between design data and operation parameters of the stove and its emissions. In particular, carbon monoxide (CO) and particulate matter (PM) emissions are correlated to the burning-pot depth.

The burning pot A, adopted by AICO S.p.A., allows to obtain near-to-zero CO emissions and low PM emissions: however, PM emissions reduction with respect to standard burning pots is not as enhanced as CO emission reduction. Here it is shown that a further reduction of PM emissions (down to 6–16 mg/Nm³) can be attained increasing the burning pot depth.

Experiments show also an increment of PM emissions in subsequent tests in the same day: there is an apparent dependence of PM release on the time from ignition. It is likely that this effect is due to ashes accumulation on the bottom of the burning pot and to their interaction with the primary air stream that flows over them.

1. Introduction
Nowadays concern about the greenhouse effect, caused also by the intense exploitation of fossil fuels, is shifting interest towards biomass fuels which have nominally zero-net emissions of greenhouse gases: generation of heat and power from biomass sources is becoming an important element of the energy scenario that will characterize the next years. Unfortunately, a poor exploitation of biomass can cause a significant generation of pollutant and particle emissions. It is generally acknowledged that aerosols are the cause of many diseases and premature death [1, 2], hence the problem of analyzing and reducing aerosols produced by biomass fueled appliances is receiving increasing attention. In particular, it is becoming more and more important to identify which factors control and influence the emission of pollutants and particulate matters and how to reduce them.

Limits of emissions in international and national regulations are becoming more restrictive. Within the framework set by the EU Ecodesign Directive [3], for example, limit of PM emissions for pellet stoves has been fixed to 20.0 mg/Nm³. This value will be enforced starting on January 1, 2022. In Italy, the public subsidies given to substitute an old heating appliance with a new, efficient one are defined by “Conto Termico 2.0” [4] and are based on a classification that
considers PM emissions: for example, the upper limit for the best class is 15.0 mg/Nm\(^3\) for pellet stoves and 10.0 mg/Nm\(^3\) for pellet boilers.

On one hand, it is clear that the need for high efficiency and non-polluting devices that use renewable energy sources is becoming more important, both for the electricity generation and for the direct heating of spaces. On the other hand, manufacturers need clear and long term indications to plan the development of low emission appliances.

An overview on emissions due to biomass combustion can be found in several papers [5, 6, 7, 8, 9]. The flue gases downstream of an ideal combustion are nitrogen (N\(_2\)), oxygen (O\(_2\)), carbon dioxide (CO\(_2\)) and water vapor (H\(_2\)O), but in real combustion conditions several other components are present: carbon monoxide (CO), nitrogen oxides (NO and NO\(_2\)), hydrogen (H\(_2\)), hydrocarbons (HC), poly-cyclic aromatic hydrocarbons (PAHs), besides particulate matter (PM). In [10] the effect of air excess on wood pellet combustion is analyzed: taking into consideration CO emissions, it is shown that for each stove exists an optimal O\(_2\) concentration in the flue gas – hence an equivalent air excess – that minimizes CO generation.

In addition to the O\(_2\) content effect, also the effect of the ratio between primary and secondary air is analyzed [10, 11]: in order to reduce NO\(_x\) emissions primary air has to be reduced as much as possible, even under stoichiometric air ratio; at the same time its residence time in the combustion chamber has to grow as much as possible; secondary air, instead, increases turbulence of gases in the combustion chamber promoting oxidation of CO and HC and tertiary air completes all the reactions in the combustion chamber feeding directly the flame.

Aerosol formation processes are investigated in several papers. For example in [5, 12, 13] theoretical models to explain how particles nucleate and how they change as a function of temperature is presented. Besides, information are given about chemical composition of PM in the flue gas. Different studies demonstrate that particle size from wood pellet combustion is mostly submicron with concentration peaks around 0.1 µm and 0.9 µm [7, 9, 12]. They are composed by inorganic compounds of potassium, chlorine, nitrogen, calcium, magnesium and phosphorus – ash particles – and by soot from incomplete combustion [14].

Other works [15, 16, 17] analyzed chimney temperatures related to fire risks of adjacent structures. Flue gas temperature, besides representing safety issues, is an important parameter of combustion efficiency. During the experiments presented in this paper, flue gas temperature, at stove outlet ranges between 450 K and 510 K.

This paper reports results of a collaboration between AICO S.p.A and the University of Brescia aimed to reduce PM emissions of pellet stoves and boilers manufactured by AICO, by improving the combustion conditions and maintaining CO emissions low.

During the first step of the project, attention was concentrated on CO and PM reduction upon optimization of the burning pot and primary air inlet. In standard burning pots, adopted by most of pellet stoves manufacturers, primary air flows through an array of holes on the bottom of the pot. In 2016, AICO developed and patented an innovative burning pot [18], shown in Figure 1, left. Extensive comparison tests showed that AICO’s innovative burning pot allowed a strong CO emission reduction, together with PM reduction as well, although not as significant as the one of CO: results of these tests are described at length in [19]. The shape of primary air inlets in AICO’s burning pot produce very good combustion conditions and quasi-zero CO emissions. As a consequence the organic part of PM is removed, decreasing total amount of particulate.

In the second step of the project which is described here and which aims to further improve PM reduction, a literature survey on primary measures to decrease wood pellet stove emissions has allowed to identify a few high performance reactors, as those described in [12, 20]. These reactors are high cylinders with several stages of secondary and tertiary air flows that feed the combustion oxidizing all the combustible gases. Considering the main features of these reactors, the burning pot patented by AICO has been modified: in particular, its depth, as well
as the distance between primary and secondary air inlets, has been increased. The findings of an experimental campaign to compare the original of AICO’s burning pot, with its modified version, are reported here. A definite improvement of PM emissions was recorded.

2. Materials and methods

2.1. Burning pot models and combustion air

The experimental data reported in this paper have been collected at AICO Testing Lab during the development of new pellet stove models. In particular, two burning pot models will be considered here, quite similar in design and dimension. The two burning pots tested will be denoted A and B and they have a nominal burning power of 8.5 kW: burning pot A is developed and patented by AICO S.p.A [18], while burning pot B is a modification of the former, characterized by a larger depth.

Burning pot A, shown in Figure 1 on the left, consists in a square solid base (85 mm per side) with a depth of 50 mm: primary air is supplied through a meandering slit between the base and the sidewall. This air flow does not pass through the bed of embers, but along/over its side and upper surface. Secondary air is supplied at the top of the burning pot and impinges directly on the flame: it passes through several holes with 7 mm of diameter. Burning pot B, shown in Figure 1 on the right, differs from burning pot A only for depth which is 120 mm. Primary and secondary air inlets are equal to those of burning pot A.

The stove is equipped with a tertiary air supply that keeps the glass door clean and feed the flame directly in the combustion chamber from the top. This inlet does not depend on the burning pot used.

Primary, secondary and tertiary air flow rates are not directly controlled. In Figure 2 a scheme of the stove with all air inlets is shown.

In all tests the same batch of pellet was used: its quality is ENPLUS A1 [21]. Elemental concentrations and heating value are specified in Table 1.

![Figure 1](image-url). On the left: burning pot adopted in the stove A; on the right: burning pot adopted in the stove B
Table 1. Characteristics of pellet adopted during tests: values on wet basis

| Element      | Concentration (%) |
|--------------|-------------------|
| Carbon (C)   | 48.12             |
| Hydrogen (H) | 5.70              |
| Oxygen (O)   | 39.80             |
| Nitrogen (N) | 0.11              |
| Water (W)    | 6.00              |
| Ash          | 0.18              |
| Low heating value (LHV) | 17371 kJ/kg |

2.2. Experimental setup and test session

For all tests reported here, we used the experimental setup and procedure proposed by the standards [22, 23, 24] and used by other authors [5, 10, 12, 14]. The whole stove, including the hopper, is put on a platform scale in order to measure the burning rate. The composition of flue gas is measured at the flue gas socket.

Each stove required some days of testing (that will be denoted as “test sessions”). A regular test session starts in the morning with operation parameters setting and the stove ignition: the burning pot, in particular, is emptied of all the residuals from the previous session. After about one hour from ignition combustion reaches quasi-steady conditions, detected upon monitoring the flue gas temperature. At this point a sequence of tests is performed. Each test lasts 30 minutes and several tests are performed during a test session.

During a test CO$_2$, O$_2$, CO and NO are measured and recorded every 5 seconds. At the end, average values over the 30 minutes are computed. At the same time, PM is also collected by a filter–gravimetric method: the sampling time being 30 minutes, i.e. the test duration. Time lag between two tests is necessary to replace the filter and calibrate the instrument and usually ranges between 15 and 30 minutes.

The gas analyzers used is ABB EL3020, equipped with cells to measure the concentration (volume fraction) of O$_2$ and CO in dry gas, i.e. the flue gas without H$_2$O. Measurement accuracy are ±0.2% for O$_2$ measures and ±3 mg/Nm$^3$ for CO measures.

The quartz fibre filter adopted has a retention efficiency of 99.998% of the particulate with 0.3 $\mu$m diameter. Measurement accuracy of the balance adopted for measuring PM weight deposited on the filter is ±0.08 mg. The pump sucks flue gases at constant flow of 25 Nl/min and it is equipped with a flow meter with an accuracy of ±0.1 Nl/min. Measures of PM emissions are normalised at 13% of O$_2$. A schematic sketch of PM and flue gas sampling system used in this study is shown in Figure 2 and reproduces the method described by the normative [23]. All measurements were performed at the end of thermal transient.

In order to make a proper comparison of results, CO and PM are normalized at the same concentration of O$_2$, using the relation $X_{\text{ref}} = X(21 - O_{2,\text{ref}})/(21 - O_2)$ (see [24]). Where X is the actual (averaged or instantaneous) concentration of CO or PM in mg/Nm$^3$, $O_2$ the actual (averaged or instantaneous) concentration of O$_2$ in %. $O_{2,\text{ref}}$, the reference concentration of oxygen, here 13%, and $X_{\text{ref}}$, the concentration of CO or PM at reference conditions, in mg/Nm$^3$. All data shown in Figures 3 and 4 and Table 2 are normalized.

3. Results and discussion

3.1. Comparison of emissions from different burning pots

Comparison of combustion tests performed with burning pot A and B shows different performances in terms of particulate emissions. Average results, obtained with the two different
burning pots, are shown in Table 2. As pointed out before, the two groups of data (A and B) differ for the burning pot depth only. The stove has, in all tests, the same primary, secondary and tertiary air inlets, it works at the same nominal burning power (8.5 kW) and at the same nominal air excess ratio obtained upon imposing the flue gas extractor velocity. As matter of fact air excess does not depend only on flue gas extractor, but also by flue draught, air inlets surface, instant amount of burnt pellet and flue gas temperature. In particular, instant amount of burnt pellet and flue gas temperature vary continuously during the combustion due to the fact that pellet is a solid fuel and each pellet load can vary in number. Therefore it is not possible to have an exact air excess ratio, then an exact O\(_2\) concentration in the flue gas with this stove technology. Concentrations of O\(_2\) fluctuate in a range during the combustion.

In Table 2, the average values during 30 minutes test of O\(_2\), CO, and PM emissions are reported. Apparently CO emissions were not affected by the burning pot depth: value for each test range between 5 and 115 mg/Nm\(^3\), with average value and standard deviation of all tests of 20 mg/Nm\(^3\) and 27 mg/Nm\(^3\), with burning pot A; while they range between 8 and 65 mg/Nm\(^3\), with average value and standard deviation of all tests of 28 mg/Nm\(^3\) and 15 mg/Nm\(^3\), with burning pot B. All these values are referred at 13% of O\(_2\). PM emissions were instead reduced from value for each test ranging between 10.7 and 23.3 mg/Nm\(^3\), with average value and standard deviation of all tests of 15.0 mg/Nm\(^3\) and 3.0 mg/Nm\(^3\), with burning pot A; to average values ranging between 6.5 and 16.4 mg/Nm\(^3\), with average value and standard deviation of all tests of 11.0 mg/Nm\(^3\) and 3.1 mg/Nm\(^3\), with the burning pot B. All these values are referred at 13% of O\(_2\). These conclusions can be seen at glance from Figure 3.

Possible internal factors that are at the base of the PM decrement obtained with burning pot B were analyzed. This reduction is probably connected with more straight flows that take place inside the burning pot B, in particular primary air feeds pellet without secondary air interferences. Pellet at the top of burning pot A is situated close to secondary air inlets and to combustion chamber entrance, therefore that portion of pellet is more exposed to primary and secondary air interferences than pellet to the top of burning pot B where entrainment effect is probably less. Secondary air feeds the flame and burns all pyrolysis gases generated from pellet heated up in air lacking conditions. In particular, with burning pot B, secondary air does not invest the pellet on the top as can probably occur with burning pot A.
Table 2. Emissions from burning pots A and B. CO and PM values are referred at 13% of O$_2$. Data represent average values over a 30 minutes test. At the bottom of the table average values and standard deviations of all tests with burning pot A and B respectively.

| Burning pot A | Burning pot B |
|---------------|---------------|
| Test number   | O$_2$ CO PM   | Test number | O$_2$ CO PM |
|               | % mg/Nm$^3$ – | % mg/Nm$^3$ – |               | % mg/Nm$^3$ – | % mg/Nm$^3$ – |
| day 1.1       | 9.3 8 23.3    | day 1.1     | 11.1 12 6.5  |
| day 2.1       | 9.3 8 13.0    | day 1.2     | 10.0 31 15.1 |
| day 2.2       | 8.3 7 14.2    | day 2.1     | 8.0 46 7.7   |
| day 2.3       | 7.8 5 17.4    | day 2.2     | 9.2 19 7.0   |
| day 2.4       | 7.8 7 18.5    | day 2.3     | 7.0 14 7.5   |
| day 3.1       | 9.6 15 11.4   | day 3.1     | 9.3 8 7.5    |
| day 3.2       | 8.3 7 16.0    | day 4.1     | 9.6 9 6.5    |
| day 4.1       | 6.6 7 13.5    | day 4.2     | 7.9 19 12.1  |
| day 4.2       | 5.5 19 15.7   | day 4.3     | 8.5 22 14.1  |
| day 4.3       | 5.2 40 15.2   | day 5.1     | 8.6 23 8.1   |
| day 4.4       | 4.9 115 19.4  | day 5.2     | 7.9 26 12.2  |
| day 5.1       | 7.3 8 10.7    | day 5.3     | 9.6 24 10.6  |
| day 5.2       | 7.1 10 11.8   | day 5.4     | 6.6 65 11.7  |
| day 5.3       | 6.6 8 14.8    | day 5.5     | 7.2 23 11.7  |
| day 5.4       | 6.8 10 14.5   | day 6.1     | 8.0 26 12.4  |
| day 5.5       | 5.7 34 13.3   | day 6.2     | 7.7 33 12.6  |
| day 6.1       | 7.0 11 14.7   | day 6.3     | 8.3 34 13.7  |
| day 7.1       | 9.7 59 14.6   | day 6.4     | 7.6 40 14.2  |
| day 7.2       | 8.3 12 13.4   | day 6.5     | 8.1 53 16.0  |
|               |               | day 6.6     | 7.7 43 16.4  |
|               |               | day 7.1     | 9.1 44 9.8   |
|               |               | day 7.2     | 7.9 27 8.7   |
|               |               | day 7.3     | 8.4 14 11.7  |
| Average       | 7.4 20 15.0   | Average     | 8.4 28 11.0  |
| St.dev        | 1.5 27 3.0    | St.dev      | 1.0 15 3.1   |

3.2. Time dependence of PM emissions
Consecutive tests within the same test session exhibit an increment of PM emissions. At the beginning, the combustion generally releases a minimum quantity of PM, then PM emissions continue to increase with time. We explain this phenomenon as caused by a change in combustion conditions due to ash accumulation in the burning pots: as the ash levels in the burning pots rise above a threshold, it interacts with the primary air, enhancing entrainment.

In Figure 4 on the left, we plot average PM measured during five test sessions using burning pot A, while in Figure 4 on the right, we plot average PM measured during four test sessions using burning pot B. Each test session lasts one day. In each day, there is an apparent trend: PM emissions tend to increase from the first to the last test of the session. With the burning pot A, for the first test of each day, that is usually performed after one hour from ignition, measured PM falls between 10.7 and 14.6 mg/Nm$^3$, at 13% of O$_2$, while for the last test of the day, that is usually performed after six hours from ignition, PM falls between 13.3 and 23.3 mg/Nm$^3$, at 13% of O$_2$. With burning pot B, for the first test of the day, that is usually performed after one hour from ignition, measured PM falls between 6.5 and 12.4 mg/Nm$^3$ while for the last test of the day, that is usually performed after six hours from
Figure 3. Average PM–O$_2$ values, on the left, and average PM–CO values, on the right, for test performed with burning pot A and B. CO and PM values are referred at 13% of O$_2$.

Figure 4. Average PM versus time from ignition for different test sessions with burning pot A, on the left, and with burning pot B, on the right. CO and PM values are referred at 13% of O$_2$.

ignition, PM falls between 7.5 and 16.4 mg/Nm$^3$.
This increment is not vanished with burning pot B, but it is much less apparent and it converges at lower PM level than in case with burning pot A. Furthermore, with burning pot B, this effect is not present in all test sessions.

4. Conclusions
This paper provides new elements in the understanding of PM generation during the combustion in wood pellet stoves. Combustion depends heavily on design of the combustion chamber, in particular of the burning pot. In this study, two different patented burning pots developed at AICO S.p.A were analyzed: burning pot A, with primary air coming from a slit between the side wall and the bottom of the burning pot, and a modified version of A, much deeper (burning pot B). The stove operated for both burning pots, at the same nominal combustion conditions and burning power (8.5 kW).

The experimental results exhibit different PM levels in the flue gases depending on the burning pot tested. When burning pot A was mounted, the amount of PM released by the stove was larger than when burning pot B was mounted. We consider these results an evidence that burning pot depth is an important factor that influence PM emissions. It is probably determined by the flow structure in the burning pot B that is straighter, minimizing entrainment effect. Furthermore, burning pot B is characterized by a larger distance between pellet and secondary air, minimizing interference between secondary air and embers that is a likely cause of PM entrainment and direct combustion.

Another experimental evidence collected during tests on both burning pots is that PM emissions tend to increase with time passed from ignition. At the beginning, when burning conditions can be considered steady (about one hour after ignition) the quantity of PM is
minimum, as time goes by, however, PM production grows. This trend is more apparent with burning pot A. We explain this behaviour as caused by the accumulation of ashes in the burning pot and by their interaction with the primary air streams.

Performance of these burning pots are due to a semi-pyrolysis process that take place in the bottom-centre of the burning pot where pellet heats up in air-absence conditions. This can happen because primary air flows from the bottom-side of the burning pot and does not touch the pellet in the bottom-centre.

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