Combustion Characteristics of Pyrolytic Oil Droplet from Sewage Sludge

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1. Introduction

Sewage sludge is the major urban waste generated from the wastewater treatment process and is also a kind of waste biomass. The traditional ways of disposing sewage sludge can be classified in three categories: agricultural use, incineration, and landfill. However, these methods have several shortcomings. Nowadays, with the increase of the sewage treatment rate, the sludge volume rapidly increases and alternative methods of sludge management are highly demanded. Thermochemical processes such as wet oxidation, pyrolysis or gasification have been studied and suggested as potential alternatives [1]. The main goal of thermochemical processes is to produce energy from the organic fraction of the sludge, while affecting the environment as little as possible. The feedstock used for the study is the typical dewatered digested sewage sludge from Anping wastewater treatment plant in Taiwan Tainan city. The pyrolytic oil from sewage sludge is obtained using an electric tubular furnace under the conditions of 450 °C pyrolytic temperature and 60 minutes residence time.

2. Experimental methods

In the analysis, Thermal analysis (PerkinElmer, STA 8000) was utilized to simultaneously carry out TGA (thermogravimetric analysis) and DSC (differential scanning calorimetry) for sludge pyrolytic oil. The temperature range for the thermal analysis was set to 30-1000 °C, with a corresponding heating rate of 10 °C/min. The testing sample was placed in a 145-μL alumina crucible, and the flow rate of nitrogen or air in the environment was set to 50 mL/min. Several combustion characteristic parameters can be deduced from a TG-DTG curve to assess the combustion properties of fuels. This study will make use of the ignition temperature (T_i), burnout temperature (T_e), combustion characteristics index (S), and flammability index (C) to evaluate the combustion characteristics of sludge pyrolysis oil mixed with different percentages of heavy fuel oil. The weight loss curve is used to define the ignition temperature. There are many studies concerning the definition of the ignition temperature using TG-DTG curves [2-4], and the method proposed by Tognotti et al. [2] is widely used to predict the ignition temperature for different fuels. In this method, the weight loss curve of fuel in the air atmosphere is overlapped with that in an inert gas atmosphere (N_2), and the ignition temperature (T_i) corresponds to the first bifurcation point in these two curves. In addition, the burnout temperature (T_e) is defined as the temperature corresponding to 99% conversion of the fuel in the TG curve of air atmosphere.

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Flammability index (C) and Combustion characteristics index (S) are also used for benchmarking the combustibility of fuels [5]. The former could reflect difficulty degree of fuel combustion burning out speed. The greater the flammability index, the better combustion stability of fuel. The latter is used to characterize the combustion characteristics of fuel. The larger the combustion characteristics index, the better the combustion characteristics of fuel. These two combustion indices could be defined as:

$$C = \frac{(dW/d\tau)_{max}}{T_i^2} \tag{1}$$

$$S = \frac{(dW/d\tau)_{max} \cdot (dW/d\tau)_{mean}}{T_i^2 \cdot T_e} \tag{2}$$

where $(dW/d\tau)_{max}$ is the maximum combustion rate, and $(dW/d\tau)_{mean}$ is the mean combustion rate.

The suspended drop method is commonly used in the study of single droplet combustion. The single droplet is suspended in a quartz fiber or a thermocouple, whereby the evaporation or combustion characteristics of the droplet during the heating process can be observed. The experimental setup of a suspended droplet heating system in the study had been used for the pyrolytic oil of castor seed [6] (as shown in Figure 1). The heating device consists of two ceramic heating plates placed in parallel with 9 mm pitch. The length and width of each ceramic plate are both 60 mm. The nickel-chromium alloy heating wires were embedded in the heating plates. Heating plates are connected to a 400 W power supply and the output power is controlled by the microcomputer programmable temperature controller. The experiment was conducted by placing a single oil droplet on the thermocouple which simultaneously measured the temperature of the oil droplet. Another thermocouple was used to control the temperature between the heating plates. Both of the thermocouples used were K-type thermocouples. After a single droplet was suspended on the thermocouple, it would move to the heating plates by a motorized stage. When the thermocouple was in the preset position, the motorized stage would touch the switch, and then simultaneously triggered a high speed camera and temperature signal from DAQ began to record.

3. Results and Discussions

Figure 2(a) shows the TGA burning profiles of sludge pyrolytic oil and heavy fuel oil at a heating rate of 10 °C /min and air flow rate of 50 mL/min. The green curve represents TG (thermogravimetry) data, the blue curve represents DTG (differential thermogravimetry) data, and the red curve represents DSC (differential scanning calorimetry) data. The TG pyrolysis curve for sludge pyrolytic oil with N_2 carrying gas is also shown to identify the ignition temperature. The main reaction always occurs between 300-600 °C in all cases. In addition, the combustion phenomena also inhibit multi-stage reactions since the composition of sludge pyrolytic oil and heavy fuel oil are very complex. From the DTG curve of sludge pyrolytic oil, the first peak at the temperature of 100 °C presents a weight loss of the moisture being evaporated. The other DTG peaks represent the combustion reactions since the DSC curve indicates these reactions are exothermic. After the burning of sludge pyrolytic oils, about 1.16 % of the mass remains as residue.

Figure 2(b) shows the TGA burning profiles of the blends at a heating rate of 10 °C/min and air flow rate of 50 mL/min. As shown in Figure 2 and Figure 3, for the case of pure sludge pyrolytic oil or the blends, the second DTG peak, which represents the combustion of volatile substance, shifts to a lower temperature when compared to the case of pure heavy fuel oil. As can be seen in TGs and DTGs for the blends of sludge pyrolytic oil and heavy fuel oil, there is obvious interaction between blend components. Table 1 shows the combustion characteristic parameters of the blends, sludge pyrolytic oil and heavy fuel oil. Sludge pyrolytic oil has a lower ignition temperature than heavy fuel oil since it has more volatile matter. In addition, the more percentage of sludge pyrolytic oil in the blend will reduce the ignition temperature to more extent. However, the burnout temperature is similar in all these cases. From Table 1, the maximum combustion rate of sludge pyrolytic oil is also higher than that of heavy fuel oil. An interesting finding is that the maximum combustion rate in the blend is even higher than that in the case of pure sludge pyrolytic oil. It really indicates there is an interaction between these blend components. Finally, the flammability index and combustion characteristics index in the blend is higher than that of heavy fuel oil. For the reason of higher volatile content in the sludge pyrolytic oil compared to heavy fuel oil, a certain amount of sludge pyrolytic oil could improve the ignition performance of heavy fuel oil, which is conductive to the stability of heavy fuel oil combustion. The co-combustion of sludge pyrolytic oil and heavy fuel oil has better combustion characteristics than pure heavy fuel oil. It is even better than pure sludge pyrolytic oil in the case of 50 % sludge pyrolytic oil mixed with 50 % heavy fuel oil.

Figure 3 shows the variation of droplet size $(D/D_0)^2$ with time (t/D_0^2) at ambient temperature of 500 ºC for the blends, sludge pyrolytic oil and heavy fuel oil. The initial droplet diameters are all close to 1.1 mm. During the heating process of the droplet, micro-explosion occurs and the droplet diameter gradually reduces to a small size due to the evaporation of moisture and volatile for sludge pyrolytic oil. However, for pure heavy fuel oil, the droplet diameter reveal two swelling period. The first one is due to the evaporation of volatile substance, and the other is due to the expansion of asphaltene content, which is difficult to evaporate. For the blend case, micro-explosion also occurs and the droplet size obviously decreases due to the effect of sludge pyrolytic oil.

Figure 4 shows the heating processes of sludge pyrolytic oil and heavy fuel oil at the ambient temperatures of 600 °C. In both cases, volatile vapor is released and the flammable mixture will form a non-premixed flame wrapping droplets after it is ignited. During the combustion process of the droplet, the droplet still maintains the appearance close to a sphere and the micro-explosion occurs continuously in the case of sludge pyrolytic oil.

Figure 5 shows the variation of droplet size $(D/D_0)^2$ with time (t/D_0^2) at ambient temperature of 600 ºC. In this figure, the vertical dash lines reveal the onset of ignition. Heavy oil has the smallest ignition delay time among these cases. The ignition delay time is influenced by droplet heating and evaporation, molecular diffusion and mixing with air, and subsequent chemical reaction of gas phase between fuel and oxygen. Since the sludge pyrolytic oil contains moisture, prior to the ignition, water evaporated at the beginning of the combustion due to its lower boiling point than the other components, leading to longer ignition delay. The ignition delay time increases with the addition percentage of sludge pyrolytic oil in the heavy fuel oil. In addition, the droplet obviously expands before ignition for heavy fuel oil. However, it does not change much before ignition for sludge pyrolytic oil. The addition of sludge pyrolytic oil in the heavy fuel oil would modify the expansion of droplet before ignition. As to the burning rate, for heavy fuel oil, the variation of droplet size reveals multiple swelling periods and it is not in accordance with d^2-law. Adding 20 % sludge pyrolytic oil in the heavy fuel oil still displays multiple swelling phenomena. In the case of adding 50 % sludge pyrolytic oil and pure sludge pyrolytic oil, the droplet size varies with time in the combustion process and it generally conforms d^2-law. As shown in Figure 5, it can be approximated by a straight line and the burning rate, K is about 1.62 mm^2/s for pure sludge pyrolytic oil and 1.484 mm^2/s for adding 50 % sludge pyrolytic oil in the heavy fuel oil.

4. Conclusions

In the study, the pyrolytic oil of sewage sludge is obtained using thermal pyrolysis. The combustion performance parameters are evaluated from thermogravimetric analysis and the suspended droplet experimental system is also used to explore the combustion characteristics of sludge pyrolytic oil and heavy fuel oil. The following findings are obtained from this study.

1. From the thermogravimetric analysis of sludge pyrolytic oil, the combustion performance parameters such as the ignition temperature, burnout temperature, flammability index and combustion characteristics index are calculated and compared with heavy fuel oil. Sludge pyrolytic oil has lower ignition and better combustion characteristics than heavy fuel oil.
2. With the blends of sludge pyrolytic oil and heavy fuel oil, the maximum combustion rate, the flammability index and combustion characteristics index obviously increase. Sludge pyrolytic oil significantly enhances the combustion of heavy fuel oil, especially in the mixture of 50 % sludge pyrolytic oil and 50 % heavy fuel oil.
3. From the suspended droplet experiment, the ignition delay time increases with the percentage of sludge pyrolytic oil in the blend. At the ambient temperature of 600 ºC, more volatile vapor will be released and the flammable mixture forms a flame wrapping around droplets after ignition in high temperature environments. During the combustion process for the droplet of sludge pyrolytic oil, the micro-explosion occurs continuously, but the droplet still maintains a sphere-like appearance. The fuel combustion characteristics generally follow d^2-law and it can be approximated by a straight line and the constant slope K, which represents the burning rate, is about 1.62 mm^2/s

Table 1. The combustion characteristic parameters of the blends, sludge pyrolytic oil and heavy fuel oil

Fuel	$(\frac{dW}{d\tau})_{max}$	$(\frac{dW}{d\tau})_{mean}$	T_i(ºC)	T_e(ºC)	$S\times 10^7$	$C\times 10^5$
Sludge pyrolytic oil	4.360	1.162	274	605	1.114	5.832
Heavy fuel oil	3.517	1.544	434	612	0.470	1.863
20%SPO+80%HFO	5.003	1.783	311	601	1.531	5.157
50%SPO+50%HFO	5.464	1.562	295	600	1.631	6.257

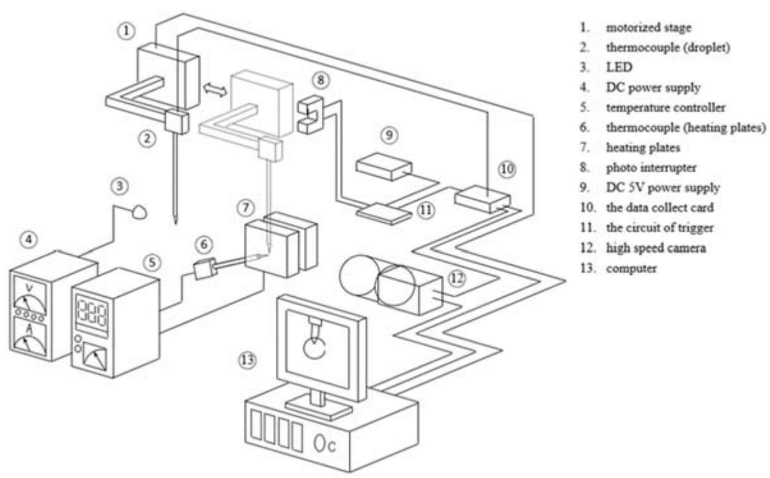

Figure 1. The schematic of the suspended droplet heating system [6]

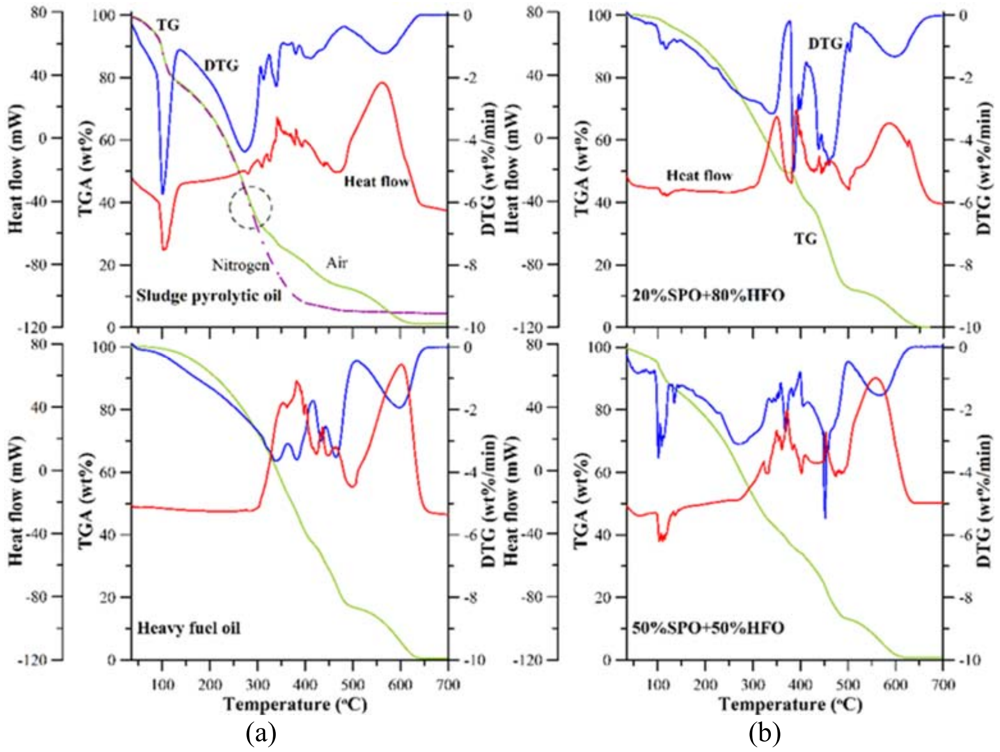

Figure 2. TGA burning profiles of (a) sludge pyrolytic oil and heavy fuel oil (b) the blends at a heating rate of 10 °C/min and air flow rate of 50 mL/min

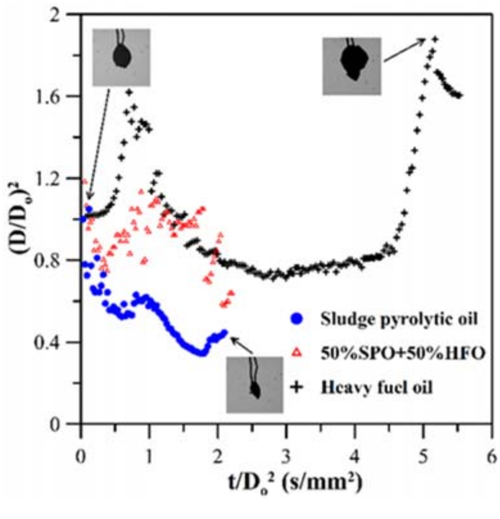

Figure 3. The variation of droplet size (D/D0)2 with time (t/ D02) at ambient temperature of 500 ^oC

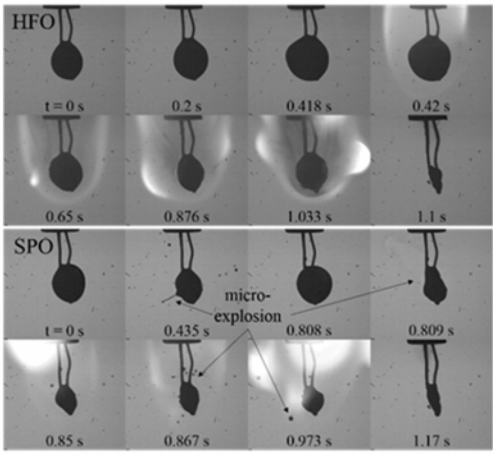

Figure 4. Heating processes of heavy fuel oil and sludge pyrolytic oil at the ambient temperatures of 600 °C

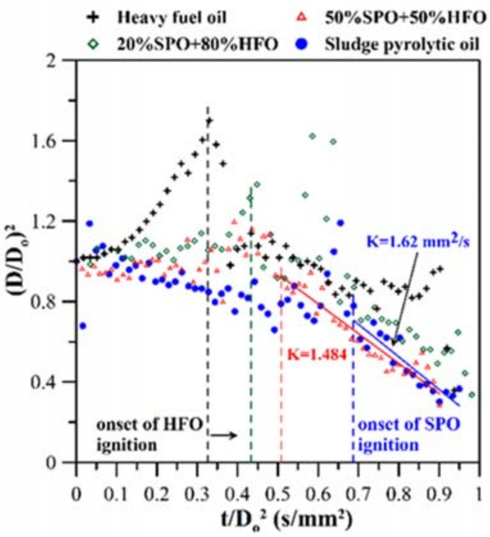

Figure 5. The variation of droplet size $(D/D_0)^2$ with time (t/ D_0^2) at ambient temperature of 600 °C

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