

## Experimental Investigation of Flash Pyrolysis Oil Droplet Combustion

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The aim of this work is to investigate and compare the combustion behaviour of a single droplet of pyrolysis oil derived from wheat straw and heavy fossil oil in a single droplet combustion chamber. The initial oil droplet diameters were in between 500  $\mu\text{m}$  to 2500  $\mu\text{m}$ . The experiments were performed at a temperature ranging between 1000 and 1400°C with an initial gas velocity of 1.6 m/s and oxygen concentration of 3%. The evolution of combustion of bio-oil droplets was recorded by a digital video camera. It was observed that the combustion behaviour of pyrolysis oil droplet differ from the heavy oil in terms both of ignition, devolatilisation and char oxidation. The pyrolysis oil is more difficult to ignite and has a shorter devolatilisation time and a longer char oxidation time.

### 1. Introduction

At present, the utilization of pyrolysis oil especially for power production is still under development and need further study for the standardization and quality improvement. However, pyrolysis oil can substitute fuel oil or diesel in many static applications including boilers, furnaces, engines and turbines for electricity generation. Many researchers performed combustion tests using different scale boilers (Solantausta et al., 1995), internal combustion engines (Solantausta et al., 1994) and gas turbine injectors and systems (Lopez and Monfort, 2000). They demonstrated that the pyrolysis oil could be burnt efficiently in standard or modified equipments..

Garcia and co-workers (2006) investigated single pyrolysis oil droplet combustion in an entrained flow reactor (EFR) using initial droplet diameters between 58 and 62  $\mu\text{m}$  at a furnace wall temperature of 700°C and 800°C. The EFR was operated in an inert atmosphere using Ar for evaporation studies, whereas mixtures of Ar-O<sub>2</sub> were used for combustion studies applying O<sub>2</sub> concentrations between 20 and 50 vol. %. The pyrolysis oils were blended with 50 vol. % of methanol in order to allow the formation of small droplets made by a Piezoelectric droplet generator (N° 36). No swelling phenomenon was observed for the pyrolysis oil combustion in EFR experiment for droplet diameters between 58 and 62  $\mu\text{m}$ . On the other hand, Liu and co-workers (2011) observed the occurrence of swelling of the oil sludge for droplet diameters bigger than 10  $\mu\text{m}$  in a lab-scale bubbling fluidized bed reactor.

The effects of char content and simple additives of methanol and water, on the pyrolysis oil droplet combustion have also been studied by Shaddix and Tennison (1998). The tests were performed by using an EFR with droplet diameters of 390  $\mu\text{m}$  for a poplar oil mixture, and 440  $\mu\text{m}$  for an Ensyn oil, at a reactor temperature of 1327°C and O<sub>2</sub> concentrations between 14 and 33 vol. %. They observed that microexplosions occurred earlier for the sample oil with high char content (Ensyn oil) and they suggested that the char particles facilitated nucleation of vapour bubbles leading to microexplosions at lower

superheat values. Besides, the addition of water and methanol to the pyrolysis oils results in the shortest burnout time as compared to the pure pyrolysis oils.

Recently, Calabria and co-workers (2007) investigated the combustion of pyrolysis oil in a fibre-suspended droplets reactor using pure bio-oil from forest residue, provided by VTT and also an emulsion (30 wt. % of bio-oil + 70 wt. % of diesel oil) diesel oil was used for comparison. The size of droplets was varied between 400  $\mu\text{m}$  and 1200  $\mu\text{m}$  and the combustion history was recorded by high speed digital shadowgraphy. They found that both pyrolysis oil and emulsion droplets experienced swelling during combustion. The behaviour of emulsions is intermediate with respect to the pure pyrolysis oil and the commercial diesel oil.

The objective of this paper is to report the experimental study on combustion of single droplets of pyrolysis oils derived from wheat straw. The combustion of the heavy fossil fuel oil is also discussed for comparison. In this study, the suspended droplet technique has been preferred because of its advantages that the droplet is stationary and easily observed. The imaging was performed by means of fast video recording. The behaviour of such droplet was investigated starting from the moment when the droplet was placed into the tube reactor (stationary), evaporated and burnt until the carbon burns out completely. The combustion stages in a single droplet combustion reactor were evaluated by measuring the time of completing of each stage: the ignition, devolatilisation and char oxidation stages

## 2. Methodology

Pyrolysis oil generated from flash pyrolysis of wheat straw was used. Wheat straw was pyrolyzed at a reactor temperature of 525°C with an oil yield of 49 wt. % (on dry-ash free basis). Also heavy fuel oil # 77 supplied by A/S Dansk Shell was used. Wheat straw pyrolysis oil and heavy fuel oil were further analyzed and shown in Table 1.

*Table 1: The physico-chemical properties of wheat straw pyrolysis oil and heavy fuel oil.*

<i>Properties</i>	<i>Units</i>	<i>Wheat straw oil</i>	<i>Heavy oil</i>
Water content	wt. %	17.8	< 0.1
pH		3.20	-
Ash	wt. %	1.6	< 0.03
Density (20 °C)	$\text{g/cm}^3$	1.1999	0.9882
Dynamic viscosity	cP		
At 20 °C		91.4	-
At 40 °C		27.4	-
At 80 °C		-	67.2
Heating value (wet basis)	MJ/kg	16.4	40.9
Elemental analysis	%, db		
C		50.2	85.0
H		6.2	11.0
O		43.6	1.0

### 2.1 Flash pyrolysis oil production

In this study, the pyrolysis oil generated from flash pyrolysis of wheat straw was used. Pyrolysis experiments were carried out in a bench scale Pyrolysis Centrifuge Reactor (PCR) as shown in Figure 1 (Bech et al., 2009). The PCR facility consists of a screw type feeder, reactor, condenser, coalescer and char separator. The principle of the process is to apply tangentially feeding of solid biomass particles into the horizontally tubular reactor at a flow rate of 20 - 23 g/min and with an approximately gas reactor residence time of 0.3-0.5 s, and an initial solids heating rate of approximately 250-1000 K/s. The centrifugal force created by the rotation of a three blade rotor keeps the particles sliding on the heated wall while passing through the reactor.

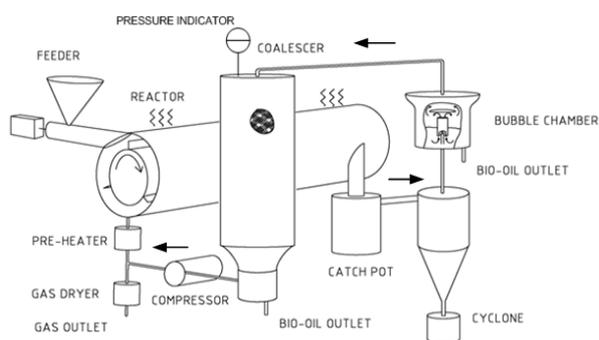


Figure 1: Schematic diagram of pyrolysis centrifuge reactor (PCR).

The solid particles pyrolyzed while moving down the reactor pipe and leave suspended in the gas through the tangential outlet. Larger char particles were removed by a change-in-flow separator whereas fines were collected by a cyclone. Vapours were condensed in a direct water cooled condenser (bubble chamber) filled with previously produced pyrolysis oil. Aerosols that were not retained by the condenser were collected in a coalescer filled with rockwool.

## 2.2 Single droplet combustion facility

The combustion properties of the pyrolysis oil were studied on a single droplet combustion facility. The set up consists of a Bunsen burner and a ceramic tube reactor that has been installed in an airtight box, and a gas control panel. The airtight box was used to hold the burner and the burner head was located just above the box lid. The ceramic tube was placed on the top of the burner and the tube has 4 holes which were used for oil sample insertion, and to view the combustion progress using a video camera. Propane was used to supply the heat. The flow in the reactor was controlled by a gas panel using five rotameters. In order to operate this set-up, the pyrolysis oil sample was placed on a sample holder made of a thin platinum wire by using syringe, and the sample holder then inserts the oil droplet into the centre of the ceramic tube placed inside the furnace. The initial oil droplet diameters were in between  $500\ \mu\text{m}$  to  $2500\ \mu\text{m}$ . The experiments were performed at a temperature ranging between  $1000$  and  $1400^\circ\text{C}$  with an initial gas velocity of  $1.6\ \text{m/s}$  and oxygen concentration of  $3\%$ . The experiments were repeated four to five times at the single operation conditions. A schematic diagram with dimensions of the burner and the ceramic tube reactor is shown in Figure 2.



Airtight box

Gas control panel

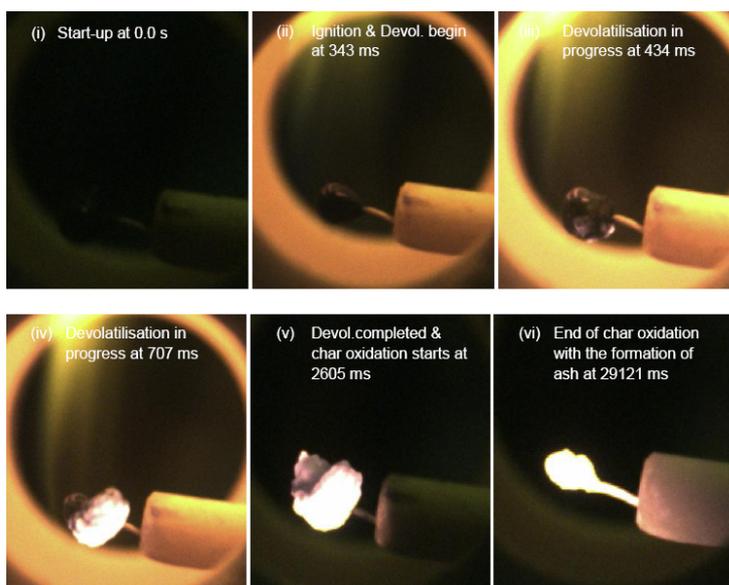
Figure 2: A schematic diagram of single droplet combustion set-up.

### 3. Results and Discussion

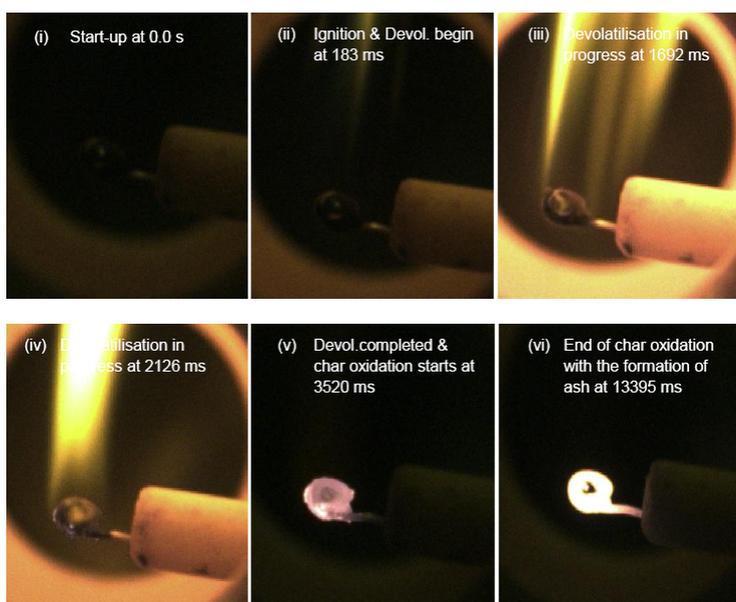
In this study, the evolution of combustion of wheat straw pyrolysis oil droplets was recorded by using a digital video camera. The initial oil droplet diameter is assumed to be spherical. It is observed that the oil droplet undergoes three main stages when it is exposed to the hot flowing gas stream which are heating and ignition, devolatilisation, and char combustion, respectively. The combustion of the oil droplets begins with an enveloping blue flame. The flame then turns to a yellow tail and finally disappears. After the flame extinction, the remaining char particle oxidizes and forms ash residues.

It should be noted that in this study, the heating and ignition time is defined as the time from the insertion of the pyrolysis oil sample into the tube reactor until the first blue flame is visible. The devolatilization time is defined as the time from the first blue flame is seen until the last flame disappears. The char combustion time is the time from the last flame disappears until the droplet diameter diminished and the char stops glowing, and forms an ash residue.

Figures 3a (i-vi) show a sequence of video images from the combustion of wheat straw pyrolysis oil droplet size of 1500  $\mu\text{m}$  at a temperature of 1000°C. An initial gas velocity of 1.6 m/s and 3% of oxygen concentration were maintained in the furnace system. The first stage, which is heating up to ignition (Figure 3a (i)), followed by the evaporation and the combustion of volatiles (Figures 3a (ii-iv)). During the evaporation and gas combustion, it was observed that the pyrolysis oil droplet was surrounded by yellow flame, showing the flame of the vapours/hydrocarbons from the droplet (Dufaud et al., 2012). Finally, as all volatiles are released, the conversion of the char starts (Figure 3a (v)) and the ash is then formed (Figure 3a (vi)). For comparison, the droplet combustions history of heavy fuel oil was recorded and shown in Figures 3b (i-vi). The experimental conditions were similar as for the wheat straw pyrolysis oil. Compared to the heavy fuel oil droplet, the ignition time of the wheat straw oil is longer. The heating and ignition time for the wheat straw oil is about 343 ms which is longer than the heavy fuel oil, 183 ms (see Figure 3a (ii) and Figure 3b (ii)). The longer ignition time of the straw oil is caused by the higher water and oxygen content of the straw pyrolysis oil (Shihadeh and Hochgreb, 2000). Figures 3a (ii-iv) and Figures 3b (ii-iv) also show the devolatilisation process for both wheat straw oil and heavy fuel oil. The devolatilisation is defined to start when ignition were seen. During the devolatilisation stage, it is observed that as the time increases, the wheat straw oil started to show bubbling and disruption, and swelling to about twice of its original diameter (Figures 3a (iii-iv)). However, this phenomenon does not occur to the heavy fossil oil droplets (Figures 3b (iii-iv)). The bubbling and swelling event could be due to the internal evaporation of lighter species such as water vapour, alcohols, and acids. The depletion of these lighter species enriches the droplets in heavier compounds, which occurs especially on the droplet surface as internally lighter species are trapped. As a result, the vaporization of the light compounds inside the droplets generates pockets of vapours that swell the droplets. This process finally produces larger particles, which are usually 2 to 3 times of the original diameter and have larger internal cavities and thin walls. Pine wood pyrolysis oil droplet combustion reported by D'Alessio et al. (1998) using smaller droplet (600  $\mu\text{m}$ ) and a furnace temperature of 1200°C showed a growing of the droplets up to 1.5-2 times of the initial diameter. This swelling phenomenon has also been observed by the other researcher (Calabria et al., 2007). However this phenomenon is not experienced during the devolatilisation stage of heavy fossil fuel oil droplets (see Figures 3b (iii-iv)). The diameter of the heavy oil droplet remains constant until the char combustion takes place. A similar observation was also reported by D'Alessio et al. (1998). Figure 3a (v) and Figure 3b (v) show the char combustion that takes place after the devolatilisation stage for the wheat straw and the heavy oil droplets, respectively. It can be seen that the flame is disappeared, showing that the devolatilisation is completed and char is started to oxidize. The char combustion of the wheat straw oil droplet begins earlier at around 2.6 s, whereas the heavy oil droplet char combustion started later at 3.5 s.



(a) Wheat straw pyrolysis oil



(b) Heavy fuel oil

Figure 3: Sequence images of combustion of the (a) wheat straw bio-oil droplet, (b) heavy fuel oil. (Experimental conditions - Initial droplet size: 1500  $\mu\text{m}$ ; Reactor temperature: 1000  $^{\circ}\text{C}$ ;  $\text{O}_2$  concentration: 3% and Gas velocity: 1.6 m/s).

#### 4. Conclusions

This study investigated the combustion of single droplets of wheat straw pyrolysis oil in a single droplet combustion chamber and compared with the combustion of heavy fossil fuel oil. The droplet combustion history was recorded and the time taken for each stage was measured. It was observed that the burning of pyrolysis oil droplet experienced large swelling up to 2-3 times of the initial droplet diameter. The growing of the pyrolysis oil droplet diameter during the devolatilisation stage is due to the swelling of the droplet as shown in Figures 3a (ii-iii). This phenomenon is more pronounced as temperature increases. However, the burning of heavy fuel oil droplet showed no swelling. The droplet combustion test with a diameter of 1500

$\mu\text{m}$  shows that heavy fuel oil had longer devolatilisation time and shorter char combustion time as compared to the biomass-derived bio-oils. The shorter devolatilisation time of the biomass-derived bio-oil is due to a higher content of light components in the pyrolysis oil, which is easily vaporized at a lower temperature. In addition, the shorter combustion time of the heavy fuel oil is due to the lower char content. At 1000°C, the droplet burning lifetimes for the wheat straw oil and heavy fuel oil are approximately 29 s and 13 s, respectively. In summary, biomass-derived bio-oil is difficult to ignite, has a shorter devolatilisation time and a longer char combustion time.

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