A note on calculation of efficiency and emissions from wood and wood pellet stoves

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Abstract. In recent years, national laws and international regulations have introduced strict limits on efficiency and emissions from woody biomass appliances to promote the diffusion of models characterized by low emissions and high efficiency. The evaluation of efficiency and emissions is made during the certification process which consists in standardized tests. Standards prescribe the procedures to be followed during tests and the relations to be used to determine the mean value of efficiency and emissions. As a matter of fact these values are calculated using fuel gas temperature and composition averaged over the whole test period, lasting from 1 to 6 hours. Typically, in wood appliances the fuel burning rate is not constant and this leads to a considerable variation in time of composition and flow rate of the fuel gas. In this paper we show that this fact may cause significant differences between emission values calculated according to standards and those obtained integrating over the test period the instantaneous mass and energy balances. In addition, we propose some approximated relations and a method for wood stoves which supply more accurate results than those calculated according to standards. These relations can be easily implemented in a computer controlled data acquisition systems.

1. Introduction
Wood is one of the most ancient sources of energy for residential heating. In some areas it is still the largely used fuel, mainly in the form of wood logs. In the last twenty years use of other forms, such as wood chips and pellets, has increased very much.

Although wood is a renewable energy source, old and inefficient appliances are a source of ambient air pollution in many urban areas. For this reason several European countries are trying to promote the development and diffusion of wood-burning appliances that ensure the best utilization of fuel. This goal is pursued through enforcement of more strict limits on efficiency and emissions from appliances and through subsidies to the more efficient models. The evaluation of efficiency and emissions is made during the certification process that consists in a prescribed series of tests made according to national or international standards. Standards on wood-burning appliances have been frequently revised, lately. In most of the revisions only standard’s sections regarding construction and safety requirements are updated. Sections reporting methods and equations to compute or to determine efficiency, emissions and related quantities are usually unchanged.

In woody biomass appliances the fuel burning rate is not constant and this leads to a considerable variation in time of concentration and temperature of flue gas. In appliances such
as wood stoves in particular, the burning rate at the beginning of the test period is very different from that at the end. Also combustion in pellet stoves and boilers is not strictly stationary. In order to take this intrinsically unsteady behavior into consideration, standards and certification procedures prescribe to calculate efficiency and emissions using as input data average values of temperature and composition. The average is taken over the entire test duration, ranging from 1 up to 6 hours depending on the type of appliance. However, it seems more correct to determine efficiency and emissions using instantaneous temperature and composition values, and then averaging the results. Differences between values obtained by the two approaches are not negligible and affect, in our opinion, the correct evaluation of appliance performance.

In this paper, in Sec. 2 we recall the main relations to calculate efficiency and emissions on the basis of flue gas data collected during a typical testing session. In Secs. 3 and 4 we present characteristic features of combustion and testing of wood and pellet stoves, respectively. In Sec. 5 we propose approximated relations and methods that can be used for the calculation of efficiency and emissions for both wood and pellet appliances. Finally in Sec. 6 experimental data for pellet stoves and wood stoves post-processed with equations introduced in Sec. 5 are compared and discussed with those obtained according to standards’ methods.

2. Combustion of wood

Wood is mainly composed by carbon, hydrogen, oxygen and nitrogen, plus traces of other elements that will be neglected here. Elements are combined in complex molecules as such cellulose, hemicellulose, lignin. The products of complete combustion are carbon dioxide and water. In real combustion other products are present: CO, NOx, hydrocarbons, dust, etc. They are the result of a non-ideal combustion and they are often unwanted because pollutant. Emissions are expressed as the quantity – either total volume or total mass – of pollutant emitted, referred to the quantity of burned fuel. In standards, emission values are usually supplied in mg/Nm$^3$ referred to a fixed quantity of O$_2$, i.e. the mass of substance present in 1 m$^3$ of flue gas at normal conditions (0 °C, 101.325 kPa) and characterized by oxygen concentration equal to O$_{2\text{ref}}$. Actually combustion does not occur in such a way that concentration of oxygen in flue gas is O$_{2\text{ref}}$, but reporting data in this way it is necessary for a meaningful comparison of different appliances. Another way to report the concentration of a pollutant is in mg/MJ, i.e. the mass of pollutant emitted referred to the input energy $m$ LHV. The analysis of the combustion can be done starting from the composition of fuel from elemental analysis and the composition of flue gas. Common gas analyzer can measure the volume concentration in the dry part of flue gases of O$_2$, CO$_2$, CO, NO$_x$, HC, etc. For this reason, flue gas is ideally divided in dry part and water vapor. The dry part of flue gas for appliances that burn wood is mainly composed by N$_2$, O$_2$, CO$_2$, CO, NO$_x$, HC. Since CO, NO$_x$ and HC concentrations are typically two or three order of magnitude lower than those of N$_2$, O$_2$ and CO$_2$, they are neglected for calculation of volume and mass flow rate. Here we consider the CO, so that we can make a comparison with relations of standards. The goal of the following analysis is to recall some useful relations for the evaluation of emitted substances and energy content of flue gas.

Treating flue gas as an ideal mixture of ideal gases, the volume flow rate of dry flue gas at normal conditions is

$$V_f = \dot{m} \frac{22.4 \cdot C}{12 \cdot (y_{\text{CO}} + y_{\text{CO}_2})} \tag{1}$$

where $\dot{m}$ is the burning rate, $y_{\text{CO}}$ and $y_{\text{CO}_2}$ are the volume concentration of CO and CO$_2$, respectively, and $C$ the mass fraction of carbon in the fuel; all quantities are in SI units. It’s worthwhile to mention that in standards the ratio 12/22.4 is expressed as 0.536. The CO mass flow rate can be expressed as

$$\dot{m}_{\text{CO}} = \dot{m} \frac{7C}{3} \frac{y_{\text{CO}}}{y_{\text{CO}} + y_{\text{CO}_2}} \tag{2}$$
Regarding the water vapor, it derives from the evaporation of moisture of the fuel and oxidation of hydrogen, hence if \( W \) is the mass fraction of water in the fuel and \( H \) the mass fraction of oxygen the volume flow rate at normal conditions is

\[
\dot{V}_w = \frac{22.4}{18} \dot{m} (9H + W) \tag{3}
\]

In standards the ratio 22.4/18 is explicitly indicated as 1.245. Here, we want to represent the emission of a substance, CO for example, as the ratio between the mass of CO which is emitted during a test and the total volume of dry flue gas at normal conditions and at \( O_{2,\text{ref}} \). Denoting \( t_{\text{test}} \) the test duration, the total mass of CO which is emitted can be calculated from the instantaneous values collected during the test,

\[
m_{CO} = \int_0^{t_{\text{test}}} \dot{m}_{\text{CO}} dt = C \frac{7}{3} \int_0^{t_{\text{test}}} \dot{m} \frac{y_{\text{CO}}}{y_{\text{CO}} + y_{\text{CO}_2}} dt \tag{4}
\]

Since the volume flow rate of flue gas at normal conditions at \( O_{2,\text{ref}} \) is

\[
\dot{V}_{f,\text{ref}} = \dot{V}_f \left( \frac{0.21 - y_{O_2}}{0.21 - O_{2,\text{ref}}} \right),
\]

the total volume of flue gas is given by the following relation

\[
V_{f,\text{ref}} = \int_0^{t_{\text{test}}} \dot{V}_{f,\text{ref}} dt = C \frac{0.536}{0.33} \int_0^{t_{\text{test}}} \dot{m} \frac{y_{\text{CO}}}{y_{\text{CO}_2} + y_{\text{CO}} + y_{\text{CO}_2}} \left( \frac{0.21 - y_{O_2}}{0.21 - O_{2,\text{ref}}} \right) dt \tag{5}
\]

It follows,

\[
\frac{m_{CO}}{V_{f,\text{ref}}} = \frac{\frac{7}{3} \int_0^{t_{\text{test}}} \dot{m} \frac{y_{\text{CO}}}{y_{\text{CO}_2} + y_{\text{CO}}} dt}{\int_0^{t_{\text{test}}} \dot{m} \frac{y_{\text{CO}}}{y_{\text{CO}_2} + y_{\text{CO}}} \left( \frac{0.21 - y_{O_2}}{0.21 - O_{2,\text{ref}}} \right) dt} \tag{6}
\]

A similar equation can be obtained for all substances measurable with a continuous analyzer, i.e. NOx, THC, SOx, etc.

Efficiency of appliances which release heat to the surroundings by convection and radiation is determined through an indirect method by the relation

\[
\eta = \frac{Q_{\text{in}} - Q_a - Q_b}{Q_{\text{in}}} \tag{8}
\]

where \( Q_a \) represents the total thermal losses, while \( Q_b \) the chemical losses in flue gas. They are defined by

\[
Q_a = \int_0^{t_{\text{test}}} \dot{Q}_a dt \quad Q_b = \int_0^{t_{\text{test}}} \dot{Q}_b dt \tag{9}
\]

\( \dot{Q}_a \) is the sum of the thermal losses in the dry part of flue gas and in water vapor

\[
\dot{Q}_a = \dot{V}_f c_{p,\text{dry}} (T_f - T_{0,i}) + \dot{V}_w c_{p,\text{w}} (T_f - T_{0,i}) \tag{10}
\]

where \( c_{p,\text{dry}} \) and \( c_{p,\text{w}} \) are the volumetric specific heat at constant pressure of the dry part of flue gas and of the water vapor, measured in kJ/m³ K. \( \dot{Q}_b \) is the power that can be obtained from combustion of CO in flue gas, i.e.

\[
\dot{Q}_b = \dot{m}_{\text{CO}} LHV_{\text{CO}} = \dot{m} C \frac{7}{3} \frac{y_{\text{CO}}}{y_{\text{CO}_2} + y_{\text{CO}}} LHV_{\text{CO}} \tag{11}
\]
Since $Q_{in} = m \text{LHV}$, the expression of efficiency is

$$\eta = 1 - \frac{\int_{0}^{t_{\text{test}}} \dot{Q}_{a,i} \, dt}{m \text{LHV}} - \frac{\int_{0}^{t_{\text{test}}} \dot{Q}_{b,i} \, dt}{m \text{LHV}} = 1 - q_{a,i} \% - q_{b,i} \% \quad (12)$$

For example, $c_{p,\text{dry}}$ depends on $T_f$ and $\gamma_{\text{CO}_2}$ and is represented by a polynomial; $c_{p,w}$ is a function of $T_f$. The other contribution is chemical losses. Since they are related to the concentration of CO in flue gas, and concentration of CO is limited by standards and laws at 400 ppm, its contribution to total efficiency is of the order of magnitude of 0.1%.

3. Wood stoves

Wood stoves are simple appliances for combustion of wood, usually in logs. In a wood stove combustion takes place in the combustion chamber. A door permits the charge of wood logs in combustion chamber. Often, in modern wood stoves, on the door is present a glass window that allows to see the flame and contributes to the release of heat to the room. Combustion air is usually supplied from the bottom grid (primary air) and from the top of the chamber (secondary air). The residues of combustion pass through the bottom grid and are collected in an ash box. Some firebricks cover the combustion chamber. They maintain a high temperature in the combustion chamber and, at the same time, regularize the heat flux by acting as thermal inertia. Hot gases formed in combustion process release heat to the body of the stove, usually steel or cast iron, and to the flue pipe that in turn releases heat to the room by natural convection and radiation. At the flue exit of a traditional wood stove it is necessary a natural draught. Regulation of combustion is done by varying the section of the primary air. The draught of the chimney, can be modified with a damper at the flue exit. These regulations are usually based on user’s experience. When the appliance is heated up and an adequate fire bed is formed, the wood introduced in combustion chamber ignites after a few seconds receiving heat from embers and wall of the combustion chamber. A similar appliance is the wood-cooker, in which part of the heat power is used to heat the cooking plate and the oven.

3.1. Combustion in wood stoves

Wood log stoves are intermittent burning appliances, i.e. appliances in which refueling of the combustion chamber is done after partial or full consumption of the previous charge of fuel. The combustion of wood logs is characterized by some consecutive phases. Just after the insertion of the wood log in the combustion chamber, it dries with the evaporation of water. Then log temperature increases, volatile gases form from decomposition of wood, and a first flame appears. The decomposition of wood reaches the maximum rate: wood mass rapidly decrease (high burning rate) and CO2 concentration in flue gas is due to the high rate of consumption of oxygen. Finally, during the burn-out phase, burning rate diminishes, tending to zero, and CO2 concentration in flue gas decreases.

The behavior of CO concentration depends on the characteristics of combustion chamber: usually at the beginning of the combustion phase increases with CO2 (low excess air), then when CO2 decreases, it reaches the lowest values and finally increases during the burn-out phase, when combustion takes place with high excess air (see figure 4).

3.2. Testing methods

Tests for determination of efficiency and emissions of wood burning appliances are made according to EN 13240 [1] for wood stoves and according to EN 12815 [2] for wood cookers. They consist in a pre-test period and one or more test periods. During pre-test the appliance heats-up and on the grate an adequate fire bed has to form, only measurements of test period are taken into account. A test period begins when a specified quantity of fuel is loaded in the combustion
chamber and finishes when the weight of the appliance return at the value measured just before the insertion of the fuel charge. The test is valid only if it lasts at least 45 minutes (for wood log). In order to perform test, the appliance must be placed on a platform scale. Temperature and composition of flue gas must be measured at the flue exit. During the test the following quantities must be measured: flue gas temperature, flue gas composition, i.e. the concentration of CO2, CO, NO, THC, with a frequency of at least one sample per minute, room temperature. For stoves with an integrated boiler, inlet and outlet water temperature and water mass flow rate must be measured in order to determine the power transferred to water.

4. Pellet stoves and boilers
Pellet stoves and pellet boilers are modern appliances, which are designed for the combustion of wood pellet. The dimension of pellet particle is suitable for automatic feeding systems that ensure a relatively regular provision of fuel in combustion chamber, usually in a burning pot. Product of combustion are evacuated by a fan placed at the flue exit. All modern pellet stoves and pellet boiler are equipped by an electronic control unit. In simple models, the user sets the power level and a control unit regulates the rotation speed of flue gas fan and of the screw auger for the delivery of fuel in the burning pot; In complex models, the control unit regulates the combustion on the basis of feedbacks from transducers like thermocouples in combustion chamber, lambda sensors, flow meters, etc.

4.1. Combustion in pellet stoves
Combustion in pellet stoves and pellet boilers takes place continuously. For this reason phases of combustion are not distinguishable, because at the same time in the burning pot there are particles just inserted that dries, particles that are in the phase of pyrolysis and gasification and other particles at the end of combustion. However, it is not possible to obtain a strictly constant burning rate, so composition and temperature in flue gas fluctuate in time.

4.2. Test methods
Tests for pellet burning appliances, with automatic feeding system, according to EN 14785 [3] for pellet stoves or EN 303-5 [4] for pellet boilers, consist in a pre-test period, during which the stove reaches steady state condition of operation, and a test period lasting 6 hours for boilers or two test periods lasting 3 hours for pellet stoves. As in tests on wood stoves, also in this kind of test flue gas temperature, flue gas composition, and room temperature, must be measured and recorded at least once every minute.

5. Emission and efficiency calculation
5.1. Method of standards
According to standards, the concentration of a pollutant substance X referred to the reference concentration of oxygen O$_{2,ref}$, on the basis of data measured during a test is

$$X \text{ content} = \frac{X \cdot 0.21 - O_{2,ref}}{0.21 - \overline{Y_{O2}}},$$

where $X$ and $\overline{Y_{O2}}$ are, respectively, the time average of $X$ and O$_2$ concentration over the whole test period.

Efficiency is determined by equation (12), where $q_{a\%,i}$ and $q_{b\%,i}$ are calculated using the average CO and CO$_2$ concentration and the average flue gas temperature. For both pellet and wood appliances, standards take into account only the average over the whole test period of all
data measured. For pellet boiler, only heat transferred to water is considered useful, therefore the efficiency is calculated with the "direct method", i.e.

$$\eta_{\text{direct}} = \frac{Q_{\text{water}}}{m \cdot \text{LHV}}$$  \hspace{1cm} (14)$$

where the power transferred to water is calculated from the measure of water mass flow rate and of water temperature increment in the boiler.

5.2. Emissions of pellet appliances

As mentioned in section 4.1, burning rate is not strictly constant, then also composition and flow rate of flue gas varies in time. CO emission is strongly correlated to excess air [5]: in particular, it results low in an optimal range of excess air, that is to say in an optimal range of oxygen concentration, while for higher or lower values of excess air it increases rapidly [6]. Concentration of a gas in flue gas depends on the concentration of other gases. For example, when combustion take place with low excess air, the concentration of oxygen is low and, consequently, the concentration of all other gases – pollutants included – is higher. Conversely, when combustion takes place with high excess air, concentration of oxygen is high, therefore the concentration of other substances results lower. Therefore, the same concentration of CO at different O2 concentrations corresponds to different total emissions: the mass of CO emitted when oxygen level is low is less than the mass of CO emitted when oxygen level is high. Equation (13) does not distinguish from the two cases, because only the overall average of O2 and CO concentration are used. Equation (7) is not affected by this and it can be used to determine a more accurate value for pollutant concentration. However, for pellet appliances is not possible to measure the burning rate \( \dot{m} (t) \) accurately, because the resolution of the platform scale, that measure the overall weight of the appliance, is not enough, often 10 or 50 grams. For the accurate measurement of pollutant emissions, Win et al. [7] measure directly the flue gas flow rate. In our opinion, this method is too complicated to be proposed for the test procedure of the Standards. What we can do is to consider \( \dot{m} \) approximately constant, since it fluctuates randomly around its mean value. Furthermore, since \( y_{\text{CO}} \ll y_{\text{CO}_2} \), we can approximate \( y_{\text{CO}} + y_{\text{CO}_2} \sim y_{\text{CO}_2} \). Then, the denominator in Eq. (7) can be simplified as follows

$$\int_{0}^{t_{\text{test}}} \frac{\dot{m}}{y_{\text{CO}_2}} \left( \frac{0.21 - y_{\text{CO}_2}}{0.21 - O_{2,\text{ref}}} \right) dt = \dot{m} \int_{0}^{t_{\text{test}}} \frac{1}{y_{\text{CO}_2}} \left( \frac{0.21 - y_{\text{CO}_2}}{0.21 - O_{2,\text{ref}}} \right) dt = \dot{m} \int_{0}^{t_{\text{test}}} v_{t,\text{ref}} dt = \dot{m} v_{t,\text{ref}} t_{\text{test}}$$

where \( v_{t,\text{ref}} \) represents the volume of flue gas at normal conditions when concentration of oxygen is equal to \( O_{2,\text{ref}} \) per mass of fuel burned. Eq. (7) can be rewritten

$$\frac{m_{\text{CO}}}{V_{t,\text{ref}}} = \frac{1.25}{t_{\text{test}}} \int_{0}^{t_{\text{test}}} \frac{y_{\text{CO}}}{y_{\text{CO}_2} v_{t,\text{ref}}} dt = \frac{1.25}{t_{\text{test}}} \int_{0}^{t_{\text{test}}} y_{\text{CO}} \left( \frac{0.21 - O_{2,\text{ref}}}{0.21 - y_{\text{CO}_2}} \right) dt$$

Therefore the CO content is the time average of instantaneous CO concentration referred at \( O_{2,\text{ref}} \). The CO emission measured in mg/MJ, can be obtained dividing Eq. (4) by m LHV:

$$\frac{m_{\text{CO}}}{Q_{\text{in}}} = \frac{7 C}{3 \text{LHV}} \int_{0}^{t_{\text{test}}} \frac{y_{\text{CO}}}{y_{\text{CO}} + y_{\text{CO}_2}} dt$$

(17)
5.3. Efficiency of pellet appliances

The efficiency of pellet appliances, can be determined using Eq. (12). Even in this case, if \( \dot{m} \) can be considered constant, the terms \( q_a \%) \) and \( q_b \%) \) become:

\[
q_a \% = \frac{1}{t_{\text{test}} \text{ LHV}} \int_0^{t_{\text{test}}} \left[ \frac{C}{0.536 (y_{CO} + y_{CO_2})} c_{p,dry} + c_{p,w} (9H + W) \right] (T_F - T_{0,i}) \, dt \tag{18}
\]

\[
q_b \% = \frac{12644}{t_{\text{test}} \text{ LHV}} \int_0^{t_{\text{test}}} \frac{C y_{CO}}{0.536 (y_{CO} + y_{CO_2})} \, dt \tag{19}
\]

Hence, terms \( q_a \%) \) and \( q_b \%) \), are the time average of their instantaneous values.

5.4. Emissions of wood appliances

With reference to Eq. (2) the time history of the emission rate (in mass) of CO, as of any other pollutant, depends on the time histories of CO concentration in the gas and of the burning rate. In intermittent wood appliances, like wood stoves, the burning rate decreases in time rather smoothly [8, 9]. CO emissions can be determined accurately upon use of Eq. (7). For the measurement of burning rate, Calvo et al. [8] measure directly the weight of the combustion grid of a wood stove by means a load cell, but this implies that the appliance must be modified. Eq. (13) prescribed by standards leads to a value of CO emissions which only approximates the result of Eq. (7). For wood appliances, we suggest here a better approximation that can be obtained by the following method:

(i) divide the test period in \( n \) sub-periods, so that for each sub-period the consumption of wood is \( m/n \) of the total mass \( m \) of the batch;

(ii) apply Eq. (13) proposed by standards, not to the entire test period, but to each single sub-period, that means to calculate the value of CO emission at \( O_{2,\text{ref}} \) for each sub-period;

(iii) calculate the value of CO as the mean of the \( n \) CO emission values calculated for each sub-period: this corresponds to a weighted average where the weights are the fuel mass burned in the sub-period.

The number of sub-periods \( n \) must be chosen univocally in order to prevent many interpretations. For wood stoves we have obtained good results upon setting \( n = 3 \). In general, \( n \) should be chosen on the basis of the weight of the batch of fuel used for each test period. In fact, in each interval the burned wood must be large enough with respect to the resolution of the platform scale, usually between 10 and 50 grams.

5.5. Efficiency of wood appliances

At the same way, for efficiency calculation it is possible to apply the same procedure of emissions calculation, i.e. calculate the efficiency as proposed by standard for each of \( n \) sub-periods, then calculate the value of efficiency as the average of the \( n \) values.

6. Examples and discussion

In this section we want to show that there may be significant differences between results obtained from exact Eqs. (7), (10), (11), and (12) and the approximate relations, like (13), prescribed by standards. In addition we show that the approximate Eqs. (16), (18), and (19) and the method proposed in Sec. 5.4 seem to supply more accurate results than standards.

6.1. Pellet stove

We consider two different tests, A and B, performed on pellet stove at Ravelli’s Lab according to standard EN 14785. Composition of wood is C = 46.9%, H = 6.3%, W = 6.0%. Its heating
Figure 1. Pellet stove, case A. Concentrations of CO, CO at 13% of O₂, and CO₂ vs. time.

Figure 2. Pellet stove, case B. Concentrations of CO, CO at 13% of O₂, and CO₂ vs. time.

Table 1. Measured data (time average) for pellet stoves.

|   | O₂ | CO₂ | CO | T_f | T_0 |
|---|----|-----|----|-----|-----|
| A | 6.7| 13.4| 298| 133.5| 18.2|
| B | 9.4| 10.9| 223| 185.9| 22.3|

Table 2. Efficiency and emissions calculated according standards and equations (18) and (19), (16) and (17).

|   | Efficiency | Emissions |
|---|------------|------------|
|   | Standard | Eqq. (18) and (19) | Standard | Eqq. (16) and (17) |
| q_a | q_b | η | q_a | q_b | η | CO 13% O₂ | CO 13% O₂ |
| % | % | % | % | % | % | mg/Nm³ | mg/MJ | mg/Nm³ | mg/MJ |
| A | 5.95 | 0.14 | 89.91 | 6.11 | 0.11 | 93.77 | 208.4 | 139.2 | 183.5 | 122.0 |
| B | 10.12 | 0.12 | 89.76 | 10.29 | 0.14 | 89.99 | 191.3 | 127.9 | 213.5 | 142.3 |

value is LHV = 17.4 MJ/kg. Time histories of CO and CO₂ concentration during tests are shown in figures 1 and 2. Time average values over the entire test are reported in table 1.

Test case A is characterized by a CO peak at low level of excess air. CO concentration at 13% O₂, calculated by Eq. (13), i.e. according to standards, is 167 ppm that correspond to 208 mg/Nm³. The concentration of CO at 13% O₂, calculated by Eq. (16) is 147 ppm that corresponds to 184 mg/Nm³. In test case B, peaks of CO are recorded in correspondence of high levels of excess air. The concentration of CO at 13% O₂ calculated according to standards is 153 ppm that corresponds to 191 mg/Nm³. The concentration of CO at 13% O₂ calculated by Eq. (16) is 171 ppm that corresponds to 214 mg/Nm³. Differences between the two methods are not negligible. For instance, if the limit of CO emission is fixed at 200 mg/Nm³, as for the German regulation BImSchV for pellet stove with integrated boiler [10], for one method law requirements are satisfied, whereas for the other are not.

Table 2 reports also the efficiency calculated by two methods. For this quantity results do
agree. In both methods, \( c_{p,\text{dry}} \) and \( c_{p,w} \) are calculated using relations proposed by standards.

Although time dependence of burning rate induces time changes of properties that contribute to efficiency, i.e. temperature, specific heats, and volume flow rates, these variations do not seem significant. For instance, taking into account that \( c_{p,\text{dry}} \), in the ranges of \( y_{\text{CO}_2} = [0.01, 0.19] \) and \( T = [25, 250]^{\circ}\text{C} \) varies between 1.303 \( \text{kJ/m}^3\text{K} \) and 1.407 \( \text{kJ/m}^3\text{K} \), the variations of \( c_{p,\text{dry}} \) during a test is small because temperature of flue gas at the exit of a pellet stove at steady state condition of operation varies within a range of 10-15\(^{\circ}\text{C}\) around the mean value. From a comparison between the results of thermal losses calculated with expression supplied by standards and thermal losses calculated using the Peng-Robinson model implemented in the software AspenPlus, we found that in the range \( T_f = [80, 250]^{\circ}\text{C} \) and \( y_{\text{CO}_2} = [0.03, 0.17] \) thermal losses are overestimated by standards and the error is between 0.4% to 1.3%.

### 6.2. Wood stove

In this example we report data recorded during a test of a wood stove performed at Ravelli’s Lab. Composition of wood is C = 43.2%, H = 5.2%, W = 12.8%. Its heating value is \( \text{LHV} = 15.0 \text{MJ/kg} \). Some properties related to flue gas and the weight measured during the test are reported in Table 3.

In figure 3 stove weight vs. time is shown: the absolute value of time derivative is the burning rate. In figure 4 measured CO and CO2 concentration vs. time are plotted. The weight of the fuel charge was 2.30 kg. The number of sub-divisions of test period is \( n = 3 \). Duration of test was 45 minutes. In Table 3 we report time average of data over the test period and over each single sub-period. As expected, the first sub-period is the shortest. Consequently, the high CO level reached during the first sub-period will contribute to estimate of overall CO emission more than in the standards’ method.

#### Table 3. Measured data (time average) for wood stove.

|           | Duration mm:ss | Consumption kg/h | \( O_2 \) % | CO2 % | CO ppm | \( T_f \) °C | \( T_0 \) °C |
|-----------|----------------|------------------|-------------|-------|--------|-------------|-------------|
| 1         | 6:05           | 7.56             | 10.6        | 7.3   | 4220   | 248.9       | 31.9        |
| 2         | 10:05          | 4.56             | 10.4        | 10.1  | 2449   | 254.4       | 32.9        |
| 3         | 28:30          | 2.15             | 14.5        | 5.8   | 699    | 226.8       | 31.8        |
| Overall   | 45:00          | 3.06             | 13.0        | 7.3   | 1588   | 236.1       | 31.8        |
Table 4. Results for wood stove.

|       | Efficiency |          | Emissions |
|-------|------------|----------|-----------|
|       | $q_a$ | $q_b$ | $\eta$ | CO 13% | $O_2$ | mg/Nm$^3$ | mg/MJ |
| Real  | 19.39 | 1.71 | 78.89 | 2345   | 1694  |
| Standard | 21.16 | 1.51 | 78.14 | 1997   | 1375  |
| Sec.5.5 | 19.11 | 1.76 | 79.11 | 2482   | 1708  |

Table 4 reports the results of test, calculated according to standards and with the procedure proposed in Sec. 5.4. Real emission and real efficiency are computed upon use of Eqs. (7) and (12), where $\dot{m}$ is estimated from the weight history represented in figure 3. There are significant differences between the real values and the ones calculated according to the standards. Differences reduce when applying Eq. (13) to sub-periods and then taking the mean value.

7. Conclusions
In this work we made a review of the methods proposed by European Standards for the calculation of efficiency and emission of wood and wood pellet appliances. We propose some modification to equations prescribed in standards in order to improve the accuracy of calculated data. The methods for the calculation of efficiency and pollutant concentration (CO, NOx, HC) presented here allow to calculate the mean concentration of these substances taking into account both the variation of the flue gas mass flow rate and composition during the test which is a peculiar characteristic of these appliances. In fact, we show that for pellet stoves the method of standard can overestimate or underestimate emissions, while for wood stove there can be considerable differences between the calculated values and real data.

For pellet stove and pellet boilers, we propose equations for the calculation of pollutant concentrations only. As a matter of fact efficiency calculated according to standards is quite accurate.

For wood appliances we propose to apply the same method proposed by standards, but dividing the test period in sub-periods. This method does not introduce new relations and it can be easily implemented in software or spreadsheets.

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