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Characteristics of single wood particle pyrolysis using particle image velocimetry

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ABSTRACT

This study examines the pyrolysis of a single cylindrical wood particle using Particle Image Velocimetry (PIV). The pyrolysis was carried out in the ATR 01/600 pyrolysis reactor designed for this purpose. The experimental setup presented in this study is capable of effectively characterizing the intensity of pyrolysis based on velocity distribution in the vicinity of wood particles. The results of the gas velocity distribution indicate the formation of a gas cushion caused by the evaporation of moisture and devolatilization. Higher heating rates increase the intensity of degassing and the thickness of the gas cushion around the particle and may temporarily slow down the intensity of convective heat transfer to the interior of the particle.

1. Introduction

Particle image velocimetry (PIV) is a widely used method in fluid mechanics [1,2]. Fu et al. [3] presented a numerical and experimental investigation of indoor airflow. This article compared PIV and 3D as a function of the tacking density index. Experiments were carried out using an experimental low-turbulence indoor airflow generated by a low-speed tailpipe. Ertür et al. [4] used PIV as a method to model the characteristics and turbulent statistics of the flow in an external gear pump. Nevertheless, there are also many applications of solid elements where the vectors are adopted to measure the displacement of bodies. This issue was presented by Baba and Peth [5] who analyzed the geotechnical testing of soil creep movements. In the paper, the authors demonstrated the large potential of PIV to examine the effect of hydraulic stresses on creep deformations due to gravity forces. Another example of PIV application in order to define the material properties was presented by Magalhaes et al. [6]. PIV coupled with particle swarm optimization (PSO) and FEM inverse analysis can be used to analyze Young's Modulus of the ASTM A36 steel.

PIV has also been used in thermochemistry. Vali et al. [7] analyzed the liquid velocity field in order to understand the transport phenomena in the liquid phase of a laboratory-scale methanol pool fire. The authors showed that PIV can effectively analyze the fluid dynamics of the fluid phase of the pool fire. Di Sarli et al. [8] used the PIV method to analyze the transient interactions that occur between hydrogen-enriched methane/air premixed flame fronts and toroidal vortex structures.

This work presents the results of applying PIV during pyrolysis of a single cylindrical wood particle. Pyrolysis is the thermochemical conversion of solid fuel to solid, liquid, and gaseous fractions in the absence of air [9,10], which for the lignocellulosic materials occurs between 300 and 500 °C [11–14]. Pyrolysis is extremely complex and includes many different processes, which can occurs simultaneously, like dehydration, deploymerization, fragmentation, condensation and carbonization. The proportion and composition of pyrolysis products depend on many factors such as feedstock type, heating rate, final temperature, pressure, resident time of fuel particles and pyrolysis gases in the reactor [12,13,15–17]. Gable and Brown [18] showed that bio-oil yields increased with biomass heating time. Experiments were carried out in a free fall pyrolysis reactor with the nitrogen as a sweep gas. Effects of heat treatment temperature on the products yields during pyrolysis of the paper sludge was presented by Li et al. [19]. The results showed that catalytic effect, caused by a high content of metals in the paper sludge, led to an increase in gas yield and decrease in bio-oils yield with increasing pyrolysis temperature. During the experiment sample was loaded on at the plate in the heated reactor. The nitrogen was used as inert gas. Açıkalın and Kacar [20] showed that temperature was the most significantly parameter during pyrolysis of walnut shell. The increase in temperature resulted in a decrease in solid yields and increase in gas yields. The samples were pyrolyzed in the tubular reactor with the nitrogen as a sweep gas.

There are also many studies reported in the literature different techniques and construction of reactors to carry out the pyrolysis. One of the common solutions is a fixed bed reactor. Pham et al. [21] presented experimental investigation of oxidative pyrolysis of wheat straw,

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pine wood and miscanthus pellets and pine in the 20 cm diameter fixed bed reactor, and their studies revealed that the sample particles shrink during pyrolysis and the ash tends to concentrate on the external surface of the particle, which can lead to accelerate secondary char-forming reactions. However, in this case, experiments were carried out without the inert gas flow through the fuel bed. Fast pyrolysis of the raw material in the fixed bed reactor was also presented by Quan et al. [13]. Nitrogen was use as carrier gas. The objectives of the work was to characterize differences in the pyrolysis behavior of the cellulose, hemicellulose and lignin. Ly et al. [22] showed experimental investigation of the macro-alga fast pyrolysis in the tubular fixed bed reactor with nitrogen flow as a sweeping gas. The authors have indicated that the temperature increase caused decreased in bio-oils yields and increase in gas yields.

Although several studies have already discussed pyrolysis technologies and upgrading of pyrolysis products, there is lack of experimental studies highlighting the effect of heat transfer and gas flow near the biomass particle on the pyrolysis process. Due to the increase of particle energy, the process can be considered as a chemical phenomenon, but the transfer of energy to the particle surface and inside the particle is primarily physical. The main aspects of this paper are focused on the phenomenon of the formation of a gas cushion during the flow of a stream of hot inert gas around a wood particle.

1.1. Transport processes during pyrolysis

The dynamics of the pyrolysis process and the composition of the pyrolysis products is strongly associated with the chemical composition of the fuel, in the case of biomass with its lignocellulosic composition. However, this process also depends on the parameters like size of the particle, its mass density, internal structure, porosity, specific heat and thermal conduction coefficient. The cause of pyrolysis is an increase in the internal energy of the material, but the rate of increase of temperature depends on the physical properties of the material and on the heat transport inside the fuel particle. In the wood particle, which is a porous material, heat transport is caused by conduction, convection and radiation.

A sample wood particle placed in the hot inert gas stream starts to heat up. The heat penetrates the inside of the particle, which is mainly related to conduction through the gas phase and with the solid matrix radiation [23]. In the first stage, the water, which determines the moisture content of solid particles, is evaporated. Above a certain temperature (for wood ~ 270 °C), the pyrolysis process takes place, during which the thermal degradation of lignocellulosic materials occurs. The result of this degradation is the formation of the gaseous fraction and char.

Fig. 1 presents the heat and mass transport processes in the single solid fuel particle during pyrolysis [24]. Heat transfer from the outer surface to the interior of particles leads to thermal decomposition in the same direction and to formation of porous structures inside the particle.

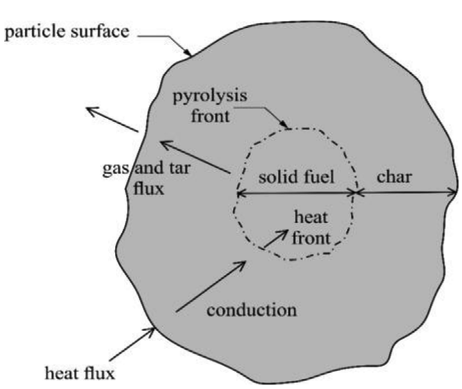

Fig. 1. Transport process during single particle pyrolysis.

Table 1
Technical and elementary analysis of the biomass.

Heating value [MJ/kg]	19.59
Technical	**[%]**
Moisture	8.40
Volatiles	67.90
Char	21.40
Ash	2.30
Elementary	**[%]**
C	45.00
H	6.40
O	47.30
N	1.30

In the opposite direction, towards the surface of particle, the diffusive transport of volatiles occurs through the formed pores. Gases and condensable tars are emitted to the surface of particle.

2. Materials and methods

2.1. Wood sample

The samples used in measurements were prepared from Scots pine (*Pinus sylvestris*), which is a very common type of wood in Poland. Table 1 presents the technical and elementary analysis of Scots pine. The calorific value was determined using a KL-11 calorimeter. The moisture content was determined using a MAC (Radwag), and an elementary analysis was performed using a Thermo Scientific CHNS—O Flash 2000 elementary analyzer. The data presented in Table 1 is in good accordance with the literature [25–27]. The low ash content results in a higher yield of solid and gaseous fraction.

2.2. Experimental setup and methodology

2.2.1. Thermogravimetric analysis

To analyze the thermal conversion rate and the temperatures at which they occur, a thermogravimetric analysis of the pine wood samples was conducted. The results of the thermal decomposition of the biomass presented in this study were obtained by using the TA Instruments SDTQ600 thermogravimeter (TGA) at a heating rate of 10, 20, 30 and 50 °C/min. The mass of the sample was equal to 10 mg.

2.2.2. Pyrolysis reactor and procedure

The ATR 01/600 reactor (Fig. 2) was designed for experimental and visual investigation of solid fuel particle pyrolysis at high temperatures. Fig. 2 shows one of the possible orientations of the reactor; apart from the default orientation at which the gravity is directed towards the spiral heater (Fig. 2; (6)) inside the chamber, the reactor can also be tilted by 90° so that the gravity is directed towards the inside the picture in Fig. 2. Pyrolysis of the wood is obtained by heating the particle with a stream of hot inert gas. The main part of the reactor is the cubic pyrolysis chamber, consisting of three high temperature glass plates of 130 mm × 130 mm x 5 mm, which allow real time visual observation of

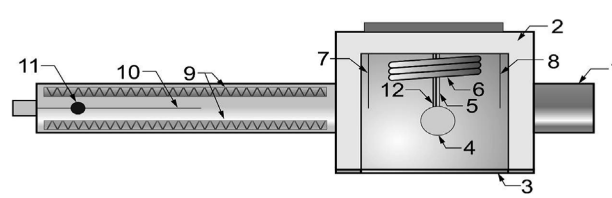

Fig. 2. Schematic diagram of pyrolysis reactor, (1) gas stream outlet, (2) mineral wool insulation, (3) transparent glass cover, (4) wood sample, (5) thermocouple, (6) heater, (7,8) thermocouples, (9) heating element of cylindrical gas heating chamber, (10) thermocouple, (11) inert gas inlet, (12) steel needle for fixing the particle.