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Experimental investigation on the fixed bed of a small size biomass boiler

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Abstract

During the last decades, the increase of the world energy consumption promoted the renewable resource development and use. Together with wind, solar and hydro energy, biomasses play a key role in the reduction of the industrial environmental impact; moreover, the biomass combustion systems are very attractive for micro-generation purpose. In this paper, experimental tests on a 140kW small size fixed bed biomass boiler were carried out. The main goal was to study the thermal behavior and some chemical products, such as CO, CO_2, Methane and Ethylene, from the combusting fixed bed of the system. In fact, despite the wide amount of literature for the laboratory scale systems, the commercial scale boilers have been seldom studied by the experimental point of view. The data were obtained by varying the operational parameters of the boiler, that are the air excess and the secondary to primary air feeding ratio. Furthermore, the collected data were analyzed and the relationship between the thermal-chemical data and the control variables was discussed.

Keywords: Biomass combustion; Small Scale Biomass Boiler; Experimental Data; Fixed Bed System

1. Introduction

The increase in the energy consumption and the purpose of reducing the pollutant emissions, lead to improve the use of renewable energies. The biomass appears to be suitable for this purpose because it can be employed as an integrative foreseeable source between solar, wind and hydro energy. The use of biofuels in combustion facilities is

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the most common way to produce heat and power; furthermore, the small-scale systems are very interesting for micro-generation purpose [1]. From the literature, the semi industrial scale systems (such as >100kWth) were seldom studied with respect to the laboratory scale or domestic systems. For instance, similar boilers were recently studied by [2,3], however, the thermal power involved was always below 100 kW thermal input. Other studies, such as [4,5], involved systems with 300 kW and more as thermal input, using moving grate feeding mechanism. Between these power levels (particularly between 100 kW and 200 kW) the combustion system presents intermediate characteristics. Firstly, these are characterized by high heating rate, and the chemical kinetics behavior is close to the higher scale systems [6,7]. For instance, [8,9,10] studied the reaction parameters both in laboratory scale and real scale burners, highlighting the many differences found. The other important issue is the modeling of the fixed bed, which is composed by discrete elements of biofuel. For instance, [11,12] use a Discrete Element Model (i.e. DEM) to calculate the biomass behavior inside fluidized bed. However, the use of DEM in fixed bed boilers requires thermal data for validation purpose. Considering the chemical emission modelling, the lumped parameter models are attractive for their simplicity and good accuracy [13], and many authors evaluated the combustion products through these models [14,15]; however, the comparison with experimental data has a key role for validation and tuning purpose, especially in these seldom studied systems. In this paper, the authors present the experimental results carried out on the fixed bed of a 140 kW thermal power biomass boiler. The main goal was to provide chemical as well as thermal data of the exhaust gases and the fixed bed. Particularly, the chemical data were collected both from the boiler outlet and from the biomass surface, in which the devolatilization products are predominant. Moreover, the relationship between the operative parameters, that are the air excess and the ratio between the primary and secondary air feeding flow, and the measures involved was studied. Finally, the results were both analyzed and discussed in the further sections.

2. Methodology

The experimental equipment is a 140kWth modified Standard Kessel Italiana S.r.l. fixed bed biomass boiler installed at the "Biomass to Energy Research Center" (CRIBE) facility in Pisa. The boiler is composed by a fixed bed combustion system and by a secondary air diffuser (Fig. 1). The big post-combustion volume ensures the ash deposit and the complete volatiles combustion. The air is totally provided by means of a primary blower of 0.75kW power.

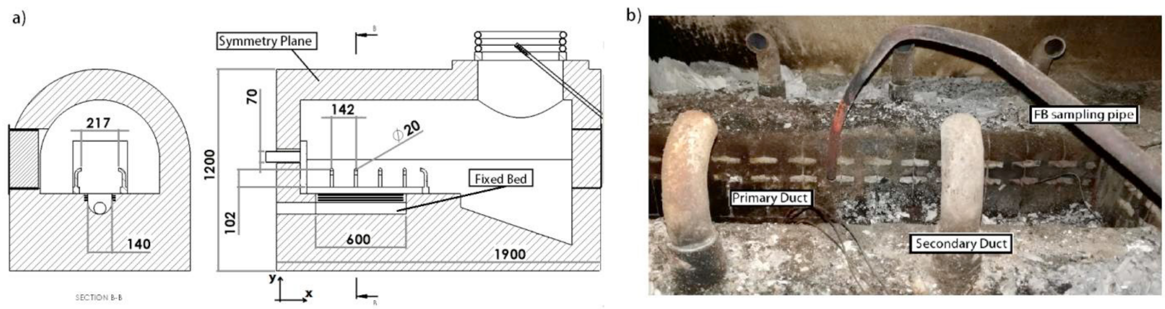

Fig. 1. (a) boiler general scheme with size in millimeters, (b) fixed bed overview

The exhaust gases pass through an oil to gas heat exchanger, in order to heat up a Seriola 1510 diathermic oil, that ensures a constant thermal load to the system; further details about the facility can be found in [16]. A secondary blower extracts the flue gases by keeping the in-chamber pressure of 20 below the atmospheric. The biomass is introduced from the bottom of the fixed bed by means of a screw conveyor, whose rotating speed was set at 2 rpm for all the test. This value was a compromise found by previous tests, that ensured both stable measuring conditions and the required thermal power. The feeding air can be divided into a primary flow, placed by the side of the fixed bed, and a secondary flow, that was inserted above and parallel to the fixed bed surface, by means of two hand actuated sphere valves. In Fig. 2 the whole system scheme is presented.

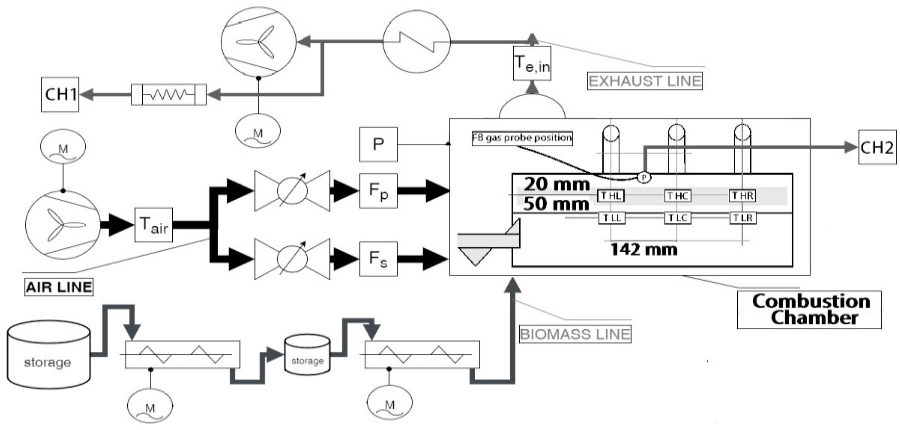

Fig. 2. Measurement and control scheme of the boiler.

The mass flow was acquired by means of two hot wire flow meters (F_p for Primary air and F_s for secondary air). The temperature values were acquired through several K-Type thermocouples: one placed in the exhaust line ($T_{e,in}$) and six inside the fixed bed (T_{ij}, in which i=H or L symbol for High and Low positioning, and j=L,C or R symbols for Left, Center and Right positioning with respect to the screw conveyor as shown in Fig. 2). By means of an optical access, it was observed that the thermocouples inside the fixed bed were always under the biomass bed surface. Finally, the air temperature (T_{air}) was acquired by means of a T-Type thermocouple. Two probes, one at the end of the gas to oil exchanger (CH1) and the other on the fixed bed surface (CH2), allowed us the sampling of the gas for the online gas analysis systems. In the CH1 case, an Environnement SA gas analyzer (equipped with paramagnetic, infrared, flame ionization and chemiluminescence detectors) was employed, while a Bruker Tensor 37 Fourier Transform InfraRed Spectrometer was used to acquire the CH2 line data. The biomass used was mixed wood cylindrical pellet (radius 2.5 mm and length 10 mm) from RZ, Austria. The biofuel was characterized with proximate and ultimate analysis as shown in Table 1.

Table 1. Ultimate and Proximate analysis for the pellet involved in the experiment.

C [$\%_{daf}$]	H [$\%_{daf}$]	O [$\%_{daf}$]	N [$\%_{daf}$]	Moisture [$\%_{ar}$]	VM [$\%_{db}$]	FC [$\%_{db}$]	Ash [$\%_{db}$]	LHV [MJ/kg]
50.13	5.94	43.78	0.15	6.24	84.85	14.97	0.18	18.88

It is important to calculate the main operative parameters of the system and correlate them with the measured emissions. The controlling parameters were the secondary to primary air feeding mass flow ratio (i.e. the split ratio) $\lambda = m_s/m_p$, and the air excess $\varepsilon = \alpha/\alpha_{st}$, in which $\alpha = m_a/m_b$, m_a is the feeding air mass flow, m_b is the biomass flow rate and the st-pedex indicates stoichiometric value. The ε can be calculated by the oxygen mass fraction Y_{O2} in the exhaust gas through the combination of the Equations 1 and 2, and the air excess definition. However, the hypothesis that m_a/m_{O2}=4.31 is considered.

$$Y_{O2} = \frac{m_{O2}}{m_f} = \frac{m_a - m_{a,st}}{4.31 m_f} \tag{1}$$

$$m_f = m_b + m_a \tag{2}$$

For the previous equations, the m_{O2} is the oxygen mass flow in the flue gases, while m_f is the flue gas mass flow. Finally, we obtain the air excess from the Equation 3.

$$\varepsilon = \frac{4.31 Y_{O2} + \alpha_{st}}{\alpha_{st}(1 - 4.31 Y_{O2})} \tag{3}$$

While the split ratio was easy to control, the air excess values were controlled by means of the total feeding air used, so through the primary blower frequency regulation and a visual feedback from the instruments. With this method, it was possible to set a total air feeding rate and modify the split ratio, according to the blower capabilities. At the end of the process, the data were acquired and elaborated in interpolated maps. Finally, the experimental error was evaluated with the error propagation theory. Because of the high statistical variability of the acquired data, the maximum between the statistical and propagated error was used as conservative criteria. In order to acquire a significant amount of data, each test condition (i.e. ε,λ couple) was maintained for 20 minutes at least, ensuring the stationary behavior of the variables involved.

3. Results and discussion

The results of the CO, CO_2, Methane (CH_4) and Ethylene (C_2H_4) from the fixed bed, together with the boiler working parameters are presented in Table 2. Finally, in Table 3 the bed and the post combustion temperatures are represented with their error.

Table 2. Results from the experimental tests

ID	m_p [kg/s]	m_s [kg/s]	ε [-]	λ [-]	CO [$_{vol}$ %]	CO_2 [$_{vol}$ %]	C_2H_4 [$_{vol}$ %]	CH_4 [$_{vol}$ %]
1	0.0477 ± 0.0008	0.060 ± 0.001	5.9 ± 0.2	1.26 ± 0.03	0.6 ± 0.3	3.7 ± 1.4	0.003 ± 0.001	0.03 ± 0.02
2	0.0468 ± 0.0008	0.055 ± 0.001	1.23 ± 0.07	1.18 ± 0.03	27.1 ± 1.1	14.6 ± 2.3	0.25 ± 0.04	4.07 ± 0.54
3	0.0606 ± 0.0008	0.096 ± 0.002	1.93 ± 0.04	1.59 ± 0.04	11.0 ± 1.4	8.2 ± 0.4	0.13 ± 0.11	1.10 ± 0.72
4	0.046 ± 0.001	0.063 ± 0.001	1.34 ± 0.03	1.39 ± 0.03	8.9 ± 0.8	7.5 ± 0.2	0.05 ± 0.03	0.46 ± 0.25
5	0.0629 ± 0.0008	0.105 ± 0.001	1.47 ± 0.02	1.67 ± 0.02	7.0 ± 2.0	7.4 ± 0.8	0.11 ± 0.09	0.63 ± 0.46
6	0.096 ± 0.001	0.093 ± 0.003	1.77 ± 0.03	0.97 ± 0.02	7.4 ± 0.7	6.7 ± 0.2	0.004 ± 0.002	0.15 ± 0.08
7	0.079 ± 0.002	0.078 ± 0.003	6.1 ± 0.2	1.00 ± 0.03	7.7 ± 1.5	6.9 ± 0.5	0.03 ± 0.04	0.44 ± 0.30
8	0.079 ± 0.002	0.082 ± 0.002	5.2 ± 0.8	1.04 ± 0.02	0.4 ± 0.01	8.7 ± 0.5	0.001 ± 0.001	0.014 ± 0.002
9	0.057 ± 0.001	0.043 ± 0.001	1.39 ± 0.06	0.76 ± 0.03	27.9 ± 0.3	6.0 ± 0.3	0.003 ± 0.003	0.26 ± 0.12
10	0.091 ± 0.001	0.063 ± 0.001	1.72 ± 0.04	0.69 ± 0.01	27.7 ± 0.6	6.0 ± 0.9	0.19 ± 0.15	1.11 ± 0.54

Table 3. Fixed bed and post combustion temperature acquired

ID	T_{air}[K]	$T_{e,in}$[K]	T_{HR}[K]	T_{LR}[K]	T_{HC}[K]	T_{LC}[K]	T_{HL}[K]	T_{LL}[K]
1	289±1	445±3	420±6	405±4	650±52	456±7	837±5	478±9
2	290±2	788±11	850±90	704±78	875±14	833±161	792±18	1329±25
3	292±2	943±14	825±39	1104±55	1442±57	1207±62	1069±14	1218±37
4	290±1	919±9	763±4	1091±15	1389±67	1144±27	895±10	1163±34
5	291±1	1025±5	809±15	899±42	1490±57	1274±50	908±47	1181±26
6	292±1	1044±9	840±12	794±17	1397±62	1161±70	1150±6	1367±31
7	291±1	754±23	516±15	574±28	896±55	681±34	1019±71	711±40
8	291±1	685±5	459±4	483±5	662±17	526±10	896±34	540±11
9	289±1	933±3	681±5	681±6	1312±27	692±3	1179±16	992±10
10	291±1	985±6	755±6	654±7	917±94	690±14	1292±18	967±59

It is important to notice that the error values for C_2H_4 and CH_4 are very high in many tests performed. This fact is due to the fixed bed surface instability, that is generated by the particles inlet from the screw feeder. The particles motion causes the bed growing and further creeping, with species generation and temperature field instabilities. This behavior is typical of the non-laboratory scale system, and the statistical error becomes representative of the amplitude

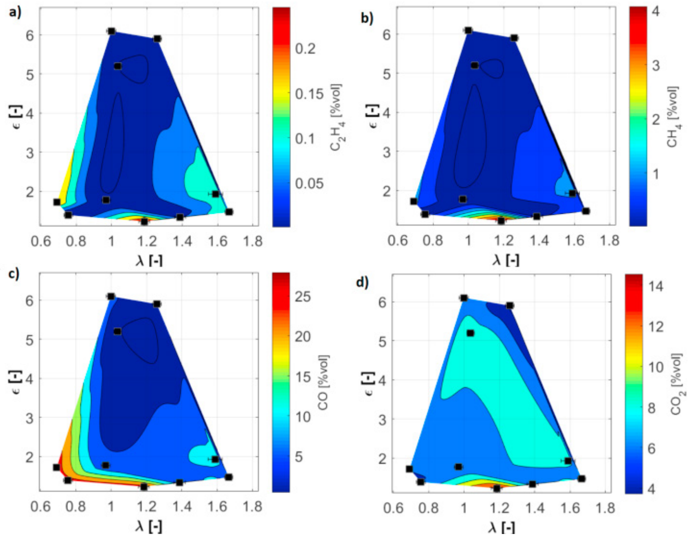

Fig. 3. Volumetric percentage of C_2H_4 (a), CH_4 (b), CO (c) and CO_2 (d) from the fixed bed sample probe, related to the air excess ε and split ratio λ

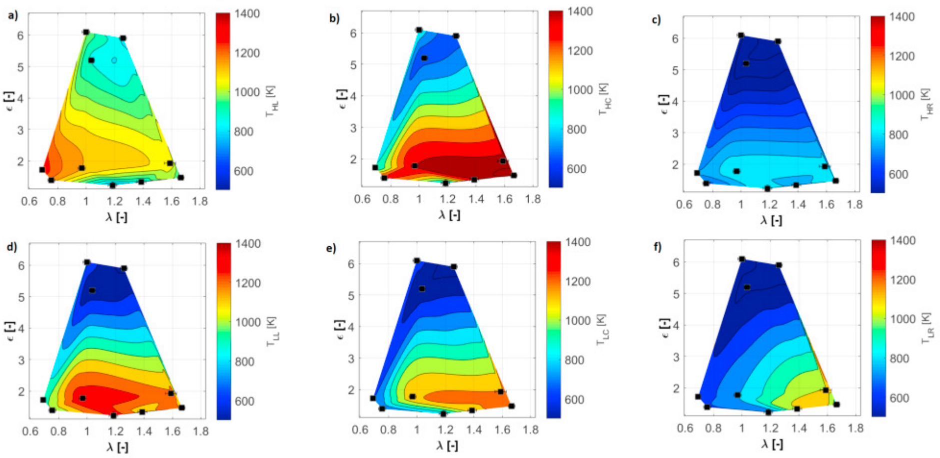

Fig. 4. Temperature from the fixed bed higher (a,b,c) and lower (d,e,f) zone, related to the air excess ε and split ratio λ

of variations in the fixed bed behavior. With the purpose of represent the Ethylene and Methane, CO and CO_2 trends, together with the bed temperatures, as a function of the operative boiler parameters, the interpolated maps are generated in Fig. 3 and Fig. 4. The data analysis suggests the division of the working range into three zones [17]. The first area is determined by stoichiometric oxygen ratio ($\varepsilon \sim 1$), in which a strong correlation between ethylene, methane and carbon monoxide can be detected, as shown by the trend similarity in Figure 3 (a,b). The related presence of C_2H_4 and CH_4 can be the marker for the presence of other devolatilization products, such as heavy hydrocarbons. Moreover, in this working zone the species production is significantly dependent from the λ parameter (specially at low split ratio), and it is important to notice that the main processes occur in the upper part of the bed, as shown by comparing the temperature maps in Figure 4 (b,c) with respect to the Figure 4 (e,f). The second zone is the low air excess zone

(1.5< ε < 2.5), where a strong dependence from λ parameter is detected. The temperature field appears to be more uniform and high in magnitude for all the working points investigated. When the system is close to the stoichiometric regime, the light hydrocarbons are strongly reduced, as well as the carbon monoxide. Finally, in the high-ε zone (ε>2.5) the volatiles production is reduced because of both the increase of the total air flow and the dilution effect; hence, the air excess appears to be the key parameter of this part of the process. Moreover, the temperature profile appears to be decreasing for all the conditions, which indicates that the quenching phenomenon takes place.

4. Conclusions

In this paper, an experimental campaign was performed in order to obtain data from a small size biomass fixed bed boiler of the University of Pisa. The measures on the CO, CO_2, C_2H_4 and CH_4 produced by the fixed bed, together with the temperatures field of the burning particle are provided. The results indicated that, around the stoichiometric working areas, species and temperature behavior are highly influenced by the split ratio parameter, and the light weight hydrocarbons productions follow similar trends. For ε> 2.5, the dilution and quench effects take place and the air excess becomes the controlling parameter of the fixed bed temperatures and species behaviors. Finally, it is important to notice that the biomass surface behavior in the combusting volume, especially for this small-scale system, can highly affect the data variability of both the species and temperatures in the boiler. The chemical and thermal data collected on the bed of such type of boilers are rarely available in the literature, and the information provided in this paper will be used to validate numerical models for small scale fixed bed systems applications.

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