FACTORS INFLUENCING SPRAY COOLING OF HOT STEEL SURFACES

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Abstract

The spray cooling is a common cooling method in the steel industry (continuous casting, hot rolling, product cooling or heat treatment). The water is sprayed on the hot surface by the nozzle which transforms the water stream into droplets. Sprays can provide very high cooling rates with the benefit of the regulation of the cooling process. The spray cooling is influenced by several parameters. They can be divided into two groups. The first group deals with spray parameters like water impact density, water temperature, water additives and droplets size. The second group relates to cooled surface: temperature, velocity, roughness and presence of scales. This paper describes non-stationary spray cooling experimental measurement and deals with factors influencing the spray cooling. The influence of each factor is experimentally investigated and the influence on the heat transfer coefficient or Leidenfrost temperature is described based on experimental results and or existing publications.

Keywords: Spray cooling, heat transfer coefficient, Leidenfrost temperature, scales, surface roughness

1. INTRODUCTION

The water spray cooling is a common cooling method in the steel industry (continuous casting, hot rolling, product cooling or heat treatment [1]). The spray cooling of hot surfaces (presence of boiling) is influenced by factors which relates to sprayed surface (temperature, velocity, roughness and presence of scales) and to spray (water impact density, water temperature, water additives and droplets size). Number of factors makes the prediction of the cooling intensity (heat transfer coefficient (HTC)) complicated and so the experimental measurement is only one way how to obtain exact value of the HTC for spray cooling of hot surfaces. The key factor is the water impact density [2]. There are some empirical correlations based mainly on this factor [2 and 3] but their quality of the prediction is limited due to other not included factors. Although sprays can provide very high cooling rates with the benefit of the regulation of the cooling process, it is necessary to account all mentioned factors to be able exactly predict and regulate the cooling process. This paper deals with all mentioned factors and its influence on the cooling intensity (heat transfer coefficient and Leidenfrost temperature). There is also a description of the experimental measurement and data processing for obtaining the spray heat transfer coefficient.

2. EXPERIMENTAL MEASUREMENT AND DATA PROCESSING

A laboratory experimental apparatus (**Figure 1**) which simulates the spray cooling (secondary cooling zone) during continuous casting of the steel, was used for tests on the influence of different parameters which influences the spray cooling. A steel frame holds three major parts of the apparatus: the test stainless steel plate (EN 1.4828) with thickness of 25 mm, a moveable mechanism with a nozzle and a heater (heating up to 900 °C - 1250 °C). The nozzle moves at a prescribed velocity under the static test sample. The nozzle moves in one direction with opened deflector and returned with closed deflector. The test plate is equipped by thermocouples which measure the temperature in the depth of 2 mm. The inverse heat conduction problem is used to compute the time dependent boundary conditions (heat transfer coefficient (HTC), heat flux, and surface temperature) from measured temperatures. Beck's sequential approach, which uses a sequential estimation of the time varying boundary conditions and future time steps, is employed [4 and 5]. Examples of time-dependent measured temperature (2 mm above the surface), surface temperature and surface heat transfer coefficient are shown in **Figure 2**. Further, the dependence of the HTC or heat flux on the surface temperature and position in the cooling section is obtained. The example of dependence of the avg. HTC and or heat flux on the surface temperature is shown in **Figure 3**. The average values are obtained by averaging the data along the position (symmetrical interval along the center of the nozzle's jet in the direction of the nozzles movement).

Figure 1 Experimental apparatus

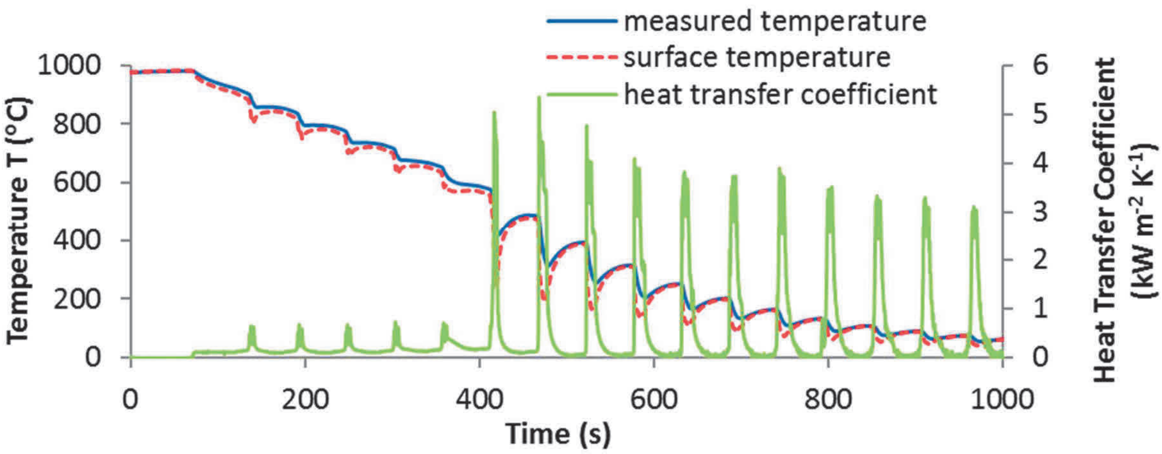

Figure 2 Measured temperature, computed surface temperature, and computed heat transfer coefficient

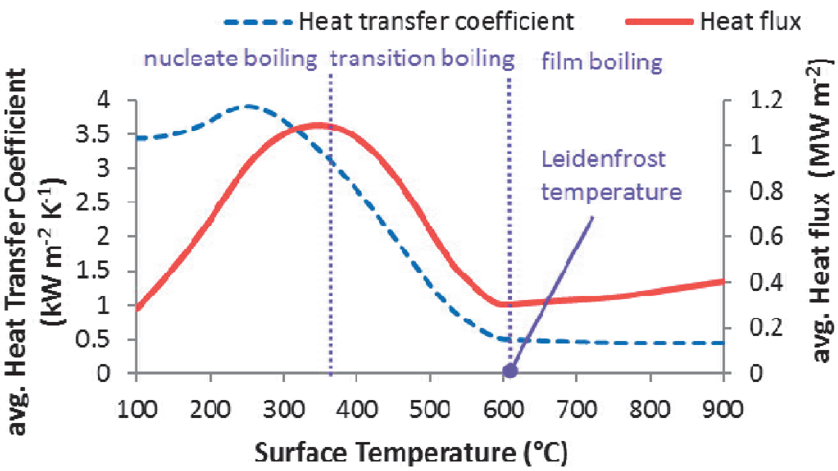

Figure 3 Dependences of the heat transfer coefficient (blue) and heat flux (red) on the surface temperature

3. FACTORS INFLUENCING SPRAY COOLING

Factors can be divided into two groups. The first group relates to cooled surface: temperature, roughness, presence of scales and velocity of the movement. The second group deals with spray parameters like water impact density, water temperature, water additives and droplets size. Later, the influence of each factor on the heat transfer coefficient and or Leidenfrost temperature is briefly described based on the experimental data measured in the Heat transfer and fluid flow laboratory (BUT) and based on existing publications. The experimental data were measured according previous description of the experimental process.

3.1. Surface temperature

The influence of the surface temperature on the spray cooling is significant and it relates to different boiling regimes. As described by many heat transfer text books [6 and 7], if a liquid is in near contact with a surface significantly hotter than the liquid's boiling point, the heat transfer boiling phenomena based on the heat flux data or a boiling curve (heat flux versus excess temperature) can be characterized by four different regimes: a) free convection (single-phase), b) nucleate boiling, c) transition boiling and d) film boiling. Based on the boiling curve, at the onset of the film boiling (between the transition boiling and film boiling regimes), the heat flux is minimal and the corresponding temperature is known as the Leidenfrost temperature (TL) or point. The critical heat flux (CHF) occurs when the heat flux reaches the maximum on the boiling curve. The CHF point is the transition point between transition boiling regime and nucleate boiling regime. Temperature areas for different boiling regimes are shown in **Figure 3**. It is evident that the HTC is significantly lower during film boiling regime than during nucleate boiling regime.

3.2. Surface roughness

Experimental research in the Heat transfer and fluid flow laboratory [8] showed that the surface roughness significantly influences the Leidenfrost point and critical heat flux point for spray cooling. It was observed that the critical heat flux increases with surface roughness (Ra) (**Figure 4 - left**) and the Leidenfrost temperature linearly increases with increasing surface roughness (Rz) (**Figure 4 - right**). Comparable results were observed during immersion cooling experiments [9].

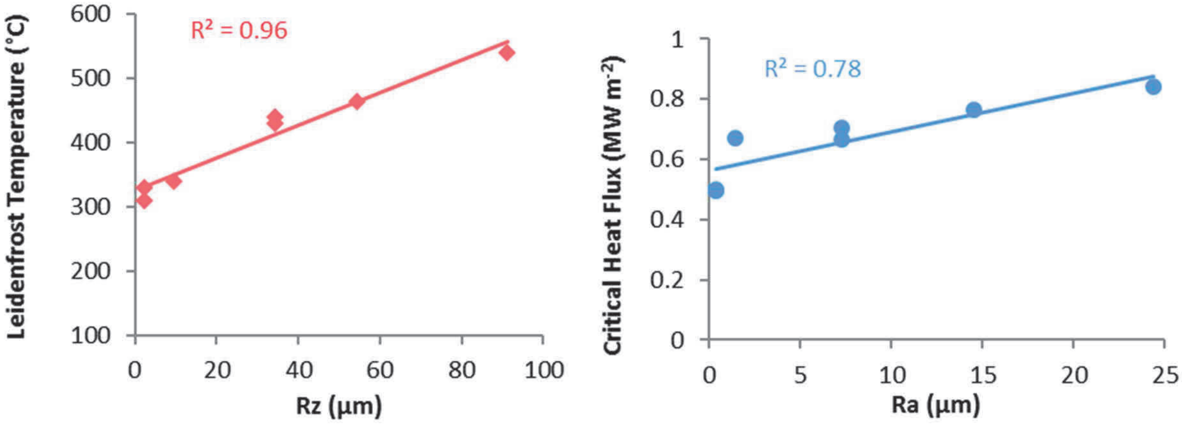

Figure 4 Dependence of the critical heat flux on the surface roughness parameter Ra (left) and dependence of the Leidenfrost temperature on the surface roughness parameter Rz (right) [8]

3.3. Scales layer on the surface

The presence of scales (oxide layer) on the steel surface can significantly influence the cooling [10]. The thickness of the oxide layer and its porosity depends on the oxidation conditions and steel composition [11]. The presence of the oxide layer on the steel surface causes increase of the Leidenfrost temperature and influences the critical heat flux (**Figure 5**). The Leidenfrost temperature linearly depends on the oxide layer thickness and thermal conductivity (porosity) of the oxide layer [12].

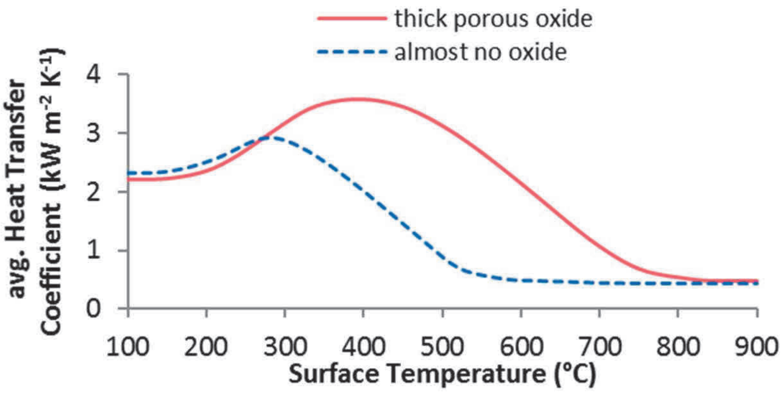

Figure 5 Influence of the oxide layer on the heat transfer coefficient [12]

3.4. Surface velocity

Raudensky and Horsky [13] by conducting experiments with a stainless steel surface cooled from 1100 °C to 900 °C by mist nozzle found that the maximum HTC decreases with the increase of the velocity. The HTC profile at 0 m/min (stationary case) was symmetrical, with a sharp peak and became asymmetric with a wider and lower peak profile as velocity increased. The above result confirms the statement that casting velocity is a significant parameter influencing heat transfer [13].

3.5. Water impact density

The amount of water which is sprayed on the cooled surface is commonly represented as water impact (impingement) density ($\dot{m}_L$ [kg m^{-2} s^{-1}]). Water impact density is significant factor, which influences the spray heat transfer. The increase of the water impact density increases the heat transfer coefficient for all surface temperatures (**Figure 6**). The increase of the water impact density increases the Leidenfrost temperature and the temperature at which occurs critical heat flux [14].

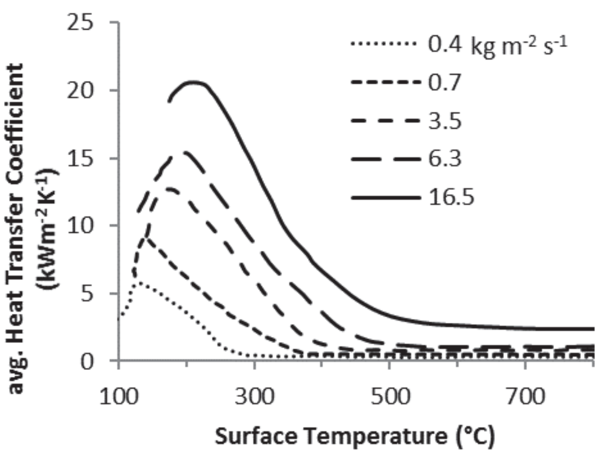

Figure 6 Influence of the water impact density on the heat transfer coefficient [14]

3.6. Water temperature

The water temperature is significant factor, which influences mainly the Leidenfrost temperature. Research performed with mist nozzles [15] and with water solid jet nozzles [16] showed that the increase of the water temperature causes decrease of the Leidenfrost temperature. Extensive experimental research in the Heat transfer and fluid flow laboratory showed that this dependence is almost linear (**Figure 7**). This research was conducted with different types and sizes of nozzles according description in the chapter 2 of this paper.

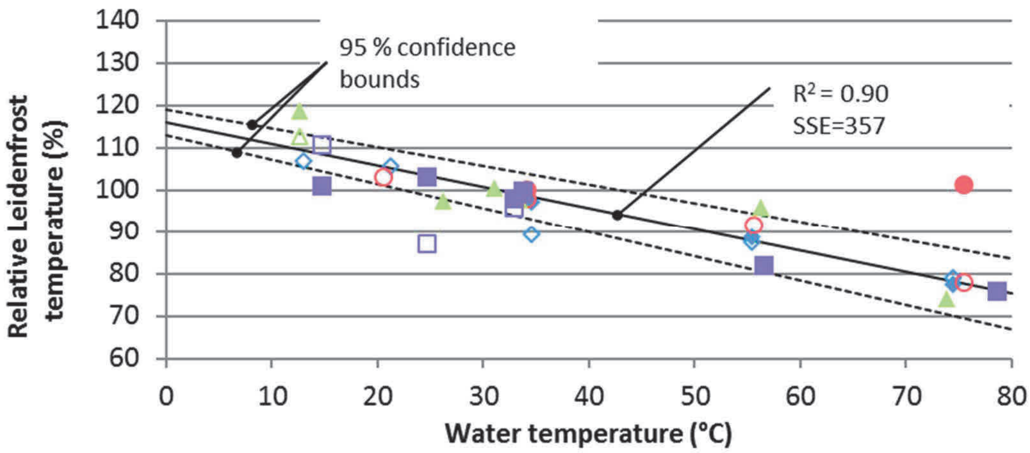

Figure 7 Influence of the water temperature on the Leidenfrost temperature

3.7. Water additives

Water additives mainly influences the duration of the film boiling regime. Additives can be split into two groups according their influence on the duration of the film boiling regime (extending and shortening). First group (extending) is composed of solid particles (ceramic particles, soot, nanoparticles [17]), gases (N_2, O_2 a CO_2) and liquids (oil and fat) insoluble or poorly soluble in water. Second group (shortening) is composed of salts, acids and alkali, which are soluble in water. NaCl is most common inorganic salt, which is commonly used during immersion quenching but its use during spray cooling is unusual. [18]

3.8. Water droplets size

Generally, the droplet diameter has negligible effect on the spray cooling. Labeish [19] observed a slight decrease in heat removal rate in film boiling with the increasing drop size. It was observed that the critical heat flux is slightly higher for nozzles which produce smaller droplets [20].

4. CONCLUSION

Except droplet size all other investigated factors (temperature, roughness, presence of scales, velocity of the movement, water impact density, water temperature, water additives) significantly influences the cooling and they should not be neglected in the modeling of the spray heat transfer. The increase in the surface roughness, oxide layer thickness (scales), water impact density or the decrease of the water temperature cause increase of the Leidenfrost temperature. The increase of the water impact density increases the heat transfer coefficient for all surface temperatures. The heat transfer coefficient decreases with the increase of the velocity of the steel plate. The increase of the surface roughness cause increase of the critical heat flux. The Water additives mainly influences the duration of the film boiling regime (change of the Leidenfrost temperature).

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