EMISSIONS REDUCTION FROM PELLET STOVES THROUGH BURNER POT MODIFICATIONS

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ABSTRACT

In this study, results of an extensive set of experiments on five wood pellet stoves (8-11 kW nominal power) have been performed to verify whether carbon monoxide (CO), particulate matter (PM) and nitrogen monoxide (NO) emissions can be reduced upon modification of burner pot geometry, depth and air inlet positions. A modification of "traditional" burner pot geometry brings CO emission close to zero. Also PM emissions are reduced but not as much as those of CO. It is verified that increasing the burner pot's depth, PM emissions can be further reduced compared to the less deep burner pot. Finally, since plots of instantaneous emissions versus O_2 content exhibit significant scattering and do not show a clear correlation, plots of mean value of emissions, over narrow intervals of O_2, versus O_2 are introduced. These plots show an optimal interval of O_2 content that minimizes emissions.

INTRODUCTION

Nowadays concern about greenhouse gases production caused by the intense exploitation of fossil fuels, is shifting interest towards biomass fuels which are nominally carbon neutral. Unfortunately, a poor exploitation of biomass can cause a significant generation of pollutants and particle emissions.

It is generally acknowledged that aerosols are the cause of many diseases and premature death [1; 2], hence the problem of reducing aerosols produced by biomass fueled appliances is receiving increasing attention and 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 emission for pellet stoves has been fixed to 20 mg/Nm^3. This value will be enforced starting on January 1, 2022. In Italy, the public subsidies given to substitute an old heating appliance with a more 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 mg/Nm^3 for pellet stoves and 10 mg/Nm^3 for pellet boilers. As a consequence most pellet stove manufacturers are actively engaged in the development of low emission appliances.

An overview on emissions due to biomass combustion can be found in several papers [5; 6; 7]. The flue gases downstream of an ideal combustion are nitrogen (N_2), oxygen (O_2), carbon dioxide (CO_2) and water vapor (H_2O), but in real combustion conditions other components are present besides particulate matter (PM): carbon monoxide (CO), nitrogen oxides (NO and NO_2), hydrogen (H_2), hydrocarbons (HC), polycyclic aromatic hydrocarbons (PAHs), and several others [8].

Emission of CO, PAHs, black carbon, and soot in general, are all results of incomplete combustion [5; 6], then the measure of CO emissions can be considered to be a tracer of unburned gases. Improvements of the combustion process that entail a reduction of CO are expected to decrease emission of PM too.

An important factor that influences PM emissions is the burner pot geometry. To reduce as much as possible PM emissions, different geometries of burner pots and different air ratios were analyzed by different authors. Optimized solutions were described in [7; 9]: these biomass reactors are high cylinders with several stages of secondary and tertiary air flows that feed the combustion oxidizing all the combustible gases. Studies presented in [10; 11] analyze the influence of primary and secondary air ratio on CO and PM emissions. A higher secondary air contribution allows fewer emissions.

The literature cited above analyzes combustion processes under controlled and steady laboratory conditions. The everyday use of combustion appliances is characterized by different combustion conditions, mainly unsteady. In [12; 13] combustion processes are analyzed in realistic conditions, hence considering all combustion phases from ignition to extinguishing the flame: emissions from incomplete combustion have much higher values than in laboratory conditions and temperature of the flue gases can reach peaks up to 800 K, negatively influencing efficiency of combustion [14]. Flue gas temperature is important not only for stove efficiency, but also for safety issues, as shown by experimental and numerical studies investigating flue gas temperature in different stove installations to avoid roof fire problems [15; 16; 17].

In this paper results obtained by means of a cooperation between an Italian stove manufacturer AICO S.p.A and University of Brescia are presented. The project's goal is a reduction of emissions. This is obtained through improvement of the combustion process by means of a redesign of the burner pot (retort) and of the combustion air inlets. Preliminary results were presented in [18; 19].

During the development of the new burner pot, experiments on five different wood pellet stoves (8-11 kW nominal power) have been performed to investigate the relations between the main operation parameters of the stoves and their emissions. In particular, carbon monoxide (CO), particulate matter (PM) and nitrogen monoxide (NO) emissions are correlated to the burner pot geometry, depth and to inlet air positions. The change of burner pot's geometry allows CO reduction nearly to zero, at the same time, PM emissions are reduced, but not as much as those of CO. It is verified that increasing the burner pot's depth, PM emissions are reduced further compared to less deep burner pots.

The tests with deep burner pots were prompted by the works of Brunner [20] which describe the importance of increasing as much as possible the distance between primary and secondary air to avoid interactions between secondary air and the fuel.

Preliminary results on NO emissions are described as well.

Finally, since plots of instantaneous emissions vs O_2 content exhibit significant scattering and do not show a clear correlation, plots of mean value of emissions, over narrow intervals of O_2, versus O_2 are introduced. These plots show an optimal interval of O_2 content that minimizes emissions.

MATERIAL AND METHODS

Burner pot and stove models

The experimental data reported in this paper have been collected at AICO Testing Lab during the development of new pellet stove models. In particular, five stoves will be considered here that differ for the pairs burner pot/nominal power. Three types of burner pot (denoted A, B and C) are tested.

The first two stoves tested will be denoted A1 and A2. They have nominal power of 8.0 kW and 11.1 kW, respectively. They are equipped with "traditional" burner pots. They have rectangular solid bases of $66 \times 80\,mm^2$ (A1) and $60 \times 90\,mm^2$ (A2). Primary air enters through an array of holes in the bottom, then it feeds the combustion flowing through the bed of embers. Secondary air is supplied from holes in the upper part of the burner pot walls and impinges directly on the flame. The relative ratio between primary and secondary air inlet areas is designed to minimize CO emissions for a combustion period of 5–6 hours. However the ratio between primary and secondary air flow rates is not controlled and can vary during combustion. For example when ashes accumulate on the bottom of the pot partially obstructing or blocking the primary air flow, the amount of secondary air increases.

Stoves B1 and B2, have nominal power of 8.6 kW and 10.1 kW, respectively. "New" burner pots, developed and patented by AICO [21], are inserted in them. They are characterized by a square base with no holes of $80 \times 80\,mm^2$ (B1) and $90 \times 90\,mm^2$ (B2). The base can rotate for de-ashing. 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 burner pot, it passes through several holes and impinges directly on the flame. Also in these stoves primary and secondary air flow rates are not directly controlled.

The fifth stove, C, has nominal power of 8.0 kW. The stove is equipped with a modified version of burner pot B, which is much deeper. Burner pots B and C have the same shape, but B's height is 50 mm, while C's height is 120 mm as shown in Figure 1

Because of shape and position of primary air inlets, ashes accumulation inside burner pots B and C does not obstruct the primary air flow for a longer time with report to pots of type A. The number and size of secondary air holes have been determined in preliminary tests conducted during the development of the burner pot. Designs presented in the article have primary/secondary inlets ratios that minimize CO emissions for a combustion period of 5–6 hours.

Stoves are equipped with tertiary air supply as well, that keeps the glass door clean and feed the flame directly in the combustion chamber from the top. This inlet is independent by the burner pot adopted.

All three burner pot models are shown in Figure 1.

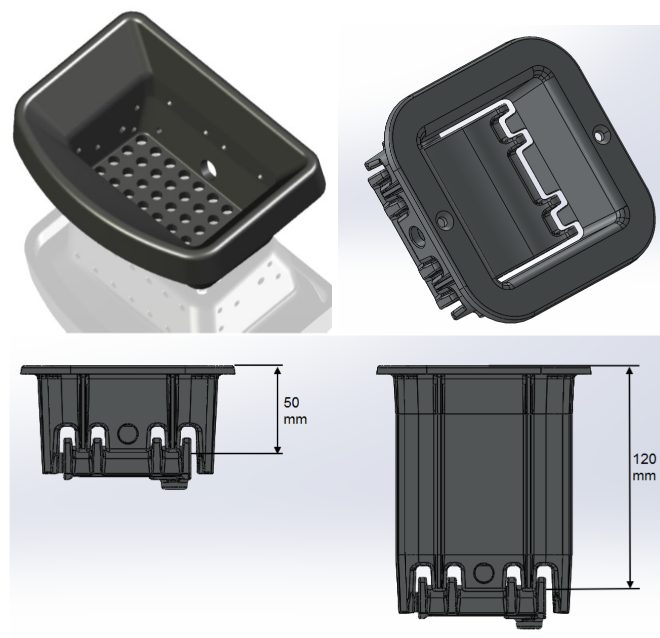

Figure 1. On the left: burner pot model adopted in stoves A; in the center: burner pot model adopted in stoves B; on the right: difference of depth between burner pot C and B1

In all tests the same batch of pellet has been used: its quality is ENPLUS A1 [22]. Elemental concentrations and heating value are specified in Table 1.

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)	17,371 kJ/kg

Experimental setup and testing procedure

For all tests reported here, we used the experimental setup and followed the measuring procedure proposed by European Standards [23; 24] and used by other authors [25; 7]. Standard EN 14785 considers space heaters fired by wood pellets up to 50 kW. It provides requirements and test methods regarding design, manufacture, safety and performances (efficiency and emissions). Standard EN 13284 describes a method for the determination of low range mass concentration of dust with a manual gravimetric method. It establishes the procedure of sampling and weighting the dust in the flue gases.

Details on the testing procedure followed in this study are specified here. Each stove required a few days of testing (each day of testing will be denoted as a "test session"). A regular test session starts in the morning with the setting of operation parameters and the stove ignition: the burner 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 gases temperature. At this point a sequence of tests is performed. Each test lasts 30 minutes and several tests are performed during a test session. Operation conditions during a test session are fixed. At the end of the test session (extinguishing stage) pellet feeding is switched off and combustion air flow rate is increased to burn quickly what is left in the burner pot. This stage lasts 15 minutes, approximately.

A schematic sketch of PM and flue gas sampling system used in this study is shown in Figure 2. The composition of flue gases is measured at the flue gas socket.

During a test CO_2, O_2, CO, NO and PM are measured and recorded every 5 seconds. At the end, average values over the 30 minute test are computed. At the same time, PM is also measured by the filter - gravimetric method described in EN 13284: the sampling time being 30 minutes, i.e. the test duration. A time lag between two tests is necessary to replace the filter and calibrate the instrument and usually ranges between 15 and 30 minutes.

Although EN 14785 prescribes to take average values of CO, O_2 and CO_2 over at least three hours, here average values are calculated over thirty minutes to have results consistent with the collection of PM on the filter.

During tests the whole stove, including the hopper, is put on a platform scale in order to measure the burning rate.

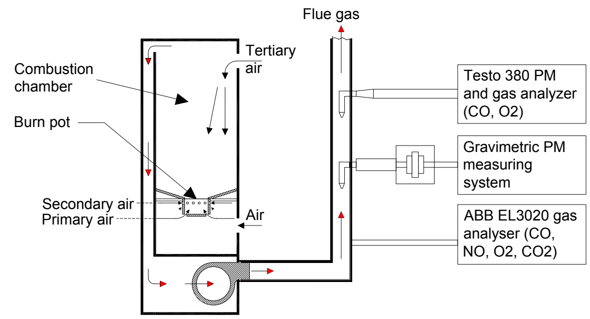

Figure 2. Sketch of PM and flue gas sampling system

The first gas analyzer used is an ABB EL3020, equipped with cells to measure the concentration (volume fraction) of O_2, CO_2, CO and NO in dry gas, i.e. the flue gas without H_2O. Measurement accuracies are $\pm 0.2\%$ for O_2 measures and ± 2 ppm for CO measures.

The second gas and dust analyzer is TESTO 380 that measures the concentration (volume fraction) of O_2 and the weight of the total solid particulate in dry gas.

The quartz fiber filter used in the gravimetric measuring system has a retention efficiency of 99.998% of the particulate with 0.3 μm 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 l/minute and has an accuracy of $\pm 2\%$, in accordance with the Standard [24].

In order to make a proper comparison of results, CO and PM are normalized at the same concentration of O_2, using the relation $X_{ref} = X(21 - O_{2,ref})/(21 - O_2)$ (see [23; 27]), 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 %; $O_{2,ref}$, the reference concentration of oxygen, here 13%; X_{ref}, the concentration of CO or PM at reference conditions, in mg/Nm^3. All data shown in Figures are normalized.

EXPERIMENTAL RESULTS

Comparison of emissions from different burner pots

The stoves tested exhibit different performances in term of CO, NO and PM emissions and combustion efficiencies. This is particularly true when comparing stoves with different burner pots: the combustion seems to be strongly affected by primary air inlet geometry and slightly affected by burner pot depth. Data reported here are divided in five groups that differ in burner pot model and nominal power. Results obtained with the five stoves are shown in Figure 3 and in Table 2. Each point in Figure 3 refers to a single test: PM values are those obtained with the gravimetric method, all values are average over 30 minutes of the instantaneous data obtained with the gas analyzers. Results shown in Table 2 are mean values of data obtained for the same

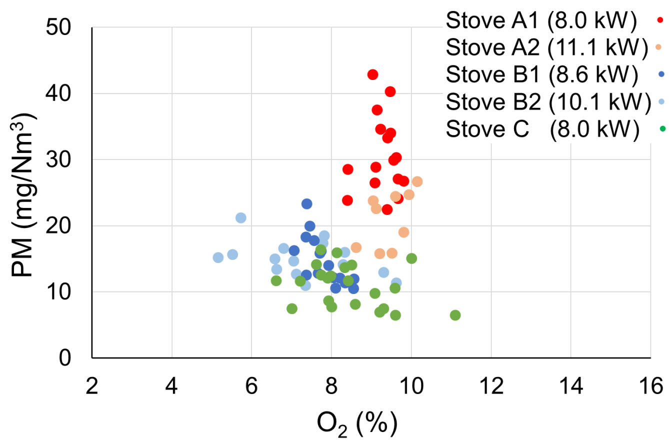

Figure 3. Average PM–O_2 values for each test performed with stoves A1 (16 tests), A2 (9 tests), B1 (15 tests), B2 (16 tests) and C (23 tests)

stove. The combustion process in AICO's stoves is not stationary, instantaneous amount of burnt pellet and instantaneous air excess ratio vary in a range. The variation of air excess ratio is due to the lack of a lambda probe on these stove models, therefore there is not any regulation of air excess ratio.

Results of Table 2 demonstrate large differences in terms of particulate emissions between burner pots A and burner pots B and C. Combustion of stoves B and C, with primary air coming from the bottom side generates much lower PM emissions that are probably correlated with lower PM entrainment. In tests performed on stoves A, PM emissions are respectively 30.7 (stove A1) and 20.1 (stove A2) mg/Nm^3–13%, while in tests performed on stoves B, PM emissions are respectively 15.1 (stove B1) and 14.9 (stove B2) mg/Nm^3–13%. The increment of burner pot depth seems to cause a further reduction of PM emissions to average values of 11.0 mg/Nm^3–13% of O_2 with stove C.

Parameters evaluated in this phase are primary air position and burner pot depth. Primary air of stoves A1 and A2 collides with all the pellet and ashes in the pot, while in stoves B1, B2 and C primary air collides only with pellet in the bottom side and on the top. Stoves B and C configuration guarantees lower entrainment of PM than stoves A.

Distance between primary and secondary air is another factor that influence PM emissions [20]: higher distance between primary and secondary air permits lower PM emissions. This reduction is probably connected with a more straight flow that take place inside the burner pot C, in particular primary air feeds pellet without secondary air interferences. Pellet at the top of burner pot B 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 burner pot C 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 burner pot C, secondary air does not invest the pellet on the top as can probably occur with burner pot B.

Table 2. Average PM-CO-O_2 valueas for each stove

	Power	**Efficiency**	**CO**	**PM**	**NO**	**O_2**
	kW	%	mg/Nm^3 -13% O_2	mg/Nm^3 -13% O_2	mg/Nm^3 -13% O_2	%
Stove A1 (16 tests)						
Mean	8.0	86.7	111	30.7	122	9.3
St. dev.	0.4	0.7	35	6.0	7	0.4
Stove A2 (9 tests)						
Mean	11.1	87.2	108	21.1	125	9.4
St. dev.	0.7	1.1	44	4.2	8	0.5
Stove B1 (15 tests)						
Mean	8.6	91.3	13	15.1	142	7.3
St. dev.	0.3	1.3	10	2.7	4	1.3
Stove B2 (16 tests)						
Mean	10.1	91.1	23	14.8	124	7.8
St. dev.	0.1	0.5	14	3.7	3	0.5
Stove C (23 tests)						
Mean	8.0	88.6	28	11.0	113	8.4
St. dev.	0.4	1.2	15	3.1	3	1.0

Differences of combustion conditions bring to different NO emissions as well. The increment of secondary air, compared to primary air, and the duration time of flue gases between primary and secondary inlets are two of the main factors that influence NO emissions [9].

Combustions of stoves A and B do not bring to relevant changes in terms of NO emissions. The change of burner pot depth (model C) seems to weakly reduce NO emissions. This result is preliminary and it needs to be confirmed by further tests.

Relationship between instantaneous PM and O_2 values

In previous works [26; 27], two of the authors reported plots of instantaneous CO values versus O_2 and illustrated how they could be used to improve the combustion process. Instantaneous data collected over one limited time interval (from 30 minutes up to few hours) can be as useful in determining CO versus O_2 dependence as average data collected in several days of testing. These plots allow to determine an O_2 interval that minimize CO production (see, for example, Figure 4 and Figure 6 on the left) and are quite useful during the setup of the operating parameters of a new stove.

In this study, we have checked whether a similar approach can be useful for PM minimization. Instantaneous PM emissions versus O_2 content in flue gases have been analyzed for stoves A1 and B1. Stoves A1 and B1 behavior differ on CO emissions, from average value of 111 mg/Nm^3 for stove A1 to average value of 13 mg/Nm^3 for stove B1. Emissions behaviors have been analyzed separately.

Instantaneous emissions of CO and PM vs O_2 for all tests developed with stove A1 are shown in Figure 4.

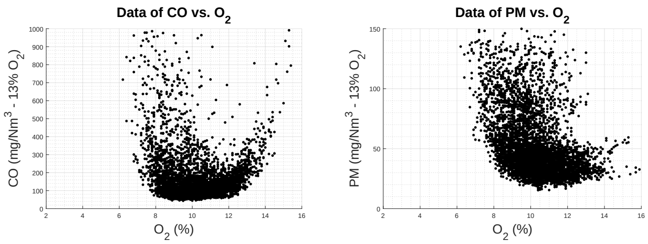

Figure 4. CO versus O_2 trend and PM versus O_2 trend of all tests of stove A1

Plot of CO vs O_2 content in Figure 4 suggests that there is an O_2 interval that minimize CO emissions, but as O_2 content moves away from this interval, emissions tend to increase both with air defect and air excess conditions. PM emission vs O_2 plot is much less clear than that of CO because of higher scattering.

In order to get a better understanding of trends despite scattering of data, O_2 range is divided in intervals and, for each interval, average values of emissions are calculated. Results of this analysis are shown in Figure 5.

These plots show a clearer correlation between emissions and O_2 content. Emissions tend to increase when the stove works in air defect rather than in air excess conditions and both CO and PM emissions have high scattering of data when the combustion works in air defect conditions. CO emissions, differently from PM emissions, have an apparent increment also when the combustion is in air excess conditions.

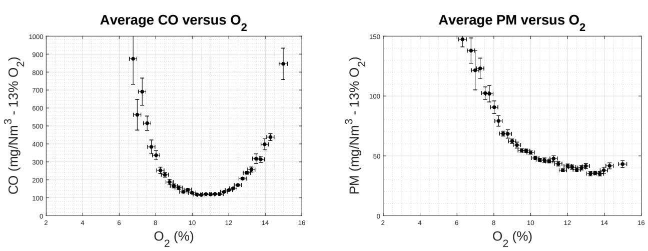

Figure 5. Average CO versus O_2 trend (on the left) and average PM versus O_2 trend (on the right) of all tests of stove A1

Instantaneous emissions of CO and PM vs O_2 for all tests developed with stove B1 are shown in Figure 6.

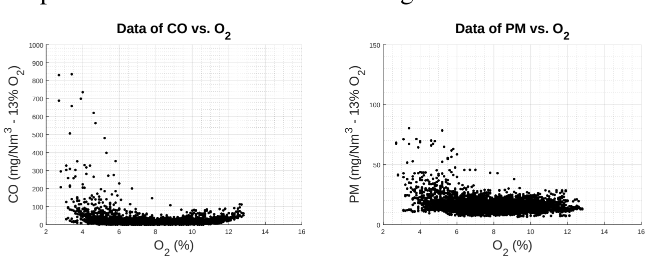

Figure 6. CO versus O_2 trend and PM versus O_2 trend of all tests of stove B1

Results of the graphs show how CO emissions have much lower dependence by O_2 content than stove A1 and they are reduced for a wider range of O_2, but as the combustion moves away from this range, CO emissions tend to increase. Instantaneous data of PM show a weak dependence on O_2 content: PM emissions seem to increase only when the combustion is in air defect conditions.

Considering only average CO and PM emissions for different O_2 intervals as shown in Figure 7, the relation become clearer.

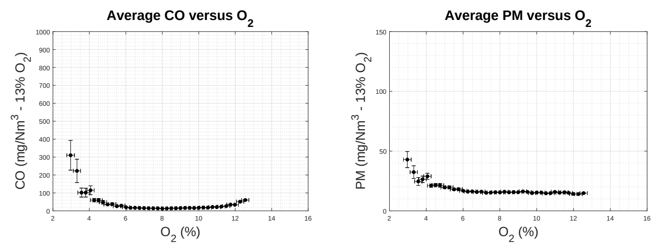

Figure 7. Average CO versus O_2 trend (on the left) and average PM versus O_2 trend (on the right) of all tests of stove B1

As in case with stove A1, CO emissions tend to increase as the combustion moves away from the optimum O_2 range in both air defect and air excess conditions, PM emissions instead increase significantly their emissions only when the combustion works in air defect conditions.

Relation between PM and O_2 content is similar for both stoves A1 and B1.

With both stoves A1 and B1, PM emissions never go below a certain value even when CO emissions are nearly-zero. It is possible categorize PM emissions in two different types: organic PM emissions that depend on combustion quality and can be minimized when CO emissions are minimized; inorganic PM emissions that are independent by the quality of combustion and are constantly released.

CONCLUSION

This paper provides new elements in the understanding of PM generation and behavior during the combustion in wood pellet stoves. It shows that improvement in emission reduction can be obtained through modification of the burner pot design.

In this study five stoves with three different burner pot models were analyzed: a traditional burner pot model with primary air passing through holes on the bottom (model A), a model with primary air coming from slits between the side walls and the bottom of the burner pot (model B) and a modification of model B, but with a larger depth (model C). Stoves operate at different burning powers and different air excess.

The experimental results exhibited quite different PM levels in the flue gases from stoves equipped with different burner pots. Stoves A (burner pots with holes in the bottom) usually release higher amounts of PM than stoves B and C (burner pots with primary air coming from slits on the bottom side).

For stoves B, strong reduction of CO emissions to levels close to zero was recorded. However, PM emission reduction was not as much. This is due to the fact that PM generation does not depend only on combustion quality, but also on combustible quality, in particular ash content. There are two different PM components released in the flue gases: organic PM, which depends on the quality of combustion and can be largely removed when CO amount is close to zero; inorganic PM, which mainly depends on the intrinsic characteristics of the fuel and on entrainment effects and is not expect to reduce as CO tend to zero.

Burner pot C has been developed to reduce as much as possible PM entrainment, reducing interferences between secondary air and pellet. Experimental results show a reduction of PM emission from average value of 15 mg/Nm^3 for stoves B to average value of 11 mg/Nm^3 for stove C.

It has been analyzed if there is a relation between PM and O_2 as in the case of CO and O_2, but because the high scattering of data, it is not possible to get a clear relation. To have a better understanding of the trend, O_2 range is divided into intervals and, for each interval, average values of PM emissions are calculated. Experimental results show that PM emissions correspond to O_2 percentage in the flue gas, i.e. on air excess ratio. There is an optimum O_2 range that is related to both CO and PM emissions.

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