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# The influence of selected parameters of spray cooling and thermal conductivity on heat transfer coefficient

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ABSTRACT

The influence of water spray pressure, water flux and the nozzle-to-surface distance on the heat transfer coefficient during spray cooling of brass and inconel samples has been investigated. The inverse method has been employed for the heat transfer coefficient identification. The objective function defines dimensionless deference between measured and calculated temperatures. The inverse solution starts with an assumption of a general form of an approximating function of the heat transfer coefficient distribution at the cooled surface as function of sample radius and time. The unknown parameters which define the heat transfer coefficients are determined by minimizing the objective function. The variable matrix method which utilizes the Broyden-Fletcher-Goldfarb-Shanno updating technique has been employed to minimize the objective function. Uncertainty of the inverse solution has been tested based on the assumed heat transfer coefficient distribution simulating nearly real spray cooling conditions. The numerical tests have indicated significant changes in the identified heat transfer coefficients depending on the quality of the heat conduction model. The experiments of spray cooling were conducted and the temperature was measured at the selected points in the cylindrical sample. The measured temperatures have been used as an input data for the heat transfer coefficient identification. The finite element model selected based upon numerical tests has been employed in computing the sample temperature field necessary for identifying the heat transfer boundary conditions. The objective function minimizations have given the heat transfer coefficients at the cooled surface as functions of time and surface temperature for brass and inconel samples. The influence of spray cooling parameters on the heat transfer coefficient has been discussed.

## 1. Introduction

Cooling is widely used in industrial processes such as metallurgy, nuclear power plants, aerospace engineering and in microelectronic or medical devices [1,2]. In high-temperature metallurgical processes there is a need for removing large amount of heat from cooled surfaces. However, the heat transfer process shall be controlled. The desired cooling rate should allow obtaining required material properties and microstructure. The thermal stresses should be controlled as well. The required cooling rate can be obtained by selecting a proper cooling technique and a cooling agent [3,4]. These goals can be achieved using spray cooling. This method allows controlling the cooling process and offers wide range of heat fluxes extracted from cooled surfaces [5]. The most popular cooling agent in metallurgy, for economical and environmental reasons, is water. Heat transfer process that takes place during transient spray cooling of metals from high temperatures reaching 1200 °C is similar to steady state pool boiling of water. The heat transfer process is governed by the cooled surface temperature and thermal properties of fluid and cooled metal [5]. Depending on the cooled surface temperature four heat transfer regimes can be observed [5,6]. Generally, natural or forced convection, nucleate boiling, transition boiling and film boiling can be recognized. Each one of the mentioned regimes is characterized by a different heat transfer mechanism and differs in the heat transfer coefficient (HTC) values. Under film boiling regime, which starts above the Leidenfrost temperature or after so-called second boiling crisis the HTC is relatively low. This type of cooling is successfully used in secondary cooling zones in the continuous casting processes of steel. Especially, it is useful in cooling zones, where the surface

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## Nomenclature

| | |
|---|---|
| $c_p$ | specific heat, J/(kg K) |
| $G$ | water flux, kg/(m$^2$ s) |
| $H$ | sample height, m |
| $H_i$ | cubic shape function |
| $L$ | distance from the spray nozzle to the cooled surface, m |
| $L_{out}$ | outer diameter of the casing, m |
| $L_{sc}$ | distance between the cylinder and the casing, m |
| $p$ | water spray pressure, Pa |
| $p_i$ | vector of the unknown parameters (heat transfer coefficients) |
| $Pr$ | Prandtl number |
| $\dot{q}$ | heat flux, W/m$^2$ |
| $r$ | coordinate, sample radius, m |
| $Ra$ | Rayleigh number |
| $R_{max}$ | maximum radius of the sample with flange, m |
| $t$ | temperature, °C |
| $T_a$ | ambient temperature, K |
| $t_{i,j}^{inv}$, $t_{i,j}^{mea}$ | calculated and measured temperatures at selected points of the sample at time, °C |
| $T_f$ | average fluid temperature, K |
| $t_s$ | cooled surface temperature, °C |
| $T_s$ | cooled surface temperature, K |
| $T_c$ | casing surface temperature, K |
| $t_w$ | cooling water temperature, °C |
| $z$ | coordinate, sample length, m |
| $\varepsilon_c$ | casing surface emissivity |
| $\varepsilon_s$ | sample surface emissivity |
| $\eta$ | dimensionless time |
| $\lambda$ | thermal conductivity, W/(m K) |
| $\rho$ | density, kg/m$^3$ |
| $\tau$ | time, s |
| $\upsilon$ | dimensionless sample radius |

*Superscripts*

| | |
|---|---|
| *inv* | computed |
| *mea* | measured |

*Subscripts*

| | |
|---|---|
| *0* | initial value |
| *a* | air |
| *c* | casing |
| *f* | fluid |
| *n* | number of the temperature sensors |
| *m* | number of the temperature measurements performed by one sensor during the time of cooling |
| *max* | maximum |
| *out* | outer |
| *s* | surface |
| *w* | water |

*Abbreviations*

| | |
|---|---|
| ATD | average temperature difference between the measured and calculated temperatures at points of the thermocouple locations |
| ETF | function defining boundary condition at the water cooled surface assumed for the inverse solution tests |
| BFGS | Broyden-Fletcher-Goldfarb-Shanno algorithm |
| FEM | finite element method |
| HTC | heat transfer coefficient (W/(m$^2$ K)) |
| PC | personal computer |

temperature is maintained above 900 °C. During transition boiling regime high the HTC values are possible. This regime exists after the first boiling crisis, which is characterized by the maximum heat flux. The transition boiling regime is successfully used in quenching processes. In these processes it is necessary of cooling specimens from a temperature of 900 °C to about 200 °C with a rate of 1000 K/s in some cases. The initial temperature and the temperature interval of quenching, as well as the cooling rate depend on the grade of steel.

Beside the physics of cooling process, on the HTC during spray cooling influence factors such as: properties of a cooled material and a cooling medium, spray nozzle type, distance from a spray nozzle to the cooled surface [7]. The majority of experimental researches on spray cooling available in literature allow explaining influence of some factors on the HTC in one of the boiling regimes e.g. the film boiling [8–10], transient boiling [11], nucleate boiling [12] or non-boiling regime [13]. The most often investigated is the effect of spray characteristics, such as droplet flux, droplet velocity and droplet diameter [14]. For example Chen et al. [15] have studied the influence of droplet velocity, droplet flux and the Sauter mean diameter on the critical heat flux and the HTC. The cylindrical sample made of cooper was heated by 500 W cartridge heaters. The heat transfer process has been assumed as steady state and one dimensional. On the basis of temperature measurements the authors have calculated the heat flux and the surface temperature. In the conducted experiments water flux varied from 7 kg/(m$^2$·s) to about 190 kg/(m$^2$·s) depending on the investigated parameters. The maximum HTC values which have been obtained varied from 50 kW/(m$^2$·K) to about 80 kW/(m$^2$·K). However, no correlation describing the influence of water flux or other investigated parameters on the HTC has been given.

Ciofalo et al. [16] have investigated the influence of mass flux, mean droplet velocity and mean droplet diameter on the heat transfer process during water spray cooling of a hot cooper-beryllium alloy. The cooper-beryllium slab was heated to 300 °C, and then has been symmetrically cooled on both sides by the water spray at three different pressures of: 2, 4 and 8 bar. Water flux employed in spray cooling varied in the range from 8 kg/(m$^2$·s) to about 80 kg/(m$^2$·s). The heat flux and the HTC under single-phase cooling were determined by solving the inverse problem in which heat conduction has been calculated from the Stefan solution. The maximum HTC values obtained from the experiments have varied depending on the spray nozzle type and pressure. For a pressure of 2 bar the HTC values varied from 41 to 63 kW/(m$^2$·K). For a pressure of 4 bar the HTC values varied from 55 to 72 kW/(m$^2$·K) and for a pressure of 8 bar from 63 to 92 kW/(m$^2$·K). The formulas defining the HTC under the single-phase cooling regime as functions of mean velocity, droplet diameter and water flux have been derived. These researches are important and play a great role in electronics or laser technology but they have limited implementation in metal industry, where the temperature of a cooled material reaches 1200 °C. In this case more practical are information about the influence of such parameters as: mass flux, nozzle-to-surface distance and spray pressure which can be easily measured and implemented to control of the cooling processes. There are some researches where descriptions of the spray pressure or nozzle-to-surface distance influence on the HTC have been presented. Such researches have been conducted by Xie et al. [17], Hou et al. [18] and Somasundaram and Tay [19]. The results of investigations presented in these papers could only be utilized in the spray