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Crown formation and atomization in burning multi-component fuel droplets

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ABSTRACT

We report the observation of a crown-like sheet expansion and its subsequent atomization in burning multi-component fuel droplets. The droplets consisting of constituents with significant volatility differential are chosen in this study. Through homogeneous nucleation, the breakup of high-pressure vapor bubble results in the formation of radially expanding crown-like hemispherical sheet. The expansion of liquid sheet and the development of radial ligaments on its destabilized rim results in the creation of several secondary droplets. This pattern of breakup bears a close resemblance to the universally recognized Worthington-Edgerton crown configuration, which forms when a liquid droplet impact on a deep pool/thin film of same liquid or another liquid. Two distinct modes of liquid sheet fragmentation are identified during the experiments: (i) unstable sheet fragmentation and (ii) stable sheet fragmentation. In particular, the breakup characteristics of stable sheet mode is comparable to the commonly observed crown breakup by drop impingements. The modes of sheet breakup are primarily influenced by the proportion of volatile component in the mixture, which in turn dictates the onset of fragmentation and the intensity of breakup.

1. Introduction

Liquid atomization is a key process in a broad range of industrial applications, such as ink-jet printing, spray painting and coating, spray combustors, and irrigation. In particular, efficient liquid fuel atomization plays a vital role in controlling combustion efficiency and exhaust gas emissions in gas turbine and internal combustion engines. One of the widely explored approaches to enhance the liquid atomization is to burn multi-component fuel droplets having components with large volatility differential. A vast difference in volatilities between the components assists the lower boiling point component to vaporize faster, leading to nucleation and growth of vapor bubble near the core of the droplet. The breakup of this trapped vapor bubble inside the parent droplet has the potential to augment liquid atomization [1–4]. Avedisian and Andres [5] were the first to report that the “micro-explosion” phenomenon is associated with the superheating of the emulsified mixtures. Since then, several significant experimental investigations have been performed on the combustion of unsupported emulsion droplets [6–8] as well as on the fiber or thermocouple supported fuel droplets [9–13]. In case of a miscible fuel droplet with relatively large volatility differential, multiple micro-bubbles coalesce to form a sufficiently large vapor bubble, which consequently ruptures into multiple droplet fragments [14–18]. It has been shown that the micro-explosion is initiated through homogeneous nucleation within a droplet consisting of components with large volatility differential [19]. More recently, it has been observed that a droplet with significantly large volatility differential results in an “abrupt explosion” of micro-bubble [20]. In this work, it is revealed for the first time that a high-intensity micro-explosion of a burning multi-component droplet with significantly large difference in boiling points, results in the formation and growth of a hemispherical crown shaped liquid sheet accompanied by the creation of spikes (ligaments) on the crown rim. Interestingly, this breakup configuration is found to be similar to the Worthington-Edgerton crown configuration that originates when a droplet impacts on a solid or liquid surface [21–24]. The mechanism of crown formation and its breakup due to drop impingements have been extensively studied and thoroughly understood [21–31]. Although abrupt fragmentation in multi-component fuels has been reported previously for ethanol/Jet A-1 mixtures, it seems that the impact strength of breakup was not adequate for the formation of crown-like configuration [20]. In case of ethanol/tetradecane mixtures (used in present study), however, the volatility differential is more significant (Table 1). The significant volatility differential between the fuel constituents ensues in a high-intensity explosion, which in turn enables the crown-like configuration to develop. In addition, the blends of ethanol with diesel have the potential to reduce the particulate emissions in gas turbine and compression-ignition engines [32,33]. A brief investigation of the atomization process is undertaken in this work to understand the essential features of the hemispherical crown such as the rim diameter, ligament diameter, and the size of the secondary droplets. Furthermore, an

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Table 1
Properties of tetradecane and ethanol.

Physical properties	Tetradecane[a]	Ethanol[b]
Molecular formula	$C_{14}H_{30}$	C_2H_5OH
Boiling point (°C)	252–254	78.4
Reid vapor pressure (kPa)	< 1	16
Density at 25 °C (kg/m^3)	763	785
Viscosity at 40 °C (mm^2/s)	< 8	1.08
Surface tension at 25 °C (mN/m)	25.5	21.74

[a] Properties of tetradecane are from Ref. [36].

[b] Properties of ethanol are from Refs. [36–39].

attempt has been made to briefly correlate the fundamental physics inherent to the aforementioned crown-like configuration with the existing literature on crown splash.

2. Materials and methods

Ethanol is selected as the higher volatile component while tetradecane (representing diesel) is the lower volatile component in the mixture. Three different proportions of ethanol are considered in this work, i.e., 10% (ED10), 30% (ED30), and 50% (ED50) by volume. Since ethanol forms a partially immiscible mixture with tetradecane at room temperature [34], the fuel components are adequately mixed using an ultra-sonicator before generating the droplets. The size of the dispersed ethanol sub-droplet was found using Malvern Zetasizer (Zen 3600). The mean diameter of ethanol droplets was observed to be similar for all the blends, which is of the order of 1 µm. It is important to note that the upper critical solution temperature (UCST) of ethanol/tetradecane mixture is 34.66 °C [35], which indicates that the fuel mixtures may not be immiscible during the combustion of droplets or before the ignition takes place. Shortly after the mixing, constant volume droplets of 2 µl (1.7 ± 0.1 mm equivalent diameter) are suspended on a quartz fiber (0.2 mm) and are burned in a closed cylindrical chamber.

The suspended fuel droplets are ignited using a 15 V DC supply through a coiled nichrome wire. The combustion process is recorded using a CMOS high-speed camera at a frame rate of 3000 fps and exposure time of 20 µs. The resolution of the camera is maintained at 800 × 600 pixels. A reverse-mounted lens arrangement is applied to capture high-magnification and sharper (enhanced depth of field) images of the droplet breakup phenomena. True color images of the droplet burning sequence are captured using a Digital SLR camera. An in-house MATLAB code [40] was employed to compute the equivalent diameter of the droplet as a function of time. The fiber is used as a reference scale to obtain the scale factor (for pixels to mm conversion). The equivalent diameter of the droplet was determined using the relation, $D = \sqrt{(D_h \times D_v)}$, where D_h and D_v are the major and minor axes of the ellipse (droplet). An image analysis software, Image-Pro Plus (version 6.0) is used to determine the ligament diameter, sheet diameter, and the diameter and velocity of secondary droplets. The experiments are conducted ten times for each blend case, and only the most probable cases (> 80%) are reported. The uncertainty in the measurement of the ejected droplet diameter and ligament diameter following the breakup of parent droplet is ± 2 µm and ± 10 µm respectively. A comprehensive description of the experimental setup and experimental uncertainties are discussed elsewhere [20].

3. Results and discussion

Due to the fact that the boiling temperature of ethanol at ambient pressure (~352 K) is significantly lower than that of tetradecane (~533 K), the ethanol component inside the parent droplet can quickly reach the superheat limit (~477 K), which is still below the normal boiling point of tetradecane. As the temperature of liquid ethanol approaches the superheat limit, nucleation of small micro-bubbles occurs. Since a smaller bubble usually possesses a significantly larger pressure ($P_{\text{int}} - P_{ext} = 2\sigma/R$), its high-intensity breakup leads to complete disintegration of parent droplet. A typical fragmentation event during the combustion of ED30 droplet is shown in Fig. 1, where $\Delta t = 0$ ms represents the onset of droplet breakup. The high-intensity breakup results in the prompt generation of fine secondary droplets, which immediately ignite and evaporate due to the presence of flame

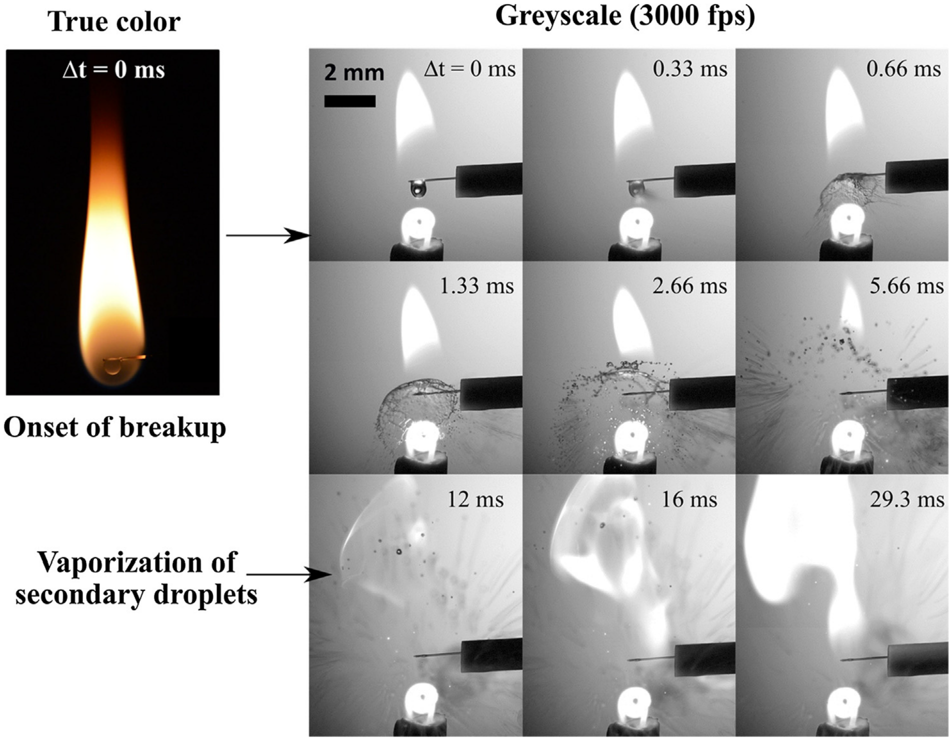

Fig. 1. High-speed flame images of a typical high-intensity explosion event and subsequent rapid vaporization of fragmented secondary droplets.