Air mass flow rate effects on ignition front propagation of solid olive waste in a fixed-bed combustor

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1 Introduction

According to the climate agreement, adopted at COP21 in Paris on 12 December 2015, all signatories committed to limit global warming below 2°C. To reach this optimistic goal, different renewable energies need to be reconsidered. Thus, biomass would be considered among these energies and it can be converted in energy (heat) in many ways such as direct burning (combustion). The use of biomass in the field of energy generation could reduce the greenhouse gases in the atmosphere caused by fossil fuels. From 2010 to 2020, European Union (EU) countries would like to double the direct use of biomass in the residential sector [1-3]. Combustion process is one of the most used biomass conversion technology since it allows recovering about 90% of waste [4-5].

Many experimental and numerical studies, concerning biomass combustion, have been conducted in laboratory scale and pilot scale boilers [6-14]. In 2005 Yang et al. [6] have examined the particle size effect on pinewood combustion in a packed-bed. The experimental system is a vertical cylindrical combustor with height of *1500 mm* and an internal diameter of *200 mm*. A numerical model was developed to simulate the pinewood combustion process. It has been shown that the burning rate is higher with smaller biomass particle sizes. Furthermore, the maximum flame temperature and higher H_2 concentration is produced with larger fuel particles. One year later, the combustion of four biomass materials that have different fuel properties has been carried out by Ruy et al. [7] in the same combustor. Effects of particle sizes, bulk density and air flow rate on the flame characteristics were highlighted using the burning rate, gas composition and temperature measurements. Kaer [8-9] has performed numerical simulation of a 33 MW grate-firing furnace with a bed model based on a one dimensional approach. It includes the energy equations for both solid and gas phase all the more because the heat transfer between the two phases is taken into account.

Khor et al. [10] studied experimentally, in 2007, combustion characteristics of three herbaceous crops in the same fixed bed reactor. The comparison between ignition front speed, burning rate, and the equivalence ratio were carried out for all cases. A peak value of 220–250 $kg/m^2/h$ has been reached by the average burning rates at air flow rates of 700–900 $kg/m^2/h$.

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Another research group, in Spain, has been working on biomass combustion characteristics in fixed bed combustor. Porteiro et al. [11] have analyzed, in 2010, the experimental study of ignition front biomass flame propagation in a fixed bed combustor. The combustion chamber is cylindrical with inner diameter of 130 mm and height of 1050 mm. The ignition front propagation was investigated for eight biomass types. For all these biomass fuels, the effect of excess air ratio on the ignition front has been shown and it was also observed that the maximum front velocity appeared under stoichiometric conditions for all cases. A three dimensional model was developed by the same research group to simulate the combustion of the densified wood in a fixed bed [12]. The model combines bed and freeboard calculations and captures the behaviour of the interaction between solid and gas phases. The results of simulations showed a good agreement with experimental data. Elorf et al. [13] have numerically studied the swirl motion effects on flame dynamics of pulverized olive waste in a vertical furnace where air is introduced through two coaxial tubes. Results showed that the biomass flame is more stabilized close to the air inlet section for the swirling jet cases and the temperature of the burned gases reaches its maximum value of 1560 K.

Recently, in 2018, Karim et al. [14] have been studied 3D numerical modelling of biomass pellet combustion in a packed bed furnace under different conditions. The comparison between reference case with air-biomass and three cases with oxy-fuel combustion varying O_2 percentage (25, 27 and 30 % of oxygen) have been investigated. The results show that the temperature maximum of oxy-fuel (30% of O_2) combustion is higher and the flame length is shorter than other cases, this is due to higher concentration of O_2 in feed gas. Also, in 2018, Ren et al. [15] investigate the effects of air mass flow rate through the bed and of the moisture content of the fuel on emissions of hydrogen chloride (HCl) gas from combustion of biomass in a fixed bed. The results show that increasing the air flow rate through the bed increased the release of HCl gas, as a result of enhanced combustion intensity and associated enhanced heat release rates.

This work is a part of VERA (Energetic Valorization of Agricultural Residues) project to valorize the solid olive waste (OW) as biomass. OW is available in large amounts especially in Mediterranean countries at a very low cost and can be considered as alternative fuels, which do not contain Sulphur [13-16]. The aim of this paper is the experimental and numerical study of the olive waste combustion in a vertical fixed-bed. Thus, the air mass flow rate influence on the ignition front propagation is highlighted for this type of biomass. Furthermore, several tests have been carried out in terms of air mass flow rate and fuel bulk density. Nevertheless, this abstract presents only the results about air mass flow rate effects on combustion characteristics. Other results about bulk density and particles sizes effects will be presented in the final version of paper.

2 Experimental facilities

A fixed-bed combustor was developed and employed to burn solid olive residue (OW). It's made up of reactor, pilot burner, grate and air supply system as schematically shown schematically in Figure 1. The reactor is a cylindrical vertical combustion chamber with a height of *450 mm*, an inner diameter of *124 mm*. It consists of an inner tube surrounded by a thick layer of insulating material around the side wall. The primary air is injected at the bottom of the combustion chamber. The grate is installed at a height of 90 mm below the air injection and consists of a perforated plate made of stainless steel with about 350 holes of 4 mm diameter and two adjacent holes are *2 mm* apart. The grate contains a triangular pitch of *6 mm* and its open area is about *40.3 %.* Seven K-type thermocouples were used to measuring the flue gases temperature in the centerline of the combustion chamber and at different height levels. These measuring instruments are identified by T1, T2, T3, T4, T5, T6 and T7 and they are located on the wall at height levels of *100, 130, 160, 190, 220, 290* and *360 mm* respectively. All these thermocouples are connected to a computer via an appropriate data logger to recording instantaneous temperatures.

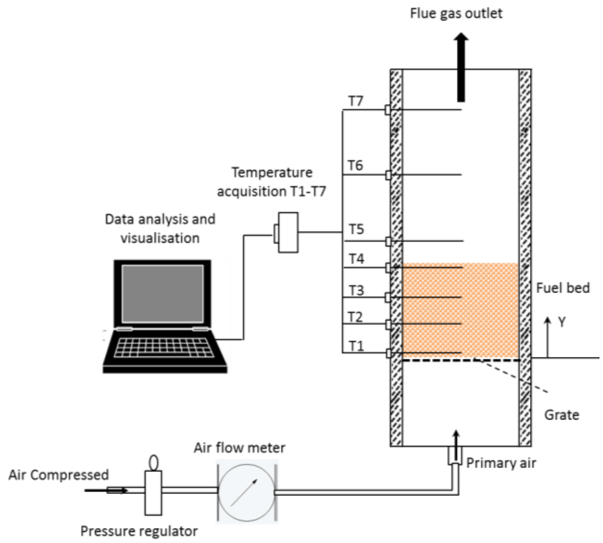

Figure1. Schematic view of the experimental setup.

The olive waste (OW) is used as a solid fuel; it comes from a Moroccan traditional olive oil extraction unit with 21.5 % moisture content and then it is dried in the open air. The percentage of extracted oil was measured using conventional Soxhlet extraction apparatus and it's about 6.4 %. The calorific value was also measured in the laboratory using a Parr 1351 adiabatic bomb calorimeter and mean high heating values (HHV) of this fuel is 20.2 *MJ/kg*. The mean particles diameter used for all tests in the present work is about *3 mm* and the measured bulk density is 456kg/m^3. Table 1 shows the fuel properties including proximate and ultimate analysis of the samples which was done as per ASTM standards.

Table 1. Fuel proprieties

Proximate analysis	*Moisture (%)*	*Volatile matter (%)*	*Ash (%)*	*Fixed carbon (%)*
	7.5	69.5	2.8	20.2
Ultimate analysis	*N (%)*	*C (%)*	*H (%)*	*O (%)*
	1.72	50.69	6.08	35.14
HHV (MJ/kg)	20.2			
Bulk density (kg/m^3)	456			

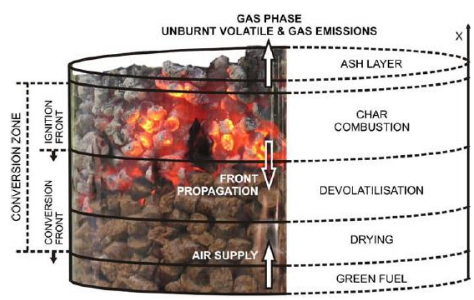

Figure 2. Propagation of the ignition front in the fixed bed [11]

Figure 2 presents the propagation of the ignition front in the fixed bed. The combustion test starts at the bed top layer and ignited by a pre-heating device after adjusting the air flow rate. Flame and velocity of the ignition front are estabilished after only a few minutes. The process is simple, the bed will be transformed to three zones. The first one is the char combustion zone which is located in the upper part of the solid phase when the char particle is oxidized with air crossing the bed. The devolatilization zone is found just below the char oxidation layer, this phase supplies heat by radiation and conduction. In the last and lower part the biomass particles will be dried by the heat conducted from the upper layers as mentionned in figure 2 [11].

3 Results and discussion

As mentioned above seven thermocouples, whose four of them are used to measure the bed temperature at different levels. These measurements allow us to quantify the time taken to reach a specific predetermined temperature between two adjacent thermocouples and calculate ignition front velocity (IFV).Theoretically, any temperature could be used as a reference, in this work; 300 *°C* was chosen to calculate IFV, in *mm/s*. The mass ignition rate (MIR), i.e., the amount of ignited mass per unit time per unit surface area (in $kg\ m^{-2}\ s^{-1}$) is obtained by multiplying the ignition front velocity (IFV) (*mm/s*) per the bulk density of the fuel. Five cases corresponding to five air mass flow rate (AMF) values: 0.16, 0.22, 0.28, 0.35 and 0.47 $kg\ m^{-2} s^{-1}$ was studied.

Figure 3(a) presents the measured temperature profiles versus time, for all thermocouples at various height levels above the grate, in the case where the AMF is equal to $0.29\ kg\ m^{-2}\ s^{-1}$. It is seen from curves of this figure that temperature profiles within the bed (T1, T2, T3 and T4) have similar variations as well as those of flue gas (T5, T6 and T7). It is also observed that each temperature profile within the fixed-bed has three main stages (or time intervals) characterizing the ignition front. Indeed, the start-up stage concerns the period in which the temperature of the bed is close to the ambient. In the second stage, temperature values increase sharply from room temperature to peak value specific to each height level, and then dropped when the ignition front passes down the considered thermocouple position (third stage). These stages correspond to different consecutive phases during which combustion process takes place: drying (If the layer temperature is between ambient temperature and 100 °C), devolatilization (generally between 100*°C* and 500 *°C*, there is a volatil matter decomposition) and char combustion (Figure 3(b)).

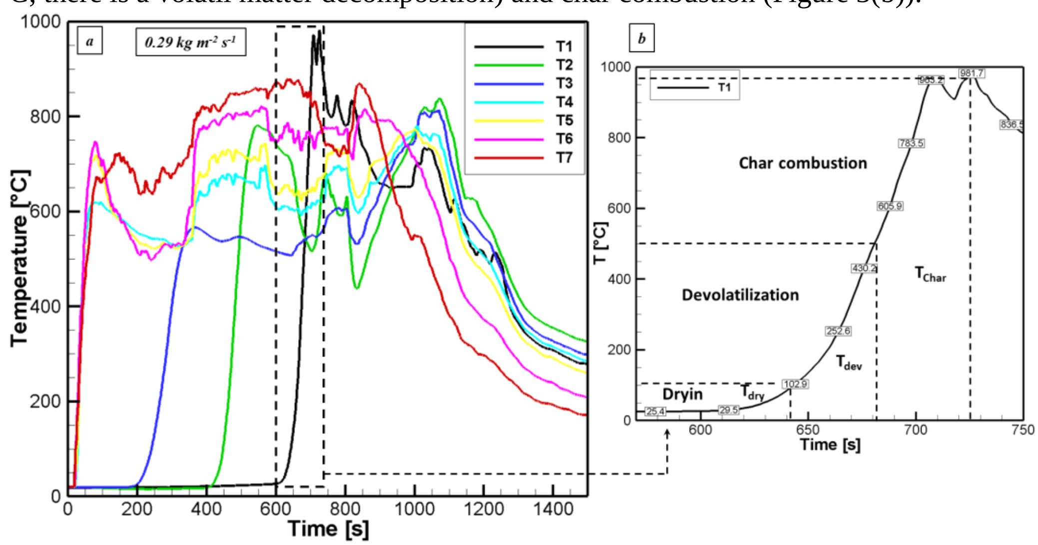

Figure 3. a) Temperature profiles for all thermocouples (AMF $0.29\ kg\ m^{-2}\ s^{-1}$), b) Zoom in on the curve (T1) to highlight the main combustion phases.

Figures 4(a) and 4(b) exhibit respectively the bed height evolution and ignition front velocity (IFV) against time for various values of AMF. The IFV(in *mm/s*) was calculated by using the relationship *IFV=d/t*, where *d* is the distance between two adjacent temperature ports*(30 mm)* and *t* is the time needed for the ignition front to move between them [17]. The bed height decreases for all AMF values because of the fuel consumption in the fixed-bed causes by the combustion process. It is obviously clear that the increasing of the AMF accelerates this process and hence reduced the time spent in it (950 *s* for $0.16\ kg\ m^{-2}\ s^{-1}$ whereas *600 s* for $0.47\ kg\ m^{-2}\ s^{-1}$). IFV and maximum temperature present nearly the same evolution trend for different air mass flow rate values. As is shown in Figure 4 with the increase of the mass air flow rate, the ignition front propagation velocity increased and heat generation was higher, this is resulting in enhanced char burning.

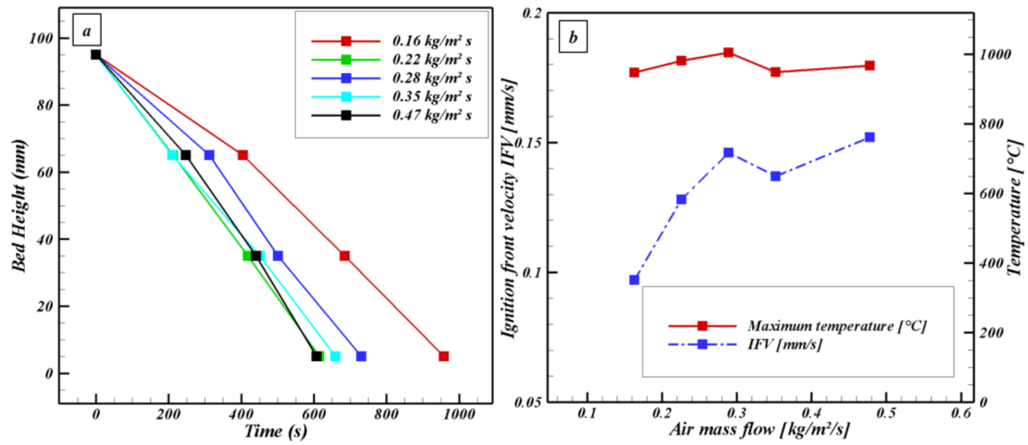

Figure 4. Bed height versus time for various AMF values (a), Ignition front velocity and maximum temperature with respect to air mass flow rate (b)

Figure 5 displays simultaneously the evolutions of the mass ignition rate (MIR) and the maximum temperature against the air mass flow rate (AMF). The reason for referring these results, especially AMF and MIR, to the cross-section area of the tube (0.012 m^2) is to facilitate their comparison with other experimental arrangements. So, a comparison of the obtained experimental results with those of Arce et al. [17], relative to the olive stone combustion in a fixed bed combustor, was done and a good agreement is observed. For both compared works, three combustion phases are distinguishable as a function of the supplied AMF. The first phase corresponds to a linear increase in the mass ignition rate (the oxygen-limited phase) and maximum temperature until their critical values. The second phase is presented by quenching phase (or convective cooling phase) where a lightly decrease in the maximum temperature and the MIR is respectively generated. The last phase is known as a speed zone that corresponds to the reaction-limited phase and where maximum temperature is almost constant.

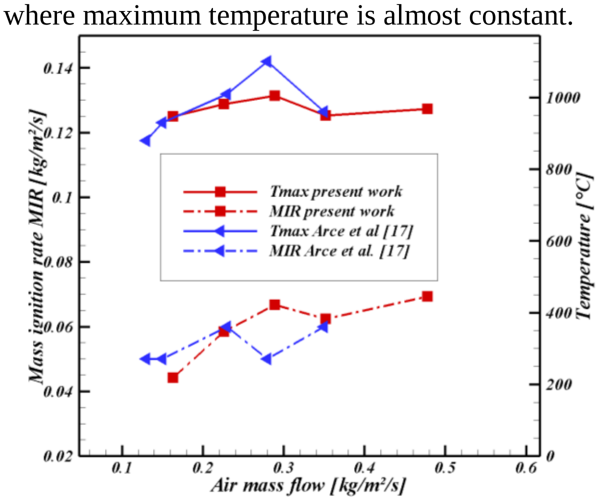

Figure 5. Evolutions of the mass ignition rate and maximum temperature: comparison with experimental results of Arce et al. [17]

4 Conclusions and perspective

The fixed-bed solid olive waste combustion is experimentally performed. The effects of the air mass flow rate on significant physical parameters especially, mass ignition rate (MIR), maximum temperature, ignition front velocity (IFV) and bed height, are highlighted. Comparison with experimental results available in the literature [17] was realized and a good agreement is recorded. Furthermore, the increasing of the AMF values accelerates the combustion process and hence reduced the time spent in it. On the other hand, the increasing of the air mass flow rate generates three different phases: the acceleration phase, convective cooling phase, and the reaction-limited phase. In the near future, supplementary tests with different bulk density and additional biomasses (such as Argan nut shell and Wood pellets) would be undertaken. The results will be used to derive data for designing and optimizing the operation of a large-scale grate-fired unit.

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