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Cooling of a Heated Surface with an Impinging Water Spray

Bo-Seon Kang* and Kyung-Jin Choi**

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Several important parameters, such as liquid mass flux, droplet size distribution, droplet velocity, and heating target conditions (roughness and surface temperature) are involved in the industrial spray cooling heat transfer process. In this study, we investigated the effect of liquid mass flux, heating target roughness, and the droplet size on the droplet wall direct contact heat transfer in spray cooling phenomena. Three different conditions of surface roughness were investigated. The measurement of test surface temperature was performed using a non-intrusive method, i. e., using an infrared thermometer. The droplet size distribution of water spray was measured with Malvern 2600. The results indicated that the most influential parameters were the liquid mass flux and the surface roughness. The droplet size and the velocity played a less important role in the direct contact heat transfer because the interactions between droplets were very strong in a dense spray. The smooth surface showed the highest heat transfer among the surfaces tested. At high air pressure (171 kPa), however, the degree of roughness did not affect much the heat transfer rate.

Key Words: Spray Cooling, Surface Roughness, Liquid Mass Flux, Dense Spray

1. Introduction

The spray cooling has been widely used in various industrial applications. A typical example is the cooling of hot metal surfaces in continuos casting process. Some reasons for use of the water spray cooling in this type of industrial application are the convenience of use, low operating cost, and high heat dissipating ability. Although the spray cooling method is considered as a superior cooling method in this area, there exist some shortcomings to be overcome in order to increase the cooling capability and to improve the quality of products through the spray cooling process. Firstly, the efficiency of coolant (water) is relatively low in the temperature range above the Leidenfrost point (film boiling region), which is generally encountered in such metal processing areas. The vapour films, which are formed between the liquid droplets and the hot solid surface, prevent good heat conduction. In addition, the bouncing-off phenomena of the liquid droplets take place over the vapour cushion, resulting in a short period of direct liquid-solid contact. Secondly, the cooling rate of a hot surface is not uniform all over the surface due to the non-uniform distribution of the liquid spray. Therefore, the main objective of this research is to develop an advanced spray cooling technique which can be practically applied to the material cooling process. As a first step towards this goal, the present paper deals with the parametric effects involved in the conventional spray cooling heat transfer.

In the past, several investigations on the film boiling heat transfer of spray cooling have been conducted either experimentally or by using several analytical models. These studies can be, in general, classified into two categories, i. e., the dilute spray heat transfer and the dense spray heat transfer. Qualitatively speaking, in a dilute spray the number density of droplets is so small that the interaction between droplets is not apparent. On

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* Department of Mechanical Engineering, Chonnam National University

** Department of Mechanical Engineering and Mechanics, Drexel University

the other hand, in a dense spray, the number density is high enough for the strong interaction between droplets. Therefore, the heat transfer process of spray cooling with a dense spray is quite different from that with a dilute spray. However, the categorization of dilute and dense sprays mentioned here are not available in a clear-cut manner, rather in a superficial manner. Delcorio and Choi (1991) classified sprays in a quantitative manner as a dilute (sparse) or dense spray by using a square matrix model. They concluded that if the liquid mass flux was greater than $0.025 \text{g/cm}^2 \cdot \text{s}$, significant interactions between droplets took place and the droplet impact dynamics didn't play an important role in the overall spray heat transfer. Other experimental studies (Mizikar, 1970 ; Bolle and Moureau, 1982 ; Choi and Yao, 1987 ; Hall, 1975) also showed that in a dense spray situation, the overall spray heat transfer was not greatly affected by the droplet size and velocity, rather, the liquid mass flux was the most important parameter.

In addition to the number density of sprays, the spray cooling rate is also greatly affected by the surface conditions. In the industrial application of the spray cooling, the heat transfer surface is normally covered by a thin oxide film. The surface oxide film actually changes surface roughness. Pais et al., (1992) experimentally investigated the effect of surface roughness on evaporation/nucleation characteristics in the nucleate and transition boiling regimes of spray cooling. Ohkubo and Nishio (1989) studied the effect of surface roughness on the spray cooling performance and concluded that the surface roughness didn't affect the heat transfer markedly but its effect couldn't be disregarded.

The objective of the present study is to conduct the experimental investigation of the spray cooling of a heated metal surface and its dependence on important parameters such as droplet size, velocity, liquid mass flux, as well as surface roughness using a laser-diffraction instrument to characterize sprays produced.

2. Experimental Apparatus and Procedure

A schematic experimental set-up is shown in Fig. 1. The main components of this apparatus

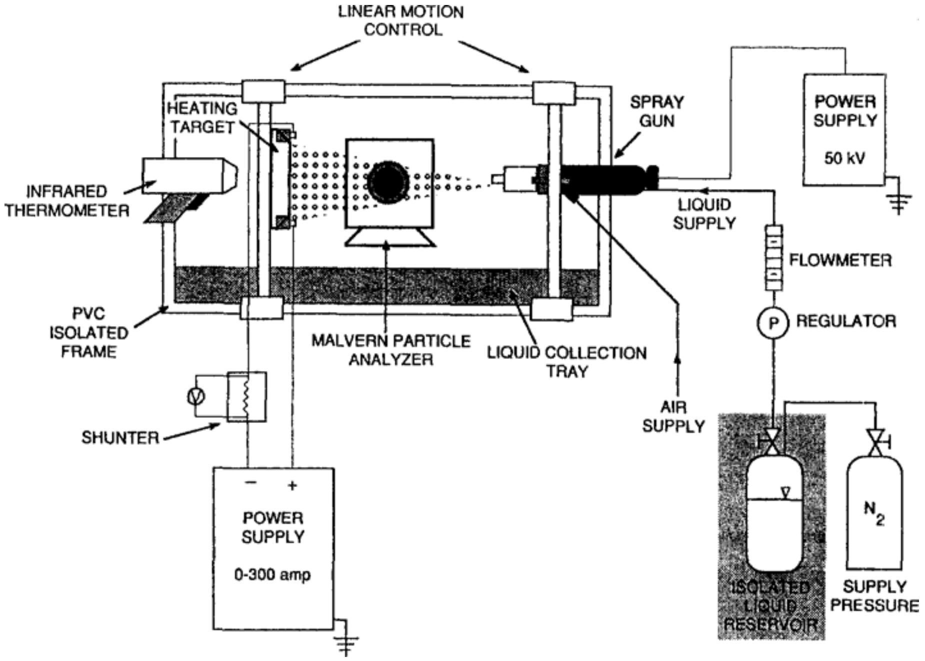


Fig. 1 Schematic diagram of the test setup.

were a liquid delivery system, a spray generator, a heated module, and the diagnostic system. The fluid delivery system consisted of a 7.5 liter compressed reservoir, N_2 pressure tank, and a positive displacement flowmeter. Distilled water was used as the working coolant. The spray generator was a commercial electrostatic atomizer(Ransberg -Gema, Model REA Ⅲ/100). This spray generator was an air-assist type atomizer and it had dual capabilities of generation of either an uncharged spray or an electrostatically charged spray. For the present study, uncharged sprays were used. With fine adjustments of shaping air pressure, round shape full-cone sprays with diameters between 5.1 and 7.6 cm were produced. Air supply pressures used for the atomization of liquid were 100 and 171 kPa.

The Joule heating method, which was used by Ghodbane and Holman(1991) for their spray cooling heat transfer experiments, was adopted for a heating target to generate sufficient heat and to maintain high surface temperature above the Leidenfrost point, so that steady state experiments could be performed. The temperature range of a heater surface was between 400 and 600℃. Only limited number of studies have been conducted in this high temperature range. The other merit of the Joule heating method was precise determination of the heat transfer rate from the heating target during the spray cooling process. A thin sheet of stainless steel 302 shim stock ($1.27\times5.08\times0.02$ cm) was used as a heating material through which high current was passing. Two copper bus bars were attached to the opposite ends of the stainless steel sheet to insure the passage of electrical current through the sheet. A Teflon plate with a portion removed at each end to accomodate the copper bus bar was used to mount the heating target to the frame. To provide high current to the heating element, a power supply(Miller XMT 300 CC) was used. The range of operating conditions were 12-36 Volts and 5-375 Amps.

To investigate the effect of surface roughness, three different surface conditions were tested ; a mirror shinning surface(surface A) and two kinds of artificially roughened surface(surface B and C). Two roughened surfaces were prepared by scratching either with a scraper or a coarse emery cloth. The degree of surface roughness was measured with a Profilemeter(Taylor Hobson Surtronic 3P).

The droplet size distribution of sprays was measured using the Particle Analyzer (Malvern 2600). This instrument based on the Fraunhofer diffraction theory of a collimated laser beam scattered by moving droplets. All the measurements were carried out at a distance of 22.5 cm downstream of the spray, where a heating target was positioned for the spray cooling tests. The measurement of the test surface temperature was done using a non-intrusive method, i. e., using an infrared thermometer(Mikron 80 AL), because the conventional contact method such as thermocouple measurements caused various problems. The infrared thermometer was positioned just behind the heating target, measuring the back surface temperature, in order to avoid interference with sprays. The temperature of the back surface was nearly the same as that of the front surface because the thickness of the steel sheet was very thin (0.02 cm). The infrared thermometer was first calibrated with the reference data such as the temperature measured with a thermocouple.

Before every experiment, the liquid mass flux was measured by using a plastic collector of which opening area was the same as the area of the test surface. While the liquid flow rate was maintained at a certain constant value, the water spray was injected on the heating target. The temperature of the test surface was held at a preset value by adjusting the electric power supply to the heating target. While temperature of the surface remained constant, the supplied electric power was measured in order to find out the heat transfer rate from the test surface later. The air convection cooling experiments without a water spray was also conducted to determine the portion of the air convection and the radiation heat transfer contributed to the total heat transfer rate. Therefore, the heat flux in this paper represents the heat flux carried out only by the liquid droplet impaction.

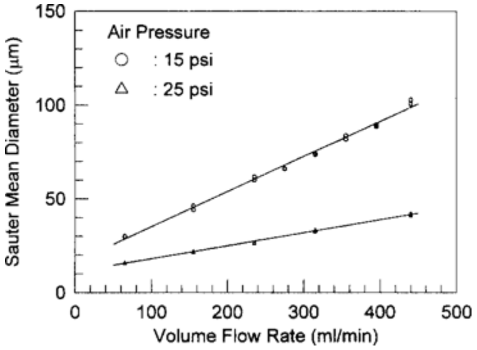


Fig. 2 Droplet size variation with liquid mass flow rate and air pressure.

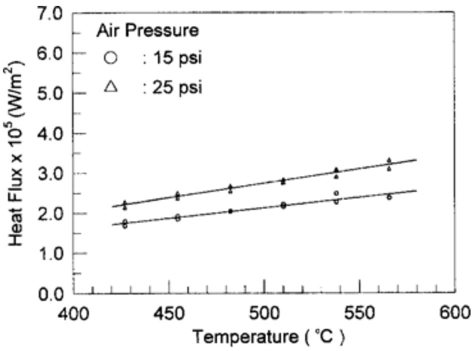


Fig. 3 Air convection heat transfer variation with surface temperature at different air pressures.

3. Results and Discussion

The mean diameters of sprays for different air pressures and liquid flow rates were measured and the Sauter mean diameters of produced sprays were presented in Fig 2. As shown in this figure, at a fixed liquid mass flow rate, sprays with smaller mean droplet size were generated at high air pressure. This result is obvious because in the air-assist atomizer, the disintegration of liquid jet occurs due to the disruptive forces provided by the high velocity of air acting on the liquid surface. It is also observed that the increase in the liquid flow rate results in larger mean diameters.

The main heat transfer modes involved in the impacting spray cooling are the droplet-wall direct contact heat transfer, the bulk air convection, and the thermal radiation. The magnitude of the radiative heat transfer is usually negligible unless the surface temperature is very high. Therefore, the first two heat transfer modes should be analyzed separately. However, it is difficult to isolate each heat transfer mode from the total heat transfer of impacting spray. To determine the magnitude of the heat transfer modes by air convection and radiation, air cooling experiments were conducted with the same spray generator but without liquid ejection. The results are presented in Fig. 3. The heat transfer mainly depends on the impacting air velocity and the temperature difference between the surface and air. As expected, the heat transfer increases with the air velocity and the surface temperature. The contribution of both air convection and radiation heat transfer to the total spray cooling heat transfer was about 60–70% for low liquid flow rate tested in this study, while it was only about 10–15% for high liquid mass flow rate. Further discussion of this point will be presented in the later part of this paper. Subtracting the bulk air convection data from the total spray cooling heat transfer, actual heat transfer performed by the droplet-wall direct contact was estimated. The following data indicate this direct contact heat transfer rates.

The effect of liquid mass flux on the droplet-wall contact heat transfer was investigated. According to the previous research (Delcorio and Choi, 1991 ; Mizikar, 1970 ; Bolle and Moureau, 1982 ; Hall, 1975 ; Yao and Choi, 1987), the major parameter to affect the film boiling heat transfer of impacting spray is the liquid mass flux. Our present results, for the smooth surface and at the air pressure of 100 kPa, are presented in Fig. 4 in comparison with Yao and Choi's (1987) correlation. In general, the heat flux increases with the liquid mass flux in the tested range. Although their experimental conditions were somewhat different from those in the present study, namely, larger droplet diameters (about 0.46 mm dia.) and slower droplet impacting velocities (2.8–3.4 m/s), the results were in good agreement. This means that the droplet-wall contact heat transfer is not much affected by droplet size and velocities in the spray cooling process.

The effect of air pressure on the droplet-wall

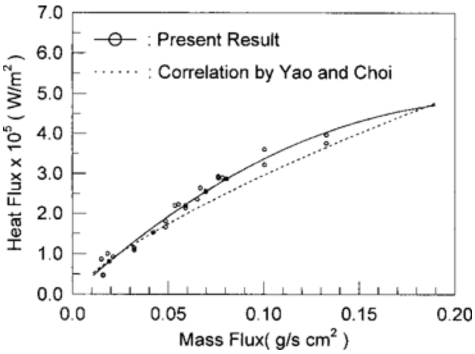


Fig. 4 Direct contact heat flux variation with liquid mass flux at P=100 kPa.

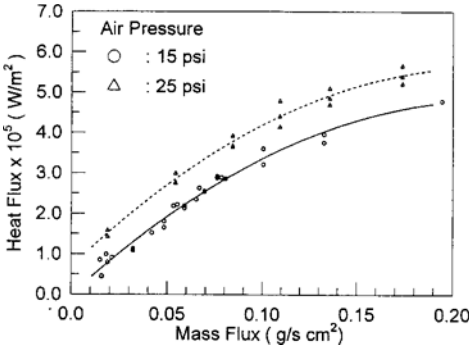


Fig. 5 Effect of air pressure on the direct contact heat transfer of smooth surface.

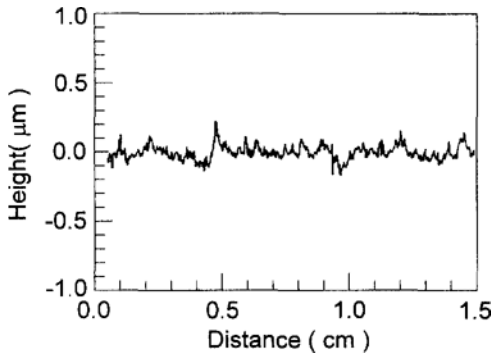
direct contact heat transfer is presented in Fig. 5. With increase in the applied air pressure, which implies that the produced droplets are smaller and faster, the direct contact heat transfer is increased. From the aforementioned notes, it is recalled that any changes in the droplet size and velocity of a liquid spray do not affect much the direct contact heat transfer. Therefore, there might be some other factors except the droplet size and velocity which affect the heat transfer with increase in air pressure. Such an example is the effect of air blowing of the vapor films which may be formed beneath the liquid layer. This issue should be further clarified in the future.

The surface conditions of the heating target such as surface temperature and roughness are also important parameters affecting the droplet -wall direct contact heat transfer or the overall spray cooling heat transfer. According to Yao and Choi's (1987) report, the heat transfer rate above the Leidenfrost temperature, namely, in the film boiling regime, didn't change much with surface temperature to a certain extent. Therefore, the effect of surface temperature was not considered in this study and the surface temperature was fixed at a constant value much above the Leidenfrost point. Rather, the effect of surface roughness on the heat transfer performance was investigated.

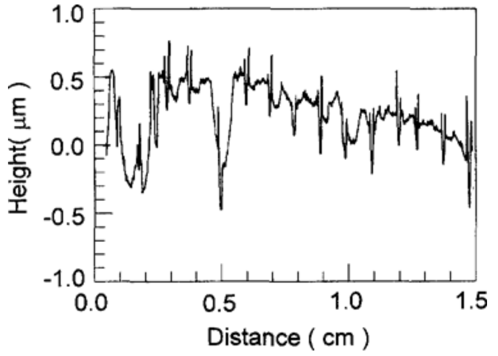
Some previous results of the pool boiling showed that there was no significant effect of surface roughness on the film boiling heat transfer. Once the film boiling starts, thin vapor layer always covers the heating surface. As a result, the heat transfer is not severely affected by the condition of surface roughness. However, the film boiling heat transfer of the impacting spray is quite different from that of the pool boiling case. For the impacting spray, there is no vapor layer which covers the entire heating surface and remains all the time like pool boiling. In addition, the droplets impacting upon the hot surface remain on the surface for a very short period of time (several tens of milliseconds) due to the bouncing-off phenomenon of the droplets. Most of droplet-wall direct contact heat transfer occurs during the initial period of droplet contact time. Consequently, one of essential factors which determine the contact heat transfer would be how fast the vapor layer is formed beneath the impacting droplet, which in general depends on the surface roughness condition.

As mentioned earlier, three different types of surface conditions were used in this study, i. e., very smooth (surface A), medium rough (surface B), and very rough (surface C). The surface profiles of surface B and C measured with a profilemeter were shown in Fig. 6. The calculated RMS values of the surface A, B, and C were 0.45, 0.62, and 4.47 μm, respectively.

The effect of surface conditions on the droplet -wall contact heat transfer at different air pressures is shown in Figs. 7 and 8. In each case, it is noted that the smooth surface has higher heat transfer than the other rough surfaces, which was also observed by Pais et al., (1992). Since the smooth surface does not provide nucleation sites,



(a) Suface B



(b) Suface C

Fig. 6 Surface profile of artificially roughened surface : (a) surface B (b) surface C.

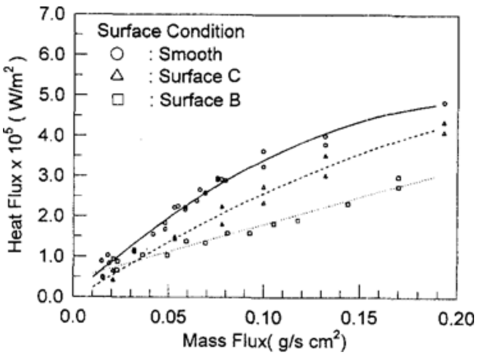


Fig. 7 Effect of surface roughness on the direct contact heat transfer at P=100 kPa.

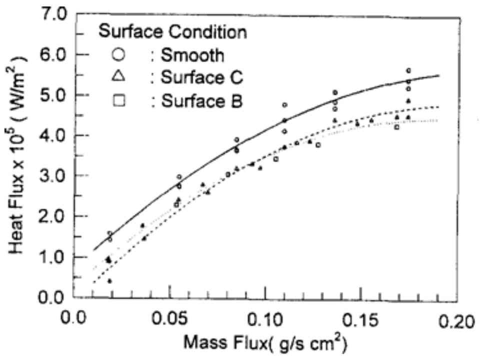


Fig. 8 Effect of surface roughness on the direct contact heat transfer at P=171 kPa.

the vapor formation is delayed, resulting in the extended period of direct contact time. On the other hand, rough surfaces have a wide range of cavities which can serve as active nucleation sites. Therefore, the vapor formation is easier and the direct contact time becomes shorter, resulting in worse heat transfer than that for the smooth surface.

At an air pressure of 100 kPa, surface B (medium rough) shows worse heat transfer than surface C(very rough). Studies on the onset of nucleation in pool boiling reveal that there exists a certain optimum size of cavity for the most active nucleation. If the cavity size exceeds this optimum size, the cavity can not play a role as an active nucleation site, resulting in better heat transfer. Based on the measurements of surface roughness as shown in Fig. 6, surface B seems to have more active nucleation sites, which is the reason why it has worse heat transfer performance than that of surface C. Ohkubo and Nishio (1989) investigated the effect of surface roughness on the mist cooling characteristics. They also observed that a smooth surface had better heat transfer and the worst heat transfer occurred at a certain roughness. However, this tendency was not observed at high air pressure (P=171 kPa), as shown in Fig. 8. Any major difference in heat flux was not observed between two rough surfaces.

4. Conclusion

The main parameters which determine the droplet-wall direct contact heat transfer characteristics of impacting sprays in the film boiling region are the liquid mass flux and the surface roughness. The droplet size and velocity play a less important role in the direct contact heat transfer, where the spray density is high enough so that interactions between droplets are not negligible. Smooth surface has better heat transfer characteristics than the other rough surfaces. At a certain condition of surface roughness, the direct contact heat transfer becomes the worst due to the existence of preferable nucleation sites.

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