EXPERIMENTAL INVESTIGATION OF SPRAY COOLING OF HORIZONTALLY AND VERTICALLY ORIENTED SURFACES

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Abstract

The spray cooling of stainless steel plates was studied using different orientations of the cooled surface. A 1.5 mm-thick test plate was moved vertically or horizontally with a velocity of 3 m/s. Experiments were conducted with mist nozzles oriented either vertically with the spray flowing down or horizontally. The water impingement density was between 0.93– 9.68 kg m$^{-2}$ s$^{-1}$. It was found that the heat transfer coefficient is similar for horizontally and vertically down oriented nozzles within the surface temperature range of 700–900°C. The vertically down spray yields a higher heat transfer coefficient for surface temperatures below 300 °C. Furthermore, it was observed that the Leidenfrost temperature is slightly higher for vertically down spray for lower water impingement densities. This shift of the Leidenfrost temperature was not observed for higher water impingement densities.

Keywords: spray cooling, surface orientation, heat transfer

1. INTRODUCTION

Spray cooling technology for high temperature surfaces plays an important role in the metal production and processing industry. Especially in steel industry, spray cooling is used as a secondary cooling procedure in strip casting, for the final microstructure optimization after hot rolling and in some heat treatment processes. Although lots of articles deal with parameters which influence the cooling for example water temperature [1], surface hardness [2], water impingement density and pressure [3, 4] for vertically down oriented nozzles, the effect of the orientation of nozzles has not been thoroughly investigated and it is not known, if the results obtained for vertically down orientation are valid for the horizontal orientation of nozzles. Only a few papers [5, 6] deal with the influence of the orientation of nozzles on cooling. An Experimental study was conducted on a cylindrical plate of stainless steel of 12.5 cm diameter and a thickness of 2.5 cm in [5]. The local mass flux of the water was in the range of 1.5 - 6.6 kg s$^{-1}$ m$^{-2}$ and nozzles were Spraying System Co. HHX-12. These experiments were conducted with a stationary plate. The results presented in [5] are: the heat flux is slightly higher for vertically down orientation of spray compared to the horizontal orientation and the Leidenfrost temperature is lower for horizontal spray than vertically down flowing spray.

This paper describes experiments, which were conducted with special mist nozzles with different orientations. The cooling of a 1.5 mm thick stainless steel sheet was investigated with nozzles both vertically and horizontally oriented.

2. EXPERIMENTAL MEASUREMENTS

The heat transfer coefficient measurements were made for two spray positions. In the first group of experiments nozzles were oriented vertically down and the test plate moved horizontally (Fig.1). In the second group of experiments the nozzles were oriented horizontally and the test plate moved vertical direction (Fig. 2). The cooling was with special mist nozzles which used a large amount of low pressure air (up to 10 kPa) and water with pressure up to 6 bars. The cooling was with three rows of nozzles. The distance between each row was 330 mm and the distance from the nozzle orifice to the test sheet was 250
mm. Three experiments, each with different water impingement density, were conducted in each group of experiments. The water impingement densities were in the range of 0.93 – 9.68 kg s\(^{-1}\) m\(^{-2}\). Detailed information about tested parameters is shown in the Table 1. As it is known that water temperature has a significant effect on cooling [1], all experiments were conducted with the same water temperature 40 °C. The velocity of the movement was 3 m/s in all experiments. This velocity corresponds to the real situation in the steel mill. The temperature was measured with four thermocouples of type K, which were welded on the rear (not sprayed) side of the test sheet near the center. Each experiment was conducted with a new stainless steel test sheet with a thickness of 1.5 mm and dimensions 320 mm x 300 mm. The furnace, which heated the test sheet to 950 °C, was on the bottom (experimental apparatus for cooling with vertically down oriented nozzles) or on the top (experimental apparatus for cooling with horizontally oriented nozzles) of the experimental apparatus (see Fig 1 and Fig 2). The heating was conducted in the protective atmosphere to minimize the effect of the oxide layer [7]. After heating at the temperature 950 °C, the test sheet repeatedly passed with velocity 3 m/s through the cooling section (spraying nozzles) until it was cooled at the temperature 200 °C. Nozzles were connected to a manometer and through a pump with flow meter to the water tank with adjustable water temperature. The test sheet holder was equipped with a position sensor and data acquisition system (data logger), which recorded the information about the position of the test sheet and temperatures for each thermocouple with a frequency of 320 Hz.

Table 1 Table of experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Water impingement density [kg s(^{-1}) m(^{-2})]</th>
<th>Water pressure [bar]</th>
<th>Water Temperature [°C]</th>
<th>Air Flow Rate [m(^3) h(^{-1}) m(^{-2})]</th>
<th>Spray Height [mm]</th>
<th>Velocity of the movement [m/s]</th>
<th>Orientation of nozzles</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>0.93</td>
<td>0.07</td>
<td>40 °C</td>
<td>1497.5</td>
<td>250</td>
<td>3</td>
<td>Vertically down</td>
</tr>
<tr>
<td>V2</td>
<td>3.48</td>
<td>0.2</td>
<td>40 °C</td>
<td>1529.5</td>
<td>250</td>
<td>3</td>
<td>Vertically down</td>
</tr>
<tr>
<td>V3</td>
<td>9.68</td>
<td>1.3</td>
<td>40 °C</td>
<td>1204.4</td>
<td>250</td>
<td>3</td>
<td>Vertically down</td>
</tr>
<tr>
<td>R3</td>
<td>0.93</td>
<td>0.07</td>
<td>40 °C</td>
<td>1497.5</td>
<td>250</td>
<td>3</td>
<td>Horizontal</td>
</tr>
<tr>
<td>R4</td>
<td>3.48</td>
<td>0.2</td>
<td>40 °C</td>
<td>1529.5</td>
<td>250</td>
<td>3</td>
<td>Horizontal</td>
</tr>
<tr>
<td>R7</td>
<td>9.68</td>
<td>1.3</td>
<td>40 °C</td>
<td>1204.4</td>
<td>250</td>
<td>3</td>
<td>Horizontal</td>
</tr>
</tbody>
</table>

Fig. 1 Experimental apparatus for cooling with vertically down oriented nozzles
**Fig. 2** Experimental apparatus for cooling with horizontally oriented nozzles

**Fig. 3** Photo of experiment - horizontal orientation of nozzles
3. RESULTS

The measured temperatures were recomputed to the surface temperatures (sprayed/cooled side) at location of thermocouples by the inverse task [8]. An example of computed surface temperatures from thermocouples is shown in Fig. 4. The recording of the temperatures started about 8 seconds before removing the test plate from the furnace. When the test plate passed through the cooling section the temperature dropped and when the test plate was outside the cooling section the measured temperature remained almost steady or increased (Fig. 4). The heat transfer coefficient was computed by the inverse conduction algorithm [9]. The average heat transfer coefficient (average value over the length of the cooling section (660 mm) from all thermocouples) was computed for all measured experiments. The comparison of them is shown in Fig. 5. The nozzles orientation was vertically down in experiments V1, V2 and V3. The orientation was horizontal in experiments H1, H2 and H3. Experiments H1 and V1 (similar for H2, V2 and H3, V3) differed only in orientation of nozzles. It is evident, that the heat transfer coefficient for nozzles orientation vertically down is similar or greater than for horizontal orientation in the film boiling regime (700-900 °C). Only experiments conducted with water impingement density 3.48 kg s\(^{-1}\) m\(^{-2}\) (V2 and H2) do not satisfy this presumption, but the difference of the HTC between H2 and V2 is not so high and can be

![Graph of surface temperature over time](image)

**Fig. 5** Example of computed surface temperatures

![Graph of HTC on surface temperature](image)

**Fig. 4** Dependence of HTC on the Surface Temperature
explained by the error of measurement, which is around 10%. This is shown in Fig. 6 (left), where the average value of the HTC was computed for the temperature range of 700-900 °C. This temperature range is well above the Leidenfrost temperature, where the surface is protected by the vapor layer. This vapor layer protects the surface before spraying water and minimizes the effect of nozzles orientation. The nucleate boiling regime show a different situation, which occurs approximately between 100 °C and 300 °C for these experiments (see Fig. 6 – right). The hot test plate is directly wetted by the spraying water. The water layer, which creates on the surface, increases the heat transfer coefficient for nozzles orientation vertically down.

The comparison of the influence of the orientation of nozzles on the Leidenfrost temperature and Critical heat flux is shown in Fig. 7. The Leidenfrost temperature is defined as the temperature at which the character of boiling changes. Film boiling is changed into transition boiling. The Leidenfrost temperature is also defined as the temperature at which the heat flux reaches a minimum on the Nukiyama’s boiling curve [10]. When the water impingement density is small (H1, V1), the Leidenfrost temperature is lower for horizontal orientation of nozzles. This result matches with the result presented in [5], where the water impingement density is also small. The Leidenfrost temperature is smaller for vertical down orientation, when the water impingement density is high. The critical heat flux, which is defined as a maximum heat flux, was higher for vertical down orientation (see Fig. 7 – right).

**Fig. 6** Average value of The HTC in the film boiling regime (left) and in the nucleate boiling regime (right)

**Fig. 7** Leidenfrost temperature (left) Critical heat flux (right)
4. CONCLUSION

Experiments with different orientation of mist nozzles were conducted. It was found that the heat transfer coefficient for nozzles orientation vertically down is similar or greater than for horizontal orientation in the film boiling regime (700 – 900 °C). The heat transfer coefficient is higher for vertical down orientation of nozzles in the nucleate boiling regime (100 – 300 °C). Furthermore, it was observed that the Leidenfrost temperature is influenced by the orientation of nozzles. The Leidenfrost temperature was slightly higher for horizontal orientation for higher water impingement densities. The Critical heat flux was higher for vertical down orientation of nozzles.

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LITERATURE