Study of Single Levitated Fuel Droplet Vaporization Process under Monochromatic Irradiation using IR-Thermography and High speed imaging

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Abstract

Liquid fuels are still the primary power source due to its higher energy density and ease of operation compared to gas fuels. Thus a detailed understanding of the spray vaporization and combustion characteristics for various liquid fuels are very important, down to a single droplet. Owing to difficulties in performing droplet level investigation in an actual spray, the spray models are mostly developed and validated by single pendant droplet experiment. However, the pendant-droplet technique has problems including heat conduction loss through the wire which leads to considerable experimental errors. In order to eliminate the wall-droplet effects, current work uses an acoustic levitator to suspend a single droplet. To understand the importance of the thermo-physical properties of fuel droplet on its vaporization process, a CO₂ laser (irradiating at 10.6 µm with a beam diameter of 2mm) has been used as a radiative heating source in current experimental study. The CO₂ laser is synchronized with an IR camera (FLIR) and a high speed camera (phantom V12). An IR camera is used to measure the droplet surface temperature variation with time, while a high speed phantom camera is used to accurately capture the droplet size variation with time. A number of different liquid droplets are tested, including water, ethanol, kerosene and diesel. A Parametric study has been done on the effect of heating rate, while the initial droplet size was maintained to be 500µm (±30µm). Results show that ethanol vaporizes faster compared to other liquids due to its high vapor pressure. Theory on vaporization shows that the vaporization rate is highly dependent on the vapor pressure. But the temperature of the droplet also plays an important role as the vapor pressure of a fuel changes with the temperature. Total amount of absorbed heating energy can be divided into two parts. The part responsible for phase change depends on the vaporization rate and value of latent heat of vaporization. The remaining part dictates the rate of temperature rise of the droplet. This shows that the vaporization rate and temperature change of the droplets are inter-related and heavily dependent on vapor pressure, latent heat of vaporization and specific heat. We found that at relatively high laser power heating, kerosene and diesel exhibit interesting phenomenon of stretching and shattering due to their small surface tensions.

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1. Introduction

Droplet evaporation is a very common natural phenomenon and has been studied extensively due to its wide applications, such as cloud physics, combustion of liquid fuels, liquid spray cooling, plasma thermal spray process for ceramic coating, ink-jet printing and surface patterning. Droplet vaporization process has been modeled by many research groups particularly for a single droplet [1-7] and vaporizing turbulent sprays [8-9]. Maqua et al. [10] has reported experimental studies of the vaporization characteristics of mono-dispersed fuel droplets in airflow. They experimentally measured the droplet temperature using two-color laser induced fluorescence thermometry. Similar experimental work on mono-dispersed ethanol droplets injected into the thermal boundary layer of a vertical heated plate has been done by Castanet et al [11]. Maqua et al. [12] also reported a computational model of droplet evaporation comprising of two vaporizing species. There have been some numerical studies available in literature on vaporization characteristics and flow dynamics of different bio-fuel blends [9, 13]. However, there are relatively less experimental studies have been reported and most of the existing experimental studies have been mainly focused on the aspect of convective heat transfer effect on the droplet vaporization process, while very few studies have considered combined convective and radiative heat transfer effects. Hence, the primary focus of this paper is to study the radiative heating process of several common fuel droplets, including ethanol, kerosene and diesel, and water is studied to serve as base fluid to compare its different vaporization characteristics compared to those hydrocarbon liquid droplets.

The common technique to study the single droplet evaporation process is by suspending the droplet on the tip of a needle where the capillary force will counteract the droplet gravity. In order to delineate the wall-droplet and droplet-droplet effects, a wall-less containerless environment has been chosen to study droplet vaporization and shaped morphology [14]. The containerless processing technique using levitation of magnetic, non-magnetic materials and live animals have been shown to be effective in counteracting gravity [15, 16]. The drop shape depends on the balance between the curvature-induced stress caused by the surface tension and acoustic radiation pressure on the drop surface [16]. The acoustic pressure on the drop surface is such that the two polar regions contract inwards and the equatorial region expands outwards. However, a small droplet of 500 μm used in this study does not deform into an oblate spheroid due to curvature effect. The experimental data provided within this study is particularly important to serve as validation data for thermal radiation model incorporated in most multi-dimensional computational fluid dynamics (CFD) codes. A detailed review of literature including some mentioned in this section has been compiled in ref [13, 14]

2. Experimental setup

This work uses similar experimental setup described in our earlier works [13-14]. As shown in Figure 1, the experimental set up included an ultrasonic levitator (Tec5 ultrasonic levitator, 100 kHz) to suspend the droplet. The suspended fuel droplet was heated by a CO2 laser irradiating at 10.6 μm with a beam diameter of 2 mm. The power of the laser can be tuned from 0 W (no heating) to 30 W (~10MW/m2) using a controller coupled with a power supply. An IR camera was placed perpendicular to the laser beam to measure the temperature of the droplet. The IR thermography has great advantages of providing contactless and non-intrusive temperature measurement compared to thermo-couple inserted into the droplet. The IR camera (FLIR Silver: calibrated for a range of -5 to 200°C with an accuracy of ± 1°C) was attached to a microscopic zoom (FLIR G3-F/2) lens to facilitate 3X magnification with a working distance of 40 mm. The IR camera was operated at 100 frames per second (fps) and the recorded images were processed by ‘ALTAIR’ software to extract the temperature data of the droplet during the heating process. The integration time of the IR camera depends on the temperature range. Most of the experiments were performed in the temperature range of 20 to 80°C which required an integration time of 1.63 msec. Although the camera is pre-calibrated for a standard emissivity of 1, the emissivity can be easily changed using the ALTAIR software in order obtain more accurate temperature data. For example, the emissivity of distilled water is 0.96, which is well known, while the emissivity of hydrocarbons is generally poorly known but usually assumed to be close to that of water ranging from 0.9 to 1 [17]. Daif et al. [17] showed a good agreement between their numerical model and their IR data when taken the emissivity at the value of 0.95. In our study, we are taking the same value of 0.95 of emissivity for all the hydrocarbon liquids.

A high speed camera (Phantom V12, with maximum speed of 100000 frames per second) along with a zoom lens assembly (Navitar 6000) was used to capture the physical processes occurring within the droplet during laser irradiation. This camera was placed at an angle of 30° to the laser axis as shown in Figure 1. The vaporization process was recorded at 1000-3000 fps. The images from the high speed camera were used to determine the instantaneous diameter of the droplet. To facilitate fine adjustment of the relative position, the IR camera was placed on an X-Y stage while the levitator was attached to an X-Y-Z stage. The high speed camera
was also positioned on a unidirectional stage (X-stage). The laser and the cameras were synchronized using an external delay generator as shown in Figure 1.

The droplets were generated and deployed to the pressure node of the levitator by a micro needle. For every experiment, the initial diameter of the droplet was maintained at 500 μm (±30 μm). The droplet was heated with the laser at different power levels until it becomes very small or it goes out of bound.

After the experiment, the IR and high speed images were analyzed to obtain the temperature and diameter data. The temperature data was obtained by defining a zone of interest around the surface of the droplet in each IR image, and the maximum, minimum, average and standard deviation of the temperature on the droplet surface were calculated. It is important to mention that the droplet sometimes oscillated from side to side with respect to the IR camera axis during experiment which resulted in some out-of-focus images. These out-of-focus images were not considered for further analysis. The high speed images with higher temporal resolution were used to calculate the diameter of the droplet using Matlab. To calculate the instantaneous diameter, an edge around the droplet was defined. An equivalent diameter was calculated from the area under the curve (edge). More details of this experiment can be found in [13] and [14].

3. Results and Discussions

Four different liquids are investigated here and their properties are listed in Table 1. Since the liquid vapor pressure is the most important parameter to influence the droplet vaporization rate, it is plotted as a function of temperature in Figure 2. The vapor pressure of kerosene is approximated by jet-A fuel, while the vapor pressure of ethanol and diesel are provided from reference [13]. The water vapor pressure is calculated by Antoine equation.

\[
\log_{10} p = A - \frac{B}{C + T}
\]  

where \( p \) is the vapor pressure in the unit of mmHg, and \( T \) is the droplet surface temperature in the unit of °C.

**with**

\[
\begin{align*}
A &= 8.07131, B = 1730.63, C = 233.426 & T &\in [1,100°C] \\
A &= 8.14019, B = 1810.94, C = 244.485 & T &\in [100,374°C]
\end{align*}
\]

where A, B, C are constants.

It can be seen that vapor pressure is a monotonically increasing function of temperature for all the fuels. Vapor pressure of ethanol is the highest among the liquids, indicating that ethanol are more volatile in nature.

3.1 The low laser power (0.75 MW/m²) cases

This section analyzes the results obtained with laser heating at a relatively low laser power. The total heating time was set at 24 seconds for all the liquids. A set of high speed and IR images for ethanol droplet is shown in Figures 3a and b for different time instants. Figure 4a and 4b show the droplet diameter reduction and surface temperature rise with time for all the liquids, respectively. Figure 4a shows ethanol droplet diameter reduced to about 100 micron, which is 26% of its initial diameter in 7 seconds. After 7 secs, the droplet became very unstable and ejected out of the levitator. As we can see from Figure 4a, water droplet reduced to 28% of its initial diameter in 16 seconds, while kerosene and diesel droplet reduced to 43% and 80% of its initial diameter in 24 seconds, respectively. Results indicate ethanol is the most volatile fuel, which can be simply explained by its high vapor pressure. Figure 4b shows the synchronized droplet surface temperature data versus time for all liquids, where all of them reach an equilibrium temperature after a period of time during the vaporization process. This equilibrium temperature is often referred as “wet bulb temperature”, by analogy to a psychrometer [3]. This can be explained as follows: When the droplet at room temperature is suddenly exposed into a hot environment, initially the surface temperature of the droplet increases quickly like a cold body suddenly placed into a hot furnace. With sudden increase of the surface temperature, the vapor pressure of the droplet will increase, resulting in an increase of the fuel vapor concentration at the droplet surface, which will in turn speed up the vaporization process. Thus, the total heat consumed by the droplet as latent heat of vaporization will increase due to higher rate of vaporization. This slows down the increase of the droplet surface temperature. At a certain point of time, the heat consumed by the droplet as latent heat will be balanced by the total heat irradiated onto the droplet. Hence the droplet temperature will remain at a constant value which is its wet bulb temperature [3]. Figure 4b shows oscillations of droplet wet bulb temperature for all the liquids, which is caused by the asymmetrical radiation heating on the droplet. As we mentioned in the experimental setup section, the laser source is only located on one side of the droplet, hence the droplet won’t be heated uniformly at one time instant, and there are always certain degrees of non-uniformity of surface temperature. However, as the levitated droplet shows rotation this non-uniformity will equilibrate out. Another reason that causes this non-uniform surface temperature distribution is that the laser beam intensity has a Gaussian distribution.

One interesting observation from Figure 4a is that initially the vaporization rate of kerosene droplet is
These effects can be collected together and described in important non-dimensional parameters, namely Bond number, Weber number and normalized drop shape. The effect of different surface and body forces acting on the levitated droplet and the size of the levitated droplet are captured by a single non-dimensional parameter Acoustic bond number, \( Ba = \frac{\rho \Omega^2}{\rho_s k_0^2} \). \( \rho \) and \( \sigma_s \) are density and surface tension of the liquid sample, \( \rho_0 \) is gravitational acceleration and \( k_0 \) is wave number of the acoustic wave; Another important parameter of levitation under gravity is safety factor, \( \phi_s = 1/\sin(2kz \Delta z) \). \( kz \) is wave number in \( z \) direction, \( \Delta z \) is displacement of the droplet centre from levitator node. Theoretically it can be shown that, with increase in \( \Delta z \), the value of \( \phi_s \) goes up increasing the aspect ratio. For fuels like, kerosene and diesel the surface tension being low, under levitation the aspect ratio becomes larger, resulting in higher displacement from pressure node, thus larger \( \phi_s \). On the other hand, for fuels with low surface tension, acoustic bond number also becomes higher. If the value of \( Ba*\phi_s \) goes beyond a critical value, the droplet goes through rapture and eventually it disintegrates [18]. This is why these fuels exhibit shattering phenomena.

3.2 The high laser power (1.5 MW/m\(^2\)) cases

This section analyzes the results obtained with laser heating at a higher laser power. Figure 5a and 5b show the droplet diameter reduction and surface temperature rise with time for all the liquids, respectively. Figure 5a shows some unusual vaporization behavior of kerosene and diesel droplet. For the initial 0.5 second, the vaporization rate for kerosene and diesel are relatively low compared to ethanol and water droplet, which is reasonable since their vapor pressure are lower. However, after 0.5 second, both kerosene and diesel droplet exhibit a much higher vaporization rate compared to water and ethanol. By closely inspecting the high speed images of kerosene and diesel droplet vaporization process, we discovered that for higher laser powers such as 1.5 MW/m\(^2\) or 2.2 MW/m\(^2\), diesel and kerosene droplets exhibit an interesting phenomenon of stretching and shattering. Figure 6 shows high speed images capturing this shattering process. Both Kerosene and Diesel show continuous shattering of droplets with or without the presence of heating. Primary investigation shows that these fuels have low surface tensions. \( \sigma_{diesel/kerosene}/ \sigma_{water} \) is close to 0.5 where the surface tension of the other liquids are close to 1.

Surface tension plays an important role in determining droplet shape and stability under levitation. Lierke [18] and Lee et al [19] discussed the effect of surface tension on levitated droplet. The effect of different surface and body forces acting on the levitated droplet and the size of the levitated droplet are captured in important non-dimensional parameters, namely Bond number, Weber number and normalized drop shape. These effects can be collected together and described by a single non-dimensional parameter Acoustic bond number, \( Ba = \frac{\rho \Omega^2}{\rho_s k_0^2} \). Another important parameter is safety factor, \( \phi_s = 1/\sin(2kz \Delta z) \). Theoretical analysis shows that these fuels exhibit shattering phenomena.

References


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**Table 1:** Properties of liquids
Figure 1: Experimental setup (adapted from [13], [14])
Figure 2: Vapor pressures of different liquids
Figure 3: a) IR images, b) high speed images of ethanol droplets heated with low laser power (0.75 MW/m²).
Figure 4: a) Diameter reduction and b) temperature evolution with time at low laser power (0.75 MW/m²).
Figure 5: a) Diameter reduction and b) temperature evolution with time at high laser power (1.5 MW/m²).
Figure 6: Morphology evolution of kerosene droplet captured by high-speed imaging (3000 fps)