Evaporation of Suspended Heavy Oil/1-Pentanol Droplets in Flame-like Conditions

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Abstract

In this work high temperature evaporation characteristics of isolated, suspended, ≈500 µm size droplets of heavy fuel oil/1-pentanol blends are experimentally studied. Flame-like ambient conditions are reproduced by developing a new suspended droplet facility such that the influence of major external effects is minimum.

Body

Alternative, difficult-to-burn (DTB) liquid fuels like residual, pyrolysis, waste, and slurry oils are under active consideration for sustainable future energy solutions. Unlike conventional fuels, they undergo complex evaporation and combustion characteristics such as bubbling, micro-explosions, etc. Their behaviors can be drastically improved by blending with lighter, more volatile bio-alcohols. Hence, in the present work, blends of heavy fuel oil (HFO) with 1-pentanol are chosen since HFO can be considered as a representative of various DTB liquids while 1-pentanol is gaining much interest today as a volatile blending fuel due to its excellent miscibility [1, 2]. Accordingly, five HFO/1-pentanol mixtures are prepared: HFO100, HFO95-P5, HFO75-P25, HFO50-P50 and P100, with 1-pentanol contents in the mixture of 0%, 5%, 25%, 50% and 100% (weight basis), respectively. An average droplet size of 500 µm is targeted for all blends with 10 experiments performed in each group.

The exhaustive review given in [3] shows that the suspended droplet configuration has been widely adopted for vaporization studies with DTB liquid fuels due to its simplicity. However, not many studies have been reported for flame-like high temperature conditions (>1000K). Therefore, to address this gap, a suspended droplet facility (SDF) has been developed whose schematic is shown in Figure 1. Major components of SDF include McKenna flat flame burner, droplet holder assembly with traverse mechanism, air shield and extraction fan. The droplet holder assembly supports a cross-fiber arrangement of two 15 µm Nicalon™-SiC fibers where a droplet is deployed using suitable means and, later, positioned coaxially below the burner in a uniform high temperature environment. The droplets evaporate in a nearly stagnant condition, with gas velocity <0.1 m/s and Reynolds number ~0.5 for a 500 µm droplet. In cold conditions, the temperature at droplet location is 325 ± 1 K, which rises quickly to 1336 ± 50 K when the test starts. During the test, the full temporal evolution of the droplet is acquired using two optical setups (details in Figure 1). In every test sequence, the necessary components and the optical setups are synchronized using Arduino Mega 2560 through a MATLAB® based interface. For the present study, only evaporation tests are conducted with 0% O_2 in the hot co-flow. Therefore, only the droplet imaging setup is used to capture the strong backlighted images which are post-processed with inbuilt MATLAB® library functions to obtain the droplet diameter.

The repeatability and reliability of the experiments as well as the careful control of droplet ambient conditions at the developed SDF are characterized by conducting calibration tests with P100. P100 being a single component fuel, at steady state evaporates close to its 1D, canonical case, known as d^2-law: the square of the droplet diameter (d) decreases linearly with time (t), with a quasi-steady evaporation rate $k = -\frac{d(d^2)}{dt}$. These regression curves are visualized by plotting normalized d^2-t curves: d^2/d_0^2 vs. t/d_0^2, where d_0 is the droplet diameter at $t = 0$. The results of P100 obtained from sets of 10 repeated tests show a notably small dispersion, with relative standard deviations (RSD) of 4.11% for d_0 and 1.10% for k. These experimental curves are also compared with simulation results using the models given in [4]. The results show good agreement between predicted and experimentally-derived k, with differences ~10% without any significant departure in the d^2-t trends. This indicates that at SDF the droplet evaporates quite close to the canonical case with minimum influence of external effects.

Figure 2 shows the experimentally obtained evaporation behavior of HFO/1-pentanol blends in terms of normalized d^2-t curves and a typical temporal evolution of the HFO75-P25 droplet. It is observed that these blends, unlike P100, evaporate in two main regimes, viz., initial heat up and fluctuating evaporating phase [2]. During the initial heat up phase, while the droplet undergoes thermal swelling, the presence of very high gas temperature (>>pyrolysis limit of 673 K) causes thermal cracking at the droplet boundary, resulting into thickening oil membrane [5]. With 1-pentanol rich mixtures, this initial heat up time decreases, and it transits into the fluctuating evaporation phase with a sharp swelling. In this phase, the droplet undergoes multiple events of weak/strong micro-explosions. An increase in 1-pentanol content imposes a major shift in the intensity and frequency of micro-explosions in HFO100. This also leads to a monotonic decrease in the total evaporation time, which reduces by 8.1% and 25% for HFO75-P25 and HFO50-P50, respectively when compared to HFO100. Moreover, the effect of micro-explosions is understood clearly by classifying the micro-explosions based on their intensity [3]. The results show that the puffing regime peaks at intermediate blend ratios whereas the occurrence of weak micro-explosions is stochastic. By contrast, the frequency of strong micro-explosions increases with 1-pentanol content, becoming almost four times in HFO50-P50 as compared to HFO100. Such effects are desirable for improving the combustion characteristics of DTBs. Further, as evaporation proceeds and just before the non-volatilized heavy components condenses into cenospheres [5], the unescaped volatile vapors cause rapid expansion of this shell (final peak just before the end of evaporation). It is seen that blending 1-pentanol with HFO100 reduces this expansion as well as the size (area) of the cenosphere. This reduction in cenosphere size is seen as 13.1% in HFO75-P25 whereas it is highest for HFO50-P50, about 42.6%.

Conclusion

The development of a facility with suspended droplet configuration is presented where it is possible to record evaporation and combustion characteristics (with $0 \leq \%O_2 \leq 21$) of reasonably sized (350–1200 µm), isolated droplets vaporizing at flame-like temperature (1336 ± 50 K) with negligible effects of forced convection and buoyancy. Increased puffing and strong micro-explosions regimes are observed in HFO by blending 1-pentanol, which significantly reduces the total evaporation time as well as the size of residual cenospheres. It is proposed to further investigate HFO/1-pentanol blended droplets for combustion tests with low O_2 conditions as encountered in practical flames.

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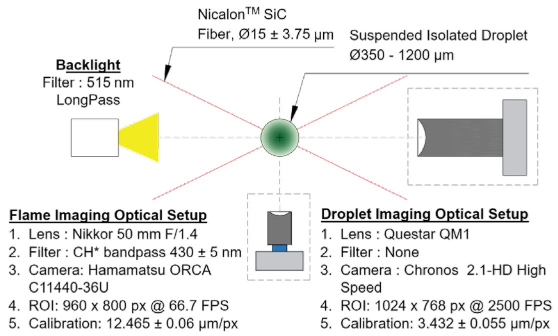

Fig.1 Schematic of the developed SDF

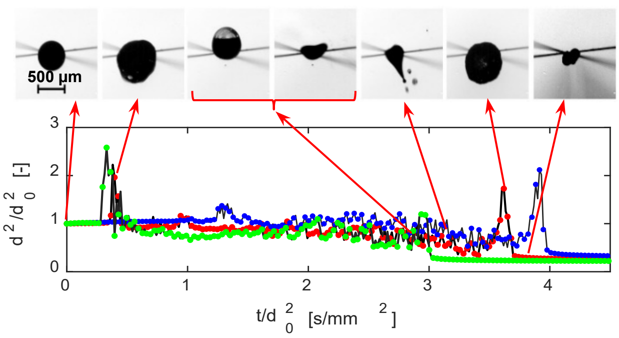

Fig. 2 Normalized droplet evaporation curves of HFO100 (blue), HFO75-P25 (red) and HFO50-P50 (green) and selected frames during the evaporation of a HFO75-P25 droplet (d_0=512 µm)