



Full Length Article

Multicomponent fuel droplet combustion investigation using magnified high speed backlighting and shadowgraph imaging



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ABSTRACT

The liquid-phase processes occurring during fuel droplet combustion are important in deciding the behaviour of the overall combustion process, especially, for the multicomponent fuel droplets. Hence, understanding these processes is essential for explaining the combustion of the multicomponent fuel droplet. However, the very fast combustion of the too small fuel droplet makes experimental investigation of these processes uneasily affordable. In the present work, a high speed backlighting and shadowgraph imaging of the multicomponent fuel droplet combustion including liquid-phase dynamics are performed. Two categories of multicomponent fuels – in which diesel is the base fuel – are prepared and utilized. The first category is biodiesel/diesel and bioethanol/diesel blends, while the second category is the water-in-diesel and diesel-in-water emulsions. Specific optical setups are developed and used for tracking droplet combustion. The first setup is associated with the backlighting imaging with the resulting magnification of the droplet images being 30 times the real size. The second optical setup is used for shadowgraph imaging, with the resulting magnification being 10 times the real size. Using these setups, spatial and temporal tracking of nucleation, bubble generation, internal circulation, puffing, microexplosion, and secondary atomization during the combustion of isolated multicomponent fuel droplets are performed. Spatial and temporal tracking of the sub-droplets generated by secondary atomization, and their subsequent combustion, in addition to their overall lifetimes have also been performed. Accordingly, a comparison of the burning rate constant between the parent droplet and the resulting sub-droplets is carried out. The rate of droplet secondary atomization is higher than those obtained by relatively low imaging rate. Additionally, it is shown that during a large portion of its entire lifetime, the droplet geometry has been affected by combustion significantly.

1. Introduction

A large portion of the global energy requirements comes from burning liquid hydrocarbons. This is due to the ease and flexibility of transporting and storing these fuels compared to the gaseous forms, in addition to their availability compared to the solid fuels. Liquid fuel combustion consists mainly of four processes, namely: atomization and droplet formation, droplet fuel evaporation, combustible mixture formation, and mixture combustion [1]. Atomization and droplet formation is important in combustion, since most of the combustion systems (such as the industrial furnaces and internal combustion engines) work on liquid fuels that cannot be used before being atomized. And it is essential in increasing the combustion efficiency in such systems because of the high liquid surface to mass ratio generated after atomization, which in turn leads to higher rates of evaporation and mixing, and then combustion [2]. Some of these liquid fuels are utilized in the form

of multicomponent fuels or fuel mixtures. This is either for increasing the performance of the combustion system by the addition of higher heating value fuels, or reducing the harmful environmental impact of the conventional fuels, or because of the depletion of the conventional liquid fuel resources. In the multicomponent fuel mixtures, no chemical reaction will occur between the fuel constituents, and each constituent sustains its own physical and chemical properties. Therefore, the combustion of the resulting mixture is more complicated than that of the neat fuel because different components are burning simultaneously at the same point and instant of time. Hence, unlike the single component fuel droplet combustion – in which droplet evaporation is the rate controlling process – the multicomponent fuel droplet combustion encompasses the effect of droplet interior heat and mass transfer [3]. As a result, the multicomponent fuel droplet combustion is much more complicated compared to the single-component droplet combustion. Firstly, the different constituents of the multicomponent fuel have

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different boiling points and different evaporation rates that leads to creating concentration gradients inside the droplet (in the liquid phase). Secondly, due to the boiling point gradient, a difference in volatility tendency is expected. Hence, the more volatile components tend to evaporate first until their concentrations are reduced, changing the concentration gradient inside the droplet. Lastly, the evaporation of the more volatile components reduces their concentrations but does not consume them completely. Thus, the remaining quantities of the highly volatile components tend to diffuse to the droplet surface due to their tendency of evaporation, and the less volatile components will tend to diffuse inward. This in turn, will create an internal circulation in the liquid phase, and will affect the evaporation rate of the droplet because of concentration difference on its surface along its lifetime [4]. Accordingly, droplet combustion of the multicomponent fuels has been and being investigated extensively both theoretically and experimentally for better understanding of the physical and chemical processes associated with this form of droplet combustion [3,5–7]. Besides, different physical processes which are associated with the combustion of multicomponent fuel droplets have been the scope of different studies, such as the puffing and microexplosion leading to droplet secondary atomization. These processes are initiating and occurring in the liquid-phase of the fuel droplet either in the surface or deep within the droplet internals, and are directly affecting the overall droplet combustion behaviour. Droplet microexplosion is defined as the prompt fragmentation of the multicomponent droplet as a result of nucleation and explosive boiling of the less boiling point component(s) [8,9]. If this fragmentation is less intensive and limited to part of the droplet, it is usually called as puffing. Though, Tsue et al. [10] and Watanbe et al., [11], gave a more specific definition for droplet puffing, that is the process of vapour jet liberation from the surface of the multicomponent fuel droplet. This vapour jet is usually filled with finely small sub-droplets of the dispersed phase. The continuous phase may also detaches from the droplet surface in the form of ligaments or small size droplets as a consequence of an intensive puffing incident [12]. This detachment of ligaments and small droplets is called secondary atomization. Therefore, the secondary atomization is defined as the processes of droplet disintegration into smaller size droplets. This disintegration results when the dynamic forces acting on the droplet are higher than the restoration force of the droplet [13]. Puffing and microexplosion are direct results of the nucleation and bubble generation within the multicomponent fuel droplets. The occurrence of these processes during the multicomponent fuel droplet combustion is firstly described by Lasheras and co-workers [14–16] who gave a general name for these processes that is the *disruptive burning* of the multicomponent fuel droplets. The same has been distinguished by Avedisian and co-workers [17–19] for n-heptane based binary fuel mixtures including emulsions. Hoxie, Schoo, and Braden [7], and Botero et al., [6] have also described the occurrence of disruptive burning during the combustion of soybean oil/butanol, and diesel/ethanol/biodiesel blend droplets respectively. Lasheras, Fernandez-Pello, and Dryer [15] studied the disruptive burning of the ethanol/n-paraffin and n-propanol/n-paraffin binary solutions under atmospheric pressure. They found that droplet disruption results from the homogeneous bubble nucleation, expansion, and explosion inside the droplet. The occurrence of nucleation within the burning droplet has been reported by Lasheras et al., [14,15] during the combustion of binary n-paraffin mixtures. They have detected droplet size increase during droplet combustion and attributed it to the bubble formation. Chung and Kim [20] have also attributed the water sub-droplets increase within a water-in-dodecane emulsion droplet evaporating on a hot surface to the formation of water bubbles. They have detected the water sub-droplet increase by comparing droplet microscope images before and after heating. Wang, Liu, and Law [3] have also conceived bubble nucleation inside freely falling, burning, multicomponent fuel droplets, and evaluated the bubble growth rate and the bubble to droplet size ratio. Tsue et al., [21] have imputed the microexplosion occurrence to the formation of water

vapour bubbles inside the burning droplets of n-dodecane-in-water and n-tetradecane-in-water emulsions. Wang et al., [22] have spotted heterogeneous nucleation occurrence as a result of trapped air bubbles inside the collision-merging methanol/alkane droplets. These air bubbles serve as nucleation sites inside the droplet. A more comprehensive theoretical description of the nucleation and bubble formation within emulsion fuel droplets is given by Shinjo et al., [9,23,24]. They have shown that droplet puffing is the result of bubble growth inside the droplet. Bubble burst at the droplet surface has also been described, and the effect of initial locations of the boiling bubble and the dispersed phase sub-droplet on the bubble burst intensity has also been evaluated. In conclusion, a substantial number of studies have been conducted to explain the physics of puffing, secondary atomization, and micro-explosion. As a result, the effects of these processes on the combustion efficiency by enhancing fuel evaporation and fuel/air mixing are well addressed. Additionally, the effect of nucleation and bubble growth in the droplet liquid-phase on the initiation and development of these processes is also established and deduced with respect to droplet size increase. However, except the numerical simulation work performed by Shinjo et al., bubble nucleation initiation, growth, and its subsequent dynamics inside the burning multicomponent fuel droplet has not been well investigated. In particular, magnified experimental investigation of the droplet liquid-phase dedicated for studying bubble nucleation is not available. Hence, further comprehension of the physics of these processes including initiation and development is required. This can be executed by conducting a magnified experimental visualization and tracking of the droplet liquid-phase for obtaining in-depth quantitative and qualitative description of these processes and the corresponding mechanisms. Therefore, the present work is dedicated to fulfil this objective, and in turn, offer experimental description of the aforementioned processes.

2. Experimental work

2.1. The multicomponent fuel preparation

The water-in-diesel (WD) and diesel-in-water (DW) emulsions have been prepared in the lab prior to the combustion experiments. Since emulsions are mixtures of two (or more) insoluble liquids, they are thermodynamically unstable. Consequently, producing a long-lasting emulsion requires a third agent that accumulates at the interface between the two liquids forming the emulsion; this agent is the *emulsifier* (or *surfactant*). The rule of the emulsifier is to form protective, elastic, and relatively strong film layer that can withstand droplet collision and prevent phase separation. However, the type of emulsifier is an essential parameter in defining the type of emulsion. Hydrophilic emulsifiers prompt the formation of oil-in-water emulsions, while water-in-oil emulsions are mostly produced by the use of lipophilic emulsifiers [25]. This is known as *Bancroft's Rule* which states that “the phase in which the surfactant is more soluble is the continuous phase” [26]. This solubility inclination is characterized by the Hydrophile-Lipophile Balance (HLB) number. The HLB number is developed by Griffin as the balance of the size and strength of both the hydrophilic and lipophilic groups within the emulsifier molecules [27]. Hence, each emulsifying agent has its own HLB number which is in the range of 0 to 20, and this number defines whether the emulsifier is oil-soluble ($0 \leq \text{HLB} \leq 9$), water-soluble ($11 \leq \text{HLB} \leq 20$), or hydrophilically-lipophilically balanced ($\text{HLB} = 10$). Accordingly, in the present work two emulsifiers have been selected for emulsion preparation. The first is the Polysorbate 80 ($\text{HLB} = 15$) for making the diesel-in-water emulsions, and the other is the Sorbitan Mono Oleate (also known as Span 80) ($\text{HLB} = 4.3$) for making the water-in-diesel emulsions. The method followed and described by Califano, Calabria, and Massoli [28] and Jackson and Avedisian [18] has been used for preparation. For each of the emulsions, the emulsifier is added to the continuous phase (diesel in the case of water-in-diesel emulsions, and water in the case of diesel-in-water

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