Study on the effect of Weber Number to heat transfer of multiple droplets on hot stainless steel surface

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Abstract. Multiple droplets are drops of water that continuously dropped onto a surface. Spray cooling is an application of the use of droplet on a cooling system. Spray cooling is usually used in a cooling system of electronic devices, and material quenching. In this study, correlations between Weber number and surface temperature decrease rate during multiple droplets impingement are investigated and analyzed. Visualization process is used to help determine the evaporation time of droplets impingement by using high speed camera. Induction stove is used to maintain a stainless steel surface temperature at 120°C, 140°C, and 160°C. The Weber number was varied at 15, and 52.5 to simulate low and medium Weber number. The result of this study shows that increase in Weber number does not increase the temperature decrease rate noticeably. Whereas the Weber number decrease the time required for surface temperature to reach its lowest surface temperature. It was also found that for low and medium Weber number, Weber number affect the evaporation time of multiple droplets after impingement.

1 Introduction

Multiple droplets are a series of droplet released with certain interval continuously onto a surface. Spray cooling is one the applications of multiple droplets. Widespread use of spray cooling in industrial application such as fire suppression by sprinkler system, cooling of turbine blades and electrical components. The rapid development of electrical components leads to smaller and more complex electronic component, but also accompanied with increase in power density. Making the conventional heat dissipation methods such as forced convection, pool boiling, jet impingement, are difficult to meet desired thermal control required. Spray cooling is known for having numerous advantages over conventional heat dissipation such as higher heat dissipation capacity, less flow rate demand, no temperature overshoot [1]. Spray cooling are also used in metal quenching process to increase the quality [2].

One of the factors that influences the heat transfer of droplet during impact onto a heated solid surface is the Weber number (We). This number is defined as the ratio of the inertia energy to the surface tension energy. Bernadin et al. [3] categorized Weber number into three regions (1) low Weber number, We < 30, (b) medium Weber number, 30 < We < 80, (c) high Weber number, We > 80. The correlation between Weber number and temperature of impinged surface to droplet spreading's characteristic has been analyzed and resulting in droplet characteristics after impingement which is levitation, disintegration, and bouncing [4]. The effects of the wettability of a droplet impingement onto a hot solid surface under medium Weber number had been studied experimentally using varying surface coating. Resulting in the higher the wettability, the larger the droplet spreading on the hot surface [5]. Analytical model approach to determine maximum spreading on low Weber and Reynold number had been made [6] with acceptable result. Research on low Weber number also had been conducted before. The result concludes that for low Weber number, the higher the static contact angle, the lower the wetting limit temperature [7].

Research on droplet evaporation on hot stainless steel plate had been conducted before [8]. With surface temperature varied between 63-605 to cover entire spectrum of heat transfer and droplet size ranging from 0.07 to 1.8 mm to simulate spray cooling diameter and also liquid included water and carbon fuel. The research resulting in droplet lifetime curve as a function of a wall temperature is similar for all liquid and all drop size. And the maximum heat transfer rate is independent of drop size.

The aim of present research is to study the effect of Weber number to heat transfer phenomena on multiple droplets impinging hot stainless steel surface, mainly the surface temperature decrease rate and droplets evaporation time. Visualization was used to help observation of droplet evaporation time after impingement.

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2 Experimental Apparatus and Procedure

The detail of apparatus used in this study is shown in Figure 1. The apparatus consists of droplet injector, droplet frequency controller, thermocouple, data logger, high speed video camera, illumination system, and personal computer for acquisition of the surface temperature data.

The fluid used is deionized water with droplet size was kept constant at 2.75 mm by using nozzle with inner diameter 0.8 mm and dropped by switching open/close the solenoid valve inside the system. Distance between the droplet injector and specimen is set to 20, and 70 mm resulting in 15, 52.5 Weber number. Droplet temperature is kept constant at 27 °C. Frequency of droplets used are 6.7 drops/second and opened only for 3.0 seconds resulting in 20 droplets impinged onto stainless steel surface.

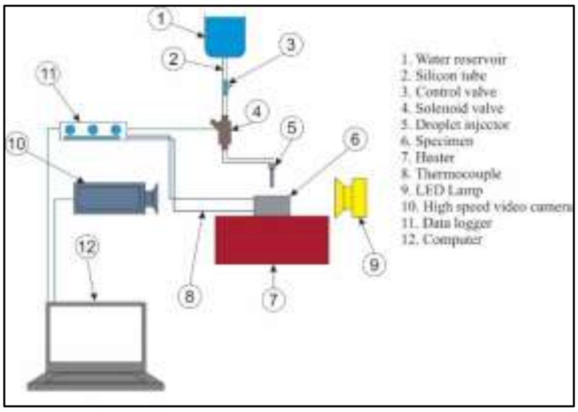


Fig 1. Schematic diagram of experiment apparatus

The specimen used is stainless steel with diameter of 50 mm and 0.06 μm hardness. Surface temperature are measured using interpolation of three thermocouples planted inside specimen in 5, 10, and 15 mm range in height. The heater used is made from induction stove, surface heating was performed until desired temperature reached. The temperature of specimen varied at 120 °C, 140 °C, and 160 °C. Surface temperature decrease data then obtained by using thermocouple connected to data logger.

In the present study, a macro lens attached to a high speed video camera is used to observe the droplet evaporation time after impingement. The video images were taken at 1000 frame per second with resolution of 640 x 480 pixels.

The initial diameter of a droplet was measured from the droplet image was not perfectly spherical. Both horizontal and vertical diameter of droplet was measured and using equation made by Šikalo [9] the equivalent diameter is

$$D = (D_h{}^2 D_v)^{1/3} \quad (1)$$

Where D_h is the horizontal diameter and D_v is vertical diameter shown in Figure 2.

Fig 2. Droplet diameter measurement

In this experiments Weber numbers are 15, and 52.5. This Weber number can be achieved from the expressions as follows:

$$We = (\rho v^2 D)/\sigma \quad (2)$$

Where ρ, v, σ are density, relative velocity of liquid, and surface tension respectively.

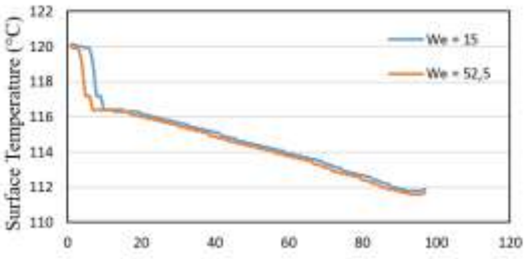
The rate of decrease in surface temperature can be determined by looking at changes in surface temperature impinged by the droplet. The rate of decrease in surface temperature can be calculated by

$$S = \frac{T_{S1} - T_{S2}}{t_2 - t_1} \quad (3)$$

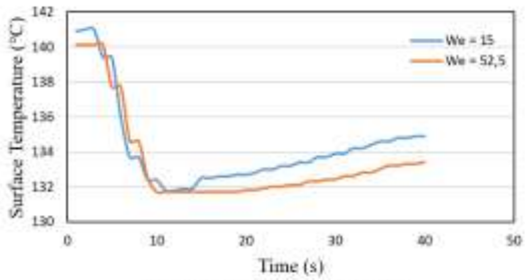
Where S, T_{s1}, T_{s2}, t_1, t_2 are initial surface temperature, final surface temperature, initial time, final time respectively.

3 Result and Discussion

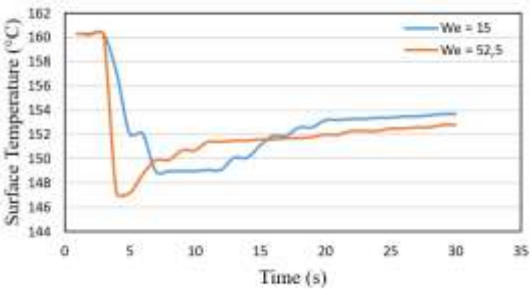
This present work is mainly focused on the effect of Weber number and surface temperature to temperature decrease rate during droplet impingement. Figure 3. Shows the temperature decrease over time value of stainless steel across all Weber numbers and surface temperatures. It is shown that in all surface temperature variation We = 52.5 has lower lowest temperature after impingement than We = 15 albeit the difference is not considerable. It is also shown that the higher the Weber number the less the time required to reach the lowest surface temperature after impingement. At surface temperature of 120 °C, the time required for surface temperature to rise again is longer than at 140 °C and 160 °C, this is due to heat transfer occurred between droplets and surface at 120 °C is lower than its counterparts. At surface temperature of 160 °C, the differences in lowest temperature and time required for temperature to rise again are notably large compared to the lower surface temperatures. This is due to surface temperature at 160 °C started to gain more increase in heat transfer rate between droplets and surface than previous surface temperature, in accordance to the droplets starting to reach its Critical Heat Flux (CHF) temperature



(a) Surface temperature = 120 °C



(b) Surface Temperature = 140 °C



(c) Surface temperature = 160 °C

Fig 3. Surface temperature decrease over time

Temperature decrease rate achieved by measuring the initial and final surface temperature and using equation (3). Figure 4 shows the temperature decrease rate impinged by multiple droplets. It is shown that by increasing the Weber number, the temperature decrease rate is also increased, the increment in temperature decrease rate is increasing as surface temperature increased. During surface temperature at 160 °C there is significant rise to temperature decrease rate for both Weber numbers. This is mainly due to surface temperature at 160 °C gain significant increase in heat transfer rate.

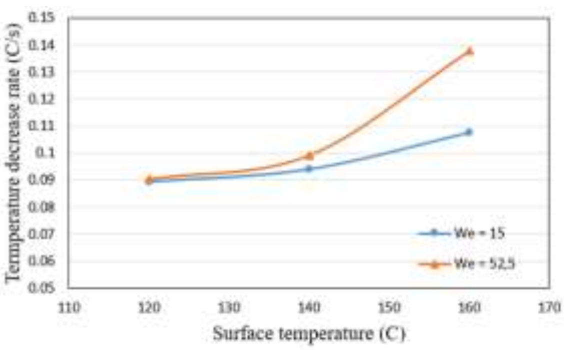


Fig 4. Surface temperature decrease rate

Figure 5 shows the evaporation time of multiple droplets impinging onto hot stainless steel surface. The evaporation time defined as time required for droplet to evaporate completely after impinging solid surface. From Figure 5 it can be seen that effect of Weber number on the evaporation time is apparent, the evaporation time decrease as the Weber number increases. The difference in evaporation time between We = 15 and We = 52.5 is getting smaller as the surface temperature is increased. The higher Weber number, the droplet spread diameter is larger, thus the contact area between droplet and solid surface is also higher, resulting a shorter evaporation time.

4 Conclusion

A study on the effect of Weber number of multiple droplets impinging hot stainless steel surface had been conducted. The surface temperature was varied from 120, 140, and 160 °C. Their effects on the heat transfer phenomena were studied, the results are summarized as follows:

1. The Weber number has not a significant effect on the lowest surface temperature after impingement. Increasing Weber number from low Weber number to medium Weber number does not change the lowest surface temperature significantly but reduce the time required to reach the lowest surface temperature.
2. At the surface temperature 120 °C, increasing Weber number does not change the rate of temperature decrease noticeably. By increasing surface temperature to 140 and 160 °C will increase the rate of temperature decrease more considerable, notably at surface temperature of 160 °C.
3. Weber number has apparent effect on the evaporation time. Which is the higher the Weber number the lower the evaporation time occurred. At lower temperature the difference in evaporation time between We = 15 and We = 52.5 is considerable, although the difference in evaporation time getting smaller as surface temperature increased. The higher the surface temperature is also making the evaporation time shorter.

References

1. Cheng, W.L., Zhang, W., Chen, H., Hu, L, Spray Cooling and Flash Evaporation Cooling: The Current Development and Application, Renewable and Sustainable Energy Reviews, **55**, pp. 614-628 (2015)
2. Fujimoto, H., Watanabe, S., Okamoto, T., Hama, T., Takuda, H., Photographic Study of Hydrodynamics of Drops of Aqueous Polymer Solution Impinging on Hot Solid, Experimental Thermal and Fluid Science, **60**, pp. 66-74 (2015)
3. Bernadin, J.D., Stebbins, C.J., Mudawar, I., Mapping of Impact and Heat Transfer Regimes of Water Drops Impinging on a Polished Surface, International Journal of Heat and Mass Transfer, **40**, pp. 247-267 (1997)

4. Kandlikar, S.G., Steinke, M.E. & Singh, A., Effects of Weber Number and Surface Temperatur on the Boiling, Proceeding of 35th National Heat Transfer Conference, pp.1–10 (2001)
5. Mitrakusuma, W.H., Kamal, S., Indarto, Deendarlianto, et al., The Dynamics of the Water Droplet Impacting onto Hot Solid Surfaces at Medium Weber Numbers, Journal Of Heat and Mass Transfer, **53**, pp. 1-13 (2017)
6. Li, R., Ashgriz, N., Chandra, S., Maximum Spread of Droplet on Solid Surface: Low Reynold and Weber Numbers, Journal of Fluids Engineering, **48**, pp. 1025-1035 (2010)
7. Deendarlianto, Yasuki, T., Sumitorno, H., Indarto, et al., Effect of Static Contact Angle on The Droplet Dynamics During the Evaporation of a Water Droplet on The Hot Walls, International Journal of Heat and Mass Transfer ,**71**, pp. 691-705 (2014)
8. Xiong, T.Y, Yuen, M.C., Evaporation of a liquid droplet on a hot surface, International Journal of Heat Mass Transfer, **34**, pp.1881-1894 (1991)
9. Šikalo, M. Marengo, C. Tropea, E.N. Ganić, Analysis of Impact of Droplets on Horizontal Surfaces, Exp. Therm. Fluid Sci. **25**, pp. 503–510 (2002)