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Experimental heat transfer evaluation in a porous media

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Abstract. The evaluation of the heat transfer coefficient between hot gases and biomass particles is not easy to estimate because of the concomitance of exothermic and endothermic reactions. However, a proper evaluation of this coefficient is fundamental to design pyrolysis apparatus. This paper presents an experimental study regarding wood pellets heating up in a batch reactor using hot exhaust gases from an engine. Temperature and flow of hot gases entering the reactor were measured over time. A first test was carried out using hemp hurd pellets with 15% of sawdust, and a second one using the carbonized pellets obtained from the previous test. Fresh pellets have a higher thermal capacity compared to carbonized pellets that is almost inert and follow a more regular heating trend. Heat transfer was calculated considering the energy released by the exhaust passing through the biomass as the sum of the energy absorbed by the pellets and the thermal losses. Convection is the predominant heat transfer mechanism and the convective heat transfer coefficient was evaluated. Finally, the energy for the pyrolysis of 1 kg of fuel was evaluated. About 0.7 kWh/kg are necessary to pyrolyze this kind of pellets while a heat transfer coefficient of 110 W/(m²K) was estimated for the inert packed bed.

1. Introduction

Heat transfer phenomena through biomass porous media lead the pyrolysis process that is the first stage of biomass combustion and/or gasification [1]. Biomass heating rate and residence time are two major parameters that influence pyrolysis products [2, 3, 4]; however, heat transfer through the biomass packed bed creates different conditions of heating rate for each biomass particle inside the bed [5]. The greater is the heat transfer, the more homogeneous is the biomass heating up inside the bed and a better control of the process can be achieved.

The evaluation of the heat transfer coefficient between hot gases and biomass particles is not easy to estimate because of the concomitance of exothermic and endothermic reactions that take place during biomass temperature increase from ambient temperature to the final equilibrium temperature [6]. However, an estimation of this coefficient is fundamental in order to design properly pyrolysis apparatus [7]. This paper presents an experimental study regarding wood pellets heating up in a batch reactor using hot exhaust gases from an engine coupled with a small-scale biomass gasifier for electrical power production. The choice of using exhaust gases instead of air was done in order to avoid pellets combustion. Temperatures of hot gas before entering the reactor and afterward the reactor were measured over time, also hot gases volume flow and pressure drop were measured over time.



Two tests were carried out. The first one using pellets obtained from a mixture of hemp-hurd (85%) and fir sawdust (15%), the second one with carbonized pellets obtained from the first pyrolysis test. Fresh pellets have a higher thermal capacity compared to carbonized pellets because of the presence of an overall endothermic reaction during the biomass heating up. Carbonized pellets are almost inert and they follow a more regular heating trend with the same boundary conditions compared to fresh pellets.

Heat transfer between hot gases and biomass particles during the biomass heating up was calculated considering the energy released by the exhaust passing through the reactor as the sum of the energy absorbed by the pellets and the thermal losses. In this case, convection heat transfer is the predominant heat transfer mechanism between gas and particles and the convective heat transfer coefficient was estimated. When the test reaches the steady state conditions, no chemical reaction takes place anymore and from the difference between the inlet and outlet exhaust temperatures, the heat loss from the reactor wall can be calculated.

Finally, the energy required for the pyrolysis of 1 kg of dry fuel was evaluated calculating the thermal energy transfer between hot gases and biomass considering also the losses evaluated in the test with carbonized biomass.

2. Materials and methods

2.1. Experimental procedure

For the purpose of this study, the experiment has been divided in two tests. The first one is carried out with a known quantity of biomass to assess how much thermal energy must be provided to a biomass packed bed for the pyrolysis reaction to be fully exploited. In the second test, the biomass after the pyrolysis processes can be seen as an inert material (i.e no thermal energy is needed for chemical reactions). With this test, it is possible to estimate the heat losses from the wall of the reactor and to assess the order of magnitude of the convective heat transfer coefficient of the packed inert bed. Given the difference between the two tests, the sole thermal energy requested for the pyrolysis reaction can be calculated in the first one.

The mass flow rates and the mean temperatures of the exhaust gas have been measured for both the tests. The specific heat of the exhaust has been calculated as the weighted average of the specific heats of the various components considering their mass fraction at the average temperature. Knowing the exhaust mass flow, the specific heat and its inlet and outlet temperatures, it is possible to calculate the thermal energy released by the exhaust passing through the reactor during the first test, which represents the sum of the energy needed for heating up the biomass, nourish the chemical reactions and the energy dissipated from the wall of the reactor itself.

As a first assumption, it is possible to quantify the thermal power dissipation caused by dispersion through the wall of the reactor during the second test, when the steady state condition is reached, using formula (1).

$$\dot{Q}_{diss} = \dot{m}_{exh} \cdot c_{p,exh} \cdot \Delta T_{exh,2^{\circ} test,s.s.} \quad (1)$$

Where:

- \dot{Q}_{diss} [W] is the thermal power dissipated through the wall of the pyrolysis reactor assumed the same for the first and the second test (exhaust temperatures and flow were very similar);
- \dot{m}_{exh} [kg/s] is the mass flow rate of the exhaust gas passing through the pyrolysis reactor;
- $c_{p,exh}$ [J/(kg°C)] is the specific heat capacity of the exhaust gas;
- $\Delta T_{exh,2^{\circ} test,s.s.}$ [°C] is the difference between the inlet and outlet temperature of the exhaust gas within the pyrolysis reactor during the second test once the steady state (s.s.) condition is reached.

Given this quantity and subtracting it from the thermal energy used during the first phase of the test, it is possible to calculate the thermal energy needed for the pyrolysis reaction only:

$$Q_{pyr} = \int_0^t \dot{m}_{exh} \cdot c_{p,exh} \cdot \Delta T_{exh} dt - \dot{Q}_{diss} \cdot t = \bar{Q}_{released} \cdot t - \dot{Q}_{diss} \cdot t \quad (2)$$

Where:

- Q_{pyr} [J] is the thermal energy needed for the pyrolysis reactions;
- $\Delta T_{exh, 2^{nd} test, s.s.}$ [°C] is the difference between the inlet and outlet temperature of the exhaust gas within the pyrolysis reactor;
- t is the test duration [s];
- \bar{Q}_{rel} [W] is the average thermal power released by the exhaust passing through the reactor during the test.

$$\dot{Q}_{released} = \dot{m}_{exh} \cdot c_{p,exh} \cdot \Delta T_{exh} = h \cdot (T_{mean,exh} - T_{sup,biom}) \cdot S_{biom} + \dot{Q}_{diss} \quad (3)$$

The aim of this study is also the assessment of the order of magnitude of the convection heat transfer coefficient “h”. It can be estimated using the formula (4)

$$h = \frac{\dot{Q}_{released} - \dot{Q}_{diss}}{(T_{mean,exh} - T_{sup,biom}) \cdot S_{biom}} \quad (4)$$

Where:

- h [W/(m²K)] is the convection heat transfer coefficient;
- $T_{mean,exh}$ [K] is the mean temperature of the exhaust gas within the reactor calculated as the average between the exhaust inlet and outlet temperatures;
- $T_{sup,biom}$ [K] is the average superficial temperature of the biomass.
- \dot{Q}_{diss} [W] is the thermal power dissipated through the wall of the pyrolysis reactor assumed the same for the first and the second test;
- $\dot{Q}_{released}$ [W] is the thermal power released by the exhaust gas

The $\dot{Q}_{released}$ considered for the h estimation was the maximum released by the exhaust during the second test. The average temperature of the exhaust considered was the average between the inlet and the outlet in the moment of maximum thermal power released. The biomass superficial temperature was not measured directly. The only moment when the biomass superficial temperature can be assumed with a certain degree of reliability is when the inlet and outlet exhaust temperatures are equal to each other (Figure 1) and it is set the same of the exhaust.

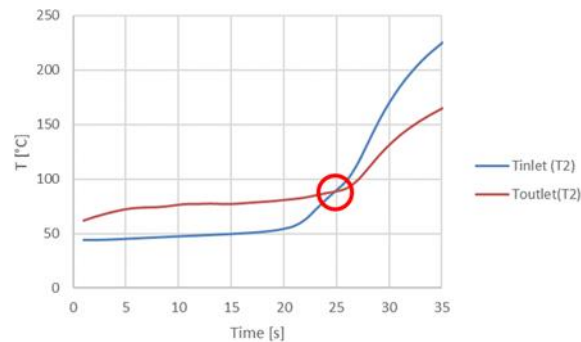


Figure 1 - Inlet and outlet temperatures of the pyrolysis reactor. Particular of the point of coincidence.

This moment is about 20 seconds before the moment of maximum heat exchange, and considering that the maximum heat exchange happens when the difference between the average exhaust temperature and the average biomass temperature is the highest, and that there is a delay in the temperature detection by the thermocouple, this known biomass temperature was considered as the one during the moment of maximum heat transfer rate.

To estimate the heat exchanging surface of the biomass, all the pellets of the sample have been measured and, considering them as cylinders, the surface is calculated geometrically as the sum of every single pellet surface. This has been done after the pyrolysis phase when the biomass has become inert, neglecting the contact surface between the single pellet of the biomass sample. This assumption leads to an overestimation of the heat exchanging surface, therefore to an underestimation of the convection heat transfer coefficient of the biomass “h”.

2.2. System layout

The pyrolysis is carried out using the heat of the exhaust gases produced by a gasifier-engine system, produced by “All Power Labs”: the PP30 (Figure 2)[8]. The core of this power plant is a downdraft gasifier with an internal heat recovery system, coupled with a spark ignition engine, an Ashok Leyland 3.8L.



Figure 2 - Gasifier-engine system by All Power Labs [8]

The gasifier is fed with high quality biomass and when the temperatures are high enough for the synthesis gas to be considered of good quality, it is possible to turn on the engine. For the purpose of this study, the temperature of the exhaust gases produced by the engine must be relatively stable, higher than 375°C, to meet the need of the pyrolysis reactions. Once this temperature (T_1 in Figure 3.a) has been reached, it is possible to deviate the flux of the exhaust gas towards the pyrolysis reactor. Both the temperatures before and after the pyrolysis chamber, are measured with type Class 1 tipe-K thermocouples that, in accordance with the EN 60584-2 standard, they have an error of 1.5 °C in the temperature range of this application. The pyrolysis system layout is shown in Figure 3.a.

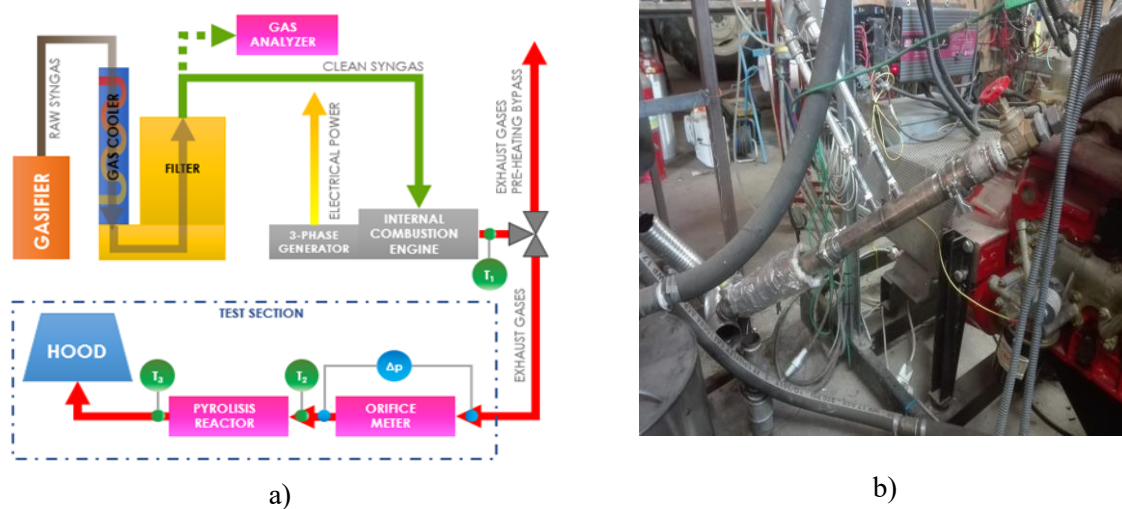


Figure 3 - a) System layout and test section. b) Picture of the test section with the calibrated orifice and the pyrolysis reactor.

2.3. Gas flow mass and thermal energy assessment

In order to estimate the mass flow of the exhaust gas produced by the engine, an indirect method has been applied. First, the composition of the synthesis gas produced by the gasifier is obtained with a gas chromatographic analysis which defines the volumetric concentration percentage of every single compound of the gas. About the uncertainties given by the gas chromatography, literature suggests a range of 2-5% of gas fraction error [9]; because of the syngas components are quite easy to analyze with micro-gc techniques, an average error of 2% is considered in this case. It must be pointed out that the syngas does not contain oxygen, but the results of the chromatographic analysis show the presence of it; this is due to the sampling procedure. Hence, there is the need to normalize the data by distributing the percentage of oxygen over the other compounds, using the formulas (5) for nitrogen and (6) for every other compound:

$$C_{N_2, norm}(\%) = \frac{C_{N_2, chr}(\%) - 3.74 * C_{O_2}(\%)}{\left[\frac{100 - 4.78 * C_{O_2}(\%)}{100} \right]} \quad (5)$$

$$C_{i, norm}(\%) = \frac{C_{i, chr}(\%)}{\left[\frac{100 - 4.78 * C_{O_2}(\%)}{100} \right]} \quad (6)$$

Where:

- $C_{i, norm}(\%)$ normalized volumetric concentration of the i-compound;
- $C_{N_2, norm}(\%)$ normalized volumetric concentration of nitrogen;
- $C_{i, chr}(\%)$ measured volumetric concentration of the i-compound;
- $C_{N_2, chr}(\%)$ measured volumetric concentration of nitrogen
- $C_{O_2}(\%)$ measured volumetric concentration of the oxygen within the sample.

The exhaust composition is determined considering the complete stoichiometric combustion of syngas with air. The air quantity is controlled by a lambda probe which controls an automatic “air servo” valve, in order to maintain the λ ratio equal to 1. The reactions consider both the composition of the synthesis gas and of the dry atmospheric air. The first is composed by H_2, CH_4, CO, N_2_{syn} e CO_2 and the latter by $N_2_{air}, O_2_{air}, Ar_{air}$, neglecting the other minor compounds. The reaction balance is based

on the moles of oxygen needed to guarantee the combustion of the synthesis gas, but as atmospheric air is used, for every mole of oxygen to be used in the combustion chamber, there are also 3.74 moles of nitrogen and 0.044 moles of argon. This consideration is to be taken into account during the equation balance as the same stoichiometric coefficient has to be applied to oxygen, nitrogen and argon. Indeed, whereas oxygen reacts with the synthesis gas compounds, nitrogen and argon are to be considered inert gases and, consequently, their amount has to be considered the same after and before combustion (i.e. within the exhaust gases). Assuming the synthesis gas as a perfect gas, and applying the perfect gas equation, it is possible to obtain the number of moles of every single compounds of the synthesis gas, by multiplying the volumetric concentration of every single compounds by the total number of moles obtained with the perfect gas equation, using the formula (7):

$$n_i [\text{mol}] = n_{tot} [\text{mol}] * V_i\% \quad (7)$$

Where:

- $n_i [\text{mol}]$ is the number of moles of the i-compound;
- $n_{tot} [\text{mol}]$ is the total number of moles;
- $V_i\%$ is the volumetric concentration of the i-compound.

Given the number of moles for every single compounds of syngas and using the stoichiometric balance, it is possible to calculate the number of moles of every single compounds of the exhaust gas; furthermore, this procedure allows the volumetric composition to be assessed as well. The third step is the calculation of the mass flow of the exhaust gas considering its density and using a calibrated orifice for the measure of the pressure drop “ Δp ” in the same instant of the temperature measuring. Through the methodology reported in the UNI EN ISO 5167 regulation [10] it is possible to calculate the exhaust mass flow with the formula (8):

$$\dot{m}_{exh} = C_d A_o \left[\frac{2\rho(\Delta p)}{1 - \beta^4} \right]^{0.5} \quad (8)$$

Where:

- C_d, A_o, β are geometrical parameters correlated to the dimensions of the orifice (inner diameter of 0.043 m and restriction diameter of 0.021 m)
- $\Delta p [\text{Pa}]$ is the pressure drop generated at the orifice;
- $\rho [\text{kg/m}^3]$ is the gas density calculated according to the molar mass and the temperature of the gas at the orifice.

Uncertainty of the flow rate measurement can be obtained from the methodology reported in the standard UNI EN ISO 5167. However, literature suggests that the relative uncertainty of the mass flow difficulty exceed 0.5% [11].

3. Results

In Figure 4, the biomass sample before (left) and after (right) the pyrolysis reaction is shown. The mass of the fresh pellet sample is 135 g and its surface is 0.104 m² while the exchanging surface during the second test (i.e, inert biomass) has been estimated in 0.034 m².



Figure 4 - Biomass sample used for the tests, fresh pellet (left) and carbonized pellet (right)

The mean temperature of the exhaust gas in the first test was 664 K and considering the composition of the exhaust gas, the specific heat coefficient is 1155.6 J/(kg K). During the second test, the mean temperature was 695 K to which corresponds a specific heat coefficient of 1167.8 J/(kg K). The mean mass flow during the first test was 29.8 kg/h and in the second test was 30.8 kg/h.

In Figure 5, the thermal power release by the exhaust within the pyrolysis reactor during the second test is shown. The part of the curve at almost steady-state condition (from 800 s onwards) has been used to estimate the dissipation of thermal power through the wall of the reactor which has been quantified in 220 W. By subtracting this value to the overall thermal power provided to the reactor during the first test, it is possible to estimate the thermal power needed over time (i.e, the thermic energy) for pyrolysis reaction only. This result is shown in Figure 6.

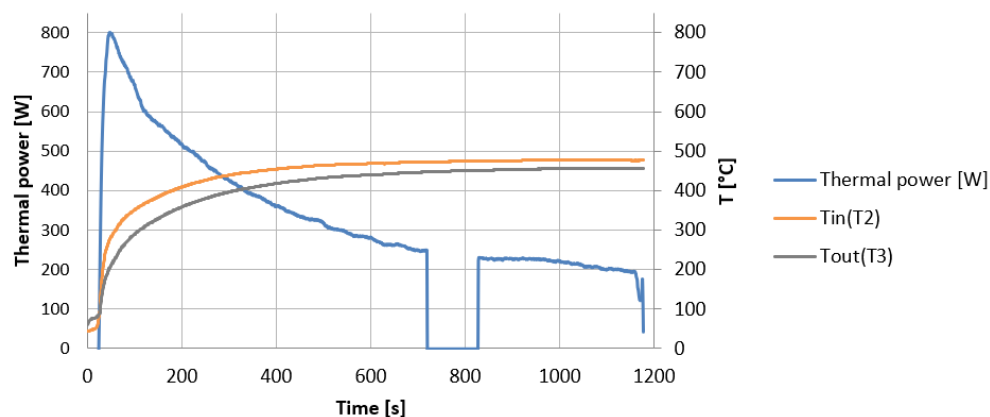


Figure 5 - Thermal power vs inlet and outlet temperature, during the second test.

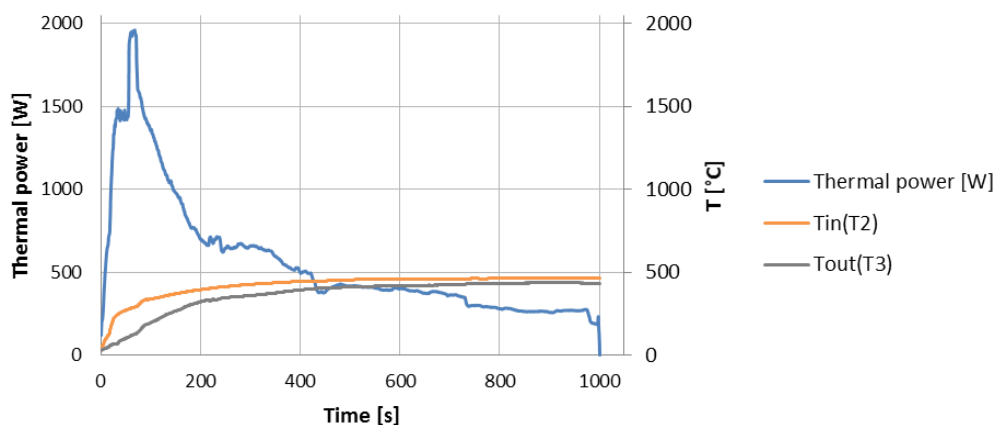


Figure 6 - Thermal power vs inlet and outlet temperature, during the first test.

The part of the curve in Figure 5 which drops to 0 W at around 800 s, is due to a momentaneous use of the calibrated orifice for extracting an exhaust gas sample for a control of the composition during the experiment. At this point, assuming the thermal power released by the exhaust during the first test equal to the thermal power needed for the pyrolysis reactions plus the estimated dissipation, it is possible to calculate the specific thermal energy needed for the pyrolysis of the biomass using formula (2), which consists in 0.7 kWh/kg of biomass 2500 kJ/kg. At last, to quantify the order of magnitude of the convection heat transfer coefficient “h”, the biomass surface temperature during the moment of maximum heat transfer in the second test has been estimated to be 89 °C, while the average temperature of the exhaust was 245 °C. The thermal power released by the exhaust was 580 W. Given these quantities, the convection heat transfer coefficient was 110 W/(m²K).

4. Conclusions

In this work a way to assess the heat transfer and the thermal energy absorbed by a biomass packed bed is presented. The calculated thermal energy needed by the biomass to completely pyrolyze was 2.5 MJ/kg, a value in line with literature [12]. The evaluation of the heat transfer coefficient during the second test with the inert bed has given a value of 110 W/(m²K), typical of forced convection for gases [13]. In a future work, a comparison between these results and the correlations for heat transfer in packed beds based on porosity and particle size will be performed. Due to the weight loss of the biomass during pyrolysis it is very difficult to evaluate the heat transfer coefficient when the biomass is reacting. A possible way to overcome this problem will be to couple this study with a thermal gravimetric analysis that provides the weight loss of the biomass over time while it is heated up.

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