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Influence of salt mixture on the heat transfer during spray cooling of hot metals

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ABSTRACT

A hot aluminum alloy AA6082 disc at 560 °C was cooled by a spray nozzle with a constant volumetric spray flux of 3 kg/m^2/s. The temperature history during the cooling process was recorded with use of an infrared camera. The influence of salinity in the cooling water was observed by dissolving various concentrations of $MgSO_4$ to the deionized water. Deionized water was used as the reference. Moreover, eight different types of real solution used in the metal processing industry were compared. The heat transfer coefficient α in the film boiling, maximum heat flux, as well as the Leidenfrost and DNB temperature increase with the electrical conductivity (EC) of the real solutions. EC is introduced as a mean to measure the salinity in the cooling water. The change of salinity content in the cooling water must be maintained by product quality control in industries as it can significantly lead to the change of the cooling rate.

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1. Introduction

During the cooling processes in the continuous casting of metals and in the hardening of metal alloys, water sprays are often used. At high surface temperatures, the heat is transferred through a vapor film until it reaches the minimum heat flux at which the temperature is called the Leidenfrost temperature. When the surface temperature falls below the Leidenfrost temperature, the heat is transferred through transition and nucleate boiling regime until the surface temperature reaches 100 °C before finally starting the single-phase convection. In the range between the Leidenfrost temperature and 100 °C, the heat transfer can reach maximum values in the range of 5–10 times higher than that in the film boiling. Therefore, the Leidenfrost temperature will have a significant influence on the overall duration of the cooling process.

In spray cooling, the primary parameter in the determination of the heat flux is the temperature of the surface. The volumetric spray flux is known as the second important parameter that can also influence the heat flux during the cooling process [4]. Gaugler

[12] found that the volumetric spray flux has a dominant effect on heat transfer compared to other hydrodynamic properties of the spray. Al-Ahmadi et al. [5] also found that the Leidenfrost temperature, critical temperature, and maximum heat flux are strongly dependent on the local spray mass flux. Other spray parameters such as droplet size, velocity, and the type of nozzle play a less significant role [2,5,18]. Müller et al. [1] presented the change of the heat transfer coefficient (HTC) vs. surface temperature for Nickel. They investigated the HTC variation at different values of volumetric spray flux. Jeschar et al. [3] found that in the range of film boiling, HTC can only be influenced by the volumetric spray flux. Other parameters, such as drop velocity, distance nozzle to surface and nozzle type, do not require to be considered separately, as they are contained in the volumetric spray flux. However, the study of Wendelstorf et al. [4] shows HTC in the film boiling depends not only on the volumetric spray flux but also on the temperature. Puschmann et al. [14] found a similar result where HTC increased with the volumetric spray flux. They also confirmed that with a lower volumetric spray flux, the drop diameter exerts no influence on the HTC obtained. However, when they doubled the droplet velocity, they obtained about a difference of 50 W/m^2/K in the HTC.

The effect of salinity has been studied as a third relevant parameter that influences the heat treatment process. Huang et al. [7] made an intensive analysis of the influence of salt on the Leidenfrost transition. They explain the reason for the elevated Leidenfrost temperature resulting from the addition of salts. In their analysis, the suppression of bubble coalescence by dissolved salt, salt deposition during the initial contact of the deposition, and earlier

collapse of the vapor film due to the increasing salt concentration at the liquid–vapor interface were studied as the mechanisms associated with the Leidenfrost transition. KCl and NaCl were used. As a result, they found that the Leidenfrost temperature was significantly increased by the presence of dissolved salt. Cui et al. [6] conducted an experiment to observe the influence of three different salts (NaCl, Na_2SO_4, and $MgSO_4$) dissolved in a water spray used for the cooling of a hot surface. Copper heated up to 240 °C was used. It was found that the individual salts influence the heat transfer process in different ways. Some increased the performance of heat transfer in nucleate boiling while others increased both nucleate and transition boiling heat transfer. $MgSO_4$ produced the largest increase in nucleate boiling heat transfer, with Na_2SO_4 producing a somewhat less increase and NaCl producing the smallest increase. In addition, it was clearly shown that a higher concentration of salts lead to a higher maximum heat flux. Alam et al. [15] also found by using atomized spray that the Leidenfrost temperature increased with higher salt concentrations dissolved in the cooling water. Jeschar et al. [16] measured the influence of salts on the cooling process of a Nickel sphere dipped into a bath of water. $NaSO_4$, NaCl, $NaHCO_3$, $CaCl_2$, and $MgSO_4$ were used as individual salts dissolved up to 1 g/l concentration. The Leidenfrost temperature was increased up to 100 K for all salts. The solution with Mg^{2+} and SO_4^{2-} content had the strongest effect.

Although previous works have reported that salinity has a strong influence on the heat treatment process, there is no extended research published quantifying the effect of salt mixture to the Leidenfrost and DNB temperature, maximum heat flux, and heat transfer coefficient in the film boiling. In this study, those parameters are quantified for eight different real solutions used in the metal processing industry containing different salts. Electrical conductivity (EC), which has often been used as an index of the total dissolved solids (TDS), is introduced as a means of estimating the salinity level of the cooling water since EC depends on the overall ionic concentration in water [9]. The use of a single salt ($MgSO_4$) with different concentrations (0.25–12 g/l) was chosen to show the correlation between the salt concentration and its electrical conductivity. Constant and accurate reproducibility of the spatial volumetric spray flux is the most important factor in order to study the effect of salinity on spray cooling heat transfer.

2. Experimental method

2.1. Experimental setup

The experimental setup is shown schematically in Fig. 1. Basically, it consists of four main units. First, there is the heating system which is an electrically-heated furnace to heat up the sample to the desired level of temperature. In this work, all samples were heated up to 560 °C. Second, a metal sample is hung up on the rail that can shift the sample cater free from the furnace to the cooling unit direction. A disc of Aluminum Alloy AA6082 with a diameter of 140 mm and a thickness of 3 mm was used in the experiments (detailed information is summarized in Table 1). Third, there is a spray cooling unit by which the quenching process takes place, which consists of a centrifugal pump supplying water at the certain level of flow rate verified by a flow meter and a hydraulic nozzle used as a spraying component producing water droplets to the hot metal sample. A constant volumetric spray flux of 3 $kg/m^2/s$ was applied in this experiment. This volumetric spray flux was produced by applying a flow rate of 20 l/h water through a hydraulic nozzle. Fourth, there is the data acquisition system which consists of an infrared (IR) camera connected to a computer system for the image recording process.

Prepared samples have to be painted black on the back side before being put into the electrical furnace for the heating process. After that, the hot metal sample is shifted manually along the sliding rail towards the stop position where the water spray will be aimed. The stop position is adjusted in such a way so that the camera focus, center point of metal sample, and center point of spray cone are aligned. Once it reaches the stop position, the spray cover is removed and the IR camera is activated to start recording the temperature history during the cooling process. The sample moving process was verified to not cause a significant temperature drop. Every time this will not cause more than 2 °C temperature difference.

2.2. Determination of emissivity

The most important parameter of the IR camera setting is the emissivity of the surface. This is the reason why the sample must
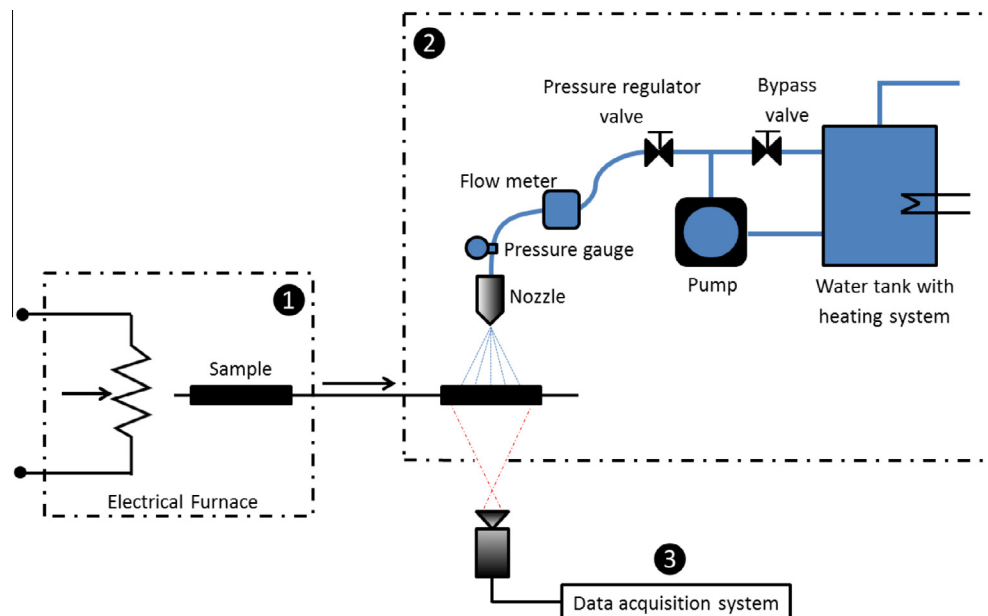

Fig. 1. Schematic diagram of quenching experimental facility (top view).