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Impact dynamics of alternative jet fuel drops on heated stainless steel surface

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ABSTRACT

There is an emerging trend of employing bio-derived alternative fuels in automobile and aircraft engines to meet the strict norms of environmental pollution. The present study deals with the impact dynamics of camelina-derived alternative jet fuel drops corresponding to Weber number, We in the range 28–886 on heated flat stainless steel surface at surface temperature, T_s ranging from 25 °C to 350 °C. The entire impact dynamics is captured using a high speed camera and analyzed to deduce the temporal variation of normalised drop contact diameter, β for the drop impact cases at different T_s. The high speed image sequences help to record the morphological behaviour of impacting alternative jet fuel drops on the heated surface at different combination of We and T_s and to arrive at phase diagram highlighting the broad regimes of biofuel drop impact dynamics. For the impact of high We drops, the average normalised spreading velocity increases in film boiling regime whereas it slightly decreases in the cases of un-heated surface, film evaporation, and nucleate boiling. The trend of maximum spread factor, β_{max} with We at different heat transfer regimes is presented. The sensitivity of β_{max} to We depends on the heat transfer regime and is the highest in the film boiling regime. Further the receding dynamics of impacting biofuel drop on the heated surface is significantly influenced by T_s. The observed trends are qualitatively explained through a temperature-dependent apparent contact angle in the available theoretical models as well as the presence of vapor flow and associated fingering at the rim of drop lamella.

1. Introduction

The impact of fuel spray droplets onto heated solid surfaces is encountered in engine combustors [1]. The final outcome of such fuel spray impingement process is governed by a multitude of factors including the characteristics of spray (such as the poly-dispersity of spray, size and velocity of spray droplets, and number flux of spray droplets near the surface); physical properties of liquid (such as density, ρ, surface tension, σ, and dynamic viscosity, μ); surface characteristics (such as surface roughness and chemical nature); temperature of liquid, surface, and ambient; and ambient pressure [2]. Various sub-processes such as droplet-droplet interaction in spray and on surface, temporal evolution of thin liquid film forming on the surface, interaction of spray droplets with this liquid film, secondary droplet formation from the liquid film due to this interaction, and interaction among secondary and primary spray droplets render a fundamental physical understanding of spray impingement process and its outcomes extremely difficult [3–6]. Owing to these complexities, the modellers of spray impingement phenomenon very often rely on the results obtained from single-drop impact studies [2,7,8].

When a liquid drop impacts on a solid surface kept at ambient temperature, it spreads radially outward from the impact point, in the form of a thin lamella bounded by a thick rim on the surface till it reaches a maximum spread, driven by impact velocity and resisted by viscous and surface tension forces. Further, depending on the surface wetting nature (completely/partially wetting, non-wetting), the drop recedes back towards the impact point driven by surface tension and wetting forces and resisted by viscous forces. Subsequent to this, the drop may undergo secondary spreading and receding processes driven by any residual drop inertia and finally settles down to an equilibrium spread by adopting a hemi-spherical cap-like morphology on the solid surface [9]. This outcome is

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referred to as deposition; other possible outcomes include splashing in which secondary droplets are ejected from the impacting liquid drop, and bouncing in which the impacting liquid drop bounces off the surface [10,11]. The parameters governing the dynamics and final outcome of the drop impact process are well-described by Rioboo et al. [9,10].

The outcomes of liquid drop impact on a heated solid surface are significantly influenced by the temperature of solid surface, T_s due to changes in the mechanisms of heat transfer from the solid surface to the liquid drop. Systematic studies [8,12–16] have been reported on the morphological dynamics of impacting liquid drops at different heat transfer regimes: film boiling ($T_s > T_L$), nucleate boiling ($T_b < T_s < T_L$), and film evaporation ($T_\infty \le T_s < T_b$) (T_L is the Leidenfrost point, T_b is the boiling point of drop liquid at ambient pressure, and T_∞ is the ambient temperature). The effect of T_s on the spreading and receding processes of an impacting liquid drop was studied by Chandra and Avedisian [12]. A number of studies on drop impact on heated surfaces aimed at understanding the dependence of critical heat flux, and Leidenfrost point, T_L of the liquid drop on solid surface on surface roughness and drop impact velocity [12,16–20]. Tran et al. [16] and Celata et al. [17], from their experiments on water drop impact on heated surfaces, observed that the Leidenfrost point increases with the increase of impact velocity. Bernardin et al. [18,19], from their experimental studies, concluded that the temperature corresponding to critical heat flux is independent of drop Weber number and surface roughness whereas the Leidenfrost point has a strong dependence on the surface roughness. Studies focusing on film boiling/Leidenfrost phenomenon reported drop contact time, restitution coefficient, and maximum spreading and how they are affected by impact velocity, surface roughness, and thickness of oxidation layer on surface [16,21–23]. Biance et al. [21] reported that the restitution coefficient of the droplet in the film boiling regime decreases with the increase of impact velocity. The droplet contact time with the surface decreases with the increase of impact velocity and with decrease of surface roughness [22] whereas the maximum spread factor increases with the decrease in surface roughness [22] and oxide layer thickness on the surface [23].

The present study analyses the impact of camelina-derived biofuel drops onto a heated surface. Blends of camelina-derived biofuel with the conventional aviation kerosene (Jet A-1) are emerging as alternative jet fuels in aviation industry with an objective to reduce engine emissions [24]. Although the emerging alternative jet fuels are not so different from the conventional jet fuels in terms of their physical properties (ρ, σ, and μ), the complex chemical ingredients involved in such new alternative jet fuels warrant an in-depth analysis on the suitability of such fuel sprays in engine combustors. Being considered as future alternative jet fuel, several studies [25–28] are reported in recent years to elucidate the behaviour of camelina-derived biofuel blends from both fluid dynamics and combustion considerations. The studies pertaining to the impact of model hydrocarbon fuel drops on heated solid surfaces are very limited in current literature. The work of Chandra and Avedisian [12] considered the impact dynamics of n-heptane fuel drops on heated stainless steel surfaces. Chen et al. [29] experimentally studied the impact of diesel drops on inclined heated stainless surface and observed that the resident time is independent of impinging angle and impact velocity. Kompinsky et al. [30] studied the impact of binary fuel drops, comprising a mixture of n-hexane and n-decane having different boiling points, on heated surfaces and observed that some of the heat transfer regimes for a binary fuel drop impact are different from that for a single component fuel drop impact.

In this study, the impact dynamics of camelina-based alternative jet fuel drops with D_o in the range 2.02–2.48 mm and U_o in the range 0.62–3.44 m/s on a heated stainless steel surface was captured using a high speed video imaging system. The temperature of target surface, T_s was varied from 25 °C to 350 °C covering the major heat transfer regimes observed in the drop impact phenomenon. Quantitative measurements on the spreading and receding dynamics of impacting fuel drops were extracted by analysing the high speed video recordings and their dependence on T_s is discussed with the help of analysis of current experimental measurements and predictions from existing theoretical models.

2. Experimental details

2.1. Experimental setup

Fig. 1 shows a schematic sketch of the experimental setup used for the present study. The main components of the experimental set up are: **(i)** liquid drop delivery system, **(ii)** target solid surface and heating system, and **(iii)** video/image acquisition system. Biofuel drops are dispensed from a drop delivery system comprising a micrometer–syringe–needle arrangement as shown in Fig. 1. The syringe filled with the biofuel is connected to the needle on one end through flexible tubes and to a micrometer at the other end (syringe piston). Two flat-tipped hypodermic needles are used to deliver drops of two different average diameters, $D_o = 2.09$ mm and 2.45 mm. The outer and inner diameters (d_o and d_i) of the stainless steel hypodermic needles were 0.45 mm and 0.27 mm (for $D_o = 2.09 \pm 0.04$ mm) and 0.72 mm and 0.41 mm (for $D_o = 2.45 \pm 0.01$ mm), respectively. Single drops of biofuel were formed by forcing it from the syringe through the hypodermic needle and letting them to detach under their own weight. The height of the needle tip from the target surface, H could be adjusted using a vertical traverse system so as to achieve different impact velocities, U_o.

The target surface of size 50 mm × 25 mm × 5 mm is prepared through diamond paste polishing of stainless steel (SS-304). The mean surface roughness, R_a, measured using Wyko NT9080 optical profiler system, of the surface is in the range 0.013–0.040 μm. Static wetting experiment of the biofuel drop on the stainless steel target surface at ambient temperature yielded a static contact angle, $\theta_e = 5.6°$ which is indicative of the high wetting nature of the surface by the biofuel drop [31]. The temperature of the target surface is maintained at a particular value through a heater and controller arrangement. The arrangement comprises of a flat plate heater (Heatcon Sensors, 150 W), a temperature controller unit (Omron EC5WL), and a K-type thermocouple. The target surface is placed on the flat plate heater just in contact. The K-type thermocouple is inserted into the target surface from its side through a hole of diameter 1.5 mm and depth 12 mm positioned at a height of 1.5 mm from the surface to measure the temperature of the target surface, T_s. In a typical drop impact experiment, T_s is set through the controller unit along with a continuous feedback from the thermocouple measurement and the steady state condition of T_s is reached within a short period of time. With this experimental setup, T_s could be maintained within ±1 °C during the experiments of drop impact on the target surface.

The video/image acquisition system comprises of a high speed digital video camera (MotionPro Y4 from IDT or FASTCAM Mini UX100 type 800K-M-16G from Photron), a LED strobe lamp (Panatech Asia), and a computer unit to control the camera operation and to visualize the captured frames. The dynamics of an impacting drop is recorded using the high-speed video camera at a frame rate of 6000 fps with an exposure of 5 μs and a total of 4000 continuous frames are stored in the computer for the analysis. The camera is inclined at an angle of 45° to the plane of target surface to capture the drop impact process on the target surface. The contact