CO and NO emissions from pellet stoves: an experimental study

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Abstract. This work presents a report on an experimental investigation on pellet stoves aimed to fully understand which parameters influence CO and NO emissions and how it is possible to find and choose the optimal point of working. Tests are performed on three pellet stoves varying heating power, combustion chamber size and burner pot geometry.

After a brief review on the factors which influence the production of these pollutants, we present and discuss the results of experimental tests aimed to ascertain how the geometry of the combustion chamber and the distribution of primary and secondary air, can modify the quantity of CO and NO in the flue gas.

Experimental tests show that production of CO is strongly affected by the excess air and by its distribution: in particular, it is critical an effective control of air distribution. In these devices a low-level of CO emissions does require a proper setup to operate in the optimal range of excess air that minimizes CO production. In order to simplify the optimization process, we propose the use of instantaneous data of CO and O₂ concentration, instead of average values, because they allow a quick identification of the optimal point.

It is shown that the optimal range of operation can be enlarged as a consequence of proper burner pot design.

Finally, it is shown that NO emissions are not a critical issue, since they are well below threshold enforced by law, are not influenced by the distribution of air in the combustion chamber, and their behavior as a function of air excess is the same for all the geometries investigated here.

1. Introduction
In Europe the use of woody biomass – of wood pellets, in particular – for residential heating has increased in recent years. In Italy, pellet heating technology was introduced in the '90s. In 2007 wood pellets accounted for 2.4% of woody biomass consumed for domestic use (Lombardy, 3.3%) [1]. Lombardy is the Italian region in which pellet appliances are more widespread: in 2007 they were the 6.9% of wood appliances (Italy, 3.9%) [1].

End-users and legislation have paid increasing attention both to energy efficiency and to pollutant emissions of wood-burning appliances. Depending on the country, some of the following pollutant substances are taken into account by legislation: carbon monoxide (CO), nitrogen oxides (NOx), organic gaseous carbon (OGC) and particulate matter (PM). In order to promote the use of efficient and clean woody biomass heating systems, several European governments have introduced subsidies or tax incentives which reduce, for end-users, the cost of purchase and installing of these devices. Focusing on Italy, subsidies have been introduced recently through the so-called ”Conto termico” decree [2]. For pellet appliances it requires the following characteristics:
pellet stoves: thermal efficiency greater than 85%; CO emission less than 250 mg/Nm$^3$ (200 ppm) at 13% of O$_2$; total particulate matter emission less than 40 mg/Nm$^3$ at 13% of O$_2$.

pellet boilers: must comply with class 5 of European standard UNI EN 303-5:2012, that is thermal efficiency must be greater than $87% + \log(P_n)$, where $P_n$ is the nominal power of the boiler; CO emission less than is 250 mg/Nm$^3$ at 13% of O$_2$; total particulate matter emission less than 30 mg/Nm$^3$ at 13% of O$_2$.

The total particulate matter (TPM) is the quantity measured by a full flow dilution tunnel or, alternatively, by the measurement of the solid particles (PM), with gravimetric method, in combination with an OGC measurement, according the standard prEN 16510-1:2013. In “Conto termico” the subsidy is determined taken into account the value of TPM also: the smaller TPM, the larger the subsidy. For all these reasons wood-appliance manufacturers are increasing their efforts to design stoves and boilers with higher efficiency and lower pollutant emissions, investing in research and development. A review of current pellet stove technology can be found in [3–5].

Here we present the results of an experimental study on CO – mostly – and NOx emissions, which is part of a research program in collaboration with a pellet stove producer. The goal is to find methods to reduce emissions of stove models already on the market and to identify design criteria for new models to keep emissions low.

In [6] we described a preliminary investigation on a pellet stove focused on thermal efficiency. We also looked at CO emission. As expected they resulted strongly dependent on combustion air mass flow rate and on its distribution.

In this work we have extended the study, testing burning pots with different combustion air inlets and pellet stoves with different combustion chamber height. This with the aim to investigate how these geometrical features influence the relation between emissions and excess air. The influence of fuel (pellet) mass flow rate – that is to say, of heating power – has been considered also.

In pellet stoves combustion air control and fuel feeding systems cause significant fluctuations of air excess and pollutant emissions. Thus legislation, standards, and literature refer to mean values obtained over long time intervals of steady operations: so, for example, several hours of testing may be necessary to verify the effectiveness of a modification of the burner pot. In Sec. 4 we propose to use plots of instantaneous CO vs. O$_2$, in addition to those of average values. We show that such instantaneous plots – obtained in less than one hour of testing – can be successfully used to determine the effectiveness of modifications of the stove or to improve settings of the control systems, both in the producer’s testing laboratory and during the periodic maintenance on an installed stove.

Emissions of PM are currently under investigation.

2. Characteristic of pellet stove emissions

The principal elements which constitute wood are C, H, O and N, furthermore, water is always present. The flue gas, produced by ideal combustion of wood with air, contains N$_2$, O$_2$, CO$_2$ and H$_2$O. Because of non-optimal combustion conditions, in real cases other substances are present: among others CO, NO, NO$_2$, H$_2$, hydrocarbons (HC), poly-cyclic aromatic hydrocarbon (PAHs) and particulate matter.

Carbon monoxide is a pollutant substance due to incomplete combustion. In many countries, it is the only pollutant limited by law because it is strongly related to the quality of combustion and then to the concentration of other products of incomplete combustion.

The main cause of incomplete combustion in grate-fired systems is poor mixing of air with combustible substances both in the fuel bed and in the combustion chamber. Advanced air supply systems and optimized grate systems can significantly enhance the mixing, reduce the excess air, improve the combustion process, and lower pollutant levels [3,7–12]. Another key
parameter for a complete combustion is the temperature of the combustion chamber. It must be high enough to allow for oxidation reactions to take place. Cold air streams or drafts, for instance as secondary air, or the contact between flame and cold walls can stop the reaction and, consequently, increase the concentration of unburnt in flue gas. Combustion quality is also influenced by the residence time of gases in high temperature zone: combustion at low temperatures requires a longer residence time [13, 14].

The value of NOx is the sum of NO and NO\textsubscript{2}, but NO is the only one present in significant amount in pellet stove flue gas. Models of NO formation in combustion processes are available in literature [15–19]: NO can derive both from the nitrogen of combustion air and from the nitrogen present in fuel. It is well known that the principal mechanism of formation of NO in biomass combustion systems is the fuel-NO mechanism [7, 14–16, 20, 21], i.e. the NO formed from oxidation of nitrogen of the fuel.

The yield of NO from fuel-NO mechanism increases with excess air [17], conversely in the absence of oxygen the fuel-nitrogen forms N\textsubscript{2} rather than NO.

Other important substances present in pellet stove flue gas and considered by legislation are PM and HC. PM are largely investigated in literature. In works as [7, 9, 14, 22–33] the problem of emission of PM is discussed in depth, with particular attention to its causes and to particle size distribution. In our work PM emissions are currently under investigation, so we do not report on them here. However, according to the results reported in [23–25], we assume that optimization of the combustion process based on observation of CO-O\textsubscript{2} behavior would lead to a reduction of formation of PM also.

The same conclusion holds for HC emissions, in general, and OGC emissions, in particular (see prEN 16510-1:2013 for correlations between HC and OGC). As a matter of fact, explicit correlations between the concentration of CO and HC in flue gas can be found in [23, 24, 32, 34], for different type of biomass combustion systems: all of them are monotonically increasing functions of CO, so lower CO emissions correspond to lower OGC emissions. Furthermore [23, 24] report also a direct correlation between OGC and PM. Similar conclusions can be drawn from data collected in [12, 14, 27, 30, 31], although in these works explicit correlations are not presented. Other results regarding OGC can be found in [11, 14, 28, 29].

Other pollutants may be present in pellet stove flue gas, such as PAHs, SOx, HCl, PCDD/PCDF (see [7, 12, 14, 23, 28–31, 35] for some experimental studies), in [35], in particular, a correlation between PAHs and CO concentration is presented. In our experimental work we are not considering them yet.

### 3. Experimental tests

For all tests reported here we used the experimental setup and procedure proposed by the standards [36] and used by many other authors [21, 27, 34, 37, 38]. The whole stove, including the hopper, is put on a platform scale in order to measure the consumption of pellets. The composition of flue gas is measured at the flue gas socket. The gas analyzer used is Testo 350 XL, equipped with cells to measure the concentration (volume fraction) of O\textsubscript{2}, CO, NO, and NO\textsubscript{2} in dry gas, i.e. the flue gas without H\textsubscript{2}O. Measurement accuracy is the following.

- **Oxygen**: ±0,2%.
- **CO**: ±10 ppm when concentration is below 100 ppm; ±5% of reading, otherwise.
- **NO**: ±5 ppm when concentration is below 100 ppm; ±5% of reading, otherwise.

The CO\textsubscript{2} and N\textsubscript{2} concentration can be deduced from the stoichiometry of combustion, therefore it is possible to describe the process accurately. In this study we have tested 3 different pellet stoves: S1, S2, and S3. Each of them has a nominal heating power of 12 kW. Stove S1 is the base model, while stoves S2 and S3 have a combustion chamber shorter (S2) or taller (S3) than S1. Stove S1 have been used with different burner pots, to test the effect of changing combustion air
distribution. The burner pot is a small holed basket (figure 1). Pellets are fed into the furnace by means of the so-called overfed burner system [4]. These stoves are equipped with an air flow meter which measures the mass flow of combustion air. Primary air enters through the bottom grate and it passes through the chars, while secondary air is supplied directly in the flame zone by means of holes on vertical walls of the burner pot. During the tests, performed with stove S1, five burner pots were used. They differ by the total inlet area, by the primary air inlet area, and by the ratio between the inlet area for primary air and secondary air (see table 1).

At the beginning of a test session the stove is lit, setting the mass flow rate of air and of fuel for the first test, but measurements are started only when the stove reaches steady state conditions, i.e. when the flue gas temperature at the exit of the stove does not change more than a few kelvin. For subsequent tests mass flow rate of air or of fuel are changed without turning off the stove, but only waiting for steady state conditions with the new settings. During the tests, each lasting at least 30 minutes, concentrations are recorded, acquiring a sample every 5 seconds, i.e. at least about 360 samples for each test. CO and NO emission data are plotted versus the concentration of O\(_2\). In this work we present two types of data: time averaged values and instantaneous values. In figures 2 and 3, for examples, average concentration of CO or NO is plotted versus average concentration of O\(_2\) and each single point represents one test. In figures 4, 5, 6, 7, 8, and 9, instead, a point represents the instantaneous concentration of CO or NO plotted as a function of excess air or O\(_2\) concentration: one test is represented by a cloud of points.

In order to make a proper comparison of results, CO and NO 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 UNI EN 14785:2006), where \(X\) is the actual (averaged or instantaneous) concentration of CO or NO in ppm, \(O_{2}\) 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 NO at reference conditions, in ppm, i.e. the one shown in the diagrams.

4. Results
For a better understanding of our experimental results it is important to recall some characteristics of testing procedure due to the way the stoves, here tested, work. Combustion air mass flow rate, \(\dot{m}_a\), is kept constant by a feedback control system which measures the velocity of air at the inlet and varies the rotation speed of the fan which evacuates the flue gas. With regard to the fuel (pellet) mass flow rate, \(\dot{m}_f\), the typical feeding systems of pellet stoves are not continuous in time. A few pellets are released and fall into the burner pot with a time period of a few seconds: it is possible to change the fuel mass flow rate by changing this time period. Actually, the mass of pellet varies at each release, depending on the number and total length of the grains. Only fuel mass flow rate averaged over time intervals of some minutes can be considered roughly constant (nominal fuel mass flow rate).

Because of time variations of the instantaneous fuel mass flow rate, the amount of char and unburnt pellets in the burner pot vary as well, and instantaneous fuel mass flow rate doesn’t
Table 1. Air flow inlet areas for burner pots used in this study.

| Burner pot | Total area mm² | Primary area mm² | Sec./Tot. ratio |
|------------|----------------|------------------|-----------------|
| A          | 1848           | 1710             | 0.074           |
| B          | 2043           | 1710             | 0.163           |
| C          | 1535           | 1358             | 0.115           |
| D          | 1715           | 1358             | 0.208           |
| E          | 1358           | 1358             | 0               |

Table 2. Mean value with indication of 5th (min) and 95th (max) percentile for burner pot geometry A and D (figure 2).

|         | O₂ (%) | CO (ppm) |
|---------|--------|----------|
|         | mean   | min      | max      |
| A       | 11.7   | 10.1     | 13.5     |
| B       | 12.2   | 10.0     | 14.0     |
| C       | 13.9   | 12.1     | 15.5     |
| D       | 14.5   | 12.5     | 16.1     |

Variation of burning rate at constant combustion air mass flow rate causes significant fluctuations of the air excess. If we express it in terms of O₂ concentration ±2% oscillations are commonly observed, even when the stove is nominally at steady state. The instantaneous burning rate of pellet, \( \dot{m}_p \), can be estimated by means of equation 1 (see [39]),

\[
\dot{m}_p = \dot{m}_a \left( \frac{79}{721} \frac{7 + 4y_{CO_2} + y_{O_2}}{1 - y_{CO} - y_{CO_2} - y_{O_2} - 1} \right) \tag{1}
\]

where \( y_X \) is the instantaneous volume fraction of O₂, CO₂ and CO in flue gas and \( \dot{m}_a \) is the combustion air mass flow rate.

4.1. Influence of excess air and air distribution

In this section we report on how the amount and the distribution of air affect the combustion, therefore the production of CO and NO. Conclusions regarding the role of distribution will be qualitative. In order to put on a quantitative base the results shown here, we are planning a new series of tests on a modified stove. Primary and secondary air mass flow rates will be independent one from the other and will be controlled and measured separately.

The combustion air mass flow rate influences not only the excess air, but also the velocity of the air in the burning pot. A different distribution of air between primary and secondary air inlet, can change the local excess air and the fluid dynamics in the combustion chamber. Figure 2 shows the average concentration of carbon monoxide versus the average excess air for tests performed with different burner pots, while figure 3 shows results for NO concentration. Five different types of burner pot were used, table 1 reports their characteristics.

The different values of air inlet areas modify its distribution in the combustion chamber: burner pot B and burner pot D, for examples, allow a larger amount of air to pass above the char with respect to burner pots A and C, while in burner pot E air can pass through the bottom holes only. Results obtained with burner pot B and D are better than those obtained with burner pot A, C, and E, characterized by poorer performances. For burner pots B and D the ratio between secondary air inlet area and total air inlet area is greater then for the other burner pots. Therefore, a large amount of air entering from the top, i.e. in the flame zone, causes lower emission of CO. A significant secondary air flow allows the char and the first zone of flame – the one below the secondary air inlet – to reach higher temperatures, because of a lower local excess air, thus improving conditions to obtain complete combustion in this zone.
In addition, a strong secondary air flow produces a better mixing of gases in the upper zone of flame.

For all burner pots the quality of combustion strongly depends on the excess air: in particular, CO concentration is an increasing function of O₂ for the O₂ interval that could be investigated. These results agree with those in [23] and are compatible with results of [38, 40]. In the latter studies the relation between CO and O₂ admits a minimum (optimum): the absence of the decreasing branch of the curve in our results is due to the high concentration of O₂ obtained with stove S1 and we expect that for lower concentration of oxygen, CO concentration would increase, as instantaneous results for stoves S2 and S3 do confirm.

In any case, the important point is that for burner pots B and D low emissions were obtained over a rather large interval of O₂ concentration, whereas with burner pots A, C and E, the O₂ interval where CO is low seems to be narrower.

![Figure 2. Average value of CO as a function of O₂ for different type of burner pots: □ A, ○ B, × C, ▲ D, + E.](image1)

![Figure 3. Average value of NO as a function of O₂ for different type of burner pots: □ A, ○ B, × C, ▲ D, + E.](image2)

The production of NO seems to be favored by an increase of air in the combustion chamber, but at the same time it is independent from the geometry of the burner pot. As a matter of fact NO emissions are the same for each type of burner pot: all points fall around the same curve. The trend of this curve is comparable with results of [15, 38, 40], in which NO concentration increase in flue gas is explained by the high conversion efficiency of fuel-NO mechanisms. With regard to the other production mechanisms of NO, the contribution of thermal-NO mechanism can be considered negligible since maximum temperatures, usually below 1000°C as shown in [6], are not high enough to produce significant amounts of NO with this mechanism.

The average concentration of CO and NO quantifies the total amount of substances emitted in the atmosphere during the test and for this reason it is used by standards to declare the emission of the stove, and in [22–25, 27, 37, 38] to report their results. As a matter of fact, during a test the instantaneous fluctuations are very high: the continuous variation of burning rate modifies the instantaneous excess air thus influencing the behavior of combustion and in particular the production of CO. This results in turn in significant oscillations of concentrations during the tests, as it can be seen in table 2. High oscillations of concentration values can be observed in the table 6 of [31] and in many test reports of [41], for instance.

As already mentioned, O₂ concentration values collected during a single test at steady conditions do span a quite large interval: about 4 or 5 percentage points. Upon plotting these instantaneous data on the O₂-CO plane, one can obtain a reasonable approximation of the CO vs. O₂ correlation for the stove configuration tested. As an example, consider data reported in figures 2 (average) and 4 (instantaneous). In order to compare performance of burning pots C and D using average data, 4 tests were necessary for each burner pot to span the range from...
11% to 15% of O\textsubscript{2}. That took more than two hours of testing. Using instantaneous data a single test (taking slightly more than half an hour of testing) was sufficient to show the better performance of burning pot D. In addition, it is evident from figure 4 that burner pot D is characterized by low and approximately constant CO emissions over a larger interval (12%,15%) of O\textsubscript{2} concentration.

Figures 4 and 5 show the results obtained with burner pot C and D. Results obtained with other burner pots are not shown only to avoid to crowd the plots with too many points. The conclusions that can be drawn from the instantaneous data agree with those obtained analyzing average values. From both points of view it is clear that the CO trend as a function of the excess of air is the same. For each burner pot it is possible to identify an optimal range of oxygen content, i.e. a value of excess air, which minimize the production of CO. In addition, burner pots with larger secondary air inlet area are characterized by a larger optimal range and by lower CO production levels.

4.2. Influence of fuel mass flow rate

The user of a pellet stove can choose and set the heating power level. As a consequence the electronic control system, present in all modern pellet stoves, sets both the fuel and the air mass flow rate. Since the combustion chamber and burner pot geometry is not adjustable, one could not expect to obtain optimal performances for all the available power levels. As a matter of fact, high CO concentration in flue gas at reduced power – about 30 % of nominal heating power, usually – is commonly observed: see, for example, the relation between O\textsubscript{2} in flue gas and input energy reported in [38].

Several tests have been performed at different heating power levels, to investigate this effect. In all cases stove S1 with burner pot A was used. At each power level tests were performed for different values of air mass flow rate.

Figure 6 shows instantaneous CO concentration versus O\textsubscript{2} concentration for four tests performed at the same heating power level, but for different air mass flow rates: these tests are useful to determine the optimal stove settings, that is the proper mass flow rate of air for a given heating level that minimizes CO emission. To interpret the data it is useful to recall that during a single test air flow rate is kept constant. Nevertheless, due to variation of the burning rate, O\textsubscript{2} concentration varies, causing the dispersion of points along the abscissa. Data seem to exhibit a regular behavior and to distribute along the same curve, independently from the particular test considered.

Figure 7 shows instantaneous CO concentration versus O\textsubscript{2} concentration for tests at different power levels. Despite a wide range of variation of fuel mass flow rate, all points fall onto the same
region of plane O₂-CO without the possibility to clearly distinguish one case from the other. For this range of variation it exists a fixed concentration of oxygen in flue gas, hence a fixed excess air, that optimizes the combustion, reducing the production of CO: the minimum CO emission level is the same for any power level. In other tests, performed at 5.8 kW, the concentration of CO increases faster as the concentration of O₂ increases, but the optimal range and CO emission in the optimal range are the same. We conclude that for these stoves, at any power level, adjustment and control of the excess air through the air regulation system is sufficient to obtain a good combustion. High CO concentration usually observed at reduced power seem to be a problem related to the air suction system, rather than to low heating power levels. In designing the combustion air supply system it is necessary to guarantee a range of mass flow rates wide enough to ensure a good combustion both at nominal and at reduced heating power.

4.3. Influence of combustion chamber and bottom grate area dimensions
The size of the combustion chamber is an important parameter to obtain a good combustion: in particular, it should be tall enough to allow the full development of the flame. Tests performed using the same burner pot in stove S2, with short combustion chamber, and stove S3, with tall combustion chamber, are compared in figure 8. It is clear from the instantaneous data that combustion in stove S3 is better than in stove S2. During the tests O₂ content spanned an interval wide enough to show the minimum of the CO-O₂ curve. In the case of stove S2, the
flame would be longer than the available space, so it hits cold walls, where the combustion of some substances stops. In stove S3 the flame can develop completely in its tall combustion chamber: this improves combustion yielding a lower level of CO emissions.

The deposition of ash on the grate is a characteristic issue of overfed burner combustor. It can be removed only by the air flow. Ash deposition can occur at reduced power level if the velocity of the air entering through the bottom grate is too low to remove the ash. At nominal heating power if excess air is too low, a thick layer of fresh pellet and char forms above the ash and inhibits its removal. In the worst case, a layer of sintered ashes (clinker) forms on the bottom of fuel bed, blocking the air flow through the bottom grate and deviating most of the air flow through the secondary air inlets. This process depends on the quality of pellet, also: in particular, on the deformation temperature of ashes. For this reason, during a long run test the behavior of combustion can vary, i.e. the CO-O$_2$ curve and optimal point of working change. Further tests must be carried out to study these phenomena in depth and, in particular, to find the optimal dimension of the combustion grate that ensures low pollutant emissions for long time periods (from few hours to some days).

5. Conclusions
CO production in pellet stoves strongly depends on the amount and distribution of air in combustion chamber. To ensure low emissions of CO and fulfill subsidy or tax incentive requirements, it is necessary to increase the ratio between secondary and total air mass flow rate. In addition, the combustion air supply system and its electronic control must be properly designed.

For each type of burner pot it is possible to find an optimal interval of excess air that reduces the emission of CO over a wide range of thermal power.

Emissions of NO depend only on the excess air. In any case, in all tests we ran it was well below limit enforced by legislation.

These conclusions can be drawn considering either data obtained as average over time intervals of steady operation or instantaneous data.

In particular, plots of instantaneous emissions versus O$_2$ concentration (i) allow us to find quickly the optimal point of working, just after one test, (ii) allow to obtain useful information from any phase of operation (start, stop, etc.) and from any thermal load, (iii) supply reliable information also for the setup after the installation – currently the stove setup is mostly based on the stove installer experience – (iv) in the future, if the installation cost of O$_2$ and CO transducer will be affordable for most stoves, they will be an important tool for the self-adjustment of the stove/boiler.

We have applied the results presented here to modify stoves with relatively high CO emissions. In figure 9, for example, the application of these solutions has made possible the reduction of mean concentration of CO and the enlargement of the excess air range corresponding to low CO emission.

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References
[1] ARPA 2008 Stima dei consumi di legna da ardere per uso domestico in Italia - Rapporto finale Progetto APAT - ARPA Lombardia
[2] DM 28/12/12 (Italia) 2012 Incentivazione della produzione di energia termica da fonti rinnovabili ed interventi di efficienza energetica di piccole dimensioni
[3] Fiedler F 2004 The state of the art of small-scale pellet-based heating systems and relevant regulations in Sweden, Austria and Germany Renewable and Sustainable Energy Reviews, 8(3), 201–221.
[4] Obernberger I, Thek G 2006 Recent developments concerning pellet combustion technologies: a review of Austrian developments Proc. 2nd World Pellets Conf., 31–40.

[5] Miguez J L, Moran J C, Granada E, Porteiro J 2012 Review of technology in small-scale biomass combustion systems in the European market Renewable and Sustainable Energy Reviews, 16(6), 3867–3875.

[6] Petrocelli D and Lozzi A M 2012 Experimental study of a pellet stove XXX UIT Heat Transfer Conf., Bologna, June 25–27 2012

[7] Yin C, Rosendahl L A, Kr S K 2008 Grate-firing of biomass for heat and power production Progress in Energy and Combustion Science, 34(6), 725–754.

[8] Obernberger I, Thek G 2006 Recent developments concerning pellet combustion technologies: a review of Austrian developments Proc. 2nd World Pellets Conf., 31–40.

[9] Wiinikka H, Gebart R, Boman C, Böström D, Nordin A, Ohman M 2006 High-temperature aerosol formation in wood pellets flames: Spatially resolved measurements Combustion and Flame, 147(4), 278–293.

[10] Strehler A 2000 Technologies of wood combustion Ecological Engineering, 16, 25–40.

[11] Scharler R, Obernberger I 2000 Numerical modeling of biomass grate furnaces Proc. of the European Conf. on Industrial Furnaces and Boilers (INFUB), (x), 1–17.

[12] Brunner T 2009 Primary measures for low-emission residential wood combustion: comparison of old with optimised modern systems Proc. of the 17th European Biomass Conf. & Exhibition, Hamburg.

[13] Pettersson E, Nordin A, Ohman M 1996 Effect of temperature and residence time on emissions of CO, THC, tar and NOx during pellet combustion Proc. of Nordic Seminar on Thermochemical conversion of biofuels.

[14] Boman C, Nordin A, Ohman M, Böström D, Westerholm R 2005 Emissions from Small-scale Combustion of Biomass Fuels: Extensive Quantification and Characterization Energy Technology and Thermal Process Chemistry, Umeå University.

[15] Glarborg P 2003 Fuel nitrogen conversion in solid fuel fired systems Progress in Energy and Combustion Science 29 89–113

[16] Klasen T and Bai X 2007 Computational study of the combustion process and NO formation in a small-scale wood pellet furnace Fuel 86 1465–1474

[17] Hill S and Douglas Smoot I 2000 Modeling of nitrogen oxides formation and destruction in combustion systems Progress in Energy and Combustion Science 26 417–458

[18] Malte P C and Pratt D T 1974 The Role of Energy-Releasing Kinetics in NOx Formation: Fuel-Lean, Jet-Stirred CO-Air Combustion Combustion Science and Technology 9 221–231 (Preprint)

[19] Fenimore C 1971 Formation of nitric oxide in premixed hydrocarbon flames Symposium (International) on Combustion 13 373–380

[20] Klasen T, Bai X S 2007 Computational study of the combustion process and NO formation in a small-scale wood pellet furnace Fuel, 86(10-11), 1465–1474.

[21] Widmann E, Scharler R, Stubenberger G, Obernberger I 2004 Release of NOx precursors from biomass fuel beds and application for CFD-based NOx postprocessing with detailed chemistry Proc. of the 2nd World Conf. and Exhibition on Biomass for Energy, Industry and Climate Protection, X, 1384–1387.

[22] Wiinikka H, Gebart R 2004 Experimental investigations of the influence from different operating conditions on the particle emissions from a small-scale pellets combustor Biomass and Bioenergy, 27(6), 645–652.

[23] Johansson I S, Leckner B, Gustavsson L, Cooper D, Tullin C, Potter A 2004 Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets Atmospheric Environment, 38(25), 4183–4195.

[24] Kelz J, Brunner T, Obernberger I 2012 Emission factors and chemical characterization of fine particulate emissions from modern and old residential biomass heating systems determined for typical load Environmental Sciences Europe, 1–18.

[25] Bäver L S, Leckner B, Tullin C, Berntsen M 2011 Particle emissions from pellet stoves and modern and old-type wood stoves Biomass and Bioenergy, 35(8), 3648–3655.

[26] Schmidl C, Luiuser M, Padovanas E, Lasselsberger L, Rzaca M, Ramirez-Santa Cruz C, Puxbaum H 2011 Particulate and gaseous emissions from manually and automatically fired small scale combustion systems Atmospheric Environment, 45(39), 7443–7454.

[27] Win K M, Persson T, Bales C 2012. Particles and gaseous emissions from realistic operation of residential wood pellet heating systems Atmospheric Environment, 59, 320–327.

[28] Olsson M, Kjällström J, Petersson G 2003 Specific chimney emissions and biofuel characteristics of softwood pellets for residential heating in Sweden Biomass and Bioenergy, 24(1), 51–57.

[29] Olsson M, Kjällström J 2006 Low emissions from wood burning in an ecolabelled residential boiler Atmospheric Environment, 40(6), 1148–1158.

[30] Boman C, Nordin A, Westerholm R, Pettersson E 2005 Evaluation of a constant volume sampling setup for residential biomass fired appliances: influence of dilution conditions on particulate and PAH emissions. Biomass and Bioenergy, 29(4), 258–268.
[31] Boman C 2005 Particulate and gaseous emissions from residential biomass combustion (Doctoral dissertation, Umea University).

[32] Brunner T 2008 Evaluation of parameters determining PM emissions and their chemical composition in modern residential biomass heating appliances Proc. of the International Conf. World Bioenergy, 81–86.

[33] Johansson L S, Tullin C, Leckner B, Sjövall P (2003). Particle emissions from biomass combustion in small combustors Biomass and Bioenergy, 25(4), 435–446.

[34] Ozil F, Tschamber V, Haas F, Trouvé G 2009 Efficiency of catalytic processes for the reduction of CO and VOC emissions from wood combustion in domestic fireplaces Fuel Processing Technology, 90(9), 1053–1061.

[35] Khalfi A, Trouvé G, Delobel R, Delfosse L 2000 Correlation of CO and PAH emissions during laboratory-scale incineration of wood waste furnitures Journal of Analytical and Applied Pyrolysis, 56(2), 243–262.

[36] EN 14785:2006 Residential space heating appliances fired by wood pellets - Requirements and test methods

[37] Persson T, Fiedler F, Nordlander S, Bales C, Paavilainen J 2009 Validation of a dynamic model for wood pellet boilers and stoves Applied Energy, 86(5), 645–656.

[38] Dias J, Costa M, Azevedo J L T 2004 Test of a small domestic boiler using different pellets Biomass and Bioenergy, 27(6), 531–539.

[39] Petrocelli D 2013 Indicazioni sperimentali per la progettazione di stufe a pellet ad alta efficienza. PhD thesis, Università degli Studi di Brescia

[40] Eskilsson D, Rönnbäck M, Samuelsson J, Tullin C 2004 Optimisation of efficiency and emissions in pellet burners Biomass and Bioenergy, 27(6), 541–546.

[41] Josephinium BLT tests report http://www.josephinum.at/blt/pruefung/pruefberichte/feuerungen/pelletsfeuerungen.html