EXPERIMENTAL STUDY ON THE SPRAY COOLING OF HIGH TEMPERATURE METAL USING FULL CONE INDUSTRIAL SPRAYS

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ABSTRACT

Experimental tests are conducted for a cylindrical plate of stainless steel of 12.5 cm diameter and 2.5 cm thickness heated to 900°C. Data from 25 tests is deduced using direct and inverse conduction numerical schemes. The local mass flux of water is in the range of 1.5-6.6 kg/m^{2}sec, which is typically used in secondary cooling in continuous casting. It has been found that the heat transfer is primarily dependent upon the local mass flux. The minimum film boiling heat flux and the maximum (critical) heat flux both increase with the increase of mass flux. The vertically down spray also gives slightly higher heat fluxes. The overflow of the residual water from the upstream induces slightly higher heat fluxes and higher Leidenfrost and critical temperatures.

INTRODUCTION

Spray cooling is used to remove heat in the slab, billet or bloom caster and should be designed to maximize steel quality. As water is sprayed onto the slab, a thin cushion of steam develops between the steel and the water. This is commonly referred to as “film boiling”. In this steam layer, the heat transfer coefficient is dependent on the mass water flux and is less dependent of the steel’s surface temperature. It becomes very important to steel quality to find the critical film boiling heat flux correlating with varying mass water flux. If the steam layer is not stable, concentrated cooling can occur and cracking will be the final outcome.

Previous investigations can be divided into two categories: individual droplet impact cooling and spray cooling of hot surfaces. Various experimental studies have been conducted for the individual droplet cooling. While the reported information is of value in basic understanding, the results describe only the single droplet heat transfer rate at very low liquid mass flux. On the other hand, some investigators have studied the spray cooling of hot surfaces, in a vertical direction. Horizontal and upward directions have generally not been covered. Gaugler (1), in his thesis, used Spraying Systems Co. full cone nozzles, 1/8GG1 and 1/8GG3001.4. A copper rod was used as a test sample.

Mizikar(2), studied three nozzles, all full cone, with mass flux up to 19 kg/m^2sec using a stainless steel test sample. Three Spraying Systems Co. full cone nozzles were used: 1/4GG6.5, 1/4GG10, and 3/8GG15. The heat transfer coefficient was found to be a linear function of water flux. Angle of spray attack is covered in this study. It is concluded that angle of spray has a negligible effect on heat transfer rate.

In the study of Ciofalo (3), the authors used four full cone Spraying Systems Co. nozzles: TG1,TG2,TG5, and TG10 . Mass flux varied from 8 to 80 kg/m^2sec. A test sample consisted of two slabs of beryllium-copper alloy, each 4×5 cm in size and 1.1 mm thick. The tests were highly transient with the complete cooling finished in about 1 second due to the very thin test samples. The heat transfer rates from this study are much higher than other authors for tests at same the mass flux.

In the present study, systemic experiments were conducted for high temperature metal using full cone industrial sprays. A range of mass flux (1.5-6.6 kg/m^2sec) was covered. Orientations with respect to gravity and spray angle were also explored in this study.

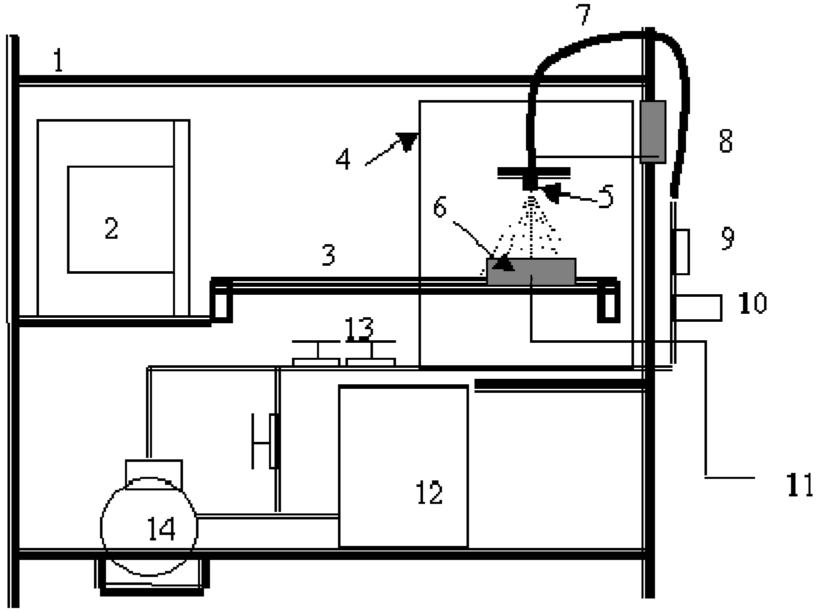
OBJECTIVES

The objectives of this study are to:

1- Establish an experimental database of the overall cooling process covering a wider range of mass flow rate, different orientations, and different spray angles.
2- Obtain the minimum film boiling heat flux, Leidenfrost temperature, critical heat flux, and critical temperature at different operating conditions.
3- Investigate the effect of gravitational orientation on heat transfer rate through downward and horizontal spray tests.
4- Explore the effects of spray angle on heat transfer rate.

EXPERIMENTAL SETUP

The experimental setup is shown in Figure 1. It is established to test the cooling of hot plates of stainless steel and consists of the following parts: metal frame, test plate, nozzle, furnace, water circulation system, rail, cooling box, and data acquisition system. The Spraying System Co. industrial spray nozzle used in this experiment is the 1/4 HHX-12 FullJet, which can typically be found in billet and bloom casters or at early segments of a slab caster’s secondary cooling system.

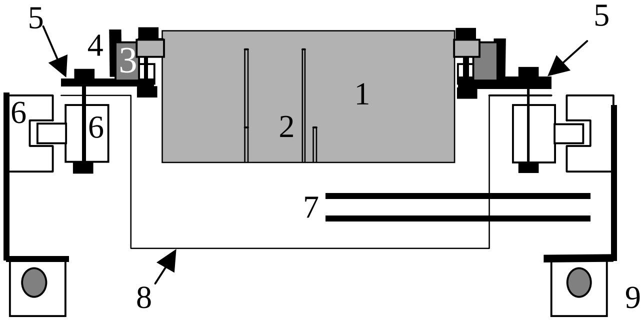


1-Unistruct frame, 2-Furnace, 3-Rail,
4-Cooling box, 5-Nozzle, 6-Test plate,
7- Flexible pipe, 8-Pressure gauge,
9-Flowmeter, 10- Filter, 11-To PC,
12-Water tank, 13-Valves, 14- Pump

Figure 1 Experimental Setup

In this study cylindrical stainless steel plates of 12.5 cm diameter with 2.5 cm thickness (Figure 2) are employed for up to 900°C. Four K-type thermocouples are accurately installed at four locations. A very small amount of high temperature thermally conductive cement (Omega Band 400) is used to ensure good contact between the tip of the thermocouples and the steel plate. The thermocouple holes are made with a very small clearance to ensure intimate contact between the metal and the thermocouples. A steel guide tube is used to protect the life of thermocouples from any abrupt thermal or mechanical stress.

The side thermocouples are used to tell if the heat conduction could be treated as one-dimensional. It will be further discussed in the data reduction section. Those thermocouples are connected to a personal computer equipped with data acquisition boards and the LabTECH software to monitor the temperatures in the plate during the cooling process. A linear motion rail is used to move the plate from the box furnace (Lindberg/Blue M Company BF51731C laboratory box furnace with chamber dimensions 33x42x27 cm was used to heat the test disks with a 33x42x57 cm. inside chamber) to the testing location in the cooling box. The cooling box has a height of 125 cm and a square-shape base with 86 cm on each side. The water circulation system consists of a 20-gallon tank, a single stage turbine pump with a 5 HP motor, pipe connections, two control valves, one on-off



1 -Stainless steel disk , 2- Thermocouples' holes,
3- High temperature cement, 4- Cement guard,
5- 1.6 mm thick steel 150 mm square plate with105mm diameter hole, 6- Steel bar,
7- Steel pipe, 8- Box, 9-Linear rail

Figure (2-a) Overall Test Plate and Rail

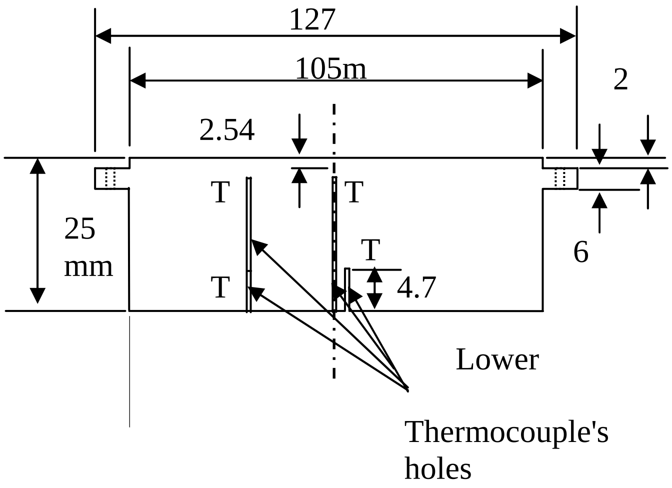


Figure (2-b) Cross Sectional View

valve, a flow-meter, a filter, a pressure gage, and the flexible hose.

EXPERIMENTAL PROCEDURE AND TESTS MATRIX

Prior to heat transfer measurements, a separate study was conducted to find the mass flux for a nozzle- target distance of 152.4 mm (6 inch) at the center of the spray and at 50.8 mm (2 inch) off center at a specified side. These are the same locations where the heat transfer tests were subsequently conducted.

Water arriving in a given time to a circular openings is collected for different operation conditions. The measurement device consists of 11 tubes arranged along a horizontal plexiglass plate with hoses connected to collection bottles. The tubes protrude 12 mm above the plexiglass plate to prevent over flow. The tubes have an inner diameter of 5.94 mm. They are kept at a center-to-center distance of 12.7 mm. The tip of the tube was tapered to prevent droplets from bouncing. The local spray distribution is calculated accordingly and plotted in Figures 5-a through 5-c.

For heat transfer tests, the experimental procedure consisted of the following steps. First the pump was switched on and the regulator valves were set for the desired water pressure and flow rate. Then these valves' positions are saved for the test; only the on/off valve will be used later. The test plate is then heated in the furnace to a temperate around 900°C. Before the test plate is moved from the furnace, theses steps are conducted in sequence: switching on the pump, check the water pressure level, and start the data acquisition program. Then the plate is moved from the furnace to the exact location under the spray. The computer will sample and record the temperatures at a specified rate (10-20 readings per second). The whole sampling time takes 3- 5 minutes until plate temperatures falls to around 100°C. Nozzle-disk distance of 152 mm (6 inch) is kept for all the runs. Two orientations are tested for the vertically down spray with horizontal test disk position, and horizontal spray with vertical test disk position. For center tests, as the name indicated, the spray center coincides with the test plate center. For side tests, 50 mm (2 inch) spray center-to-disk center lateral distance is maintained.

Table I: Tests Types

Group #	Orientation	Relative location
G1	Vert. down.*	Centered
G2	Horizontal	Centered
G3	Vert. down.	Side
G4	Horizontal	Side

* Vertical Downward Spray Direction

The tests are categorized in four groups. For each group at least three tests are performed for different mass flux. For some groups up to eight tests are performed to insure good coverage and precise results. Tap water is used for cooling with temperature in the range 20-23° C.

DATA REDUCTION

Data smoothing was applied in the data reduction. This was done by time weighting the individual thermocouple readings. Using 5 readings before and 5 readings after an individual temperature being considered, with increased weight of the readings near the considered ones. A triangular weighted average is used. Averaged results were then used for heat transfer calculations. Figure 3 shows the raw and smoothed temperatures. As shown, this procedure gives smooth data.

Two heat transfer problem solutions are needed to obtain heat transfer and temperature at the test plate surface. Direct heat conduction takes place between x1 and x2 between the thermocouples (Figure 4). The solution of this direct conduction part will give the heat transfer rate at plan x2, which is different from the surface heat transfer rate. Then, the inverse conduction problem was solved in the region between plan x2 and plate surface x3.

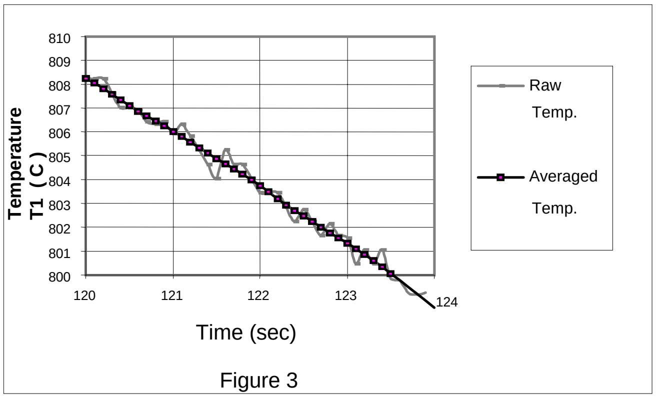


Figure 3

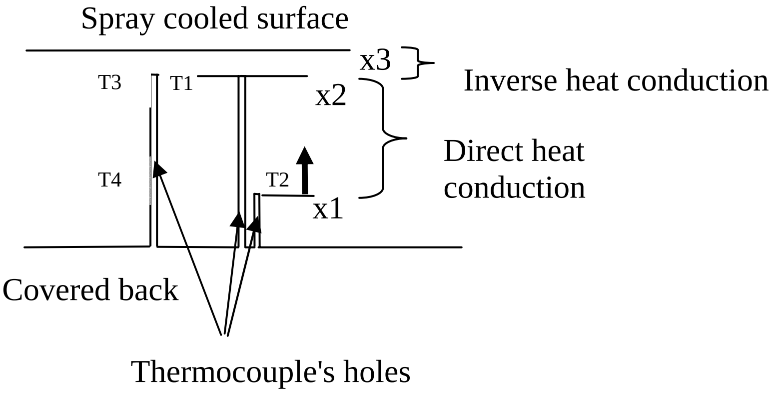


Figure 4 Direct and Inverse conduction regions

Direct Conduction -Iterative Implicit nonlinear numerical scheme used to solve heat equation for one-dimensional transient conduction with variable thermal conductivity for temperature field between x1and x2 and hence heat flux at x2 plane.

Inversed Conduction-The Weber's method for solving inverse heat conduction based on reformulation of the linear transient conduction from equation (3) to this form

$$\alpha \frac{\partial^2 T}{\partial x^2} = \frac{\partial T}{\partial t} \qquad (1)$$

$$\alpha \frac{\partial^2 T}{\partial x^2} = \frac{\partial T}{\partial t} + \gamma \frac{\partial^2 T}{\partial t^2} \qquad (2)$$

γ is a non-negative constant small enough to make equation (2) resemble (1). And at the same time it does not permit instantaneous transfer of heat as equation (1) does.

T	Temperature (C^o)
k	Thermal conductivity (W/m*K)
Cp	Specific heat (J/kg*K)
x	Spatial variable
t	Time variable

ρ	Density
α	Thermal diffusivity $(k/\rho^* C_p)(m^2/sec)$

In inverse heat conduction, the surface heat flux at time t depends on the interior temperature values at times both before and after t. For this reason the numerical solution is obtained for all time steps at a given spatial node before any temperature values are computed at the next spatial node.

$$\frac{(T_{i+1}^{n} - 2T_{i}^{n} + T_{i-1}^{n})}{(\Delta x)^2} = (1/\alpha) * \left[\frac{T_{i}^{(n+1)} - T_{i}^{(n-1)}}{2*\Delta t} + \frac{\gamma}{\Delta t^2} (T_{i}^{n+1} - 2T_{i}^{n} + T_{i}^{(n-1)}) \right] \qquad (3)$$

T_i^n Temperature at node (x_i, t^n)

Total time 300 seconds

Total spatial space (x3-x2)= 3.937 mm (0.155 inch)

$\Delta x = 0.0667$ mm $\Delta t = 0.1$ second

This explicit scheme, which is solved for T_{i+1}^{n+1}

RESULTS AND DISCUSSION

Spray Density Results-Spray mass flux distributions are reported in Figures 5-a,5-b, and 5-c. Figure 5-a shows the distribution along the plane A-A, see figure 5-d. At a higher pressure, the mass flux is increased; however, the local distribution pattern is changed. The nozzle has a vane with two large angled slots which introduce turbulence thus creating the full cone pattern. The mass flux is non-uniform and dependent upon the orientation of the vane. As shown in Figure 5-d, if mass flux is measured along axis A-A, mass flux is larger at the outer edges of the nozzle. If measurement is taken along axis B-B, mass flux is slightly higher in the center of the nozzle. When pressure and flow rate changes, the distribution of mass flux also rotates. For a fixed location, the mass flux could vary significantly when nozzle pressure changes.

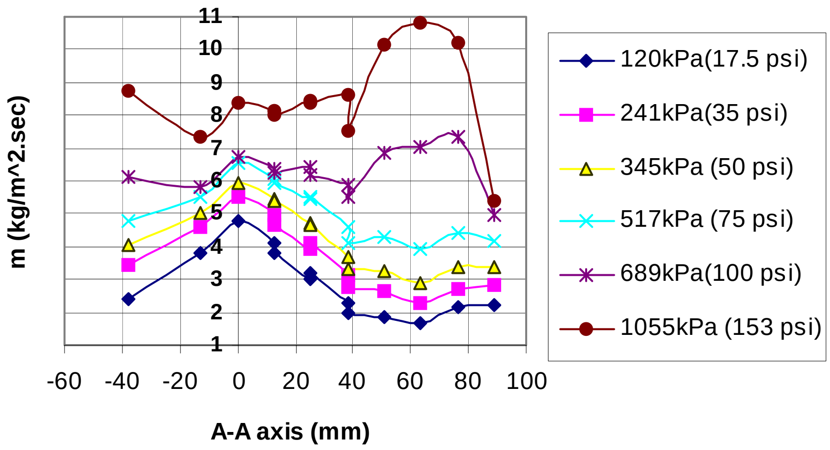


Figure 5-a Spray density along A-A

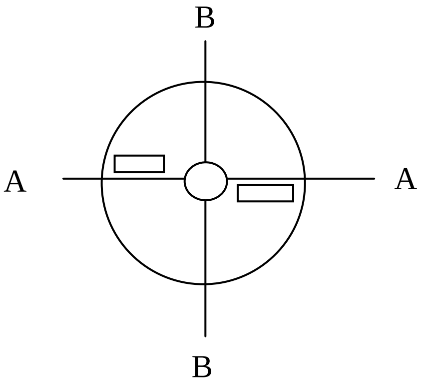


Figure 5-d
Axis A-A and B-B

The distribution along plane B-B at the center of the spray is shown in Figure 5-b, and the side is shown in Figure 5-c. At a higher pressure, the mass flux is increased; however, the local distribution pattern is not changed very much.

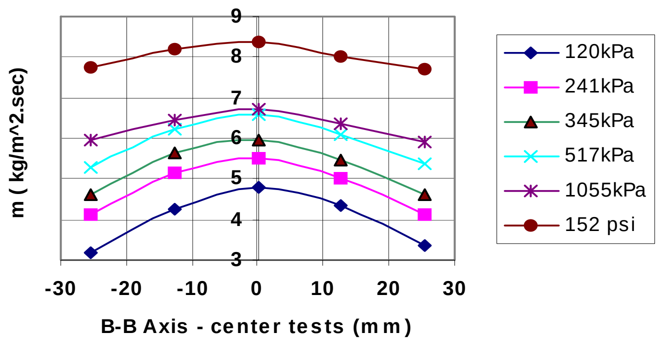


Figure 5-b

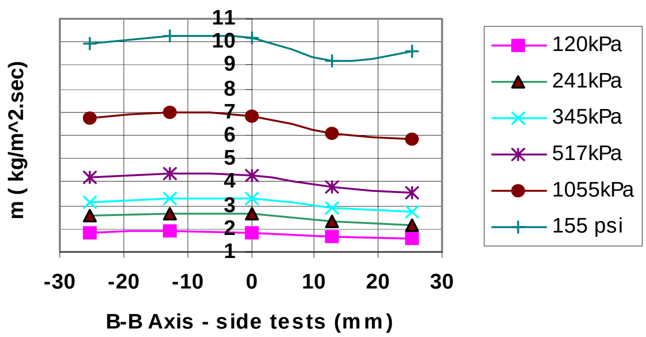


Figure 5-c

Heat Transfer Results-A typical Temperature vs. Time curve during the spray cooling is shown in Figure 6, for each thermocouple. Figure 4 indicates the locations of these thermocouples. The radial temperature distribution is rather uniform. T2 and T4 are almost identical. T1 and T3 are also very close except during a short period of the cooling process. At early stage of nucleate boiling the difference in radial temperature is more observable. It is believed that the heat flux could be overestimated to up to 10% near the critical heat flux. Uniform one-dimensional heat conduction inside the plate i.e. neglecting the heat loss from the side of the plate is believed to be a good assumption for the more important regimes of film boiling and transient boiling.

Figure 7 shows a typical heat flux versus temperature at point x2, the end of the direct conduction region. The result of the inverse problem solution for same case is also shown. Using only a direct conduction result will result in a significant error. The result of inverse conduction is improved from the direct conduction solution. This makes the inverse conduction solution essential to achieving reliable results.

Figure 8-a shows the results for four typical tests, The spray heat transfer curve is similar to that of pool boiling heat transfer with distinctly different boiling regimes. At high surface temperatures, where Film Boiling is dominant, a vapor film adjacent to the solid hot surface prevents or minimizes direct droplet contact with the surface, resulting in a low heat transfer rate. The heat flux drops gradually with surface temperature in the film boiling range. As surface temperature gets lower, the droplets begin to penetrate the vapor film and a sharp increase in heat transfer rate begins.

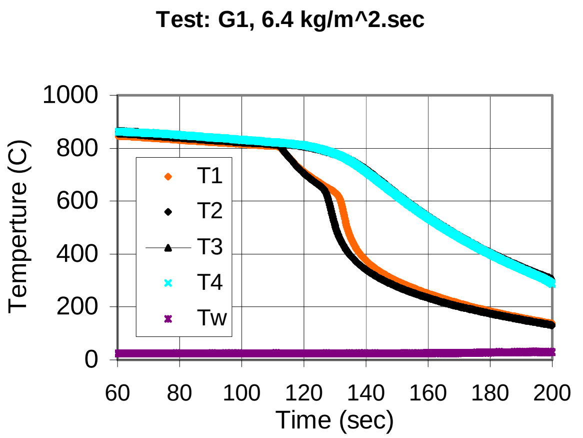


Figure 6

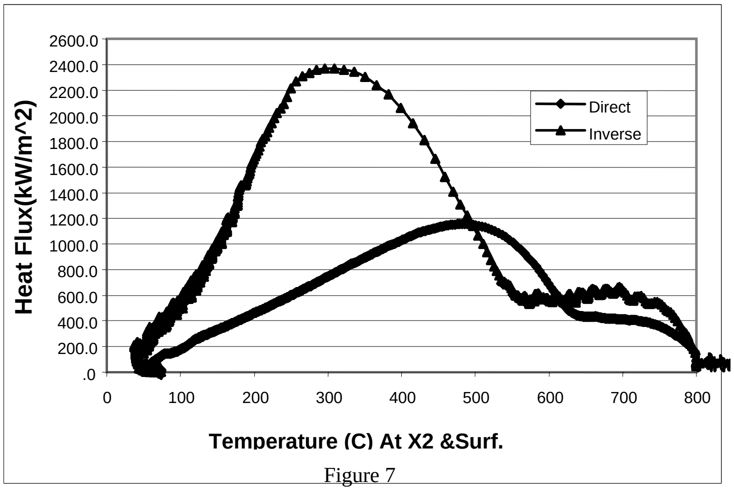


Figure 7

This is the start of Transition Boiling heat transfer regime. Just before transition boiling, the heat flux experiences a minimum at the Liedenfrost point. Sharp increase in heat flux due to surface wetting occurs below Liedenfrost temperature. At this point the thin layer of steam is very unstable and instantaneous cooling is the result. After reaching the maximum critical heat flux the curve starts decreasing, going through the Nucleate Boiling and finally to the convection cooling.

The four curves in figure 8-a include the effects of mass flux, spray angle, and orientation. However, the most apparent effects come from mass flux. The portion of the film boiling heat transfer is plotted separately in Figure 8-b showing the same feature of sharp mass flux influence.

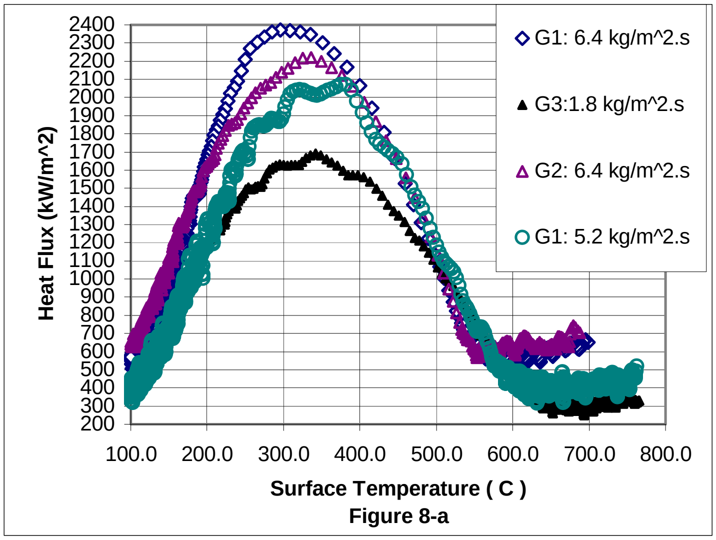


Figure 8-a

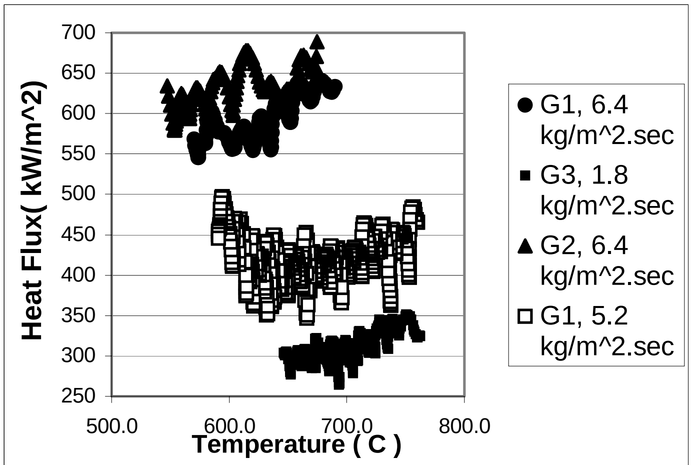


Figure 8-b Film Boiling

Figure 9 presents the data of critical heat flux. The critical heat flux is due to forced flow pushing the droplets closer to the hot surface therefore increasing the heat flux in the film boiling regime significantly. After the critical heat flux is reached, Nucleate Boiling begins There is a very clear trend of critical heat flux which increases with increasing mass flux. Tests from the first and second groups show that the heat flux is higher for the vertically down tests compared to the horizontal spray tests. Figure 10 shows that the critical temperature is generally higher for side tests than for centered tests even though the mass flux is lower. This could be due to the combined effect of mass deposition and overflow from center of the plate. The overflow along the plate causes the nucleate boiling to occur at a higher surface temperature.

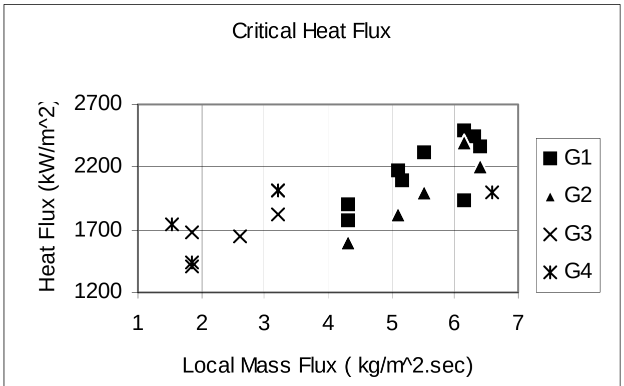


Figure 9

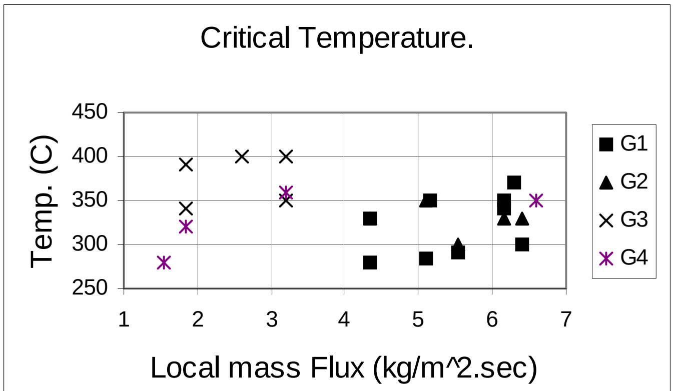


Figure 10

Figure 11 presents the heat flux for the Leidenfrost point where heat flux is the minimum. Minimum heat flux was found to increase linearly with increases in water mass flux. Spray angle shows a slight effect, at a small angle of impact the minimum heat flux is higher in the trend line. It is believed that this is the effect of the combined mass deposition and overflows from the center of the plate. The cross flow makes quenching occur at higher heat flux and temperature, this point is particularly relevant to continuous caster operations as it represents a predictable, stable range. Figure 12 shows that the Ledinfrost temperature is general higher for side test than for centered tests even though the mass flux is lower. This could be also due to the combined effect of mass deposition and overflow from the center of the plate. Ledinfrost temperature is lower for horizontal spray tests than vertically down flowing sprays.

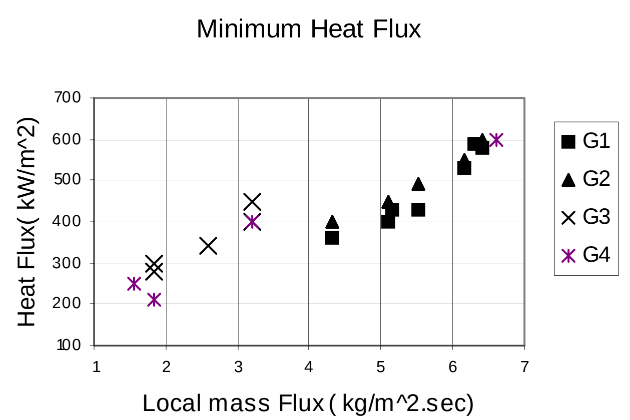


Figure 11

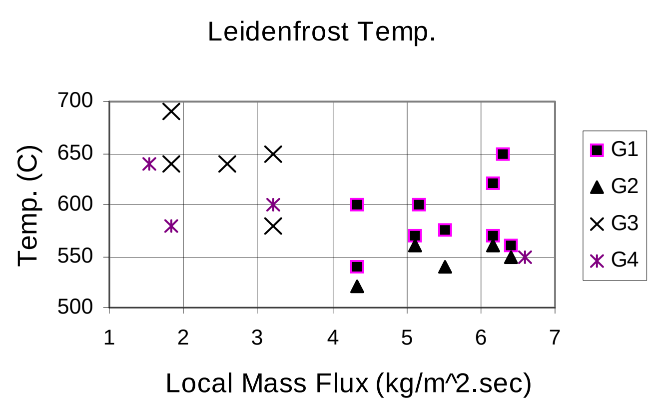


Figure 12

CONCLUSION

Systemic study for the spray cooling of high temperature metals using a full cone spray nozzle was conducted. Inverse conduction problem solution was applied to find the transient heat transfer rate and temperature of the surface using temperatures at two different depths inside a test plate of stainless steel. Two orientations of the spray are investigated, vertical down flow and horizontal flow, to reveal the gravity effect.

In general, it has been found that the minimum film boiling heat flux and the maximum (critical) heat flux both increase with the increasing of mass flux. The vertically down spray also gives slightly higher heat fluxes. The overflow of the residual water from the upstream induces slightly higher heat fluxes and higher Leidenfrost and critical temperatures. The results of this research can be used to design the proper spray cooling system to maximize steel quality.

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