Droplet Impact on a Superheated Concave Surface Having a Curvature Ratio of Unity

B. S. Renjith, K. Niju Mohammed, and Ranjith S. Kumar

1 Introduction

Droplets striking solid surfaces is a crucial event in many contexts, particularly during processes like ink-jet printing, fuel injection, spray cooling, etc. [2, 4, 8, 10] [19]. Single droplet impact on solid objects maintained at various temperatures is an important phenomenon in various industrial applications such as nuclear reactor cooling, quenching, fuel injection on to the combustion chamber walls [3, 18]. In heat transfer problems effective surface contact between the drop and heated surface plays an important role. When surface temperature equals to the Leiden frost temperature, the rate of heat transfer will be minimum. This is as a result of the extremely thin layer that developed between the drop and the surface [5, 15].

In order to explain the spreading properties and duration of contact with the surfaces, the single droplet impact method is frequently utilized [10]. The two main non-dimensional characteristics that are utilized to illustrate the underlying theory of the problem are the Weber number We and the maximum spread factor β. The maximum spread factor (β) is the ratio of maximum spread diameter with initial diameter (d_0), $\beta = d_{\max}/d_0$. The weber number $\text{We} = \rho\, V_d^2 d_0/\sigma$ denotes the ratio of inertia force to surface tension force, where ρ is the density, V_d is the droplet velocity, d_0 is the initial diameter of the drop. Another parameter which is very significant is the residence time ($\tau_r^* \sim \sqrt{\rho d_0^3/\sigma}$) [14, 16].

The effect of droplet impingement on heated symmetrical surfaces like flat [1] and spherical surfaces [7, 9] has been investigated in the past. However, the impact dynamics of droplets on superheated asymmetric semi-cylindrical surface is still

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need to be explored. The present work involves in study of dynamics of droplets on semi-cylindrical concave superheated surface with cylinder-drop curvature ratio of unity. The ratio of droplet diameter to curvature diameter is known as the curvature ratio, $\delta = d_0/D_s$.

2 Methodology

This section explains the details about the experimental set-up and droplet impact procedure. The major components of the experiment's set-up include a high-speed camera, a droplet dispensing system, a temperature controller, a test surface, a back-light for illumination, and a computer linked to the camera for image storage and processing. Figure 1 provides a schematic illustration of the experimental set-up. For the investigation, a semi-circular concave surface with a curvature diameter of 2 mm is cut from a pure aluminium block using wire-cut EDM. Deionized water (DI) is taken as the test liquid. The whole experiment is conducted at room temperature, Tf = 27 ± 2 °C. The properties of DI water are taken as, density (ρ) = 0.998 g/cm^3, surface tension (σ) = 0.0720 Nm^{-1}, Absolute viscosity (μ) = 1.005 mPa.s. To create droplets, a drop dispensing system is employed in which the fluid's properties and needle diameter determine the drop's size. The photographs were taken with a Hi-spec2 high-speed camera from Fastec Imaging (USA) using a Tamron 90 mm f/2.8 macro lens. At a shutter speed of 146 µs and 4500 frames per second, the high-speed camera records images with a resolution of 176 × 276 pixels. Within a temperature range of 250 and 450 °C, the experiment is carried out. For both concave and flat surfaces, the impact dynamics are recorded in the azimuthal direction. The curvature diameter of concave surface here is 2 mm, and the drop diameter also adjusted to 2 mm by suitable needle so that the curvature ratio becomes unity. The schematic diagram of droplet spreading over a concave surface with a 2 mm curvature diameter is shown in Fig. 2.

The analysis of images is done with software ImageJ 11.53e.

3 Results and Discussion

3.1 Dynamics of Droplet Contact on Superheated Flat and Concave Surfaces

The chosen temperature range is between 250 and 450 °C. Every test is conducted at a temperature higher than the static Leiden frost temperature, ($T_L = 170^0$ C) [12, 17]. Figure 3a–f depicts the droplet morphology with respect to time following impact on a concave surface with a curvature ratio of ($\delta = 1$) at $T_s = 250$ °C and We = 16 in an azimuthal orientation.

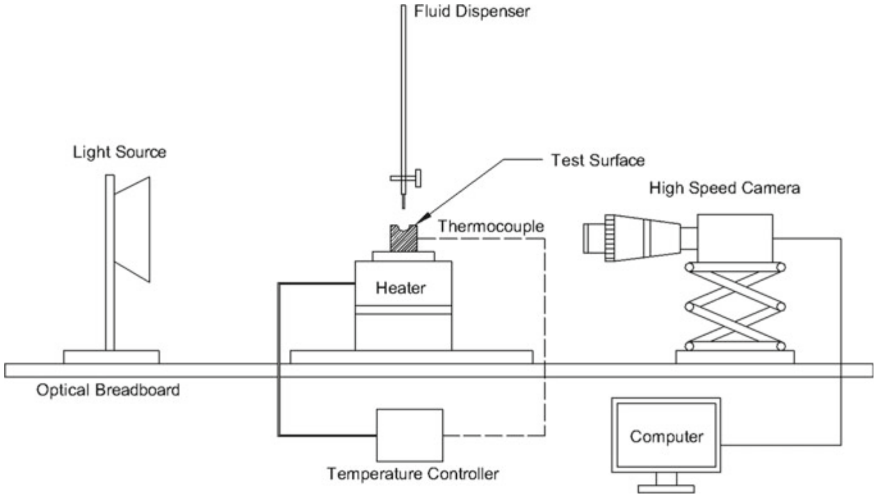
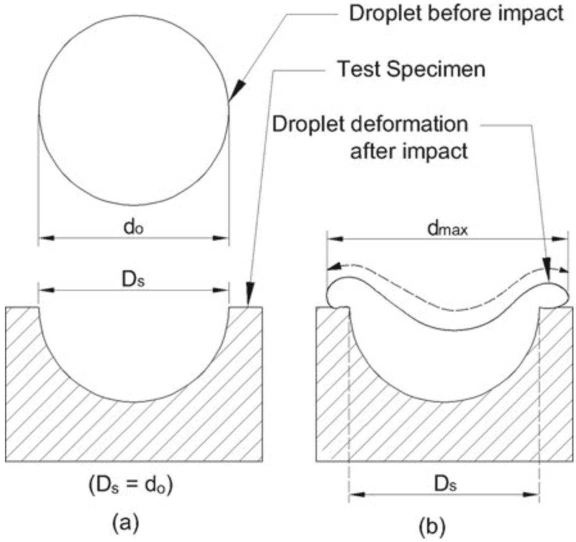


Fig1 Schematic of experimental set-up for droplet impact

Fig. 2 Schematic of droplet spreading



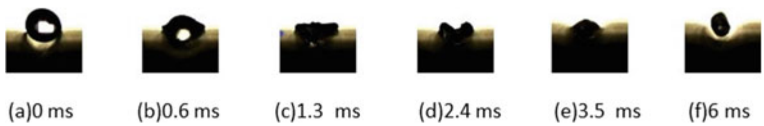


Fig. 3 Morphology of droplet hitting on concave surface with $\delta = 1$ kept at a temperature of $T_s =$ 250 °C, We = 16

Figure 3a shows the droplet of diameter (d_0) 2 mm about to hit a concave surface with curvature diameter of 2 mm. As the drop hits the hot surface, due to momentum, it spreads little over the cavity to its maximum diameter (d_{max}). Afterwards, it dips back to the cavity because of exhaust of momentum and domination of surface tension force as shown in Fig. 3d. Finally, it lift-off from the cavity due to the retraction of radial momentum back in vertical direction and vapour layer developed in the space between a droplet and surface. Because of the concave geometry's curvature effect, the droplet's lift-off is further improved. Due to unsymmetrical nature of the surface, the spreading pattern is anisotropic.

More research is done to examine the droplet growth over time between a flat surface and a concave surface with $\delta = 1$ at a surface temperature of $T_s = 450$ and We = 8.16.

Figure 4 depicts the change in droplet characteristics over time

The drop after impact spreads radially on a flat surface since it is a symmetric surface, however on a concave surface, the spreading is different because of its asymmetric geometry [13]. It is clear from Figure 4 that the way a droplet deforms on a concave surface differs greatly from how it does on a flat surface. For a flat surface, maximum spread diameter d_{max} is increased with respect to Weber number. But for concave surface, there is decrease of about 56% in d_{max} compared to the flat surface. This is because after hitting, the droplet is not free to spread like in flat

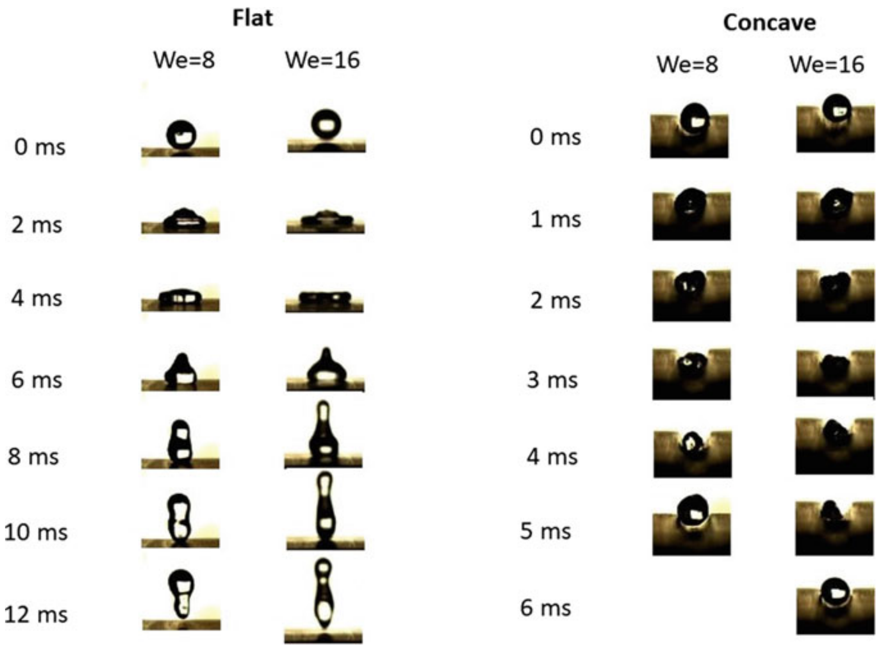


Fig. 4 Changes in droplet characteristics over time for flat and concave surfaces at $T_s = 450$ °C, $We = 8, 16$

surface. Moreover, the spreading momentum in azimuthal direction is opposed by gravity force due to the curvature effect. Since the maximum spreading diameter determines the possible contact area between the droplet and the hot surface during impact, it is a crucial parameter in heat transfer problems.

Figure 5 depicts the drop diameter deformation over time on a flat, concave surface ($\delta = 1$) at T_s =450 °C and Weber number We = 8. Immediately following impact, the drop diameter rapidly rises until it achieves its maximum spreading diameter. Following this, the drop spread diameter shrinks as the distorted fluid retracts towards the point of impact, attempting to reach its minimal value and lift-off vertically from the surface. The lift-off is due to the regain of momentum, pressure force by vapour layer and curvature. It can be noted from Fig. 5 that about 2.5 ms, the maximum spreading diameter is reached for flat surface and then starts receding. In concave surface, the maximum diameter is reached little early around 2.2 ms. The spreading and receding will take place at a faster pace for concave surface compared to flat surface, since the spreading has to take place against the gravity. Moreover, the vapour layer created between droplet and concave surface also enhances the lift-off. The vapour pressure force is significantly high in concave surface because of the force acting from bottom, left and right side of the cavity, whereas direction of the vapour pressure force in flat surface is only from the bottom. It is also evident that the drop bounces off from the flat surface about 12 ms, whereas it takes nearly 6 ms on by concave surface.

Further investigation is done by plotting dimensionless factors such as maximum spread factor $\beta = d_{\max}/d_0$ in the azimuthal direction with superheat factor $K = \frac{T_S - T_{\text{sat}}}{T_{\text{sat}} - T_f}$ which is the ratio of surface superheat to liquid sub-cooling, where $d_{\max}$ is the maximum spread diameter, d_0 is the initial droplet diameter before impact. The

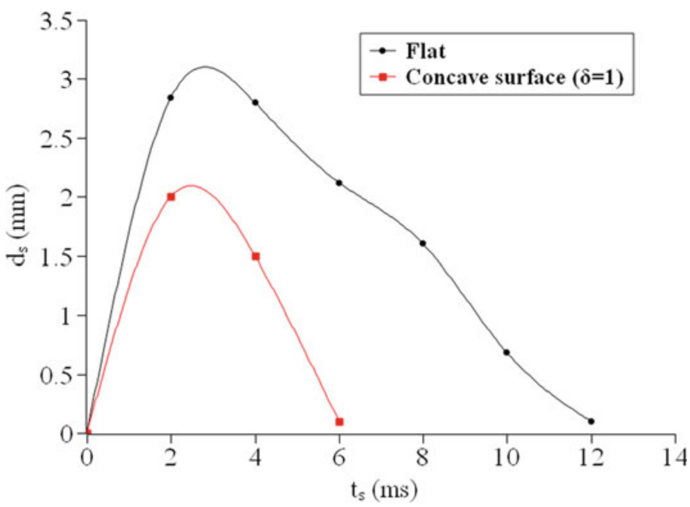


Fig. 5 Change in droplet diameter over time for flat and concave surface ($\delta = 1$) at $T_s = 450$ °C, $We = 8$

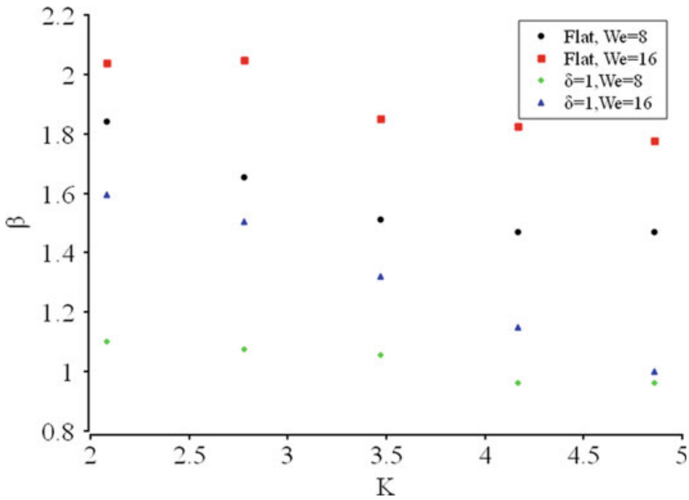


Fig. 6 Variation in β with K at different Weber numbers on the flat and concave surface ($\delta = 1$)

surrounding temperature is taken as $T_f = 270$ °C *and* the saturation temperature of water taken as $Ts = 100$ °C. Figure 6 shows the variation of β with different values of K for impact Weber numbers 8.16 on flat and concave surfaces. Shown in Fig. 6. It is evident from Fig. 6 that for the same Weber number, β decreases with increase in surface temperature. This is due to the fact that at higher temperature, rapid formation of vapour layer takes place which enhances the hydrophobic character of the surface [11]. The hydrophobicity restricts the spreading and help to regain the spherical shape early. Moreover, high pressure vapour layer trapped in between the droplet and the cavity pushes drop upward from all three directions (from bottom, left and right side of the cavity). The pressure force from left and right side of cavity helps to regain the spherical shape. In flat surface, there is very little entrapment of vapour between droplet and surface since it can easily escape radially to the atmosphere.

More insight of droplet dynamics is done by comparing normalised residence time, $\tau*$ [6, 16] with surface temperatures. The duration of contact between a droplet and a hot surface is known as the residence time. By achieving more residence time, the quantity of heat transfer can be increased considerably. From Fig. 7, it is evident that with the increase in surface temperature, the residence time is decreased by a small amount for both flat and concave geometry separately. But there is drastic drop-in residence time when the concave surface is compared with flat surface under the same condition. Due to the dominance of surface tension forces over momentum, the spread diameter has diminished. The vapour layer that forms between flat and concave surfaces further improves lift-off. Spreading and residence times are further decreased by the gravity effect of surface curvature.

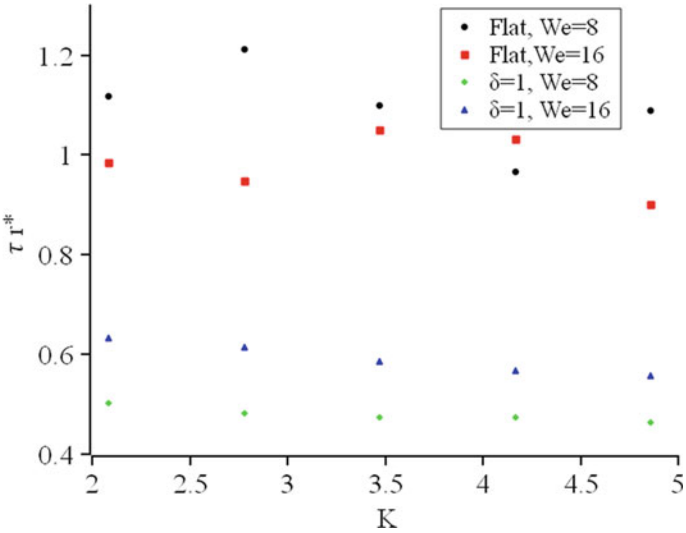


Fig. 7 Variation in τ_r* with K at different Weber Number s on the flat and concave surface with δ = 1surfaces

4 Conclusions

This study examines the dynamics of a water drop's impact on a superheated concave surface with curvature ratio of unity ($\delta = 1$) is examined experimentally and compared with a flat surface. The main goal is to investigate how curvature effect affects droplet impingement. Noticeable difference in droplet dynamics is found between flat and concave surface. There is significant reduction in spread diameter and residence time for concave surface compared to flat surface. In fact, about 56% reduction in contact time is found in concave surface compared to flat surface which greatly influences the rate of heat transfer. Higher temperature range from 250 to 450 °C also influences the impact dynamics.

Nomenclature

We	Weber number –
τ*	Normalised residence time –
δ	Curvature ratio –
β	Maximum spread factor –

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