Droplet impinging behavior on surfaces
Part II - Water on aluminium and cast iron surfaces

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Abstract. Droplet cooling of metal surfaces is an important area of research in industrial applications such as material quenching, nozzle spraying, etc. Fluids (water) act as an excellent agent in heat transfer to remove excess heat in various processes by convection and conduction. Such cooling process varies the material properties. The bubbles formed during droplet impinging on the surface act as heat sink and causes variation of height and spreading radius of the droplet with increase in temperature. In the present work, an experimental study of the droplet impinging behavior on Aluminium and Cast iron surfaces is reported. The water droplets are made to fall on the surface of the specimens from a specific height, which also influences the spreading radius. The effect of temperature on droplet height and droplet spreading radius is detailed.

1. Introduction
Spray cooling is the one of a significant cooling technique adopted for heat removal and for changing mechanical properties of materials during heat treatment processes such as quenching. It is a combination of convection and phase change mode of heat transfer using a liquid drop to achieve high heat flux. Excess heat generated is removed by making the droplets to impinge on the surface of the heated specimen. This was proved experimentally with the help of stainless steel specimen in [1]. A suitable edge detection algorithm was used by [2] for studying the morphology of a droplet image. Edge detection techniques were used to get the edges of droplet at various temperatures. Canny edge detection gave best results than other edge detection methods [3, 4, 5]. An extension of droplet cooling is spray cooling where droplets are shattered into large number of small water droplets [6]. The vaporization of water droplets includes the phenomenon of boiling (evaporation, nucleate boiling, film boiling and Leidenfrost transition) [7]. The cooling effect of spray cooling is greater than the conventional laminar quenching as more heat flux is removed in spray cooling [8]. The droplet cooling has various applications and one such application is that it is used to remove the heat developed due to friction in braking pads [9]. The drops can be made from various liquids like water, isopropanol, nanofluids etc. depending upon the application and amount of heat load [10, 11]. Most of the hot metal surface undergoes wetting at a surface temperature equivalent to critical heat flux, which causes the part to cool very rapidly as reported by [12]. The author initiated the study of spray dynamics by observing the behavior of single droplet exposed on the hot surface. Because of this ability, it has various industrial and domestic application, like spray cooling in continuous casting of steel and aluminium and heat extraction from overheated utensils by sprinkling few drops of water.

The above-mentioned literature works shows the importance and application of droplet cooling. The present work aims at comparing the effect of droplet cooling on two different surfaces (Cast Iron and Aluminium) at three different surface temperatures. The droplet behavior on the hot surfaces will give an idea about the mode of cooling process and the rate of heat transfer process. Since the liquid impinging on the surface evaporates and boils depending upon the surface temperatures, phase change behavior is also reported.
2. Experiment

A detailed explanation of the experimental set up used in the present work is detailed in part I of this study. The set up used is the same as that of Ref. [1]. Water droplets of measured and controlled sizes are made to fall on the surface of the specimen. The behavior of droplet from the beginning until the end is recorded with a high-speed camera. Images of the droplet during the entire process are obtained with the help of the Streampix software with which a frame by frame analysis can be made. The high speed video graphs are later converted into jpg format. The variation in radius and height is examined with the help of MATLAB software. Edge detection techniques are used to determine the boundaries of the droplet clearly. Cast iron and aluminium are the materials used for this analysis. The thermo-physical and surface properties of the material have a great influence over the droplet diameter and height at various temperatures.

Analysis in MATLAB software is done in the following way. The image is imported using `imread` command. Image is viewed with help of `imshow` which is an inbuilt command. Image of the surface of the specimen was also obtained, which was later used for subtraction. A subtracted image was obtained by using `imsubtract (or) abs` command. Then the subtracted image edge is detected with help of edge detection command `canny`. Other edge detection commands that can be used are `roberts, sobel, prewitt, log` etc. After edge detection the diameter and height of the droplet are measured with help of `imtool` command. This gives the pixel distance. The pixel is converted to millimeter. It should be noted that during subtraction two images should be of same size and they should be a binary image. If there are more noises, `thresh` can be used.

Stages of image detection:

![Figure 1. Original image](image1.png)

![Figure 2. Surface image without droplet](image2.png)

![Figure 3. Subtracted image](image3.png)

![Figure 4. Edge detected image](image4.png)
At lower temperature the variation of diameter is small. The number of frames obtained at lower temperature is high without much change in diameter. So analysis is done with every 100th frame. The evaporation rate is also very slow and the number of bubbles formed is less at 78 °C. A notable change in diameter is observed after many frames. While at higher temperature the number of frames obtained for the droplet to vaporize is less. With variation in temperature larger changes in diameter and height of the bubble is observed in each frame.

3. Results and discussion

The water droplet is made to fall on the surface of the specimen with help of a syringe pump at controlled rate. Different surface temperatures are obtained with help of variae varying the input voltage and current. The droplet is released from a fixed height of 5 cm. As it falls from such a height it gains potential energy before falling on the surface. When the droplet falls on the surface it takes few seconds to spread and settle on the surface of the specimen. Then it attains a specific height and diameter. These two parameters changes with increase in time, as the exposure to the surface of the specimen increases. The specimens considered for analysis are aluminium and cast iron. The analysis is made at 78°C, 98°C and 110°C temperature. At lower temperature, there is a slight decrease in spreading radius in the case of aluminium (Figure 6) whereas in the case of cast iron (Figure 5) the spreading radius remains same until the end. But in both cases there is a steady decrease in the height. The fluctuations in the curve is as a result of bubble formation due to onset of nucleate boiling and collapsing.

![Figure 5](image-url)  
**Figure 5.** Cast Iron surface with drop at 78°C (a) Height and spreading radius (b) droplet behavior
Figure 6. Aluminium surface with drop at 78°C (a) height and spreading radius (b) droplet behavior

From Figure 5 and Figure 6, it is inferred that there is not much change in the spreading radius of the droplet. This is because there is less or no bubble formation at lower temperature and these bubbles do not cause much change in the spreading radius of the droplet. In case of cast iron, there is not much change in spreading radius because with increase in time the height decreases with the same spreading radius, which does not occur in the case of aluminium. Though there is not much change in the spreading radius of the droplet at 78°C (both cast iron and aluminium), there is a constant decrease in the height of the droplet with increase in time. There are some variations in the curve which is due to the formation of bubbles which varies the height of the water droplet. Also the conversion of liquid into vapor and thereby reduction in height of the liquid drop is clearly visible in the graphs.

With increase in temperature, the spreading radius of the droplet changes with increase in time. The case for surface temperature at 98°C is shown in Figure 7 & 8. It is observed that the spreading radius is maximum at the center of the graph. At these points, the cooling effect will be more as there is a large surface contact, which is achieved by increase in surface radius due to the bubble formation. Bubbles formed reach a maximum size and then explodes. These vapor formation at which there are no coalescence between the bubbles increases the radius of the spreading. However with increase in time such bubbles coalesce and there is decrease in radius. In the case of Aluminium, which is having a smooth surface, the number of nucleation sites are less when compared to CI and the number of bubbles are limited when compared to CI.

The Figure clearly shows that the number of bubbles formed and explodes increases in case of CI while in case of aluminium there are not so many bubbles. Smaller bubbles formed take larger time to grow and then it explodes. At a temperature of 98°C where formation of bubbles would be high causes a wide variation in the height of the droplet. There is no uniform decrease in height. The peak points are the
points of bubble formation. Drop in the curves are the points where the bubble bursts and releases heat to the surrounding thus bringing the cooling effect. At such a higher surface temperature, the film (vapour) layer formed between the droplet and the specimen also influences the height of the droplet. This layer affects the surface contact. The droplet appears as if it is hanging from a support. Thus at higher temperature the height is influenced by the layer than the bubbles.

![Figure 7](image1.png)

**Figure 7.** Cast Iron surface with drop at 98°C (a) Height and spreading radius (b) droplet behavior

![Figure 8](image2.png)

**Figure 8.** Aluminium surface with drop at 98°C (a) Height and spreading radius (b) droplet behavior
Figure 9. Cast iron surface with drop at 110°C (a) Height and spreading radius (b) droplet behavior

Figure 10. Aluminium surface with drop at 110°C (a) Height and spreading radius (b) droplet behavior
At a much higher surface temperature such as at 110°C, the spreading radius remains almost constant. Film layer formation can be observed at this temperature which reduces the rate of heat transfer thus reducing the cooling effect. The water droplets are observed to be levitating on the surface as shown in Fig. 10 (b), which indicates a clear formation of vapor blanket beneath the surface.

The specific heat capacity of aluminium is higher than that of cast iron. The spreading radius of droplet that falls on aluminium is larger than the spreading radius of cast iron. It means the area of contact of the cooling fluid is more in case of aluminium. However in the case of Cast Iron the drop falls on the surface but didn’t spread much. This results in more absorbing of heat by the droplet on a concentrated surface in cast iron which is indicated by drop in temperatures of around 3-4°C in the case of cast iron. For the same conditions in the case of aluminium the drop in temperature is 1°C which is clearly shown in Figure 11 & 12. The Figures show the temperature vs time history from the moment the drop falls and boils completely.

![Figure 11. Cooling effect – Cast iron 112°C](image1)

![Figure 12. Cooling effect – Aluminium 112°C](image2)

4. Conclusion

In the present work an experimental study of droplet impinging behavior of water on cast iron and aluminum is done. The effect of temperature on droplet spreading radius and droplet height is detailed. The roughness of material played a vital role in initiating the nucleation sites, which in turn changed the behavior of formation of bubbles inside the droplets. The larger the spreading radius, the larger is the surface contact which results in cooling effect over a wider area in the case of aluminium. In the case of cast iron the spreading radius is smaller, resulted in large number of bubbles, and increased cooling effect over a concentrated area.
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