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EFFICIENCY ASSESSMENT OF A DOMESTIC WOOD GASIFICATION BOILER

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Energy source will play an important role in the world's future. Energy is considered a significant factor in economic development and wealth. In this article the use of biomass (wood) to produce energy by a thermochemical process is dealt with. The purpose of this work is to evaluate the efficiency of the combustion process considering various flue gas outlet temperatures (50, 100, 150, 200, 250, 300 °C). The data to be analysed are referred to a combustion test, performed through a high efficiency wood stove applying a downdraft gasifying technology. The data obtained from the test have also been used to calculate the energy losses, in order to evaluate the overall energy efficiency of the thermal conversion stage.

Keywords: biomass, combustion, efficiency, gasification, wood stove.

1. Introduction

Nowadays, the prime energy source in the word, is represented by fossil fuels such as oil, coal and natural gas. It is known that these resources will not last forever. The excessive use of fossil fuels is one of the primary causes of global warming, acid rain and urban smog, which have started to affect the earth's climate, weather, vegetation and aquatic ecosystems [1]. Due to the continuous rise of the cost of the fossil energy resources, there is a growing worldwide interest about the development of technologies allowing the exploitation of renewable energy sources, both for environmental and economic reasons. For that, biomass looks as one of the most promising and viable alternatives to recover energy [2, 3, 4]. If biomass is adequately managed and exploited, it can be termed as a truly renewable energy source, which can contribute to displace the

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consumption of non-renewable fossil sources [5]. Moreover, the expected environmental damages have tempted the world to try to reduce carbon emissions by 80% and shift towards utilizing a variety of renewable energy resources (RES) which are less environmentally harmful such as solar, wind, biomass etc. in a sustainable way [6, 7, 8]. Indeed, in the last years, the depletion of fossil fuels and the increasing of the world energy demand, has foster the interest for renewable energies, including biomass for energy production [9].

The utilisation of biomass is a very important source of energy in many parts of the world, especially for areas remote from supply of high-quality fossil fuel. Biomass energy conversion technologies, especially pyrolysis and gasification, have been substantially studies to promote renewable energy utilization and solving partially the environmental issues [10, 11, 12].

The 2009/28/EC Directive on the promotion of the use of energy from renewable sources sets the objective of reaching at least 20% of the EU’s final energy consumption through renewable energy sources by 2020. It sets for each Member State mandatory national targets for the overall share of RES in gross final energy consumption as well as a mandatory share of 10% in transport. Currently, the energy produced and/or derived from sources infinitely renovated (hydro, solar, wind) or generated by renewable fuels (sustainably produced biomass), which is defined as renewable energy, contributes to the total world energy consumption for less than 20% [13]. In the last years, the biomass contribution at the world energy demand was about 13% [14] and in European Union (EU27) in 2012, the primary energy production from biomass was 82.3 Mtoe (million tons of oil equivalent) [15]. On average, in the industrialized countries biomass contributes some 9% to 14% to the total energy supplies, but in developing countries this is as high as one-fifth to one-third [16].

Biomass derives from plant and animal materials such as wood from forests, crops, seaweed, material left over from agricultural and forestry processes, and organic industrial, human and animal wastes [17, 18, 19, 20, 21].

It has been found that utilizing biomass in boilers offers many economic, social and environmental benefits such as financial net saving, conservation of fossil fuel resources, job opportunities creation and CO_2 and NOx emissions reduction [6, 7]. The biomass carbon, when is burned or used after converting it to other types of fuel (solid, liquid and gaseous), reacts with oxygen in the air to form carbon dioxide which is released into the atmosphere. Therefore, if biomass is totally combusted, the amount of CO_2 produced will be equal to the quantity that is taken from the atmosphere during the growing stage. Indeed, plants use sunlight through photosynthesis to metabolize atmospheric carbon dioxide. Hence, there is no net addition of CO_2 and biomass can be regarded as a carbon sink. This process is known as the carbon cycle or zero carbon emissions [5, 6].

For upgrading the energy in terms of more easily handled fuels, in the past decades there has been a high interest for thermochemical conversion of biomass. Among the most widely known methods to convert biomass into available forms of energy, there is the thermal conversion (combustion, gasification, and pyrolysis) [22]. The biomass gasification represents an alternative to improve innovative energy processes, in particular for small rural communities. In fact, the large amount of waste biomass, widely spread on rural territories, looks promising for syngas production as fuel for electric power generation by direct utilization in conventional internal combustion engines or, after clean up and reforming stages, for innovative generation systems as fuel cells [23].

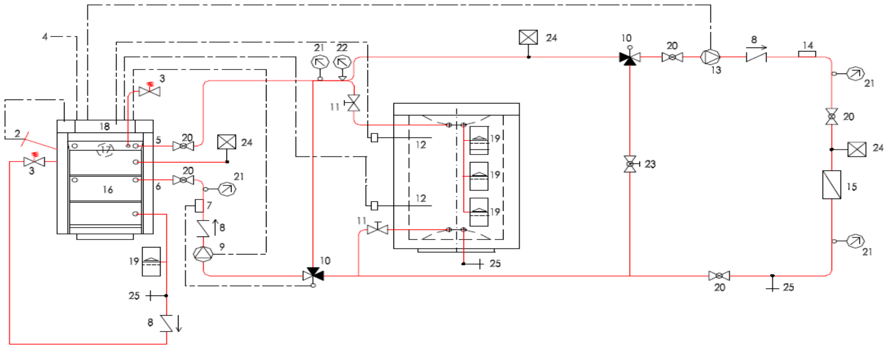
Gasification is a process of conversion of solid carbonaceous fuel into combustible gas by partial combustion. The resulting gas is a mixture of carbon monoxide, hydrogen, methane, carbon dioxide and nitrogen. The produced gas is more versatile in its use than the original solid biomass. It can be burnt to produce process heat and steam or used in gas turbines to produce electricity [23, 24, 25].

The aim of this study is to evaluate the thermal efficiency of a domestic gasification boiler, considering different exhausted gas outlet temperatures (50, 100, 150, 200, 250, 300 °C). Notions of combustion theory were used to assess the quantities necessary to calculate the process heating losses and the Lower and Higher Heating Value (LHV, HHV).

2. Materials and methods

2.1 Reverse flame boiler

The experimental investigation has been carried on a gasifying wood stove, whose thermal power is between 11.0 kW and 25.9 kW. The schematic diagram of the used instrumentation is reported in Fig. 1. As reported in [26], the stove is divided in three sections. In the upper part, the feedstock is initially dried during the heating up of the system. Then the temperature grows up to the operating temperature (900-1000 °C) and the pyrolysis and char oxidation processes take place. The produced gas flows through a grid in the combustion chamber, placed below the previous one, in which two processes take place: firstly, the gas is partially oxidized in substoichiometric conditions by means of the primary air stream; secondly, by means of the secondary air, the effective combustion process takes place. The third section of the stove is just a chamber where ash is collected.



1 Thermostatic valve
2 Boiler sensor
3 Safety group
4 230V power supply
5 Heating flow
6 Heating return
7 Feed water temperature sensor
8 Check valve
9 Electric motor-driven pump
10 Three-way mixing valve
11 Thermostatic valve
12 Buffer
13 Circulating pump
14 Temperature sensor
15 Convector heater
16 Boiler
17 Flue outlet
18 Digital control panel
19 Closed membrane expansion tank (24 l)
20 Ball valve
21 Thermometer
22 Pressure gauge
23 Regulating valve (manual)
24 Automatic vent valve
25 Outlet

Fig. 1. Schematic diagram of the domestic gasification boiler

An electrochemical analyzer was used to measure the gas composition at the stack, for analyzing the flue gas concentrations and combustion data such as O_2, CO, NO and SO_2. Subsequent calculations are made considering the stationary phase of the combustion process. So no transient phase was considered. The test duration was about 2.5 hours, of which 1 hour was assumed as stationary phase.

For the experimental runs 27.42 kg of beech wood was used. Its relative chemical-physical characteristics is reported in Table 1.

Table 1

Chemical-physical characteristics of beech wood (percentage values, mass and mole fractions). TS: Total Solids; VS: Volatile Solids

Element	% kg_j/kg_{fuel}	kg_j/kg_{fuel}	$kmole/kg_{fuel}$
C	44.58	0.446	0.037
H	5.44	0.054	0.054
O	38.40	0.384	0.024
N	0.36	3.64E-03	2.60E-04
S	0.02	1.78E-04	5.55E-06
H_2O	10.51	0.105	0.006
Ash	0.69	0.007	
Moisture	10.51		
TS	89.50		
VS	88.80		

In order to obtain the HHV, it was used the Dulong formula [27]:

$$HHV = \left\{7{,}831[C] + 35{,}932\left([H] - \frac{[O]}{8}\right) + 2{,}212[S] + 1{,}187[O] + 578[N]\right\} 4.1868 \quad [kJ/kg_{VS}] \tag{1}$$

2.2 Stoichiometric and non-stoichiometric combustion

Known the mass fractions of the elements that make up the fuel and assuming that the atmosphere is an ideal gas mixture of two components with ideal behaviour, it is possible to evaluate the stoichiometric oxygen (Eq. 2, Eq. 3) and the combustion air (Eq. 4, Eq. 5) necessary for the process. The atmosphere is assumed di be composed of 21% oxygen and 79% equivalent nitrogen with molar mass respectively 32 kg kmole^{-1} and 28.16 kg kmole^{-1}.

$$\left[m_{O_2}\right]_s = 2.67[C] + 8[H] + [S] - [O] \qquad \left[kg_{O_2} / kg_{fuel}\right] \tag{2}$$

$$\left[n_{O_2}\right]_s = nC + \frac{nH}{4} + nS - \frac{nO}{2} \qquad \left[kmole_{O_2} / kg_{fuel}\right] \tag{3}$$

$$\left[m_{air}\right]_s = 4.31\left[m_{O_2}\right]_s \qquad \left[kg_{air} / kg_{fuel}\right] \tag{4}$$

$$\left[n_{air}\right]_s = 4.76\left[n_{O_2}\right]_s \qquad \left[kmole_{air} / kg_{fuel}\right] \tag{5}$$

Where the subscript *s* indicates the stoichiometric quantities and *n* the numbers of mole of the element *j*. It is important to highlight that the oxygen, which makes up the fuel, is subtracted for obtaining the remained amount of oxygen necessary for the process.

Similarly, is possible calculate the stoichiometric concentrations of other elements (N_2, CO_2, H_2O and SO_2) present in the exhaust gas, through the following equations:

$$\left[m_{N_2}\right]_s = 0.79\frac{28.16}{28.97}\left[m_{air}\right]_s + [N] \qquad \left[kg_{N_2} / kg_{fuel}\right] \tag{6}$$

$$\left[m_{CO_2}\right]_s = 3.67[C] \qquad \left[kg_{CO_2} / kg_{fuel}\right] \tag{7}$$

$$\left[m_{H_2O}\right]_s = 9[H] + [H_2O] \qquad \left[kg_{H_2O} / kg_{fuel}\right] \tag{8}$$

$$\left[m_{SO_2}\right]_s = 2[S] \qquad \left[kg_{SO_2} / kg_{fuel}\right] \tag{9}$$

In order to evaluate the non-stoichiometric mass fractions (the real composition of exhaust gas), it is necessary to calculate the excess air, which is used during the combustion process. For this step the excess air (Eq. 10) and the mole fraction of smoke (Eq. 11) are defined as:

$$E=\frac{[O_2]_{air}-[O_2]_s}{[O_2]_s} \tag{10}$$

$$[Exhaust\,gas]=\frac{[C]+[S]+\frac{0.79}{2}[H_2]+0.21[N_2]-0.79[O_2]}{0.21+\frac{0.79}{2}v_{CO}-v_{O_2}} \quad \left[\frac{kmole_{Exhaust\,gas}}{kg_{fuel}}\right] \tag{11}$$

As it can be seen from the last equation, it is necessary to introduce the real mole fractions [$kmole_j\ kg_{fuel}^{-1}$] and the volume fractions v_j of the molecules, which are in the biomass and in the exhaust gas. These values were obtained from an electrochemical analyser, which was used to measure the gas composition at the stack. From the equation 11 and by data in Table 1 and the mean value of volume fractions of components measured by the electrochemical analyser it is possible to calculate the concentration of exhaust gas.

The next step is to calculate the excess air. It is possible to write the Eq. 10 in a different way, obtained through the following equations:

$$[O_2]_s=[C]+[S]+\frac{[H_2]}{2}-[O_2] \tag{12}$$

$$[O_2]_{air}=[Exhaust\,gas]\left(v_{O_2}-\frac{v_{CO}}{2}\right)+[C]+[S]+\frac{[H_2]}{2}-[O_2] \tag{13}$$

$$[N_2]+[N_2]_{air}=[Exhaust\,gas]v_{N_2} \tag{14}$$

The new equation that defined the excess air is the following.

$$E=\frac{[Exhaust\,gas]\left(v_{O_2}-\frac{v_{CO}}{2}\right)}{\frac{0.21}{0.79}\Big[[Exhaust\,gas]v_{N_2}-[N_2]\Big]-[Exhaust\,gas]\left(v_{O_2}-\frac{v_{CO}}{2}\right)} \tag{15}$$

Known the real mass of air introduced in the combustion process that was extracted from Eq. 15, it is possible to calculate the real concentrations of components (O_2, N_2, CO_2, H_2O and SO_2) present in the exhaust gas. The relations for CO_2, H_2O and SO_2 (Eq.7-9) do not change, whereas for the oxygen and nitrogen the following equations are used:

$$\left[m_{O_2}\right]=0.232\left([m_{air}]-[m_{air}]_s\right) \qquad \left[kg_{O_2}/kg_{fuel}\right] \tag{16}$$

$$\left[m_{N_2}\right]_s=0.79\frac{28.16}{28.97}[m_{air}]_s+[N] \qquad \left[kg_{N_2}/kg_{fuel}\right] \tag{17}$$

2.3 Heating losses of combustion process and thermal efficiency

The thermal efficiency is calculated according to the LHV and HHV. For this reason, it is necessary to determine the sensible heat (Qs) (which is the energy lost by hot exhaust gas), the heat lost by the unburned material (Qu) and the latent losses due to the evaporation of water (Q_l).

The sensible losses are determined considering different flue gas outlet temperatures by the following equation:

$$Q_s = m_i C_{pi} \left|_{t_a}^{t_g} \left(t_g - t_a\right)\right. \tag{18}$$

Where m_i is the mass fraction of the generic elements of the exhaust gas and C_{pi} is the specific heat at constant pressure calculated between the temperature of exhaust gas (t_g) and the ambient temperature (t_a). The gas outlet temperatures evaluated are 50, 100, 150, 200, 250, 300 °C and the recorded ambient temperature was 23.3°C.

To obtain the specific heat at constant pressure it was used the Eq. 19, where the C_{pi} based on the t_0=0°C was derived by the [28].

$$C_{pi} \left|_{t_a}^{t_g}\right. = \frac{C_{pi} \left|_{t_0}^{t_g}\right. \left(t_g - t_0\right) - C_{pi} \left|_{t_0}^{t_a}\right. \left(t_a - t_0\right)}{t_g - t_a} \tag{19}$$

The energy lost by the unburned material and latent losses are obtained, respectively, by the product of the mass fraction of carbon monoxide and its LHV and the mass fraction of water present in the exhaust gas with the latent heat.

Note the heating losses, it is possible calculate the thermal efficiency by the Eq. 20 and Eq. 21 which are based, respectively, on HHV and LHV.

$$\mathrm{P_{HHV}} = 1 - \frac{Q_s + Q_u + Q_l}{HHV} \tag{20}$$

$$\mathrm{P_{LHV}} = 1 - \frac{Q_s + Q_u}{HHV - Q_l} \tag{21}$$

3. Results and discussion

In order to obtain the HHV from the data in Table 1, it was used the Dulong formula (Eq. 1), which has reported a higher heating value of about 19,710 kJ kg_{VS}^{-1}. In the second step, the stoichiometric mass fractions of the oxygen and air and the mass fractions of molecules that exist in the stack gas were calculated. Eq. 2-3-4-5-6-7-8-9 were used. In the Table 2 the values are reported.

Table 2

Stoichiometric mass and mole fractions of O_2, N_2, CO_2, H_2O, SO_2, exhaust gas and air

Component	kg_j/kg_{fuel}	$kmole_j/kg_{fuel}$
O_2	1.242	0.039
N_2	4.114	0.147
CO_2	1.636	0.037
H_2O	0.595	0.033
SO_2	3.55E-04	5.55E-06
Exhaust gas	6.345	0.217
Air	5.353	0.185

In the Table 3 the mean values and the standard deviation of the exhaust gas, recorded by the electrochemical analyser, during the stable phase are reported. The concentration of N_2 was calculated as the remaining proportion of the volume not occupied by other gases.

Table 3

Mean values (*v*) and standard deviation (*std*) of volume fractions of components, measured by electrochemical analyser, of exhaust gas

Component	*v* [% in volume]	*std* [% in volume]
O_2	7.703	0.341
CO_2	12.289	0.325
CO	0.092	3.91E-02
NO	0.012	1.72E-03
SO_2	7.28E-05	2.91E-04
N_2	79.916	

From the equation 11 and by data in Table 1 and the mean value of volume fractions of components measured by the electrochemical analyser (Table 3) it is possible to calculate the concentration of exhaust gas, that is equal to 0.288 kmole kg_{fuel}^{-1}.

The next step was to calculate the excess air, which was possible through the Eq. 15. The excess air calculated is 0.564, which coincides with a non-stoichiometric mass fraction of 8.372 kg_{air} kg_{fuel}^{-1}.

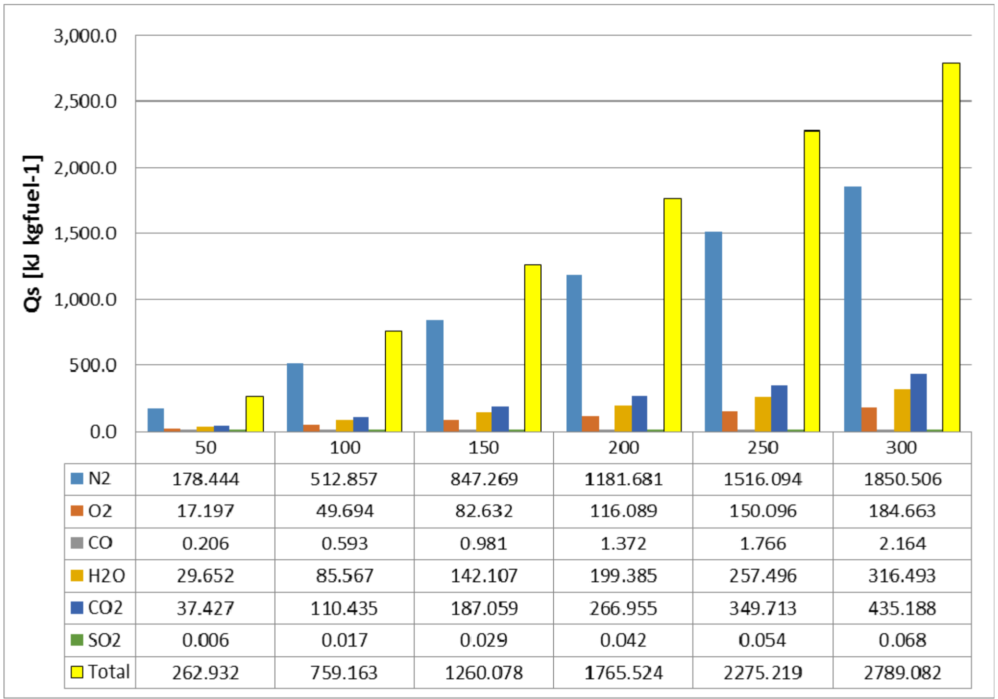
Known the real mass of air introduced in the combustion process, it is possible to calculate the real concentrations of components (O_2, N_2, CO_2, H_2O and SO_2) present in the exhaust gas. The relations used are Eq. 7-8-9 and Eq. 16-17. In the Table 4 the results obtained are described.

Table 4

Non-stoichiometric concentrations of components of exhaust gas

Component	kg_j/kg_{fuel}
Exhaust gas	9.365
O_2	0.701
N_2	6.433
CO_2	1.636
H_2O	0.595
SO_2	3.55E-04
CO	0.007

As described above, the thermal efficiency is calculated according to the LHV and HHV. The values of Qs, relating at each component of exhaust gas and the total sensible losses for different outlet temperatures, are reported in Figure 2.



	50	100	150	200	250	300
🟦 N2	178.444	512.857	847.269	1181.681	1516.094	1850.506
🟧 O2	17.197	49.694	82.632	116.089	150.096	184.663
⬜ CO	0.206	0.593	0.981	1.372	1.766	2.164
🟨 H2O	29.652	85.567	142.107	199.385	257.496	316.493
🟦 CO2	37.427	110.435	187.059	266.955	349.713	435.188
🟩 SO2	0.006	0.017	0.029	0.042	0.054	0.068
🟨 Total	262.932	759.163	1260.078	1765.524	2275.219	2789.082

Fig. 2. Sensible heat (Qs) relating at each component of exhaust gas (O_2, N_2, CO_2, H_2O, SO_2) and total losses obtained from different outlet temperatures

The energy lost by the unburned material is 74.899 kJ kg_{fuel}^{-1}, which is the product of the mass fraction of carbon monoxide and its LHV, assumed equal to 10,100 kJ kg_{CO}^{-1}. The latent losses, which are 1,460.235 kJ kg_{fuel}^{-1}, were obtained multiplying the mass fraction of water present in the exhaust gas with the latent heat, assumed equal to 2,453.3 kJ kg_{H2O}^{-1}.

The thermal efficiencies, evaluated by Eq. 20-21, are reported in the Table 6. It is possible observe as the P_{LHV} is always higher than P_{HHV}. This due to the definitions of LHV and HHV. Indeed, the HHV explains the energy produced by the complete combustion where all products are cooled down to the ambient temperature so the water vapour formed during combustion is condensed, whereas the second assumes the water at the vapour phase. Furthermore, it highlights as the thermal efficiency decreases with increasing of temperatures; this is due to greater sensible losses at the exhaust gas. In the end, supposing a linear relation between t_g and PLHV (Figure 3) and calculating the mean outlet temperature in the stable phase during the test, equal to 291°C, this has allowed to determine the efficiency value equivalent at 83%.

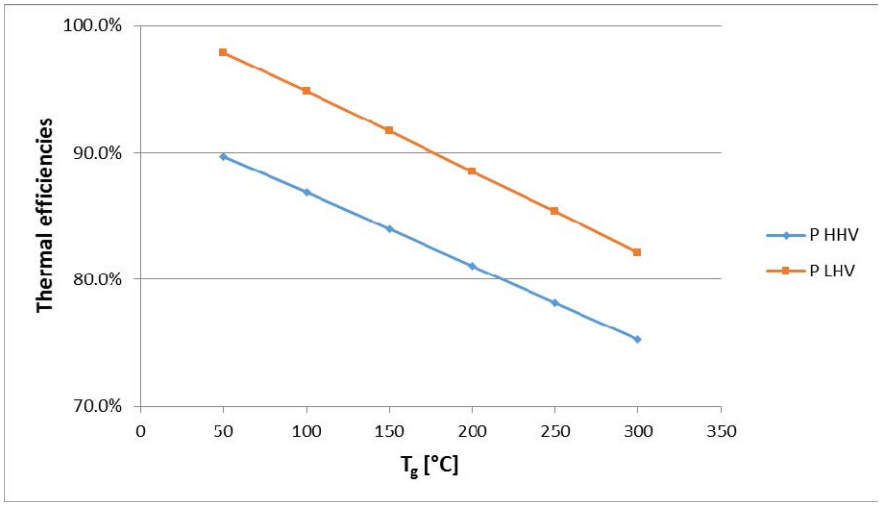


Fig. 3. Thermal efficiencies of air gasifying wood stove considering different flue gas outlet temperatures

4. Conclusions

In this paper, a theoretical approach, sustained by an experimental combustion process through a gasifying wood stove, was applied to beech wood.

The test was conducted in a laboratory scale stove with a thermal potentiality between 11.0 kW and 25.9 kW, in order to be assimilated with the results from a domestic heating system. The data obtained have highlighted as the greater is the performance of cooled system, the greater is the thermal efficiency and the lesser are the sensible losses. It can be seen that the sensible heat losses depend nearly linearly on the temperature of the flue gas. The results obtained are in line with the most recent literature on the gasification stoves on the market emitting exhaust gas between 70 °C and 300 °C.

Following the introduction of UNI EN 303-5:2012, the energy recovery has become a key issue in order to reach the new and more restrictive efficiency standards for the domestic boilers of new construction. The challenge lies in the recovery of the latent heat through the cooling of the flue gas below the dew temperature of the water vapor. Some condensing heat exchangers for small scale (< 35 kW) biomass boilers exist: these are either integrated into commercially available stoves or can be retrofitted to existing ones. So as it is desirable for Governments to take measures to stimulate a renewal of boilers fleet by means of incentives to purchase high efficiency boilers, also capable of limiting the emissions of pollutants into the atmosphere.

Hence, verified the increasing demand of energy, especially in the residential heating, the use of this biomass combustion system can be considered a suitable and enhanced technology to improve the utilization of this renewable energy resource.

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