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Study of Characteristics for Slant Slit Jet Cooling on Hot Rolled Plate

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Abstract -The objective of the study is a systematic experimental analysis of slant slit jet cooling of hot rolled steel plates with different flow rates, nozzle gaps and nozzle to plate distance.

Experiments were performed on a pilot scale run-out table with a moving bed. The stainless steel test plates were conveyed through the cooling section of the facility at a speed of 1 m/s.

A slit jet nozzle with a gap of 3, 5 or 10 mm, and located at a distance of 30 mm ~ 100mm above the top surface of the plate provided a slant slit jet for cooling.

Experimental data collected during experiments included thermocouple signals for temperature measurements of the plate, water flow rate, water temperature and speed of plate. In addition video images during cooling of the steel plates were collected using a high-speed camera.

Temperature data were processed using an Inverse Heat Conduction Model (2D finite element) to calculate the corresponding surface heat fluxes. Heat flux data were integrated over a specified area to calculate the amount of heat extracted from the test plate under different experimental conditions.

The flow rate had a relatively minor effect on heat transfer rate. The only noticeable effect was for the flow rates between 180 l/min and 360 l/min where a decrease of flow rate decreases the values of peak heat fluxes and heat extraction rates.

The effect of the spray angle on cooling was significant between 15^o and 30^o with higher peak heat fluxes and higher heat extraction at a spray angle of 15^o.

The effect of spray height on cooling was minor within the experimental conditions.

Concerning the effect of the nozzle gap, the experiments performed at three different flow rates consistently show that the most efficient heat transfer was obtained with the gap of 5 mm compared to the 3mm and 10 mm gap.

The speed of the plate has a significant effect on the heat fluxes and also the amount of extracted energy from the plate. Slower moving plates spend more time in the cooling section which results in larger heat extraction.

The water temperature has negligible effect on the heat extraction within the experimental conditions of this study.

Keywords**:** water cooling, heat transfer, slant slit jet, plate cooling, inverse heat conduction

1. Introduction

Run-out table cooling of steel products after hot rolling is recognised as one of the critical steps for the control of microstructure and mechanical properties of steel strips and plates. The strip or plate is cooled by an array of water jets impinging on the surface of the steel. Different types of nozzles and different cooling arrangements can be employed during the production of hot rolled products which will result in various, generally very high cooling rates. These high cooling rates are achieved by boiling of water in contact with steel. Depending on the surface temperature of the strip or plate as well as a number of other parameters, such as water temperature or water flow rates, for example, different cooling patterns on the steel surface can be observed [1] and detailed knowledge of boiling heat transfer during jet impingement is necessary to further improve this processing stage.

A limited number of experimental studies are available in the open literature that deals with jet impingement boiling with industrial scale jets. The objective of this study is the experimental investigation of jet impingement using slant slit jets. The experiments were carried out on a pilot scale facility using industrial size nozzles.

2. Experimental Apparatus and Procedures

The pilot scale run-out table, located in the Centre for Metallurgical Process Engineering at the University of British Columbia (UBC) in Vancouver, Canada has been constructed to accommodate experiments very close to industrial cooling conditions. A hydraulic moving bed carries the test plates through the cooling section where various, industrial size nozzles can be employed. The main components of the facility, as shown in Figure 1, are the electric furnace (1), the hydraulic motor (2) which controls the motion of the test bed (3), and the cooling section (4), an overhead water tank equipped with an electric heater for control of the water temperature, a network of water lines feeding the water into the header, and the bottom water tank for collecting the water used for cooling. During the test, a controlled amount of water is circulated in the cooling section via a water pump in a closed loop. A detailed description of the facility, instrumentation of plates, test procedures and analysis of the accuracy of experimental data can be found elsewhere. [2]

The cooling section for the present experiments consists of a header and a slant slit nozzle attached to the bottom of the header. This design allows the use of the same header with various nozzles and 3 different slant slit nozzles with slot widths of 3, 5 or 10 mm were used in these experiments. The length of the slot was 300 mm for all 3 nozzles. The header is connected to a water line with a flow meter which monitors the flow rate into the header. Figure 2 depicts the header box with the slant slit nozzle and Figure 3 shows the slant slit jet in operation. During slant slit jet experiments the nozzle-to-plate distance was 30 mm, 60 mm and 100 mm.

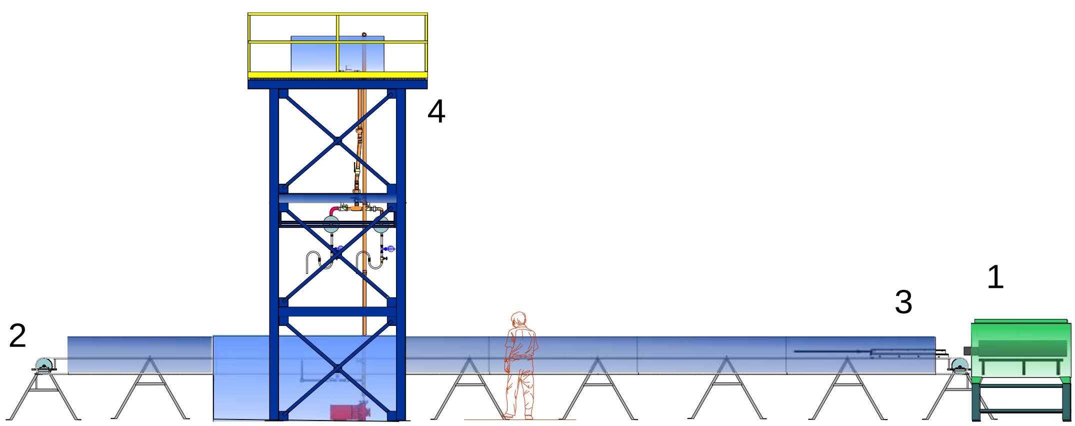

Fig. 1. Schematic of the pilot scale run-out table

The process parameters controlled during experiments include the speed of the moving bed, water temperature and water flow rate. In the present experiments the speed of the moving bed and the water temperature were kept constant at 1 m/s and 25 ^{o}C respectively whereas the flow rate was varied along with the nozzle width and nozzle-to-plate distance. Three different flow rates (180 l/min, 360 l/min and 520 l/min) were employed.

Test plates were made of stainless steel (304 L) and instrumented with internal thermocouples for temperature measurements. The size of test plates was 1200x300mm with a thickness of 10 mm.

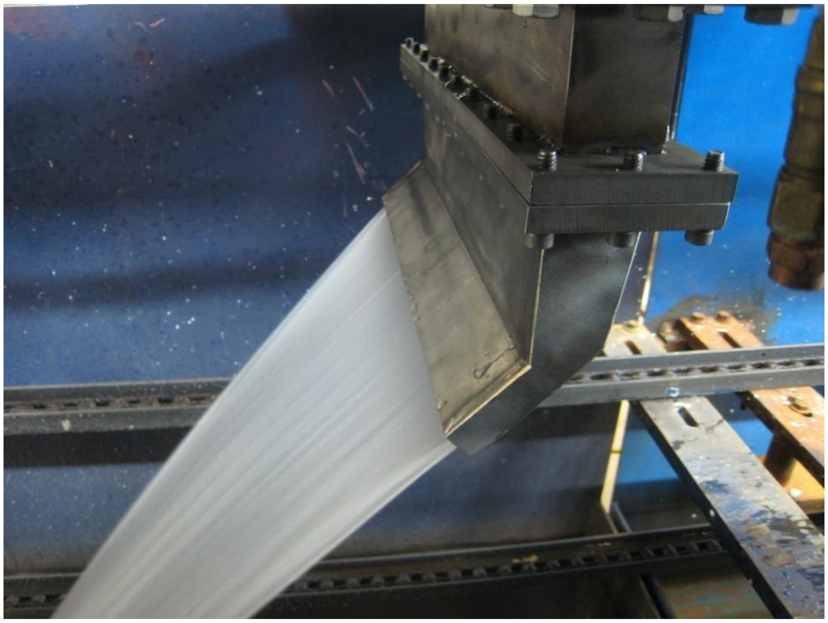

Fig. 2. The header box with installed nozzle

Fig. 3. Slant slit jet cooling system in operation

In preparation for the experiment the test plate was placed into the furnace and heated up to a temperature above 900^{o}C. Before the start of an experiment, the speed of the moving bed, water temperature and water flow rate were adjusted to obtain the required values. The test plate was, subsequently, removed from the furnace, placed on the guides of the moving bed and driven through the test section where cooling takes place. Multiple passes through the test section simulated the cooling process on the run-out table. The internal temperatures at the various locations, all at the depth of about 1mm inside the plate, were collected during experiments. Surface temperatures and surface heat fluxes were subsequently calculated for each temperature data point using an Inverse Heat Conduction code [3]. During each pass through the cooling section the plate cools down which is indicated by a dip in the surface temperature. It should be noted that this large temperature drop can be observed only close to the surface. Inside the plate the temperature, although also decreasing, remains much higher than the surface temperature which is due to the limited thermal conductivity of steel. After the test plate has left the cooling section, the surface temperature rebound as heat, due to temperature difference, is supplied from the inside of the plate. In the same way, the surface heat flux increases dramatically during a pass through the cooling section reaching peak values in the order of 2-5 MW/m2 but drops quickly after the test plate has left the cooling section.

Two types of data were chosen to compare different cooling conditions: a) Peak heat fluxes (PHF), in MW/m2; b) Heat extracted per unit area, in MJ/m2. Peak heat fluxes are maximum surface heat fluxes obtained during a pass through the cooling section. Peak heat fluxes can be linked to corresponding surface temperatures to obtain a form of a boiling curve. The extracted heat represents the amount of energy removed from the test plate during each pass.

To obtain the heat extracted per unit area the following procedure was employed: Upon obtaining the local heat fluxes, the average heat flux was found by integration over distance for the sequence of thermocouples in the lateral direction. This represents the heat flux across the width of the test plate at any instant during the experiment. Next, the average heat flux was integrated over time for the duration of a pass of the plate under a header. One data point is generated for each pass and it represents the amount of heat extracted per unit area (J/m2) during the pass of the plate under the header. Heat extraction is plotted as a function of the entry temperature which is the temperature of the plate at entrance to the cooling section. These two parameters allow for comparison of different cooling conditions.

3. Results and Discussion

3. 1. Effect of Flow Rate on Cooling

The increase in the flow rate for the same experimental conditions of nozzle gap and nozzle to plate distance will generally result in an increase of peak heat fluxes. This is illustrated in Figure 4 for 3 different flow rates and a nozzle gap of 3 mm.

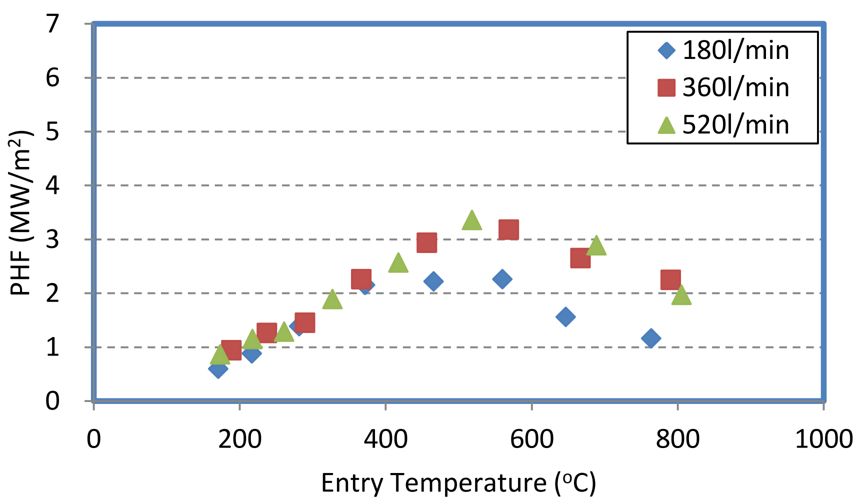

Fig. 4. The effect of flow rate on the magnitude of heat fluxes during the slant slit jet cooling, nozzle gap 3 mm, height 60 mm, spray angle of 15^{o}, speed of plate 1 m/s and water temperature 25 ^{o}C

3. 2. Effect of Spray Angle on Cooling

The effect of the spray angle on cooling has been analyzed for 3 different nozzles, all 3 having a gap of 5mm. A smaller spray angle (i.e. 15^{o}) will result in higher peak heat fluxes and higher heat extraction rate than for larger spray angles (i.e. 30^{o} or 45^{o}). This is illustrated in Figures 5 for flow rates 180 l/min and a nozzle to plate distance of 60 mm.

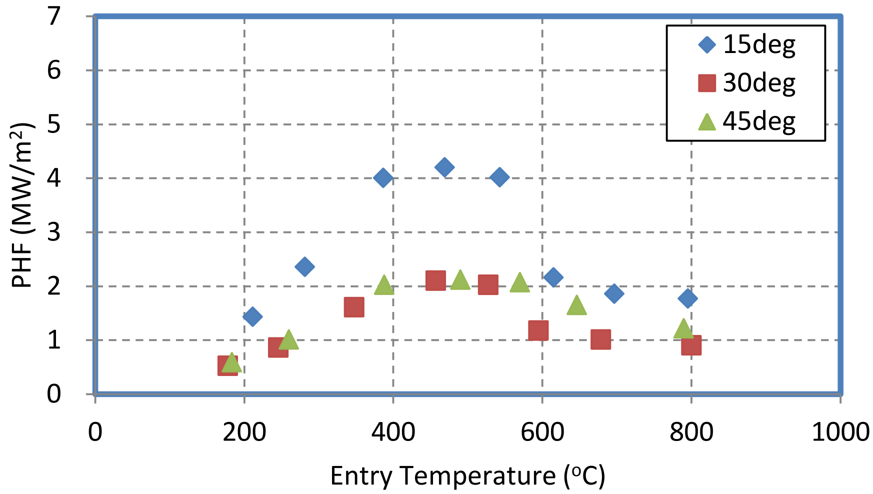

Fig. 5. The effect of spray angle on the magnitude of peak heat fluxes during slant slit jet cooling: nozzle gap 5 mm, height 60 mm, flow rate 180 l/min

3. 3. Effect of the Nozzle to Plate Distance on Cooling

Slant slit jet experiments with a gap of 5mm and spray angle of 15^{o} were performed with 2 different nozzle to plate distances, i.e. 60 mm and 100 mm, for all 3 flow rates. As shown in Figures 6 and 7 for the flow rate of 180 l/min peak heat fluxes decrease with an increase in distance, but there is no significant effect on heat extraction. These findings are similar to those made at higher flow rates (i.e. 360 l/min and 520 l/min).

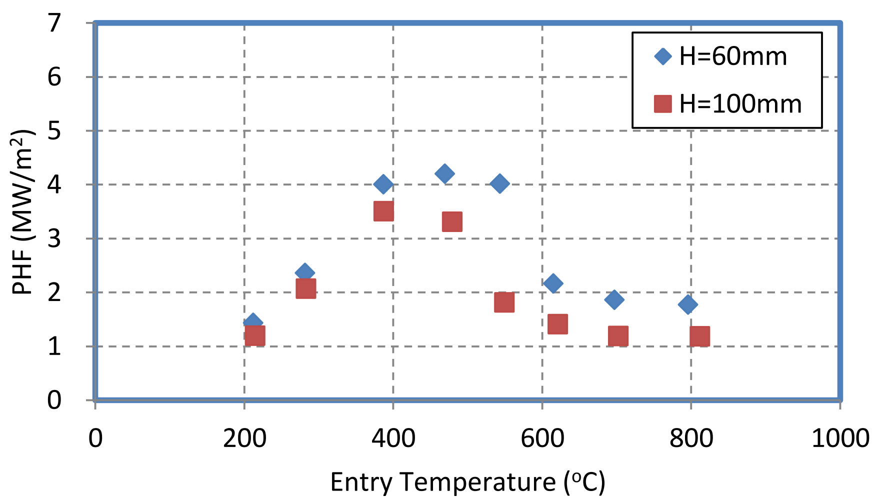

Fig. 6. The effect of nozzle to plate distance on the magnitude of heat fluxes during slant slit jet cooling: nozzle gap 5 mm, spray angle 15^{o}, flow rate 180 l/min

3. 4. Effect of the Nozzle Gap on Cooling

The analysis of the effect of the nozzle gap on the cooling with slant slit jet was performed with the spray angle of 15^{o} and at the nozzle height of 60 mm. The 3 nozzle gaps were 3, 5 and 10mm. The results are illustrated in Figures 8 for flow rates 520 l/min.These results reveal that the highest cooling rates were obtained with a gap of 5 mm regardless of the flow rate. This may indicate a coupled effect of the jet impingement velocity. As already discussed in the section on water curtain experiments, while it is commonly accepted that an increased water velocity increases the cooling rates (by increasing the convective portion of heat transfer) it may also contribute to splashing and generally less efficient flow patterns on the surface of the plate thus reducing heat transfer rates.

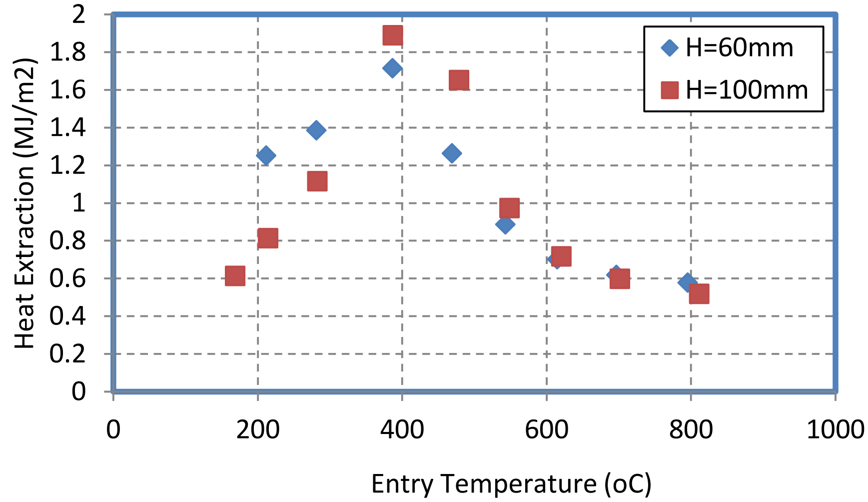

Fig. 7. The effect of nozzle to plate distance on the heat extraction during slant slit jet cooling: nozzle gap 5 mm, spray angle 15^o, flow rate 180 l/min

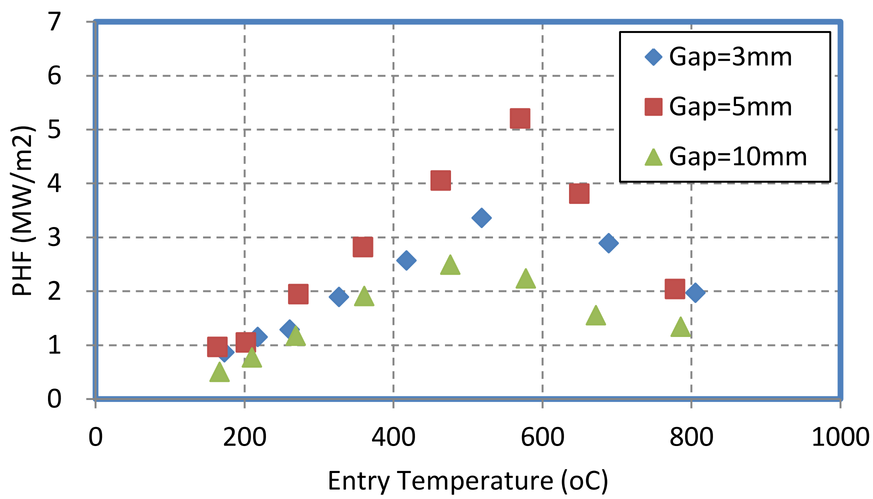

Fig. 8. The effect of nozzle gap on the magnitude of heat fluxes during the slant slit jet cooling, nozzle height 60 mm, spray angle 15^o, flow rate 520 l/min

3. 5. Effect of Plate Speed on Cooling

The experiments used in this analysis were all performed with the nozzle gap of 5 mm, nozzle to plate distance of 60 mm, spray angle of 15^o, water temperature of 25 ^{o}C and three different flow rates. The results are illustrated in Figures 9 for the peak heat flux with the speed of plate in experiments with the flow rate of 180 l/min. As expected, the speed of the plate has a significant effect on the heat fluxes and also the amount of extracted energy. Plates moving slower through the cooling section have more time to spend under the nozzle and larger peak heat fluxes and heat extraction are achieved. This can be consistently observed in all experiments regardless of the flow rate. The difference in heat fluxes and extracted energy can be clearly observed in the high temperature region. In the low temperature region the influence of the speed of plate on the peak heat fluxes is less pronounced, particularly in the experiments with higher flow rate. The heat extraction is, however, higher for the lower speed over the whole entry temperature range.

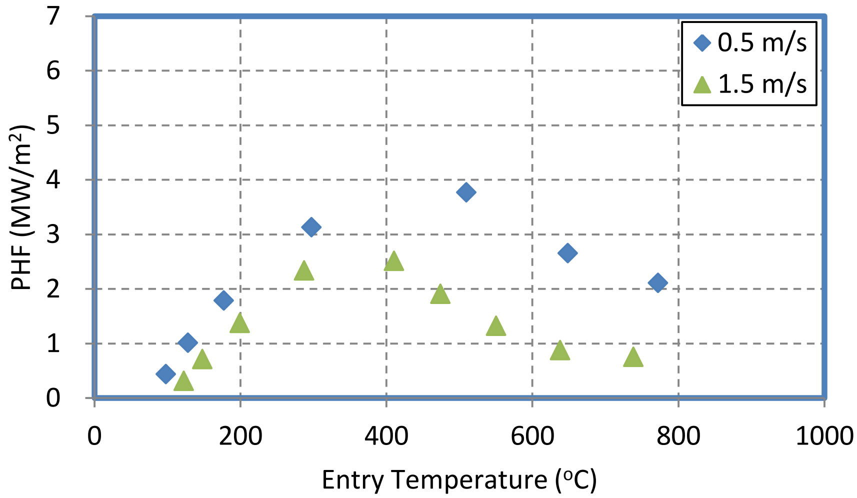

Fig. 9. The effect of the speed of plate on peak heat flux during slant slit jet cooling: Nozzle gap 5mm, nozzle height 60 mm, spray angle 15^o, flow rate 180 l/min

4. Conclusion

Slant slit jet experiments were carried out at 3 different flow rates (180, 360 and 470 l/min), 3 different nozzle gaps (3 mm, 5 mm and 10 mm) and 2 different nozzle-to-plate distances (400 mm and 1000 mm) using the speed of plate of 1.0 m/s and a water temperature of 25 ^{o}C. We can conclude that:.

A total of 31 experiments has been carried out in Phase 2 which, with additional 13 experiments from Phase 1 of the project provides an experimental database covering 3 different flow rates (180, 360 and 520 l/min), 3 different nozzle gaps (3 mm, 5 mm and 10 mm), 3 different nozzle-to-plate distances (30 mm, 60 mm and 1000 mm), 3 different spray angles (15^o, 30^o and 45^o), 3 different plate speed (0.5 m/s, 1.0 m/s and 1.5 m/s) and 3 different water temperatures (15 ^{o}C, 25 ^{o}C and 35 ^{o}C).

Slant slit experiments were analyzed in regard to variation of flow rates, spray angle, spray height, nozzle gap, speed of the plate and water temperature

- The flow rate had a relatively minor effect on heat transfer rate. The only noticeable effect was for the flow rates between 180 l/min and 360 l/min where a decrease of flow rate decreases the values of peak heat fluxes and heat extraction rates.
- The effect of the spray angle on cooling was significant between 15o and 30o with higher peak heat fluxes and higher heat extraction at a spray angle of 15^o.
- The effect of spray height on cooling was minor within the experimental conditions of phase 2.
- Concerning the effect of the nozzle gap, the experiments performed at three different flow rates consistently show that the most efficient heat transfer was obtained with the gap of 5 mm compared to the 3mm and 10 mm gap.
- The speed of the plate has a significant effect on the heat fluxes and also the amount of extracted energy from the plate. Slower moving plates spend more time in the cooling section which results in larger heat extraction.
- The water temperature has negligible effect on the heat extraction within the experimental conditions of this study.

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