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THE INFLUENCE OF SELECTED PARAMETERS OF WATER SPRAY COOLING ON THE HEAT TRANSFER COEFFICIENT

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Abstract

The water spray cooling is widely used in many industrial processes like metallurgy, microelectronics, nuclear safety and aerospace engineering. The metallurgical industry uses spray cooling for quenching of steel and cooling of strands in continuous casting process. A parameter which has a great influence on microstructure and residual stresses in steel specimens is the heat transfer coefficient. This parameter allows to control the cooling rate and thus allows to improve and optimize productivity and quality of the products.

There are many parameters affecting the heat transfer coefficient, which include the physics of the cooling process, the properties of cooling material and properties of the cooling medium.

In this paper an experimental study has been made to determine the effect of water spray cooling parameters on the heat transfer from a hot metal surface. The investigated parameters are water flux, the distance of the spray nozzle from the cooling surface and the spray pressure.

The experimental sample is metal cylinder of 20 mm in diameter and 20 mm long, which has been heated in a resistance heater furnace to about 530°C and then rapidly and symmetrically cooled by water spray using the full cone water nozzle. To measure the temperature inside the sample, three fast response thermocouples have been used.

The heat transfer coefficient has been determined by the boundary inverse problem of heat conduction. A finite element method has been applied to solve the problem. As a result, cooling curves expressing the heat transfer coefficient as a function of surface temperature have been obtained.

Key words: spray cooling, heat transfer coefficient, boundary inverse problem, heat conduction

1. INTRODUCTION

In many industrial processes there is a need to use a high heat fluxes during cooling of hot surfaces. One of the most effective way is spray cooling, which may provide heat fluxes of 10^7 W/m^2 [3], and thus spray cooling is widely used in many industrial processes like metallurgy, microelectronics, nuclear safety and aerospace engineering.

The cheapest and the most frequently used cooling medium is water. The heat transfer process while water spray cooling is complex and is similar to heat transfer process during boiling. As a result of rapid metals cooling from a high temperature by water, the heat transfer process initiates phase change. The heat transfer process during spray cooling can be divided into four different regimes (figure 1): a film boiling regime, a transition boiling regime, a nucleate boiling regime and single-phase liquid cooling. In film boiling regime the heat transfer rate and heat transfer coefficient are relatively small because of an insulating vapor layer which develops at the point of con-

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tact between impinging spray and the hot surface. This regime results in the temperature limit known as Leidenfrost point. Below this limit the transition boiling starts and the vapor layer begins to collapse and the droplets begin to make more effective and prolonged contact with the cooling surface. This transition boiling regime is marked by the higher heat transfer rates, thus causing a faster decrease in surface temperature. At the lower temperatures boundary of the transition boiling regime in which the vapor bubbles occur, the critical heat flux point exists. In this regime the highest value of heat flux and heat transfer coefficient are obtained. Below the critical heat flux temperature is the nucleate boiling regime where heat fluxes are quite large but decrease rapidly with decreasing surface temperature. At the lower boundary of the nucleate boiling regime, bubble nucleation ceases and heat transfer occurs by conduction through thin liquid film created due to the impinging spray.

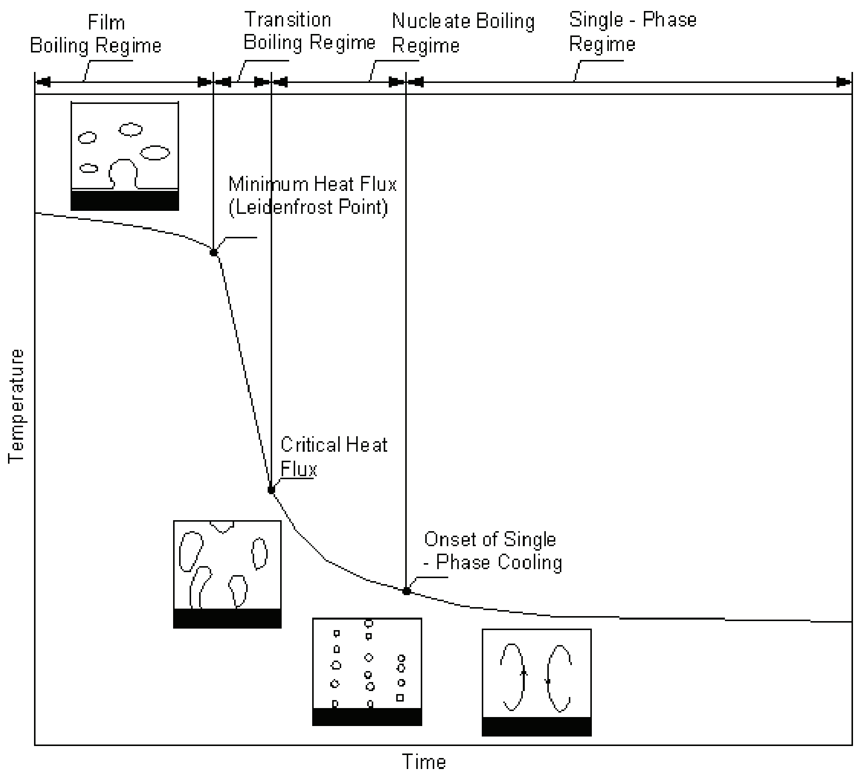

***Fig. 1.** Temperature and time influence on a surface phenomena during spray cooling.*

Heat flux convected to the environment during water spray cooling depends on many factors such as droplet size, droplet size distribution, droplet velocity, droplet number density, surface roughness, thermophysical prosperities of cooling material and cooling medium. The results of the investigations of the influence of the parameters mentioned above are published in numerous literature [2,4-8]. Unfortunately, it is very difficult to determine the effects of only one of them because all of these parameters influence on each others.

The aim of this paper is to examine the affect of water flux, the distance of the spray nozzle from the cooling metal surface and the spray pressure into the heat transfer coefficient during water spray cooling.

2. EXPERIMENTAL EQUIPMENT AND PROCEDURES

The experimental procedure has made it possible to measure the temperature at selected points of the heated up sample during water spray cooling. Thus, the response of the sample temperature to an unknown boundary heat flux has been determined in the test.

As a sensor brass cylinder of 20 mm in diameter and 20 mm long has been used in the experiment. The cylinder completed with a flange has been placed in a cylindrical casing. The cylinder and its casing have been made of the same material. The sensor has been heated uniformly to about 530 °C in a resistance heater furnace. After that it has been quickly placed in the grip vertically to water flux and the specimen has been rapidly and symmetrically cooled by water spray using the full cone water nozzle. The schematic diagram of the experimental equipment is presented in figure 2. To measure the temperature inside the cooling sample, three fast response, NiCr - NiAl thermocouples have been used. Thermocouples had been placed in the symmetry axis of the cylinder, in a distance of 2, 4, 6 mm from the cooling surface. The temperature variation in time has been recorded by the data logger continuously, while the water spray has being impacted the test specimen.

3. COMPUTATIONAL PROCEDURE

Heat transfer coefficient is determined by the solution of the boundary inverse heat conduction problem. The inverse problem is defined as one in which the unknown parameter value is to be determined. It has to be used if the parameter cannot be directly measured. Thus, conclusions concerning the parameter characteristic are being drawn following indirect measurements of factors which influence directly on it.

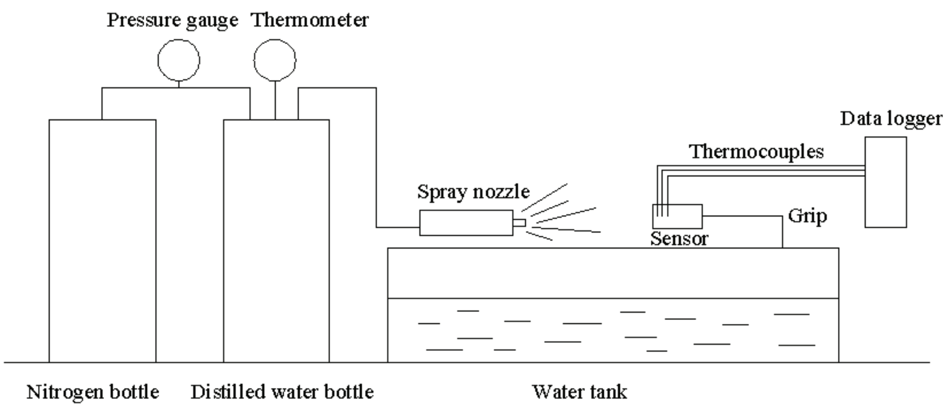

Fig. 2. *Schematic diagram of the experiment.*

We look for the boundary conditions of heat transfer. The process is determined by the temperature changes in points located inside the specimen. In these case the whole procedure of solving the inverse problem starts with assumption of a general form of the function approximating the heat transfer coefficient. The final aim of the calculation is to determine the particular form of that function with a preset solution convergence criterion. In our case the target function is the error norm [1]

$$\Phi = \sum_{i=1}^{n}\sum_{j=1}^{m}\left[\Theta_{i,j}^{num}(\tau) - \Theta_{i,j}^{inv}(\tau)\right]^2 \qquad (1)$$

where $\Theta_{i,j}^{num}(\tau)$, $\Theta_{i,j}^{inv}(\tau)$ are the computed and measured temperatures, respectively, at selected points of the body; i, j denote number of measuring point.

The Fourier – Kirchhoff equation of transient heat conduction is solved by the finite element method. The error norm (equation 1) is minimized by the Broyden – Fletcher – Goldfarb – Shanno method (BFGS) [1]. The problem is consider in a one dimension, along the cylinder axis. The rear face and the side surface of the sample are thermally insulated.

The heat transfer coefficient has been interpolated by the Hermitian polynomial. For each time interval (τ_k, τ_0), the polynomial has the form

$$\alpha(\tau) = a_1 H_1^0(\xi) + a_2 H_1^1(\xi) + a_3 H_2^0(\xi) + a_4 H_2^1(\xi) \qquad (2)$$

where

$$H_1^0(\xi) = 1 - 3\xi^2 + 2\xi^3, \qquad H_2^0(\xi) = 3\xi^2 - 2\xi^3,$$

$$H_1^1(\xi) = \left(\xi - 2\xi^2 + \xi^3\right)\Delta\tau, \quad H_2^1(\xi) = \left(\xi^3 - \xi^2\right)\Delta\tau,$$

$$\xi = \frac{\tau_i - \tau_0}{\Delta\tau} \quad \left(\tau_0 \le \tau_i \le \tau_k\right) \quad \Delta\tau = \tau_k - \tau_0$$

and a_1, a_2, a_3, a_4 are the polynomial coefficients to be found.

The verification of the inverse solution was carried out by replacing the sensor temperature response with the numerically calculated data. In these case the temperatures at the measuring points locations were taken from the solution to the Fourier equation for the given boundary conditions. The finite element method was used to solve the heat transport equation. Then the inverse solution was used to calculate back the heat flux at the boundary surface. The heat transfer coefficients have been approximated by the Hermitian interpolation functions. The accuracy of the solution depends only on the form of that function. The problem is illustrated in the following example.

The cooling of brass cylinder is considered. The sample initial temperature is 650 °C. The heat transfer coefficient on the front surface is described by the function $\alpha(\tau) = 0.001\exp(10-\tau)$ kW/(m^2·K). The rear and side surfaces of the cylinder are thermally insulated. The process is being considered in a time interval of (0, 5 s). The temperature in selected points of the cylinder was computed from the solution to the Fourier equation. The computed temperatures have replaced the measured data in the inverse solution. First, the heat transfer coefficient was interpolated in the whole time interval $\Delta\tau$ by the one Hermitian polynomial. The results of these solution have given an average temperature deviation of 2.0 K. The calculation results are presented in figure 3.

That solution is the first approximation and it illustrates the character of the sought function. The second approximation was carried out for three intervals of 0 – 1; 1 – 3; 3 – 5 s. This solution resulted in an average temperature deviation of approximately 0.1 K and has been assessed as the satisfactory one. In figure 4 the absolute error of the first and second approximation is shown.

4. RESULTS OF MEASUREMENTS AND NUMERIC CALCULATIONS

The heat transfer coefficient in inverse solution is approximated in all tests by the Hermitian polynomials. In view of the specific variation of temperatures during the tests, the locations of nods of intervals are individually adjusted for each measurement. Calculation results included the surface temperature of the cooling cylinder, the temperature in measurement points, the coefficient of the heat transfer approximating function, the difference of calculated and measured temperatures and the error norm value. This paper presents the dependence of the heat transfer coefficient on the surface temperature, cooling water pressure and water flux for selected tests. The graphs in figures 5 and 6 illustrate effects of the various distances of the spray nozzle from the cooling surface. The graphs in figures 7 – 10 present the dependence of the heat transfer coefficient on the water flux for various spray pressures. In figure 11 variations of the heat transfer coefficient as a function of the sample surface temperature for various spray pressures are presented.

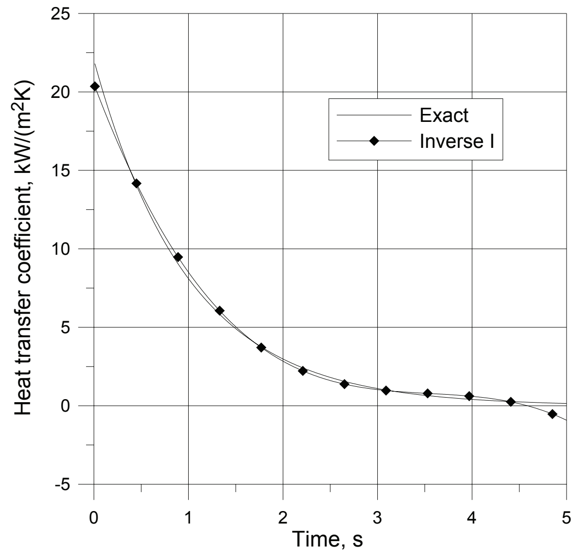

Fig. 3. *Exact solution and the first approximation.*

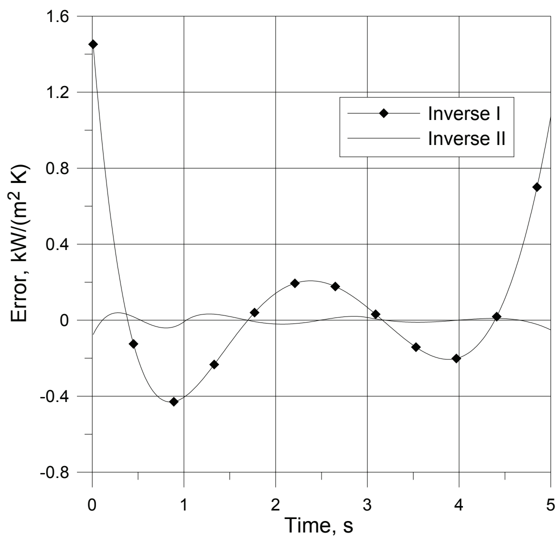

Fig. 4. *Absolute error of the first and second approximation.*

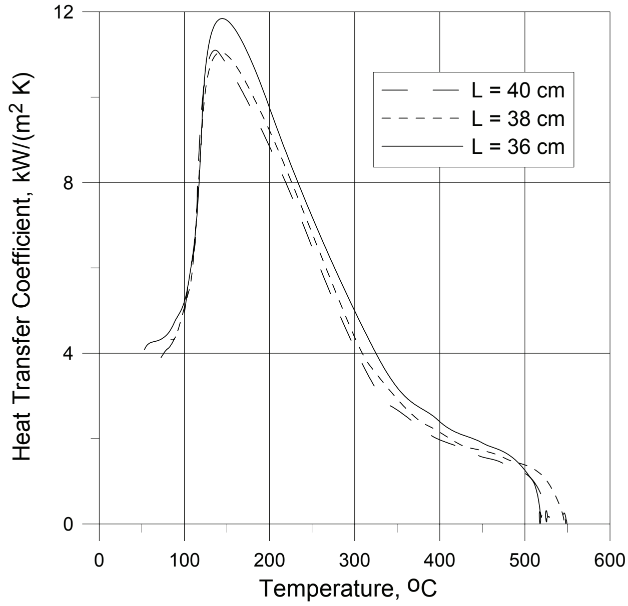

Fig 5. *Dependence of heat transfer coefficient on temperature at various distances of the spray nozzle form the cooling surface (L), G = 0.6 kg/(m^2·s), p = 0.36 MPa.*

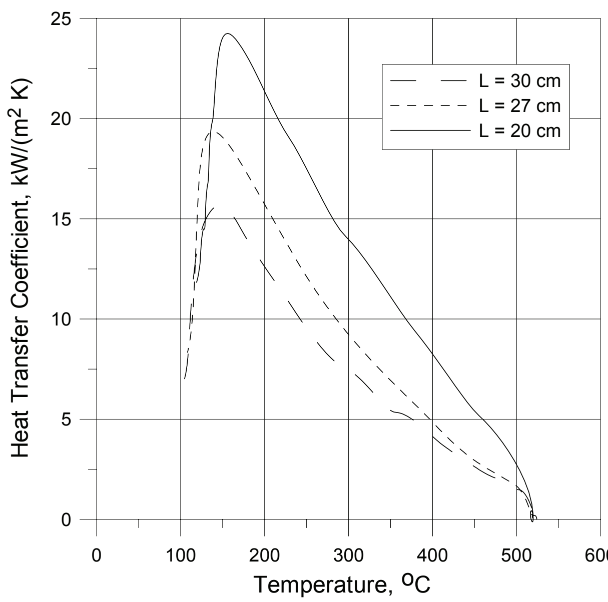

Fig 6. *Dependence of heat transfer coefficient from temperature at various distances of the spray nozzle on the cooling surface (L), G = 1.5 kg/(m^2·s), p = 0.5 MPa.*

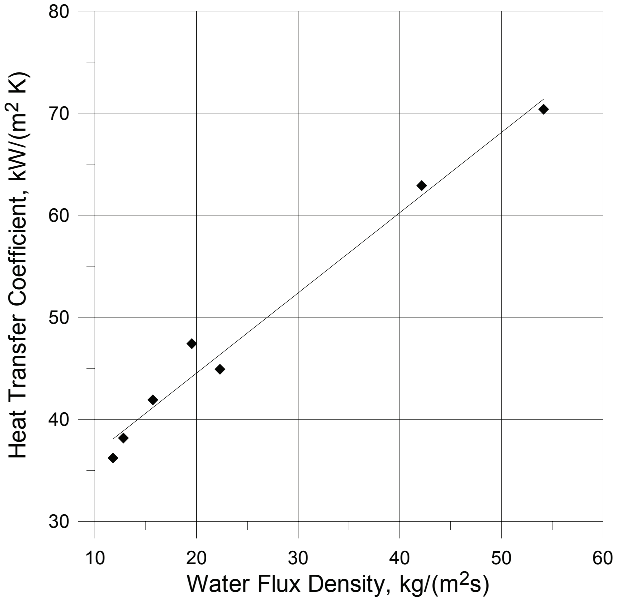

Fig. 7. Dependence of heat transfer coefficient on the water flux for p = 0.36 MPa.

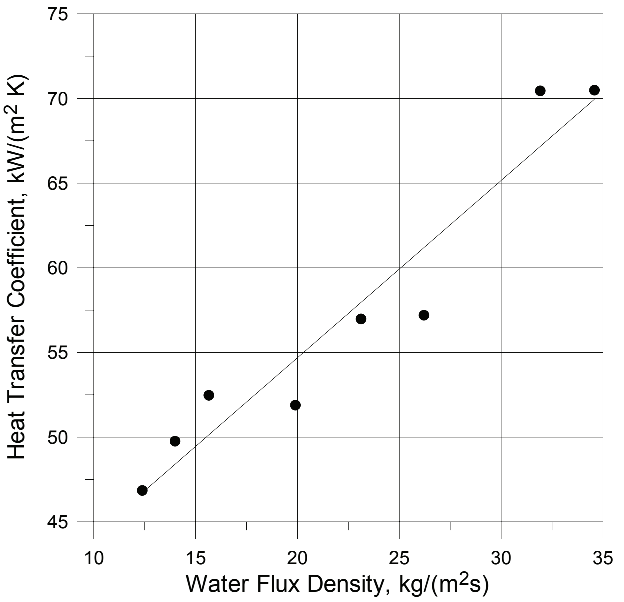

Fig. 8. Dependence of heat transfer coefficient on the water flux for p = 0.5 MPa.

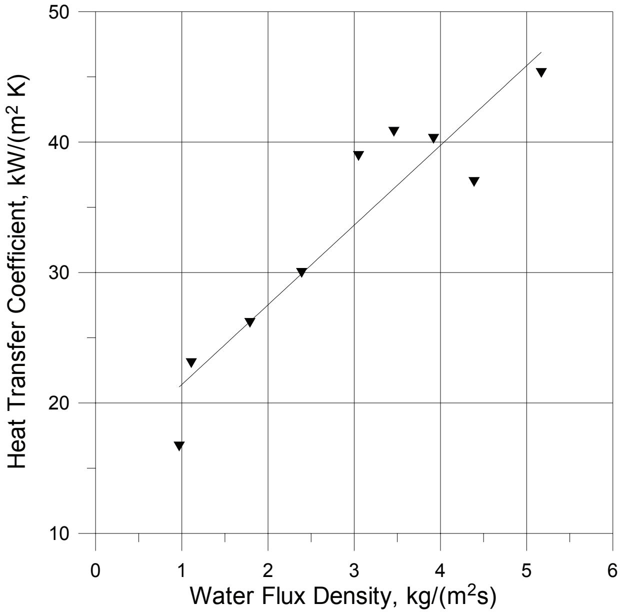

Fig. 9. Dependence of heat transfer coefficient on the water flux for p = 1 MPa.

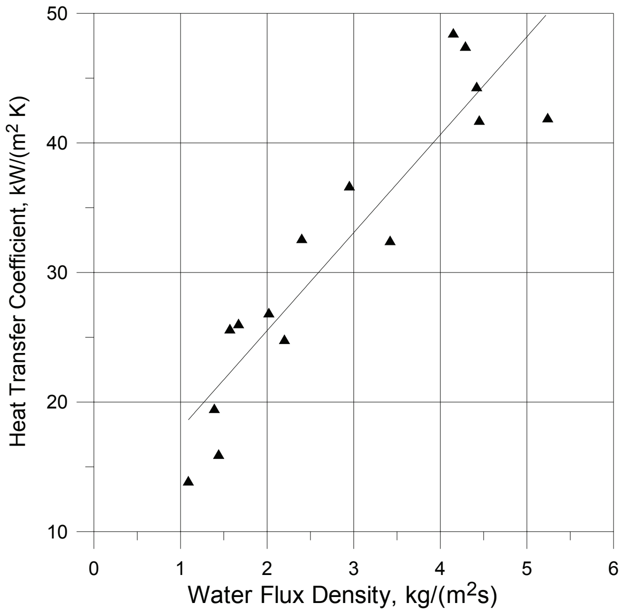

Fig. 10. Dependence of heat transfer coefficient on the water flux for p = 2 MPa.

5. CONCLUSIONS

An attempt is made to describe an independent influence of three different parameters on heat transfer coefficient, which are: the water flux, the distance of the spray nozzle from the cooling surface and the spray pressure. The problem is complex because all of these parameters are coupled and it is difficult to change one of them without changing the two others. On the basis of many tests it has been accomplished, it has been applied to find a separate influence of each parameter on the heat transfer coefficient.

The results of the calculus have shown that variation of the distance between the spray nozzle and the cooled surface cause the increase of heat transfer coefficient when the distance is getting smaller. The difference between the values of heat transfer coefficient is small when the distance of the spray nozzle is shifted by 2 cm (figure 5). In the case of larger variation in the distances, as shown in figure 6, the difference is significant.

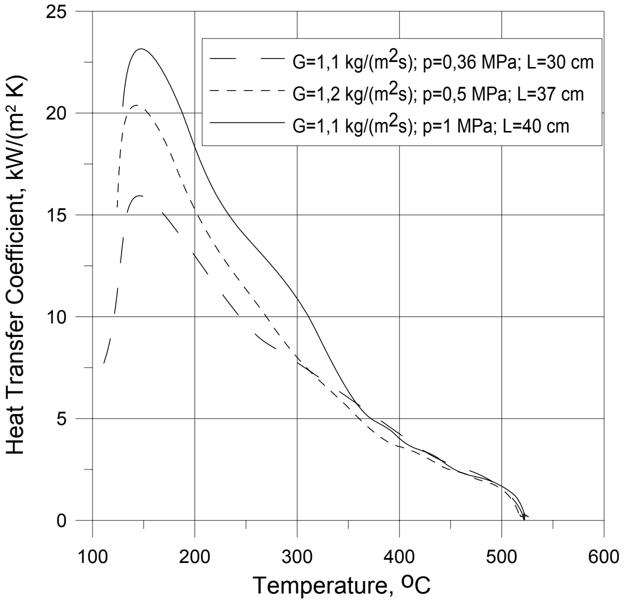

***Fig 11.** Dependence of heat transfer coefficient on temperature at various spray pressure.*

Figures 7 – 10 denote the relation between heat transfer coefficient and the water flux at different spray pressures. The points at these figures presented the values of the heat transfer coefficient for the selected testes which have been accomplished. The distance between the spray nozzle and the cooling surface varied from 20 cm to 40 cm. The heat transfer coefficient increases with the water flux and the correlation is linear. Considering the influence of both the water flux and the spray pressure we can see, that at the highest spray pressure it is possible to achieve the same values of the heat transfer coefficient for minor water flux then in case of the lowest spray pressure. For example the heat transfer coefficient of 40 kW/($m^2 \cdot K$) can be achieve at spray pressure p = 1 MPa for water flux of about G = 4 kg/($m^2 \cdot s$), whereas the same value of heat transfer coefficient occurs at p = 0,36 MPa for G = 15 kg/($m^2 \cdot s$) (figures 7 and 9).

The relation presented in figure 11 leads to the conclusion that at constant water flux density it is possible to achieve higher heat transfer coefficients if higher spray pressure is used. For spray pressure of 0.36 MPa heat transfer coefficient is about 15 kW/($m^2 \cdot K$), but when the spray pressure increases to 1 MPa the value of heat transfer coefficient goes to over 22 kW/($m^2 \cdot K$) at the same water flux (figure 11).

The temperature at which the maximum heat transfer coefficient occurred has not changed with the variations of any of considered parameters.

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WPŁYW WYBRANYCH PARAMETRÓW PROCESU CHŁODZENIA NATRYSKIEM WODNYM NA WSPÓŁCZYNNIK PRZEJMOWANIA CIEPŁA

Streszczenie

Chłodzenie natryskiem wodnym stosuje się w wielu dziedzinach przemysłowych jak na przykład metalurgia, mikroelektronika czy inżynieria kosmiczna. W przemyśle metalurgicznym chłodzenie natryskiem wodnym jest wykorzystywane do polepszenia i zoptymalizowania wydajności i jakości produktów wytwarzanych w procesach odlewania, kucia czy obróbki cieplnej. Parametrem, który pozwala kontrolować proces chłodzenia jest współczynnik przejmowania ciepła.

Określenie zmian współczynnika przejmowania ciepła w procesie chłodzenia jest zadaniem trudnym ponieważ jest on zależny od szeregu różnych parametrów do których zalicza się: fizykę procesu chłodzenia, własności chłodzonego materiału oraz własności medium chłodzącego.

W pracy przedstawiono wyniki badań eksperymentalnych dotyczących wpływu wybranych parametrów procesu chłodzenia natryskiem wodnym na współczynnik przejmowania ciepła podczas chłodzenia metalowej próbki. Parametrami tymi były:

gęstość strumienia wody, odległość dyszy od czoła powierzchni chłodzonej oraz ciśnienie wody.

Próbką do badań był metalowy walec o średnicy 20 mm i wysokości 20 mm, który nagrzewano w piecu oporowy, a następnie gwałtownie chłodzono przy pomocy natrysku wodnego. Do badań użyto dyszy rozpylającej pełnostożkowej. Do pomiaru temperatury wykorzystano termoelementy typu K.

Współczynnik przejmowania ciepła określano poprzez rozwiązanie brzegowego odwrotnego zagadnienia przewodzenia ciepła. Do rozwiązania problemu wykorzystano metodę elementów skończonych. Otrzymane wyniki przedstawiono w postaci zależności współczynnika przejmowania ciepła od temperatury chłodzonej powierzchni.

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