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Solution strategy for the inverse determination of the specially varying heat transfer coefficient

Beata Hadała, Zbigniew Malinowski [*], Artur Szajding

Department of Heat Engineering and Environment Protection, AGH University of Science and Technology, Mickiewicza 30, 30-059 Krakow, Poland

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ABSTRACT

The solution strategy for the inverse determination of the heat transfer coefficient (HTC) distribution over the water cooled plate has been developed. The HTC distribution in space and time has been approximated using the finite element method with the nonlinear shape functions. The HTC values at nodes of elements have been determined minimizing the objective function. Four objective functions have been tested. The uncertainty of the inverse solutions has been estimated using the developed test function. The test function defines the HTC varying over the cooled plate similarly to the water spray cooling. Based on numerical tests it has been shown that the objective function which has been defined as a norm of the measured and computed temperatures difference should be extended with the norm of the temperature gradients difference. The objective function extension of about 10% of the norm of the temperature gradients difference has reduced low frequency fluctuations of the HTC resulting from the HTC maximum moving over the cooed surface. The inverse solutions to the measured temperatures have been achieved as well. Temperature of the inconel plate heated up to 920 °C and then cooled with the full cone water spray nozzle has been measured by 25 thermocouples located 2 mm below the cooled surface. The variations of the HTC in time at 9 points located at different distances from the nozzle axis have been presented. It has been shown that the HTC varies significantly as the distance from the water stream axis grows.

1. Introduction

In metallurgical industry water cooling is widely used in continuous casting processes [1], in hot rolling lines [2] and during heat treatment of products [3]. In continuous casting processes of steel products spray cooling is necessary for extracting heat from the solidifying strand. The productivity of the process depends on casting speed and it is a tendency for keeping the casting speed as high as possible. The casting speed is limited mainly by the solidification process which depends on the steel grade and efficiency of the spray cooling system. Designing of the spray nozzles arrangement and controlling the water flow reduces significantly the risk of cracks formation [4]. Optimization of the spray cooling system can be done using numerical simulation of the strand temperature [4–9]. Hardin at al. [4] have developed transient two dimensional heat transfer model for predicting the temperature field of the continuously casted slab. The heat transfer coefficient (HTC) in the spray cooling zones has been calculated from the power function of the water flux developed by Nozaki at al. [10] for spray cooling under film boiling regime. The HTC has been calculated for the average water flux in zones of cooling. The HTC average in zones has been divided by the correction factor obtained from iterative matching the computed slab surface temperatures with the measured ones. In the two dimensional model of slab temperature developed by Chaudhuri at al. [5] the same method as in [4] has been employed for the HTC calculation in the water spray zones. The system makes it possible to automatically adjust the water flow rate in the zones of spray cooling. Petrus at al. [6] have also implemented the same method of the HTC calculating in the developed system for on line control of the strand temperature. Luo at al. [7] have utilized ABAQUS software to model the beam blank continuous casting. The HTC in the spray cooling zones has been also calculated from the formula developed by Nozaki at al. [10]. A correction factor has been employed as in the work of Hardin at al. [4] to adjust the boundary condition to the test data. The equation developed by Nozaki at al. [10] in the year 1978 is simple in form and takes into account only the influence of the water flux on the HTC assuming that the water temperature is constant. Such simple formula needs a correction factor and after that can be implemented for on line control of the water flow rate in zones

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[*] Corresponding author.
E-mail addresses: Beata.Hadala@agh.edu.pl (B. Hadała), malinows@agh.edu.pl (Z. Malinowski), Artur.Szajding@agh.edu.pl (A. Szajding).

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Nomenclature

ATD	average temperature difference between measured and computed temperatures, K
AGD	average difference between measured and computed temperatures gradients, K/s
B	width of plate, m
BFGS	Broyden–Fletcher–Goldfarb–Shanno algorithm,
c	specific heat, J/kg
CPU	central processor unit,
$C(\tau)$	scaling function, W/(m^2 K)
DTD	dimensionless temperature difference computed from Eq. (19),
$D(\tau)$	scaling function,
DG	average value of the objective function derivatives,
$E(p_i)$	objective function,
F	parameter defined by Eq. (22), K/s
FEM	finite element method,
$h(x_2,x_3,\tau)$	function defining heat transfer coefficient distribution in space and time, W/(m^2 K)
$H(\tau)$	scaling function,
HTC	heat transfer coefficient, W/(m^2 K)
KT	number of time periods,
L	length of plate, m
N_{HTC}	total number of the minimized parameters,
NP	number of the temperature measurements performed by one sensor,
NT	number of the temperature sensors,
NTD	temperature difference normal to the measured temperature curve, °C
p_i	parameters to be determined by minimizing the objective function, W/(m^2 K)
P_i	temperature sensors locations,
$\bar{r}(\tau)$	scaling function, m
Ra	Rayleigh number,
q_v	heat source, W/m^3
$\dot{q}(x_2,x_3,\tau)$	heat flux distribution to be determined, W/m^2
S_k	cooling chamber surface, m^2
S_s	plate surface, m^2
t	temperature, °C
T	temperature, K
T_a	cooling water temperature, K
$t(\tau)^{nm}$	computed temperature for the sensor m at the time τ_n, °C
$t_e(\tau)^{nm}$	sample temperature measured by the sensor m at the time τ_n, °C
T_k	cooling chamber surface temperature, K
T_s	cooled surface temperature, K
W_m	penalty coefficient coupled with the temperature sensor m,
x_1, x_2, x_3	Cartesian coordinates,

Greek symbols

ε_k	emissivity of the cooling chamber surface,
ε_s	emissivity of the plate surface,
λ	thermal conductivity, W/(m K)
λ_a	thermal conductivity of air, W/(m K)
ρ	density, kg/m^3
τ	time, s
$\Delta\tau$	time increment, s

of cooling in the continuous casting lines equipped with low pressure nozzles operating under film boiling regime only.

In the work of Hadała at al. [8] the HTC model developed by Hodgson at al. [11] has been implemented in the three dimensional solution to the temperature field and stress field in the continuously casted strand. The Hodgson at al. model [11] takes into account the water flux and the surface temperature influence on the HTC under film boiling, transition boiling and nucleate boiling regimes. The water flux and the surface temperature are important factors which largely affect heat transfer under water spray cooling. Ito at al. [9] have determined the HTC for water spray cooling of the steel plate heated to 1000 °C. It has been shown that the average HTC for the same water flux was 2.8 times lower in the case of the spray nozzle operating at a pressure of 0.7 MPa in comparison to a high pressure of 5 MPa. In the work [12], it has been shown that the numerical solution to the strand temperature highly depends on the boundary conditions of heat transfer. Thus, knowledge of the HTC as function of the water flux, water pressure and strand surface temperature starting from about 1200 °C and ending at nucleate boiling is essential for the reliable and effective simulations of the continuous casting processes.

Similar problems are encountered in modeling controlled water cooling in the hot rolling lines [2]. The cooling starts at about 850 °C and ends at nucleate boiling. In multi pass hot rolling lines accurate prediction of roll force, roll torque and microstructure evolution are of prime interest in numerical simulations [13]. The flow stress models and microstructure evolution models which are part of the hot rolling models are coupled with the strip temperature [14–16]. Accurate prediction of the strip temperature requires heat transfer boundary conditions for air cooling, water cooling and for rolls contact with the deformed material.

Heat transfer models for modeling of heat treatment processes [3,17] are even more complicated from that required for continuous casting or hot rolling processes. Not going into a deep discussion of the heat treatment problems it is worth to mention that designing of cooling rate must take into account a steel grade [18], shape and dimensions of the cooled object [17,19].

It has been recognized decades ego that the HTC varies spatially in the water spray zone [3]. The results presented in [3] has been obtained for the steady state temperature of the cooled sample what is not common in metallurgical processes but the conclusions concerning the importance of the spatial variation of the HTC in numerical simulations are still valid. Further researches conducted under transient cooling of steel plates heated to 700 °C [20], 850 °C [21], 925 °C [22] and then cooled by the water spray nozzle have confirmed spatial variation of the HTC. The results obtained by Li and Wells [20] indicate that the water flow rate has a significant influence on the heat flux variations versus plate temperature. Moreover, as the water flow rate increases the Leidenfrost temperature increases as well and for the water flow rate over 2.5 kg/s film boiling was not observed. In such a case the plate surface temperature decreases rapidly and a critical heat flux of about 8 MW/m^2 can be reached in a few seconds of cooling. The results obtained by Dou at al. [21] using the full cone spray nozzle has confirmed the water pressure and water flux influence on heat transfer. The film boiling was not observed for a water pressure of 0.5 MPa or higher. A critical heat flux of about 16 MW/m^2 has been obtained for that pressure. The results obtained have allowed developing the formula defining heat flux as function of the plate surface temperature and the local water flux for transition boiling regime. Since the local water flux is a function of the distance from