

Combustion Stages of a Single Heavy Oil Droplet in Microgravity

M. Ikegami, G. Xu, K. Ikeda, S. Honma, H. Nagaishi,
D. L. Dietrich*, P. M. Struk*, and Y. Takeshita**

National Institute of Advanced Industrial Sci. and Tech. (AIST), Sapporo 062-8517, Japan

*NASA John H. Glenn Research Center, Cleveland, OH 44135, USA

**Japan Space Utilization Promotion Center, Tokyo 169-8624, Japan

INTRODUCTION

Heavy oil is a common fuel for industrial furnaces, boilers, marines and diesel engines. Previous studies showed that the combustion of heavy oil involves not only the complete burning of volatile matters but also the burn-out of coke residues [1-3]. Detailed knowledge about heavy oil combustion therefore requires an understanding of the different burning stages of heavy oil droplets in the burner. This in turn, demands knowledge about the single droplet evaporation and combustion characteristics.

This study measured the temperature and size histories of heavy oil (C glass) droplets burning in microgravity to elucidate the various stages that occur during combustion. The elimination of the gravity-induced gas convection in microgravity allows the droplet combustion to be studied in greater detail. Noting that the compositions of heavy oil are various, we also tested the fuel blends of a diesel light oil (LO) and a heavy oil residue (HOR).

EXPERIMENTAL

The microgravity facility used was the drop shaft of Japan Microgravity Center (JAMIC) which can generate microgravity conditions better than $10^{-5} g_0$ ($g_0=9.81 \text{ mm/s}^2$) with a duration of 10 sec. Figure 1 shows a schematic of the experimental apparatus. Thermocouples made of platinum (Pt) and platinum-rhodium (Pt-Rh, 13 wt.% Rh) wires with diameters of 0.1 and 0.025 mm, respectively supported the droplets and also measured the temperature inside the droplet. The thermocouple was mounted on a metal arm that both rotated and translated up-and-down under the controls of two DC motors. Image data were taken using two orthogonally located video cameras that connected to two Hi 8 mm VCRs. One view was backlit to image the droplet and the other was a direct image of the flame. The backlight view provided a measure of the droplet size. The video images of both the views gave a framing rate of 30-Hz.

The test began with the formation of an oil droplet at about 1.0 min before microgravity started (dropping the capsule). To form a droplet, the thermocouple arm first rotated to a position

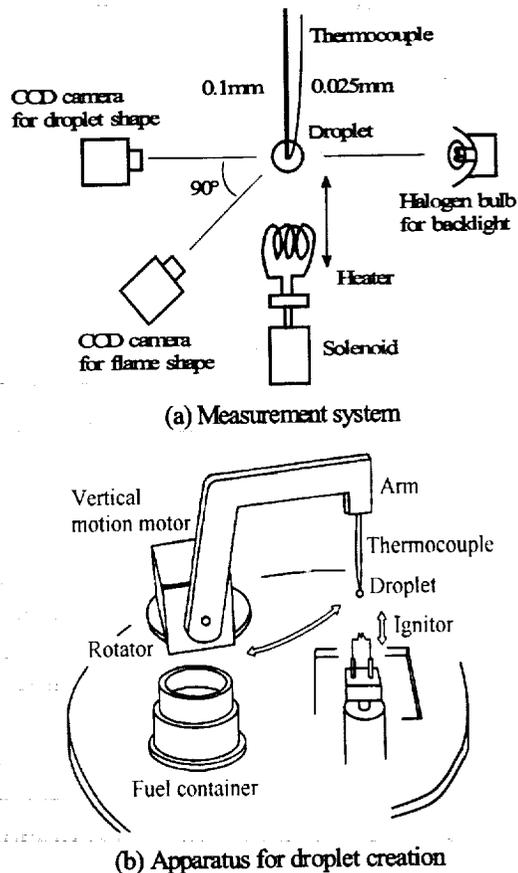


Fig. 1 Experimental apparatus

above a fuel container, and then moved down to immerse the thermocouple into the fuel reservoir. The arm and thermocouple then moved up, causing a fuel droplet to form on the thermocouple bead by the fuel viscosity. The arm finally rotated back to a position above the igniter and to have the droplet ready for burning. The record of the thermocouple data started at the onset of microgravity. One second later the igniter moved just beneath the droplet (1–2 mm) and turned on for a preset period of time, typically 1.6 sec. The actual time, however, varied slightly from test to test to ensure that the igniter withdrew shortly after ignition.

The stated droplet size in this report is an equivalent droplet size given as the cube root of the product of the droplet radius squared and the droplet length, $d = (\text{radius})^{2/3} \times (\text{length})^{1/3}$. While the heavy oil (C class) used was bought commercially, the heavy oil residue (HOR) was made by fractionating the heavy oil at a fractional temperature of 563 K and a pressure of 35 mmHg. Three HOR-LO blends were tested. They were made by mixing the resultant HOR and a commercial diesel light oil (LO) at LO weight fractions of 45%, 35% and 17%.

RESULTS AND DISCUSSION

The combustion of the heavy oil droplets involves significant sooting, droplet swellings and contractions, and disruptive burning behavior, all of which were obvious from the video data. Figure 2 compares the droplet temperature and size histories of heavy oil (2a) and HOR (2b), showing clearly the following vaporization and combustion stages.

1. Pre-ignition heating and start-up Before ignition (event A), there is a pre-ignition stage where fuel vaporizes from the droplet surface, forming a vapor cloud surrounding the droplet. Figure 2 shows that the ignition of the HOR droplet occurred at a higher droplet temperature and at a later time (longer ignition delay time).

After ignition, a rapid increase in droplet temperature was obvious for both the fuels until event B in Fig. 2a and event D in Fig. 2b (events B and C did not occur for HOR). This increase of temperature was related to the lower droplet temperature at ignition and the enforced heating by the flame encircling the droplet. It in fact made the whole droplet reach high temperatures rapidly, and was essentially a start-up of the succeeding burning stage.

2. Inner evaporation For the heavy oil droplet in Fig. 2a, the start-up stage ended with the onset of inner fuel evaporation stage. This stage (event B) corresponds to a plateau in the droplet temperature history. We denote this plateau temperature as the evaporation temperature, T_e . After event B, the rate of temperature increase is much slower, as most of the energy transported

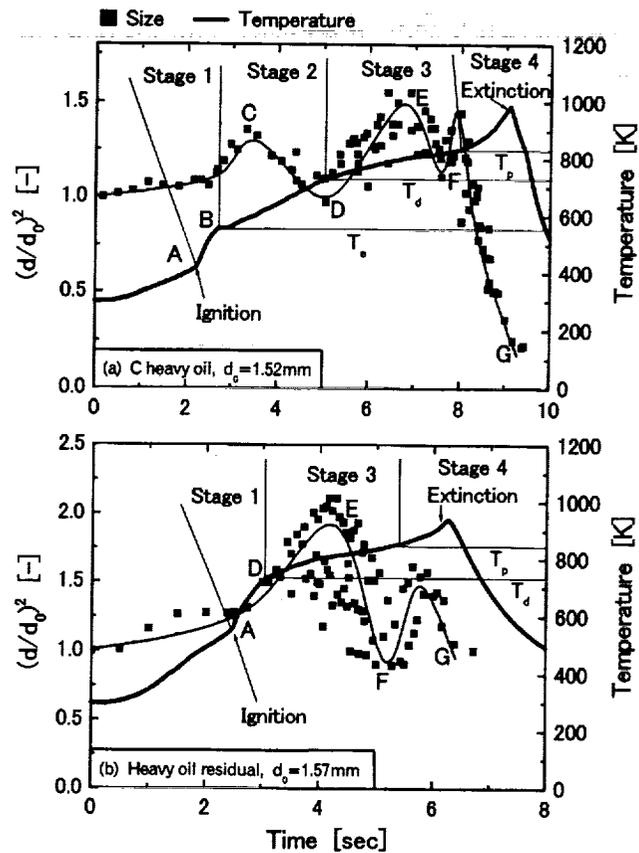


Fig. 2 Temperature and size histories for heavy oil and HOR droplets

from the flame to the droplet goes to vaporizing the fuel. The temperature increases as the higher volatility constituents begin to vaporize [2].

Rapid vapor generation within the droplet (probably at many positions) occurred during this stage. Those vapors near the droplet surface might escape from the droplet with only mild disruptions to the droplet and flame, causing the splashing phenomenon that occurred early in the stage. The other vapors that formed deep in the interior of the droplet could not reach the droplet surface. They tended to nucleate, combine and swell the droplet. Fig. 2a shows this as the increase in droplet size from events B to C. The droplet swelling ended at a sudden droplet contraction, usually as a microexplosion, at event C. After event C, the evaporation rate decreases with time, as a result of the depletion of most volatile species between events B and C. In response to this, Fig. 2a shows a decrease in droplet size and an increase in droplet temperature from events C to D. The burning then involved less splashing but more explosive behavior.

Figure 2a shows that the stage starts at approximately 560 K and ends at a temperature around 700 K. Baert [4] explained that the weakest chemical bonds in heavy oil do not begin to break below 625 K, and thermal cracking is not important until the temperature is over 700 K. Therefore, we can be reasonably certain that the stage between events B and D corresponds to vaporization of the light fuel components rather than thermal decomposition of the fuel. Therefore, one would not expect an HOR droplet to have an inner evaporation stage. Figure 2b shows that this is in fact the case. The figure, however, shows a start-up stage between events B and D for the HOR droplet where the droplet temperature increases rapidly. The fuel vaporized in the HOR droplet is certainly heavier than the lighter species of heavy oil. Thus, the droplet temperatures in Fig. 2b are higher than the corresponding temperatures in Fig. 2a during the start-up stage.

3. Thermal decomposition After the volatile components vaporize from the droplet, the remaining fuel begins an endothermic decomposition. At the beginning of this stage there is another plateau or an inflection point in the droplet temperature history, denoted by event D. In Fig. 2a, the onset of the decomposition stage is coincident with a local minimum in the droplet size history. This indicator is not present in Fig. 2b since such a decrease in droplet size is due to the inner vaporization of volatile constituents. The large energy required for thermal decomposition causes the inflection or plateau in the droplet temperature history, and also decreases the rate at which the droplet temperature increases. We identified the decomposition temperature, T_d , as the droplet temperature at this plateau or inflection. Figure 2 shows that this temperature is nearly the same for the heavy oil (2a) and HOR (2b) droplets, and is approximately equal to 740 K [4].

The thermal decomposition produced volatile gases, which made the droplet swell again. Figure 2 (a and b) shows this as an increase in the mean droplet size. The thermal decomposition stage can be further sub-divided into two periods. The fuel constituents that easily decompose produce volatile gases during the first period, between events D and E, and cause the gradual increase in droplet size. At event E, the droplet size reached a maximum, which corresponds to the most violent frothing of the droplet. Then, the production of the volatile gases decreases, as the more stable components begin to decompose. This leads the droplet to shrink gradually between events E and F. In comparison with the inner evaporation stage, microexplosions in the thermal decomposition stage were more intensive and frequent.

4. Polymerization After the thermal decomposition stage (event F), the rate of the droplet

temperature rise, the first derivative of droplet temperature with time, started to increase with time. The corresponding video images indicate that the droplet entered the last period of swellings and contractions, with each contraction resulting in a rough droplet surface. The droplet then began to look like a soft bituminous coal particle [4] until a coke particle formed at flame extinction. Therefore, the beginning of the polymerization stage is when the rate of droplet temperature rise begins to increase with time. The primary reason for the increase in the droplet temperature rise rate is that the droplet temperature is no longer controlled by the vaporization of fuel. The droplet temperature at event F is defined as the polymerization temperature, T_p . Figure 2 shows that this temperature is nearly identical for the heavy oil and HOR droplets, and equal to approximately 840 K.

Thermal decomposition takes place simultaneously with polymerization in this stage. The thermal decomposition produces radicals that are stable for further decomposition but active for re-combination. The volatile gases produced in the fuel decomposition continued to make the droplet swell and contract, resulting in the final parabolic size area in the droplet size history. Due to the rapid reactions of polymerization [1, 2], this area was much narrower than earlier ones for the other stages. In addition, Fig. 2 shows, as expected, that the final coke particle was much larger for HOR (2b) than for heavy oil (2a).

5. Mixture effects Figure 3 compares the droplet temperature histories for three different HOR-LO mixtures, with the LO mass fractions ranging from 0.17 to 0.45. The qualitative characteristics of temperature variation is obviously similar to that of the heavy oil droplets in Figs 2a. That is, the different burning stages can be separated by the three characteristic temperatures, T_e , T_d , and T_p . Further, Fig. 3 shows that T_d and T_p were almost independent of fuel composition, while T_e obviously decreased with increasing LO mass fraction. Also, the lower the initial LO mass fraction, the greater the rate of temperature increase during the start-up stage. The ignition delay time and the temperature at ignition decreased monotonically with the increase in the initial LO mass fraction. Finally, Fig. 3 identifies that the oil blends with higher initial LO mass fractions have longer inner evaporation stages but shorter thermal decomposition and polymerization stages. Conversely, the droplets with higher initial HOR mass fractions show longer thermal decomposition and polymerization stages.

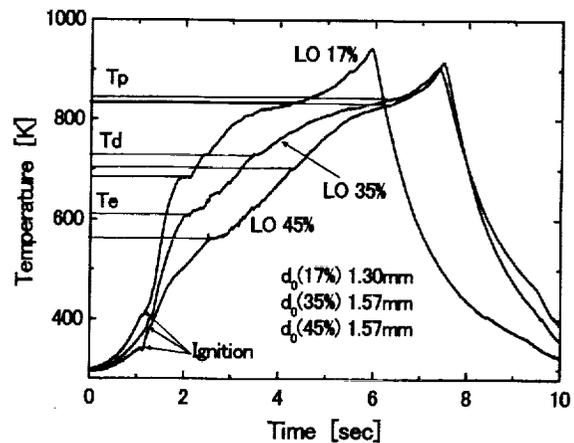


Fig.3 Droplet Temperature histories for different HOR-LO blends

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