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Experimental investigation of biofuel drop impact on stainless steel surface

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ABSTRACT

Blends of conventional fuels such as Jet-A1 (aviation kerosene) and diesel with bio-derived components, referred to as *biofuels*, are gradually replacing the conventional fuels in aircraft and automobile engines. There is a lack of understanding on the interaction of spray drops of such biofuels with solid surfaces. The present study is an experimental investigation on the impact of biofuel drops onto a smooth stainless steel surface. The biofuel is a mixture of 90% commercially available camelina-derived biofuel and 10% aromatics. Biofuel drops were generated using a syringe–hypodermic needle arrangement. On demand, the needle delivers an almost spherical drop with drop diameter in the range 2.05–2.15 mm. Static wetting experiments show that the biofuel drop completely wets the stainless steel surface and exhibits an equilibrium contact angle of 5.6°. High speed video camera was used to capture the impact dynamics of biofuel drops with Weber number ranging from 20 to 570. The spreading dynamics and maximum spreading diameter of impacting biofuel drops on the target surface were analyzed. For the impact of high Weber number biofuel drops, the spreading law suggests $\beta \sim \tau^{0.5}$ where β is the spread factor and τ, the nondimensionalized time. The experimentally observed trend of maximum spread factor, β_{max} of camelina biofuel drop on the target surface with *We* compares well with the theoretically predicted trend from Ukiwe–Kwok model. After reaching β_{max}, the impacting biofuel drop undergoes a prolonged sluggish spreading due to the high wetting nature of the camelina biofuel-stainless steel system. As a result, the final spread factor is found to be a little more than β_{max}.

1. Introduction

Understanding the mechanisms of fuel spray–wall interaction process is of importance in the design of engine combustors. Often the interaction process results in an increase in unburned hydrocarbons, secondary atomization, wall-film formation, etc. Several single-drop impact studies have been devoted to understand the problem of spray–wall interaction [1–3]. Although any direct use of results arrived at from single-drop impact studies to spray impingement problems poses limitations [4], the studies of single-drop impact still provide valuable tools to the modeling of spray impingement phenomenon [5].

In addition to fuel spray impingement encountered in engine combustors, the single-drop impact on a solid surface has been studied in the context of numerous practical applications such as ink-jet printing [6], droplet-based manufacturing [7,8], and thermal spray coating [9]. On a solid surface, the dynamics of drop impact is primarily governed by the competition between liquid inertia (resulting from the droplet kinetic energy), surface (resulting from the fluid interfaces), and viscous (resulting from the drop-surface interaction) forces. An impacting liquid drop spreads on the surface axisymmetrically during the initial stages of drop impact process. This regime of drop spreading is dominated by the drop inertia. The drop reaches a maximum diameter at the end of inertia dominated spreading and then starts to recede. Often, depending on the characteristics of the solid surface and liquid properties, the drop liquid undergoes a series of post-spreading oscillations and reaches an equilibrium final drop diameter on the surface. Previous studies characterized the drop impact phenomenon in terms of Weber number, *We*, which compares the inertia to the capillary forces, Ohnesorge number, *Oh*, which compares the viscous to the capillary forces, and Reynolds number, *Re*, which compares the inertia to the viscous forces [3,10].

Rioboo et al. [11,12] studied the temporal evolution of drop impact phenomenon by altering several control parameters such as drop impact velocity, drop diameter, liquid viscosity, surface tension, surface wettability and mean surface roughness. The effect of control parameters on the phenomenon is seen mainly in the spreading and receding processes as well as the final outcome of

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Nomenclature

Re	Reynolds number
Oh	Ohnesorge number
We	Weber number
$E_{s,o}$	surface energy of the drop at the tip of needle (J)
$E_{s,i}$	surface energy of the drop just prior to impact (J)
W_d	work done in overcoming resistance due to drag (J)
C_f	drag co-efficient
g	acceleration due to gravity (m/s^2)
k	constant
D_{max}	maximum spreading diameter (mm)
D_o	diameter of the drop before impact (mm)
S	sphericity of the drop before impact
U_o	drop impact velocity (m/s)
d_o	outer diameter of the needle (mm)
H	impact height (mm)
m	mass of the drop (kg)
R_a	mean surface roughness (μm)
t	time elapsed from the start of the drop impact (ms)
t_{max}	time taken to reach the maximum diameter (ms)
t_f	time taken to reach final equilibrium of drop impact-driven processes (ms)
$<dD/dt>_{spr}$	average spreading velocity (m/s)

Greek symbols

ρ	density of biofuel (kg/m^3)
σ	surface tension of biofuel (N/m)
μ	viscosity of biofuel (Pa s)
θ_Y	Young's contact angle of biofuel drop on solid surface
θ_e	equilibrium contact angle of biofuel drop on solid surface
ρ_{air}	density of air (kg/m^3)
γ_{SV}	solid–vapor interfacial tension
γ_{SL}	solid–liquid interfacial tension
α_1	fraction of drop weight taking part in the drop detachment process
β	spread factor
β_{max}	maximum spread factor
β_f	final spread factor
τ	non-dimensionalised time
τ_{max}	non-dimensionalised time to reach the maximum diameter
α	slope of β versus τ in log–log scale
$<d\beta/d\tau>_{spr}$	average normalized spreading velocity

impacting drops. The maximum spreading diameter, D_{max} of an impacting drop increases with the increasing We and Re [13]. Several studies have analyzed the variation of D_{max} with the control parameters theoretically using the energy balance approach [2,14–20]. These models predict D_{max} reasonably well. For low viscosity drop impacts, Clanet et al. [21] found that $D_{max} = D_o We^{0.25}$ with a pre-factor of 0.9. A recent work by Bayer and Megaridis [22] on drop impact on different solid surfaces varying in their surface wettability proposed that $D_{max} = 0.72\ D_o(ReWe^{0.5})^{0.14}$. Ukiwe and Kwok [17] proposed a model for D_{max} by incorporating the solid–liquid and solid–vapor interfacial energies in the surface energy term of the energy balance equation. The predictions of D_{max} obtained from the new model agree very well with the experimental measurements of D_{max} for the impact of moderate to high We water and formamide drops on well-prepared flat polymer surfaces. The effect of surface temperature on drop impact dynamics on heated surfaces, which is of relevance in practical applications such as spray cooling, has been studied by various research groups focusing on various aspects such as morphological dynamics – film boiling, nucleate boiling, and contact boiling – of liquid drop [2,23,24]; Leidenfrost phenomena and its characteristics such as drop contact time [25], restitution coefficient [26], as well as how it is affected by surface roughness, drop impact velocity, surface inclination, and oxidation layer thickness on surface [24,27–29]; and maximum drop spreading [24,25,28]. Numerical simulations of drop impact phenomenon by considering the fluid dynamics of the spreading lamella have been reported in the literature [18,30–35]. The comprehensive reviews of drop impact phenomenon by Rein [36], Yarin [37], and Marengo et al. [38] provide further details associated with the drop impact phenomenon.

The drop impact dynamics of bio-derived fuel drops on solid surfaces at ambient room temperature is the topic of present investigation. Bio-derived alternative fuels, produced from biomass sources such as camelina, jatropha, and algae (referred as synthetic paraffinic kerosene, SPK), can significantly reduce engine-related emissions produced by the aviation industry. The American Society for Testing and Materials (ASTM) has already approved the use of a 50% blend of Jet A-1 (conventional aviation kerosene) and SPK in aircraft engines. Currently, camelina-derived biofuel is being considered as a future alternative fuel for airplanes [39] and several studies have been reported in recent years on the characteristics of camelina-derived biofuel in the context of aircraft engine technology [40–43]. Limited studies have been reported on the impact of hydrocarbon fuel drops [2,44]. It has been observed that the impact dynamics of such fuel drops exhibits no droplet receding owing to the reduced surface tension.

The current development and rapid advancement on the use of bio-derived fuels in the engine combustors necessitates an in-depth analysis of such fuel behavior on several fundamental research topics including spray and drop impact phenomena. The present study investigates the normal impact of bio-derived camelina fuel drops released from a hypodermic needle on a smooth stainless steel surface at ambient room temperature. The impact velocity of drop was varied in the range 0.6–3.0 m/s. Quantitative experimental measurements on the diameter of drop released from the needle, drop spreading characteristics, maximum spreading diameter, and final drop diameter were obtained. The applicability of existing models for the estimation of some of the abovementioned quantities for impact of camelina fuel drops was explored.

2. Experimental details

2.1. Details of drop liquid (camelina biofuel)

As mentioned earlier, camelina biofuel is being considered as an alternative aviation fuel. It is derived using hydroprocessing of camelina seed oil which go through the conventional refinery process to deoxygenate and remove undesirable materials including nitrogen, sulphur and residual metals and break down carbon chain lengths. It was procured from UOP (www.uop.com). Since camelina biofuel is free from any aromatic content, 10% aromatics was added with camelina biofuel obtained from UOP to meet ASTM D1655 aviation fuel specifications. The blending and characterization of fuel was carried out at Indian Oil Corporation Limited (IOCL) and Hindustan Petroleum Corporation Limited (HPCL). The physical properties of fuel such as density, dynamic viscosity, and surface tension are known to influence the dynamics of drop impact