Study on the Behavior of Small Droplet Impinging onto a Hot Surface

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Keywords: Droplet Impinging, Surface roughness, Evaporation, Impinging velocity

Abstract The effects of droplet diameter, surface roughness, and impinging velocity on the behavior of droplet impinging onto a hot surface have been studied. The surface samples used in the experiment were cylinder blocks of stainless steel having four different degrees of roughness, i.e., Ra 0.04, 0.2, 3, and 10. The diameter and impinging velocity were controlled independently by using a micro-jet dispenser. Their values were in the ranges of 300–700 μm and 1.0–4.0 m/s, respectively. The contact time was found to increase with an increase in the surface roughness and was of the order of the self-oscillation of the water droplet. The maximum spread of droplet decreased with increasing impinging velocity. The cooling curve was obtained for the range of surface temperatures from 500°C to 100°C, and it was found that the cooling time decreased with an increase in the surface roughness of stainless steel. Moreover, the cooling effectiveness of each droplet increased with an increase in the surface roughness.

Keywords: Phase transition, Droplet Impinging, Surface roughness, Evaporation, Wettability

1. Introduction

Water cooling technique plays important role in various industries such as a steel production or an emergency cooling of nuclear power plant. The phenomenon of the collision of a water droplet with a hot surface is used for various purposes such as water cooling processes in steel production industries. Moreover, how to control a cooling rate in spay cooling is one of the most important issues. In the cooling techniques currently used, the required cooling is achieved mainly by varying the conditions of water spraying such as by changing the type of nozzle, water mass velocity, temperature, impinging velocity, and droplet diameter of the water. In addition to these factors, other factors, which include conditions of the cooled surface, are also important. These include the roughness and wettability of the cooled material as well as its thermal properties such as thermal conductivity and heat capacity. In future studies, these surface conditions will have to be considered to introduce greater effectiveness in cooling ability by ensuring a uniform cooling rate over a wide area of a steel slab. However, the extent to which these parameters affect the cooling rate have not been well understood yet, except for some dominant parameters like the flow rate and the temperature of sprayed water and the effects of these dominant parameters on the cooling rate were summarized [1]. One of the reasons why the effects of these parameters are not clear is because in cooling experiments, it is difficult to vary one parameter while keeping the other parameters constant. This is because the flow rate of sprayed water, impinging velocity, and size of droplets vary simultaneously. In addition, wettability of a surface is one of important factor that affect on phase change heat transfer [2-4]. We studied the effects of boiling and evaporation on surface wettability using photoinduced hydrophilicity of titanium oxide (TiO_2) [5-9]. The TiO_2 changes its contact angle for water when it is exposed by ultraviolet ray. Therefore, it is possible to change only a wettability of a surface.

This study focused on the behavior of impinging water droplets, especially at high temperatures. In addition, the diameter of the droplets considered in this study was less than 1 mm because the droplet size of a typical practical spray system is approximately 300 µm. The behaviors of small water droplets on a hot metallic surface were observed by using a high-speed camera and the photographic images were analyzed; using this information, the solid-liquid contact time, and the maximum spread of a droplet on the hot surface were measured.

2. Experiment

2-1. Experiment setup

Figure 1 shows the schematic illustration of the experimental apparatus. It consists of a micro-jet dispenser, a high-speed camera, a date logger, and a hot metallic sample. The hot metallic sample consists of a stainless steel cylinder that is 30 mm in diameter and 5 mm in length. The sample surfaces used are finished with four roughness of Ra 0.04(Mirro), Ra 0.2, Ra 3, and Ra 10, respectively. A thermocouple with a diameter of 0.5 mm is embedded into the axial center at a depth of 2 mm through the hot surface. A single droplet is injected from the micro-jet

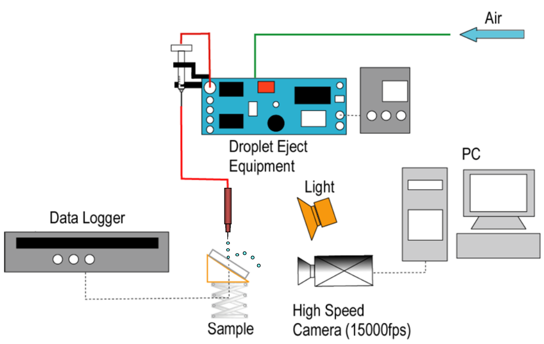

Figure 1. Schematic illustration of experiment apparatus. A single droplet is injected from the micro-jet dispenser nozzle onto the sample surface.

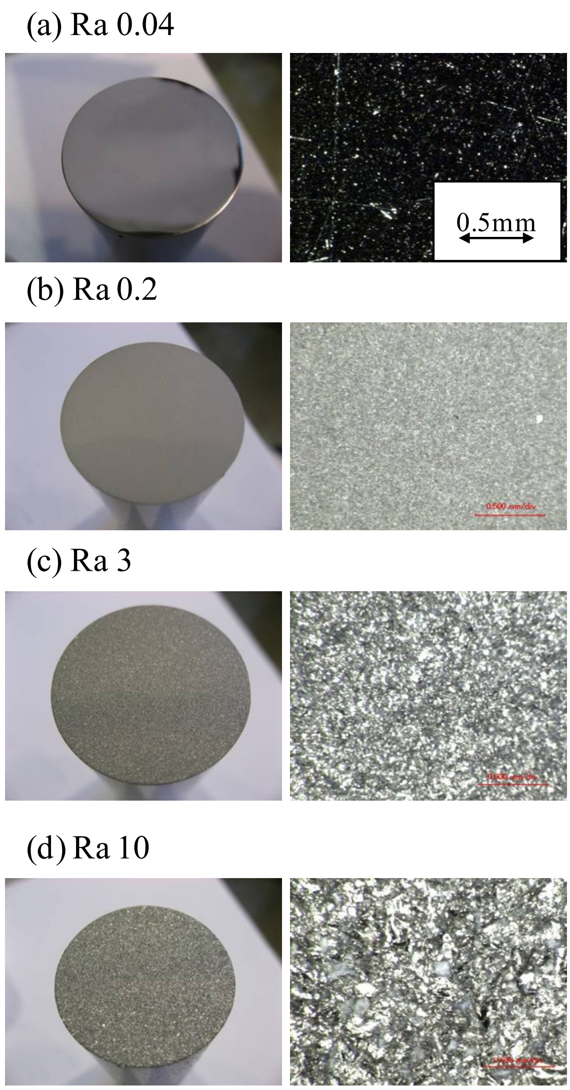

Figure 2. The optical microscope images of sample surfaces where (a) Ra 0.04(Mirro), (b) Ra 0.2, (c) Ra 3, and (d) Ra 10. A sandblast method is employed to prepare a surface with roughness of Ra 0.2, Ra 3, and Ra 10, while another surface is polished for obtaining Ra 0.04 roughness.

dispenser nozzle onto the sample surface. By varying the opening time of the electromagnetic valve, the injection pressure and nozzle tip diameter of the micro-jet dispenser, the droplet diameter, and the droplet speed can be controlled independently. The temperature was measured after every 0.12 s during the experiment.

Figure 2 shows the optical microscope images of sample surfaces where (a) Ra 0.04(Mirro), (b) Ra 0.2, (c) Ra 3, and (d) Ra

10. A sandblast method is employed to prepare a surface with roughnesses of Ra 0.2, Ra 3, and Ra 10, while another surface is polished for obtaining Ra 0.04 roughness.

2-2. Droplet collision experiment

First, the sample is washed with acetone and then heated up to 620°C in an electric furnace. The furnace is filled with N_2 gas (0.2 MPa, O_2 concentration < 3%) in order to prevent the oxidation of the sample. When the sample temperature is heated to 620°C, it is removed from the electric furnace and installed in the experimental apparatus. When the sample temperature becomes 600°C, the behavior of the water droplet when collided with the hot surface of the sample is recorded with the digital high-speed camera. The solid-liquid contact time and the maximum spread of the droplet during the first collision were evaluated by analyzing the photographs obtained. We defined the solid-liquid contact time as the duration of time that the water droplet remains in contact with the hot surface during the first collision. The maximum spread of the droplet is defined as the maximum diameter of the film. The parameters of the droplets are summarized in Table 1. The diameters listed in Table 1 are the nominal values because the actual diameter varies slightly with ejection conditions.

2-3. Water cooling experiment

We also perform a water cooling experiment to obtain the cooling rate of the water droplet system. The sample is heated under conditions similar to that of the collision experiment. When the sample temperature reaches 500°C, water drops (with a diameter of

Table 1. The experiment parameters of the droplets

Diameter (μm)	Velocity (m/s)
300	1.0m/s 2.5m/s 4.0m/s
500	
700	

700, 500 300 μm) are ejected from the four needles of the micro-jet dispenser until the sample reaches a temperature of 100°C. Water droplets are injected with a frequency of 400 drops per min. The cooling rate is also obtained without carrying out droplet ejection to examine the effect of natural convection heat transfer.

3. Result and Discussion

3-1. Solid-liquid contact time

We measured the solid-liquid contact time and the maximum spread of the droplet instead of measuring the heat transfer rate from the hot surface to the droplet. The solid-liquid contact time and the maximum spread of droplet can be obtained by analyzing the photographs taken from the high-speed camera. The solid-liquid contact time may be related to the duration of heat transfer. Hence, the heat transfer rate seems to increase with an increase in the contact time. The maximum spread of the droplet is related to the heat transfer area. Therefore, the larger the maximum spread of the droplet, the larger the heat transfer between the hot surface and the droplet.

Figure 3 shows the solid-liquid contact time of the droplet with an initial diameter of 700 μm. It is obvious that the contact time decreases with the increase in impinging

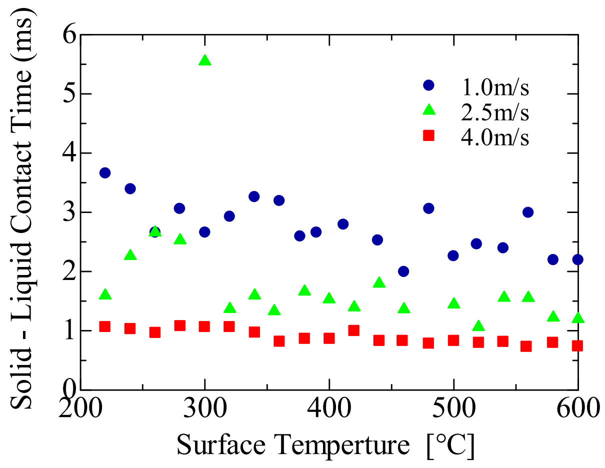

Figure 3. The solid-liquid contact time of the droplet with an initial diameter of 700 μm. The impinging velocity of the droplet is 1.0, 2.5 and 4.0 m/s.

velocity. The large impact velocity causes a strong contact with the heat transfer surface and this result in violent evaporation. The contact time decreases with the increase in surface temperature with impinging velocity of 1.0 m/s. However, the same change does not occur at an impinging velocity of 4.0 m/s and when surface temperature increases. In the case when the velocity is 4.0 m/s, we observe that *We* = 154, which is greater than 80 and, thus, the droplet breaks up completely. It is thought that break up droplet is hard to be affected by surface temperature.

Figure 4 indicates the effect of the surface roughness with an impinging velocity of 1.0 m/s. The diameter of the droplet is (a) 700 μm and (b) 300 μm, respectively. The roughnesses are Ra 0.04(Mirro), Ra 0.2, Ra 3,

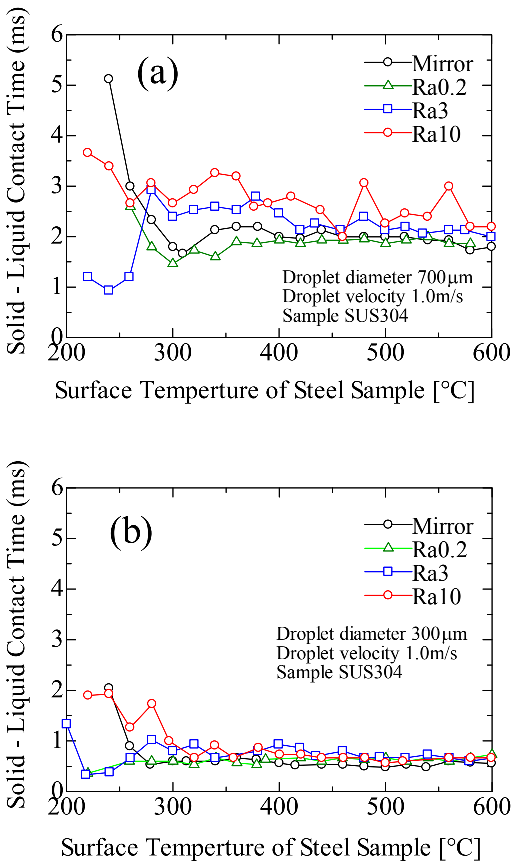

Figure 4. The effect of the surface roughness with an impinging velocity of 1.0 m/s. The diameter of the droplet is (a) 700 μm and (b) 300 μm, respectively. The roughnesses are Ra 0.04(Mirro), Ra 0.2, Ra 3, and Ra 10.

and Ra 10. In general, the solid-liquid contact time for rough surfaces is longer than that for smooth surfaces. In low-temperature regions, the solid-liquid contact time for rough surfaces is longer than that required for smooth surfaces, and in higher temperature conditions, the difference between them reduces. This tendency is almost constant for other impinging velocities. The experimental results vary greatly at around 250 °C because the boiling phenomenon is unstable.

3-2. Maximum spread of droplet

The effect of the impinging velocity on the maximum spread for Ra 0.04(Mirro) surface is shown in figure 5 for three different velocities. The maximum spread of the droplet increases with an increase in the impact velocity. This tendency is almost the same as those for varying roughness, and this result seems quite reasonable. The maximum spread of droplet can be estimated from equation (1) [10]. In figure 5, the maximum spread estimated by the following correlation equation is also plotted for comparison.

$$R_{\max} = 0.613 \cdot r \cdot We^{0.39} \qquad (1)$$

where R_{max}, r and W_e are the maximum spread, initial drop radius and Weber number,

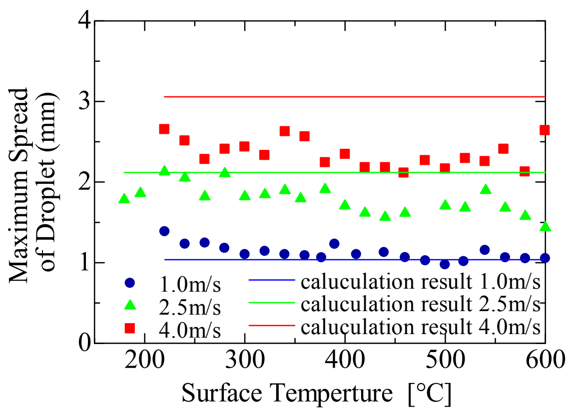

Figure 5. The effect of impinging velocity on the maximum spread of the droplet. The diameter of the droplet and surface roughness is 700 μm and Ra0.04, respectively. The impinging velocity is 1.0 m/s, 2.5 m/s and 4.0 m/s.

respectively. The estimated values are 1.04 mm for 1.0 m/s, 2.12 mm for 2.5 m/s and 3.06 mm for 4.0 m/s. The results agree with the experimental results when the impinging velocity is 1.0 m/s. However, the calculated result does not agree with the experimental results when the impinging velocity is increased.

Figure 6 shows the effect of surface roughness on the maximum spread of the droplet. The diameter of the droplet is (a) 700 μm and (b) 300 μm, respectively. The roughness are Ra 0.04(Mirro), Ra 0.2, Ra 3, and Ra 10. The maximum spread of the droplet increases with an increase in diameter of the droplet. When the diameter of the droplet is same, four curves in the figure agree with each other. This tendency was unexpected because we thought initially that roughness of the surface interrupts the drop to spread over the surface and hence the maximum spread of rough surface becomes smaller than smooth surface. If it is appropriate to consider the maximum spread of drop is in proportion to the area of heat transfer during contact with hot surface, the heat transfer area of four cases is the same with each other. Hence, the solid-liquid contact time will determine the heat transfer rate. Since the solid-liquid contact time increases with roughness, heat transfer during collision also increases with the roughness.

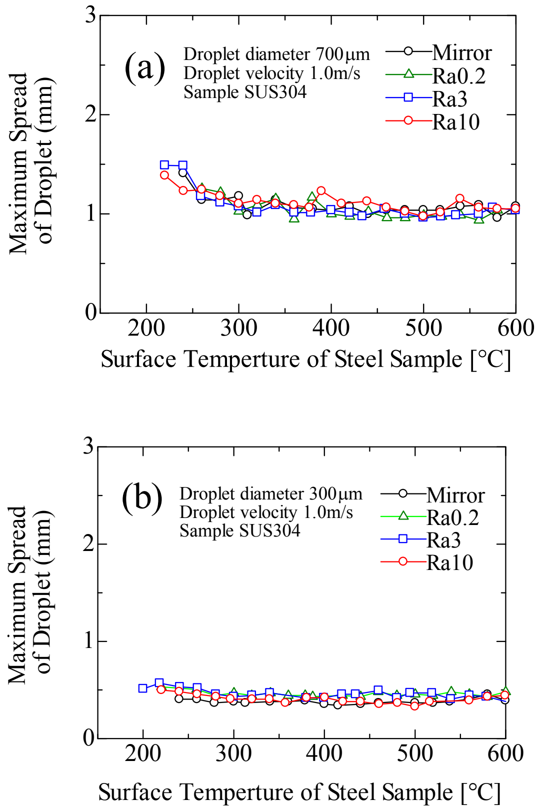

Figure 6. The effect of surface roughness on the maximum spread of the droplet. The diameter of the droplet is (a) 700 μm and (b) 300 μm, respectively. The roughness are Ra 0.04(Mirro), Ra 0.2, Ra 3, and Ra 10.

3-3. Water cooling rate

Figure 7 shows the effect of the surface roughness on the water cooling rate. The droplet diameter and the impinging velocity are 700 μm and 1.0 m/s, respectively, and the injected frequency of the water droplets is 400 drops per min. The broken and thick lines in the figure correspond to air cooling and water cooling, respectively. The cooling time decreases with an increase in the roughness in both air-cooling and water-cooling processes. It observed that in the film boiling regime, the cooling rate varies with roughness. The difference in the contact time of the surface with the droplet can be a possible reason for this behavior. This fact reveals that the solid-liquid contact time in a high-temperature region during the first collision of a droplet

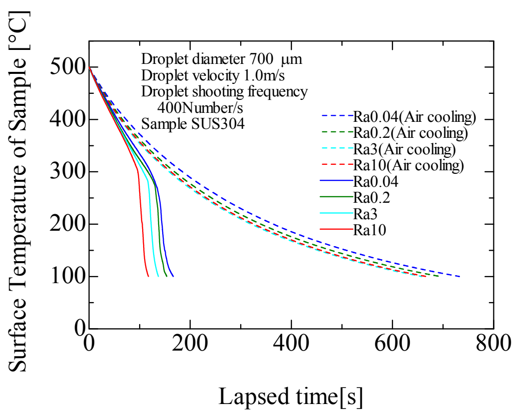

Figure 7. Effect of surface roughness on the cooling curve with droplet diameter of 700 μm, impinging velocity of 1.0 m/s, and injected frequency of 400 drops per min.

with a surface is considerably influenced by the surface conditions. This tendency can be explained by the solid-liquid contact time as discussed in the previous subsection. This result reveals that the effect of surface roughness on cooling rate attributes to the solid-liquid contact time in higher temperature region

4. Conclusions

The behavior of water droplets impinging onto a hot surface was observed in terms of the following parameters: surface roughness, impinging velocity, and droplet diameter. We measured the contact time of the droplet with the hot surface and the maximum spread of droplet by photographic analysis. Additionally, the effect of the surface roughness and impinging velocity on the cooling rate was studied. The results of this study can be summarized as follows:

(1) The contact time increases with a decrease in the impinging velocity and with an increase in the droplet diameter. It is in the order of self-oscillation of droplet.
(2) The maximum spread of the droplet increases with an increase in the impinging velocity. It is related to the ratio of droplet and the Weber number.
(3) The cooling rate increases with an increase in the surface roughness.

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References

[1] L. Bolle and J. C. Moureau, Spray Cooling of Hot Surfaces, Multiphase Science and Technology/edited by G. F. Hewitt et al., Hemisphare, vol. 1, pp. 1-97, 1982.

[2] Wenzel, R. N., Resistance of Solid Surfaces to Wetting by Water, Industrial and Engineering Chemistry, Vol.28, No.8, pp. 988–994, 1936

[3] Fujishima, A., Hashimoto, K. and Watanabe, T., TiO2 Photocatalysis – Fundamentals and Applications–, BKC, Inc. (1999)

[4] Takamasa, T., Hazuku, T., Okamoto, K., Mishima, K. and Furuya, M., Radiation Induced Surface Activation on Leidenfrost and Quenching Phenomena, Experimental Thermal and Fluid Science, Vol. 29, Issue 3, pp.267-274, 2005

[5] Takata, Y., Hidaka, S., Yamashita, A. and Yamamoto, H., Evaporation of Water Drop on a Plasma-irradiated Hydrophilic Surface, International Journal of Heat and Fluid Flow, Vol.25, No.2, pp.320-328, 2004

[6] Takata, Y., Hidaka, S., Yamamoto, H., Masuda, M. and Ito, T., Evaporation of Water Drop on Photo-Induced Hydrophilic Surface, Proceedings of the 12th International Heat Transfer Conference, Vol. 3, pp. 413-418, 2002

[7] Takata, Y., Hidaka, S., Yamashita, A. and Yamamoto, H., Evaporation of Water Drop in a Plasma-irradiated Hydrophilic Surface, International Journal of Heat and Fluid Flow, Vol. 25, No. 2, pp. 320-328, 2004

[8] Takata, Y., Hidaka, S., Cao, J. M., Nakamura, T., Yamamoto, H., Masuda M. and Ito, T., Effect of Surface Wettability on Boiling and Evaporation, Energy, The International Journal, Vol. 30, Issues 2-4, pp. 209-220, 2005

[9] Hidaka, S., Yamashita, A. and Takata, Y., Effect of Contact Angle on Wetting Limit Temperature, Heat Transfer-Asian Research, Vol. 35, No. 7, pp. 513-526, 2006

[10] Araki, K. and Moriyama, A., Theory on Deformation Behavior of a Liquid Droplet Impinging onto Hot Metal Surface, Transactions ISIJ, Vol.21, pp.583-590, 1981