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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 conducted inside a pyrolysis reactor designed for this purpose. The experimental setup presented in this paper 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 show that evaporation of moisture has as a major impact on the formation of the gas cushion as devolatilization.

**Keywords:** Pyrolysis; Particle image velocimetry; Gas cushion

## 1 Introduction

Particle image velocimetry (PIV) is a widely used method in fluid mechanics [1–2]. Fu *et al.* presented a numerical and experimental investigation of indoor airflow [3]. This paper 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.* used PIV as a method to measure the characteristics and turbulent statistics of the flow in an external gear pump [4]. PIV has also been used in thermochemistry. Vali *et al.* analyzed the liquid velocity field in order to

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understand the transport phenomena in the liquid phase of a laboratory-scale methanol pool fire [5]. The authors showed that PIV can effectively analyze the fluid dynamics of the fluid phase of the pool fire. Di Sarli *et al.* used the PIV method to analyze the transient interactions that occur between hydrogen-enriched methane/air premixed flame fronts and toroidal vortex structures [6].

This paper 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 [7]. The main aspects of this paper are focused on the analysis of the influence of temperature on the flow around a wood particle and presents a phenomenon of the formation of a gas cushion during the flow of a stream of hot inert gas around a wood particle.

## 2 Transport processes during pyrolysis

The transport processes during pyrolises go through the following stages. 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 [8]. In the first stage, the water, which determines the moisture content of solid particles, is evaporated. Above a certain temperature (for wood $\sim 270\,^{\circ}$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.

Figure 1 presents the heat and mass transport processes in the single solid fuel particle during pyrolysis [9]. 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. 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.

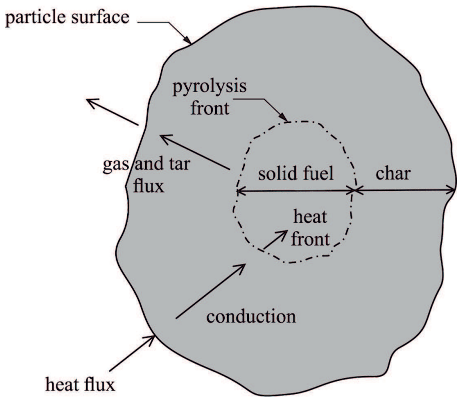

Figure 1: Transport process during single particle pyrolysis.

# 3 Materials and methods

## 3.1 Wood sample

The samples used in measurements were prepared from Scots pine (*Pinus sylvestris* L.), 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) moisture analyzer, and an elementary analysis was performed using a Flash 2000 (Thermo Scientific) for five elements (CHNS-O) simutaneously elementary analyzer. The data presented in Tab. 1 is in good accordance with the literature [10–12]. The low ash content results in a higher yield of solid and gaseous fraction.

## 3.2 Experimental setup and methodology

### 3.2.1 Experimental setup

The ATR 01/600 reactor (Fig. 2) was designed for experimental and visual investigation of solid fuel particle pyrolysis at high temperatures. Figure 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 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

Table 1: Technical and elementary analysis of the biomass.

| **Heating value** | **19.59 MJ/kg** |
|---|---|
| **Physical parameters** | |
| Moisture | 8.40±0.5% |
| Volatile matter | 67.90±1.3% |
| Fixed carbon | 21.40±1.1% |
| Ash | 2.30±0.1% |
| **Elemental concentration** | |
| C | 45.00±0.4% |
| H | 6.40±0.2% |
| O | 47.30±0.7% |
| N | 1.30±0.1% |

part of the reactor is the cubic pyrolysis chamber, consisting of three high temperature glass plates of 130 mm x 130 mm x 5 mm, which allows real time visual observation of pyrolysis process as well as coupling the reactor with the PIV equipment for velocity field measurements. The sample is fixed inside the chamber by placing it on the steel needle next to the thermocouple. This thermocouple is then placed inside the wood particle.

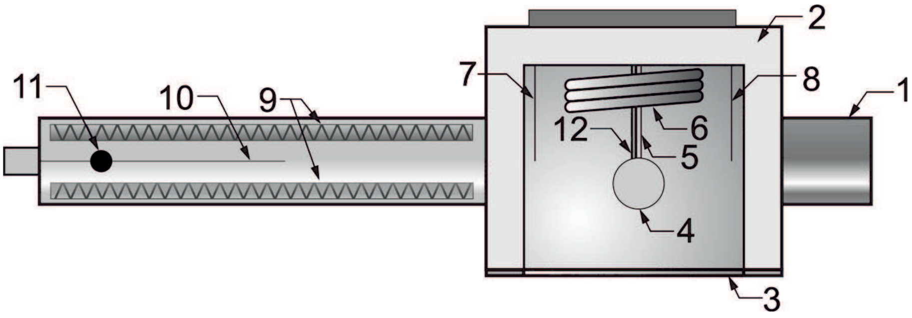

Figure 2: Schematic diagram of pyrolysis reactor: 1 – gas stream outlet, 2 – mineral wool insulation, 3 – transparent glass cover, 4 – wood sample, 5 – thermocouple, 6 – heater, 7,8 – thermocouples, 9 – heating element of cylindrical gas heating chamber, 10 – thermocouple, 11 – inert gas inlet, 12 –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

The design of the ATR 01/600 reactor allows us to couple it with PIV equipment for velocity field measurements. Figure 3 shows the scheme of

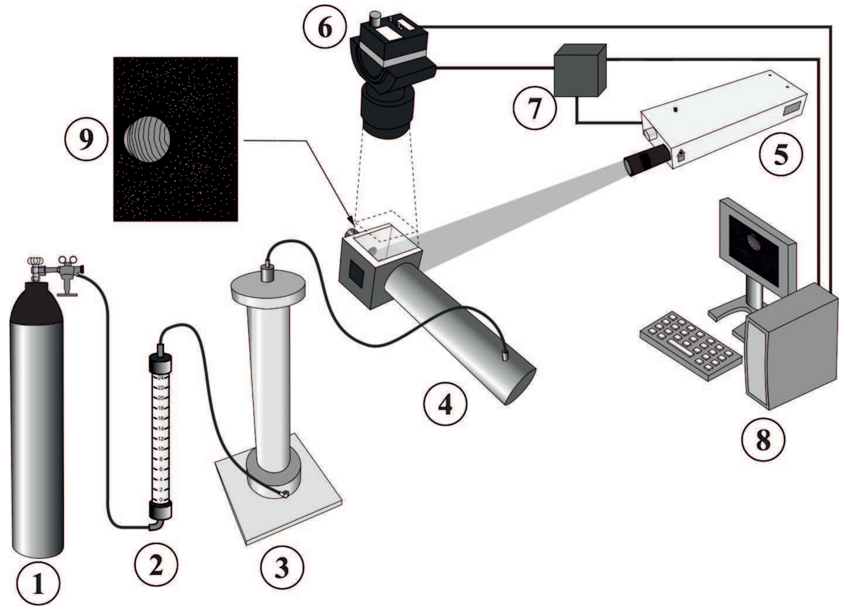

Figure 3: Schematic diagram of the experimental setup for PIV: 1 – inert gas cylinder, 2 – rotameter, 3 – $TiO_2$ seeding dispenser, 4 – pyrolysis reactor (Fig. 2), 5 – Nd:Yag laser unit, 6 – camera, 7 – timer box, 8 – computer unit, 9 – PIV image.

the experimental stand used in this work. The reactor was placed in the middle of the setup and tilted by 90° so that the laser sheet entered the chamber through the upper glass plate. At the same time, the light sheet was perpendicular to the FlowSense EO 4M camera, which provided an image of the inside of the chamber through the side glass plate. The laser unit was synchronized with the camera by the timer box, which was connected to the PC computer. In order to obtain PIV images, the seeding was necessary. In this case, $TiO_2$ particles were used as it allowed measuring the velocity fields of gas at high temperatures. The seeding particles were released into the gas by the dispenser (seeds generator, (3) in Fig. 3), which was connected directly to the reactor gas inlet (Fig. 2). Before entering the seeding dispenser, the gas was released from the container (Fig. 3) and flowed through the rotameter. The $TiO_2$ particles were used in this experiments because they do not evaporate at high temperatures, and their small size allows to follow the flow, and on the other hand is enough to reflect the light.

The experiment was based on heating the wood sample by a hot inert gas inside the pyrolysis chamber of the reactor and measuring the 2D velocity field simultaneously. A wood particle was placed in the chamber before heating the gas. The volume flux of the gas was constant and equal to 18 l/min. Seeding particles were constantly released to the gas during both experiments so that PIV images could be taken at any moment.

The PIV equipment worked in a double-frame mode. The light sheet consisted of two laser pulses of different wavelengths of 532 nm and 1064 nm, one for each frame. It was produced by a Litron lasers Nd:Yag DuaPower Nano L200-15PIV laser unit. In double-frame mode, the camera takes a pair of 2048 pixels x 2048 pixels pictures, which consists of one image for each laser pulse. A given $TiO_2$ particle visible in one image of the pair is in a different location in the second image due to its movement velocity and the time gap between both frames. The time between pulses could be set in the Dynamic Studio software. This time gap should be long enough so that movement of particles between images from both frames is visible; however, it cannot be too long in order to avoid errors in vector computing. During the experiment, the time between the pulses was constant and set to 800 $\mu$s. Since the heated wood particle increased their temperature during recording, the pairs of images were taken in series of 50 with 10 Hz frequency for a given particle temperature in order to obtain both statistically significant amount of data and as small of a range of changing temperatures as possible.

# 4 Results and discussion

## 4.1 Velocity maps calculated from PIV images

Figures 4 and 5 show maps of mean velocity, which are each calculated from a series of 50 PIV images for a given temperature. The maps were visualized by exporting the numerical data from Dynamic Studio and creating color fields of velocity vectors and contours using ParaView software. The particle image was exported from the PIV picture and placed in the same spot in the color map. The vector lengths are scaled to the scalar value of velocity at a given point.

Figure 4 shows a color map of velocity for a cold flow of gas at 18 l/min. The part of the PIV image behind the wood particle (from $y = 63$ mm to $y = 70$ mm) was invisible for the camera as the laser plane could not pass through wood and illuminate particles. Thus, the values of velocity are

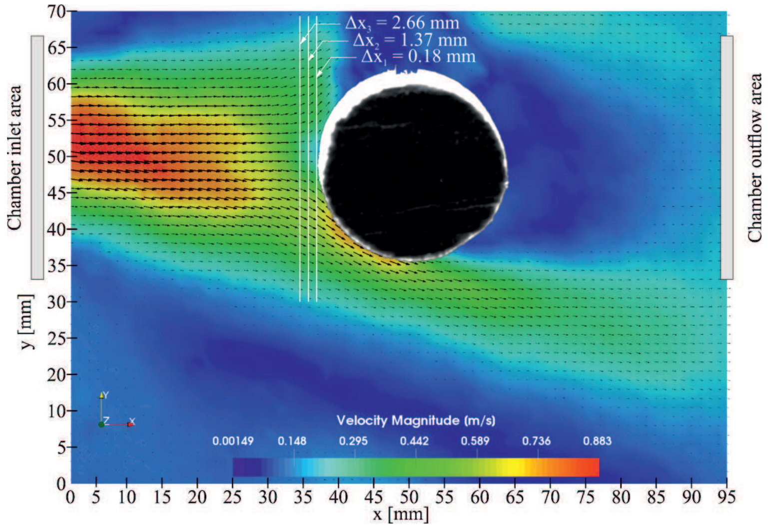

Figure 4: Color map of mean velocity for cold flow.

close to 0 m/s in that area in every map. Areas of inlet and outflow are marked (diameter of inlet and outflow is equal to 34 mm). White lines represent subsequent distances (from the edge of the particle towards inlet) at which the horizontal component of the mean velocity field is shown in Fig. 6.

Figure 5 shows maps of mean velocity for 100, 270 and 320 °C respectively. Since the area of the inlet is not important from the pyrolytic point of view, it was removed from maps for high temperature flows; thus, the $x$-axis begins at 20 mm. During pyrolysis, gases are released from the inside of particle in all directions, and they form a gas cushion, which significantly modifies the velocity field. This fact can be observed in the form of the areas of low velocity (cushion) around the particle. The released gases block the hot stream flowing around particle in its closest distance.

Moreover, at higher temperatures, pyrolytic gases significantly contribute to the mean velocity in the areas closer to the outflow from the chamber. This phenomenon is represented as the areas of high velocity (around 0.7 m/s) in the range of the $x$-axis from 62 mm to 95 mm in every picture are more intense for higher temperatures.

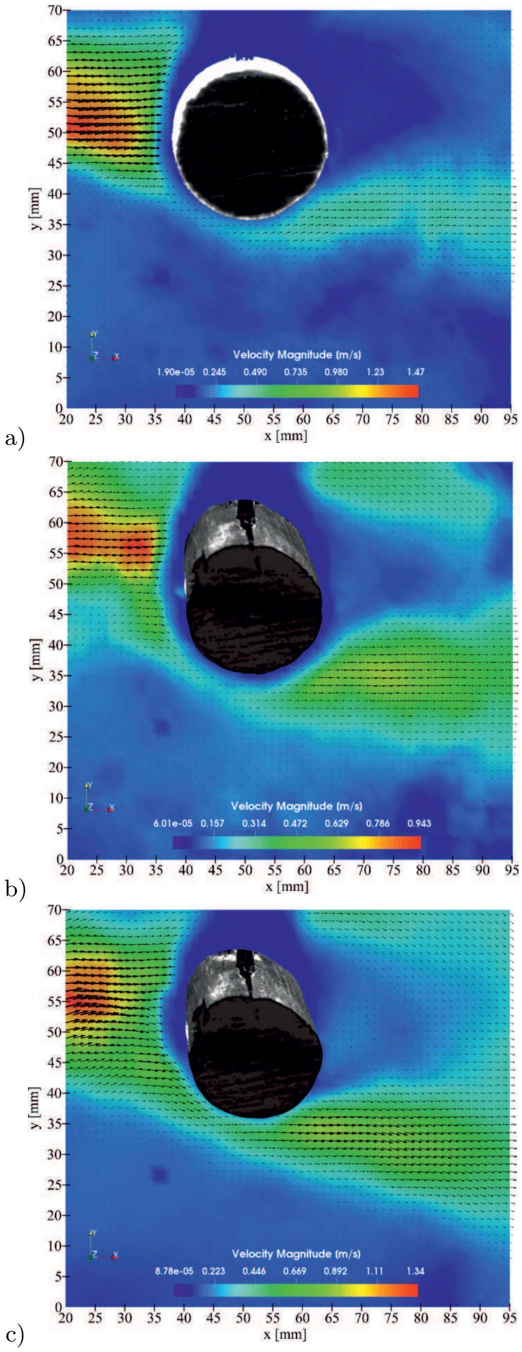

Figure 5: Mean velocity fields during the flow of gas at various temperatures a) 100 °C, b) 270 °C, c) 320 °C.

## 4.2 Profile of gas velocity in the vicinity of wood particle

Figure 6 presents the distribution of the horizontal component of the mean velocity of the gas flowing towards the particle during pyrolysis at 25 °C, 100 °C, 210 °C, 270 °C, 320 °C, 370 °C, and 400 °C. The results show that for a distance of $\Delta x_3 = 2.66$ mm from the wood particle at $y = 50$ mm, the increase of particle temperature from 25 °C to 100 °C and then to 270 °C results in a slowdown in the gas velocity from 0.35 to 0.15 m/s. This is related to the creation of the gas cushion, which is caused by evaporation of moisture followed by degassing of volatiles from the wood. The increase of velocity at higher temperatures indicates the completion of the pyrolysis process.

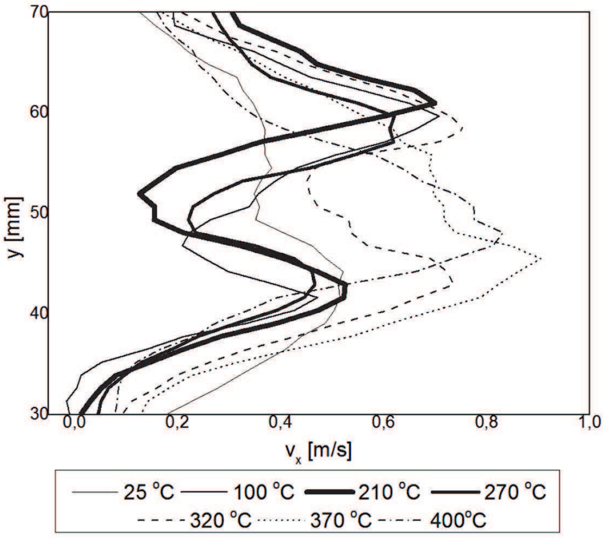

Figure 6: Velocity distribution $v_x$ in the distance $\Delta x_3 = 2.66$ mm from the fuel particle.

Figure 7 present the distribution of the horizontal component of the mean velocity, $v_x$, as a function of temperature, $T$, and distance $\Delta x$ from the wood particle (at $y = 50$ mm). The gas velocity at $\Delta x_3 = 2.66$ mm is 0.26 m/s at 100 °C and 0.22 m/s at 270 °C, while at $\Delta x_1 = 0.18$ mm, these values are 0.005 m/s and 0.03 m/s, respectively, which indicates a small thickness of the gas cushion.

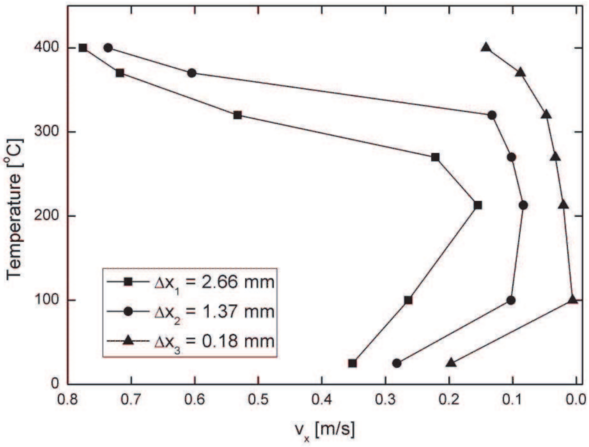

Figure 7: Velocity distribution, $v_x$, as a function of temperature, $T$, and distance, $\Delta x$, from the wood particle at $y = 50$ mm.

## 5 Conclusions

The main objective of this work was to present the characteristics of a single wood particle pyrolysis using particle image velocimetry. However, since PIV provides only 2D data on the velocity field and it is characterized by some uncertainties caused by using relatively heavy seeding particles, the results are mainly qualitative. Nevertheless, the results are novel and allow us to observe some interesting phenomena. The thickness of the gas cushion, which results from the velocity distribution in the vicinity of wood particle, can be considered as a measure of intensity of mass loss, including moisture evaporation and degassing of volatiles. The largest thickness of the cushion is present in the backflow point, which is located in the axis of gas flow (also the axis of gas inlet, $y = 50$ mm) and reached 0.18 mm. The obtained results indicated that evaporation of moisture has as a major impact on the formation of the gas cushion as devolatilization. Moreover, the higher pyrolysis temperature increases the intensity of degassing and increases the thickness of the gas cushion.

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