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Experimental investigation on the characteristic of jet break-up for butanol droplet impacting onto a heated surface in the film boiling regime

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ABSTRACT

In view of the importance of atomization, droplet breakup induced by high Weber number and vapor bubble during droplet impacting onto a solid and heated surface has been studied extensively, but the understand on jet break-up phenomenon in the film boiling regime is still lacking. Thus, the work is trying to study the dynamic of jet break-up of n-butanol, a potential alternative biofuel for internal combustion engine, under the influence of Weber number. During experiment, a high-speed camera, set at 512 × 512 pixels, 10,000 fps, and 20 μs exposure time was used to visualize the droplet impacting behavior. The droplet falling height was set from 1 cm to 9 cm with interval of 0.5 cm, with corresponded Weber number around from 6.94 to 102.12. The heated surface temperature was set at 250 °C, to ensure the impact locates at the film-boiling regime. The results show that the jet break-up is dominated by Rayleigh-Plateau instability, the secondary droplet is formed through contraction of symmetric unstable surface waves since the waves are clearly observed on the jet column. Under tested wall conditions, the jet break-up only takes place when the Weber number of butanol droplet is around from 14.34 to 89.13. Within the jet break-up regime, the number of separated droplets first increases then decreases with Weber number increasing, and reaches the maximum at $We = 65$. The length of jet break-up first increases slowly then decreases rapidly and then increases with Weber number. While, the time of jet break-up first decrease then increase with Weber number and also reaches the minimum at $We = 65.20$. In addition, the timing of jet break-up is fitting well with the theory of Rayleigh instability.

1. Introduction

Droplet impacting onto a solid surface, usually hot surface, is observed in numerous applications, such as spray cooling, inkjet printing, plasma spraying, liquid coating, metal forming and fuel injection in internal combustion engine [1,2]. For the direct injection engine, the fuel droplet is easy to impact and attach on the cylinder wall and piston, forming a wall-fuel film, which has been regarded as one of the main reasons that result in super knocking and particle emissions [3–5]. Thus, it has been concerned widely in the internal combustion engine research field [6–9].

As known, the droplet impacting dynamics is a complex multi-scale process which involves heat transfer, mass transfer and phase transition. Usually, it is largely influenced by surface temperature, surface roughness, surface materials, fuel density, surface tension, viscosity, droplet size, and impacting speed, etc. [10–13].

Under the low impact velocity condition, the heated surface temperature is a parameter that dominates the dynamics, and also was typically used to classify the impacting and evaporating phenomenon. In general, according to the droplet's evaporation rate and heat flux after impacting onto a heated surface, the boiling regime is divided into four types from low to high temperature: liquid-film type vaporization regime, nucleation-boiling type vaporization regime, transition-boiling type vaporization regime, and film-boiling type vaporization regime [14]. Specifically, in the liquid-film type vaporization regime the droplet will deposit on the surface. In the nucleation boiling and transition-boiling type regimes, mass of secondary droplets could be formed on the deformed surface during evaporation. Besides, in the film-boiling type regime, a vapor layer is produced rapidly to keep the droplet away from the heated surface, which is well known as Leidenfrost effect.

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At the same time, the role of droplet size and impact velocity are considered in the Weber number. It acts as a key parameter that dominates the impacting dynamic phenomenon. When the *We* number is high enough ($100 \le We \le 3500$), the intense droplet breakup always occurred during impacting no matter locates into what vaporization type regimes [15,16].

Droplet breakup, as a very common phenomenon during droplet impacting onto wall, usually affects its application performance significantly, have drawn extensional studies.

Under the low wall temperature condition, the droplet will splash and rebound several times and finally deposit on the surface if the Weber number is low ($We \approx 5$) [17]. When the Weber number increases to a higher level, the deforming droplet as a torus would occurred and dominated by Rayleigh instability. If the instability leads to torus breakup before the torus reaches its maximum diameter, splashing will occur. If not, the torus will be contracted to its center and rebounding occurs. In addition, there are many impact models like fingering, finger break-up, prompt splash, corona splash, which are all affected by the impact energy [18]. When the crown splashing occurs, the droplet first transforms into a crown and the crown then disintegrates to produce much smaller secondary droplets [19]. Recently, Tang et al. [20] found that some secondary droplets were ejected from the periphery of the contact line.

When the surface temperature is higher than the liquid saturation temperature the secondary atomization is not generated through the so called "crown splash" or the other possible outcomes for impact onto cold surfaces, but from the vapor bubble formation and break-up at the liquid–air interface of the spreading lamella [21]. In fact, decades ago, Wachters and Westerling [22] and Naber and Farrell [23] had found the phenomenon. They indicated that when the wall temperature was below the Nukiyama temperature, even under low Weber numbers there exist a strong contraction of the lamella after spreading, and with the production of secondary droplets. As reported, a high heat transfer can take place during the impact of liquid droplet on thin liquid film if the vapor bubble is growing [24,25]. It has been applied widely in spray cooling industry [26].

In the regime that the wall temperature is above the Leidenfrost point, central jet with intense breakup, is formed under a relative high Weber number impacting condition. Cossali et al. [27] noted that a central jet was formed for a water drop at *We* of 247 in the film boiling regime, and regarded that the secondary atomization produced by the impact of a liquid drop on heated walls was only due to thermal (boiling) effects. Later, they then stated that central jet characteristics depends slightly on surface roughness but strongly on wall temperature and impact velocity [28]. Liang et al. [29] stated that the central liquid jet for NaCl solution drop could be formed under lower roughness surface. They regarded that the central jet forming is related to the bubble entrainment at the impact point during droplet impacting while the NaCl contained in the solution is able to intensify the bubble nucleating violently due to the effect of the dissolved NaCl. Since the breakup phenomenon is complicated, they classified the phenomenon near the Leidenfrost point into three types: reflection rebound, explosive rebound, explosive detachment, respectively. Generally, for wall temperature larger than Leidenfrost temperature in the film boiling regime, the secondary drop characterized by a lower number and larger size than that under lower wall temperature condition, larger than saturation temperature but lower than Leidenfrost temperature [27].

Based on the literature review, it is found that the droplet breakup for drop impacting onto both heated and unheated surface under high Weber number conditions is focused and studied widely. However, there is another droplet breakup phenomenon in the film boiling regime, named jet break-up here, usually occur at relative low Weber number conditions, has not received enough attention. In this case, the droplet spread and rebound after the droplet impacting onto a heated surface, but the droplet rebound to form a column and break up into one or more secondary droplets. It should be noted that not all rebound is able to developed into breakup. Biance et al. [30] reported that when $We \ll 1$ a droplet may bounce hundreds of times, and always coming back to the same height. In addition, droplet with low Weber number usually spread laterally then recoil and bounce off the heated wall several times, finally fall by gravity onto the heated wall [10]. Wachters and Westerling [31,32] reported a disintegration phenomenon during recoiling and riding process, which was jet break-up, but only occurred when the Weber number between 30 and 80. Wang et al. [33] also mentioned a dry satellite rebounding impact patterns, which was similar with the jet break-up, when they studied the dry rebound critical temperature for ethanol. Similar phenomenon also has been found in the process of droplet impacting on the superhydrophobic plate, so called "Worthington jet". Adrianus et al. [34] reported that for an unheated superhydrophobic carbon nanotube arrays plate, the jet break could occur when Weber number was between 11 and 106. They found that the secondary droplet formed by a Worthington jet were significantly larger than those formed by the aforementioned micro-jet, and the intensity of breakup increased with the increase of Weber number. However, detailed information about jet break-up on the heated surface has not been reported yet.

In this case, this study introduced a type of phenomenon happening in the process of rebound which was similar to the phenomenon of jet break-up. High speed camera was used to record the phenomenon. Three parameters, respectively, the number of separated droplets, the length of jet break-up, the time of jet break-up, were used to describe and analyze this phenomenon.

2. Experimental setup

2.1. Experimental system

The schematic diagram of the present experimental setup is shown in Fig. 1. The apparatus consists of a high-speed camera, a plate with heater, a lighting system, a droplet generator and a computer. A syringe driven by an injection pump was used to produce droplet. In order to produce droplet as desired, an injection pump was set to moving at the rate of 0.03 mm per second.

A high-speed camera, Phantom V7.3, was used to record the dynamic process of individual droplet impacting onto the heated surface. Due to the short shooting time of the high-speed camera, a trigger consists of slotted photoelectric switch, photoelectric switch detector and delay control system, was installed at a distance of 1 cm below the syringe needle in order to synchronize the camera. When the droplet passed through the trigger, a step signal generated from the photoelectric switch would be detected by the photoelectric switch detector and be sent to the delay control system to control the camera's trigger timing.

The heated surface, with the size of 150 mm × 100 mm, was made from polished aluminum substrate. The thermostat heater, whose maximum heating temperature was 450 °C, had a built-in ceramic heating plate to ensure uniform heating. The temperature was controlled by a PID system. The temperature error of each point on the hot surface under constant temperature condition was within 1 °C. In order to control the error, a K-type contact thermometer was used to measure the temperature to keep the surface temperature at 250 °C. In addition, after several droplet impact, the local surface temperature will decrease a little. In this case, the impacting frequency should not be too high, and after every five times of droplet impact, the surface temperature will be monitored