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Influence of Material Properties and Water Pressure on the Boundary Condition of Heat Transfer during Jet Cooling

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Abstract – In the paper the average values of the heat transfer coefficient (HTC) during water cooling of cylindrical sensors made of alloys: Inconel 600 and Armco steel, heated to 500°C, were determined. For the identification of HTC, the inverse solution for the heat conduction equation was used. Determining the HTC value on the surface included: measuring the temperature during cooling at two points inside the cylinders and performing numerical calculations to obtain the average values of HTC on the cooled surface. The tests were carried out for three water pressure values: 0.05MPa, 0.1MPa and 0.2MPa. The results of the calculations are presented in the form of graphs of changes in the average values of HTC with the surface temperature and with time. Thanks to the analysis of the diagrams, it was possible to determine the effect of water pressure and the material used for the research on the average value of the heat transfer coefficient on the cooled surface.

***Keywords*:** water jet cooling, heat transfer coefficient, inverse solution for heat conduction equation, boiling.

1. Introduction

With the development of industry and many areas of human life, it is necessary to ensure the reception of large amounts of heat from the surfaces of solids. Such a need exists, among others in the metallurgical industry in the processes of rolling, continuous casting or quenching. The development of industry has also led to increase in the requirements for metallurgical products manufactured in the industry. It is necessary to ensure appropriate mechanical properties, which depend on the rate of heat dissipation from the hot surface of the cooled product. Meeting these requirements is possible, among others, thanks to the use of appropriate cooling methods, which include water jet cooling. This method consists of directing a stream of water fed from a nozzle of a certain diameter onto the cooled surface. As a result of the application of such a cooling system, three areas differing in the amount of heat received and the speed of the liquid are distinguished on the surface, which include: stagnation zone, flow acceleration zone and parallel flow zone. The stagnation zone is located in the stream axis and is the area in which heat dissipation is the most effective. As the distance from the stagnation point increases, there is a zone of flow acceleration and a zone of parallel flow, where the obtained HTC values are lower than in the stagnation zone [1]. Water jet cooling in the metallurgical industry is used to cool components heated to temperatures up to several hundred degrees Celsius and is used, among others, during sheet rolling. During the contact of water with the surface of the product heated to several hundred degrees Celsius, the liquid boils, so that the amount of heat energy dissipated from the cooled surface is higher than in the case of single-phase cooling.

The HTC during boiling depends on many parameters, including temperature of the cooled element surface, its roughness and hydrodynamic parameters of the liquid, which include, among others pressure and flow rate of the liquid. However, the surface temperature value depends on the properties of the cooled element, which include thermal conductivity, which is responsible for the rate of heat supply from the depths of the material to its surface, from which heat is received during cooling. The research allowing to determine the heat transfer during cooling with water jet was carried out by Li et al. [2], who investigated the effect of water impact velocity on HTC. Their research proved that an increase in the velocity of water impact causes an increase in HTC on a cooled surface. Hauksson et al. [3] investigated the effect of the distance from the stagnation point on the heat flux. The researchers proved that the highest values of heat flux occur at the stagnation point and in its close vicinity. Dou et al. [4] conducted research on the influence of the surface roughness of a stainless steel plate on the heat flux transferred during cooling with water jet. The authors of the research proved that providing a greater surface roughness results in an increase in the intensity of heat transfer on the surface cooled by a water jet. The influence of thermophysical parameters on the rate of transport of thermal energy from the cooled material was proved in [5].

The development of many areas of human life initiated the era of the use of steel wherever possible. Steel products are used in construction, mechanical industry, shipbuilding and many others. However, the effective removal of heat from the surface of some steel products may be disturbed by the formation of the scales, i.e. layers of metal oxides, formed on the hot surfaces of steel products as a result of the oxidizing atmosphere. The thermal conductivity of the formed oxide layer is relatively lower than that of steel, which means that the oxide layer formed on the surface can act as an insulating layer between the hot surface of the product and the coolant. A lower value of thermal conductivity of the scale in relation to steel were demonstrate by Slowik et al. [6] and Li et al. [7]. On the other hand, Wandelstrof et al. [8] proved that the occurrence of scale on the surface may shift the Leidenfrost point towards higher temperatures, which contributes to increasing the cooling efficiency. To similar conclusions came Köhler et al. [9], who in their research also proved a significant shift of Leidenfrost temperature towards higher temperatures for a steel sample with a scale layer. As the reason for this, the authors mention the variable surface properties that occur during the formation of oxides. The authors of the paper [10] came to similar conclusions, who proved that the presence of an oxide layer on the surface significantly facilitates heat transfer during transition boiling.

The aim of the paper is to determine the average values of HTC during water cooling of sensors made of Armco steel and Inconel 600, heated to a temperature of 500℃. The tests were carried out for three values of water pressure: p=0.05MPa, p=0.1MPa and p=0.2MPa, thanks to which it was possible to determine the influence of pressure on the obtained values of the average HTC. The research was carried out for two materials, differing in thermo-physical properties and the morphology of the surface of the jet impact. The sensor, made of Inconel, had anti-corrosion properties, thanks to this it did not show any scale on the cooled surface. On the other hand, the Armco steel sensor, under the influence of the oxidizing atmosphere, formed a scale that may affect the heat transfer. In order to identify HTC, experimental tests were carried out, which consisted in measuring the temperature inside the sensor during cooling. The obtained temperature measurements were implemented in a numerical program using the inverse solution for the heat conduction equation to identify the average values of HTC on the cooled surface.

Nomenclature

c_p	specific heat, J/(kg·K)
h	sensor hight, m
R	sensor radius, m
r, y	cylindrical coordinates
t	temperature, °C
$t_{ij}{}^{o}$	sensor temperature calculated by the heat conduction model, °C
$t_{ij}{}^{z}$	temperature obtained as a result of the measurement inside the sensor over time, °C
t_m	cooling medium temperature, °C
t_s	temperature of the cooled surface, °C
α	heat transfer coefficient, W/(m^2·K)
λ	thermal conductivity, W(/m·K)
ρ	density, kg/m^3
τ	time, s

Abbreviations

HTC	Heat transfer coefficient, W/(m^2·K)

2. Experimental Set-Up

The experimental tests were carried out on the test stand (Figure 1) for two materials, made of alloys: Inconel 600 (Figure 2) and Armco steel. These materials were placed in casings made of the same materials in order to minimize heat loss from the surface to the environment. From the combination of both parts, a measuring sensor was obtained. Measurements of sensor temperature changes during cooling were measured with two NiCr-NiAl thermocouples with a diameter of 1 mm [11]. The thermocouples were located inside the cylindrical materials, 2 mm from the cooled surface in the middle of their radii and 1.5 mm from their edges (Figure 3). Temperature measurements during cooling were recorded using the MGCplus data acquisition system [12]. The maximum temperature reading by the thermocouples was 501℃. The maximum error of temperature measurement with a thermocouple was ± 0.4% of the measured temperature [11]. The maximum temperature measurement error, resulting from the accuracy class of the thermocouple, was ±2.0℃. The maximum temperature measurement error resulting from the accuracy of data recording by the data acquisition system was ±3.1℃ [12]. The maximum temperature measurement error, taking into account both the temperature measurement error resulting from the accuracy class of the thermocouple and the temperature measurement error resulting from the accuracy of temperature registration by the data acquisition system, was 5.1℃.

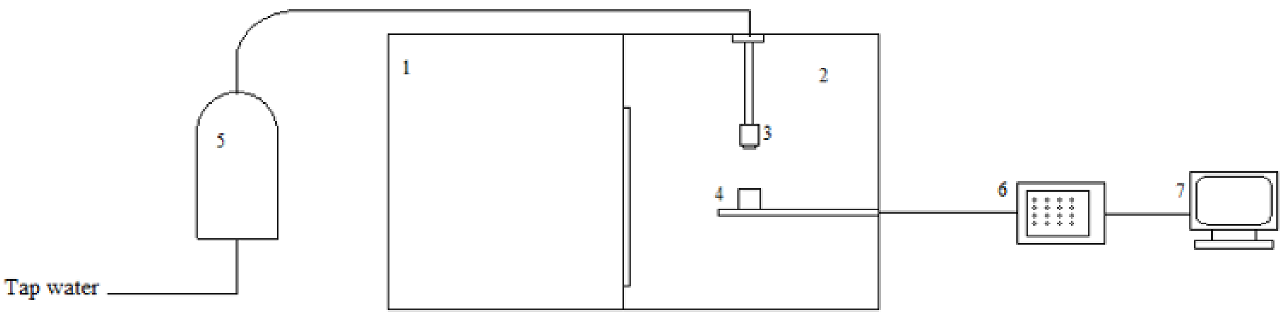

Figure 1: Measuring stand: 1- electric resistance furnace, 2 – cooling chamber, 3 – nozzle, 4 – cylindrical sensor, 5 – water tank, 6 – data acquisition system, 7 – computer.

Figure 2: Sensor, made of Inconel with thermocouples.

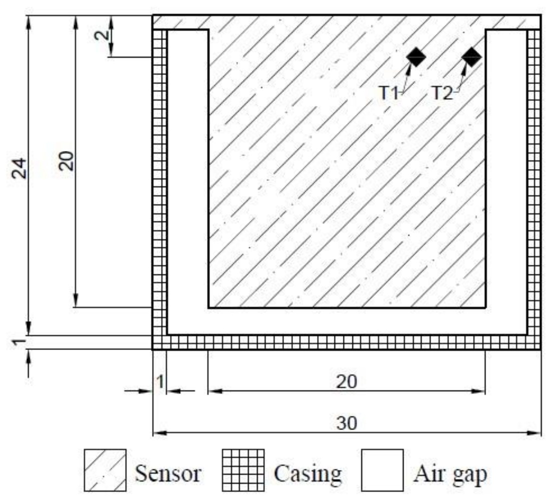

Figure 3: Diagram of the sensor with the location of the thermocouples (T1, T2).

The sensors were heated in a resistance furnace to a temperature of 500℃. After reaching the assumed temperature, the sensors were transported by a mechanical arm to the cooling chamber, where they were cooled with a water jet. The water was fed from a nozzle with a diameter of 2.7 mm, and the water temperature was 16℃. The front surface of the sensors was cooled. During transport from the furnace to the cooling chamber, the sensor was cooled with air. The transport time was about 3 seconds. The distance of the nozzle from the cooled surface was 25 mm. The parameters of the cooling process are presented in Table 1.

Table 1: The parameters of the cooling process.

Sensor material	Pressure, MPa	Cooling time, s	Initial temperature of sensor, °C
Armco steel	0.05	30.0	501
	0.1	30.0	499
	0.2	37.0	499
Inconel 600	0.05	70.0	497
	0.1	80.0	496
	0.2	60.0	497

3. Heat Conduction Model Used To Determine the HTC Values on a Cooled Surface

The average values of HTC on a cooled by water jet surface were determined based on the measurement of the sensor's temperature change over time and the calculation of the sensor's temperature field from the heat conduction equation:

$$\rho c_p(t)\frac{\partial t(r,y,\tau)}{\partial \tau}=\frac{1}{r}\frac{\partial}{\partial r}\left[\lambda(t)r\frac{\partial t(r,y,\tau)}{\partial r}\right]+\frac{\partial}{\partial y}\left[\lambda(t)\frac{\partial t(r,y,\tau)}{\partial y}\right] \tag{1}$$

Assuming that: $(0<r<R\,;\;0<y<h\,;\;\tau>0)$.
The solution of equation (1) was obtained by the finite element method [13].

In the numerical calculations assumed a change in the thermophysical properties of the materials from which the sensors were made with temperature [20–21]. The boundary conditions in the air gap and on the outer surface of the lower casing was adopted according to the model presented in [5], and on the outer side surface of the casing according to the model described in [22].

4. Solution of the Inverse Problem for the Heat Conduction Equation

The boundary condition on the surface cooled by a water jet was searched for in the form of a time-dependent function that allows the determination of the average value of the boundary condition on the cooled surface:

$$\dot{q}=\alpha(\tau)(t_s-t_m) \tag{2}$$

In the first stage of numerical calculations, the general form of the function approximating the change in HTC over time was adopted. The objective function was adopted in the form of:

$$E(p_i)=\sum_{i=1}^{n}\sum_{j=1}^{m}\left[\frac{t_{ij}{}^{z}(\tau)-t_{ij}{}^{o}(p_i,\tau)}{\sqrt{1+\left(\frac{\Delta t_{ij}^{z}}{\Delta\tau}\right)^2}}\right]^2 \tag{3}$$

Determination of unknown parameters p_i took place thanks to the minimization of the objective function. For this purpose, the variable metric method [14] was used, which is based on the BFGS algorithm [15–18]. A more detailed description of the heat conduction model used for the calculations is presented in the publication [19].

5. Results of Numerical Calculations

The results of the numerical calculations were presented in the form of the dependence of the average values of HTC on the cooled surface on the temperature (Figure 4A) and time (Figure 4B).

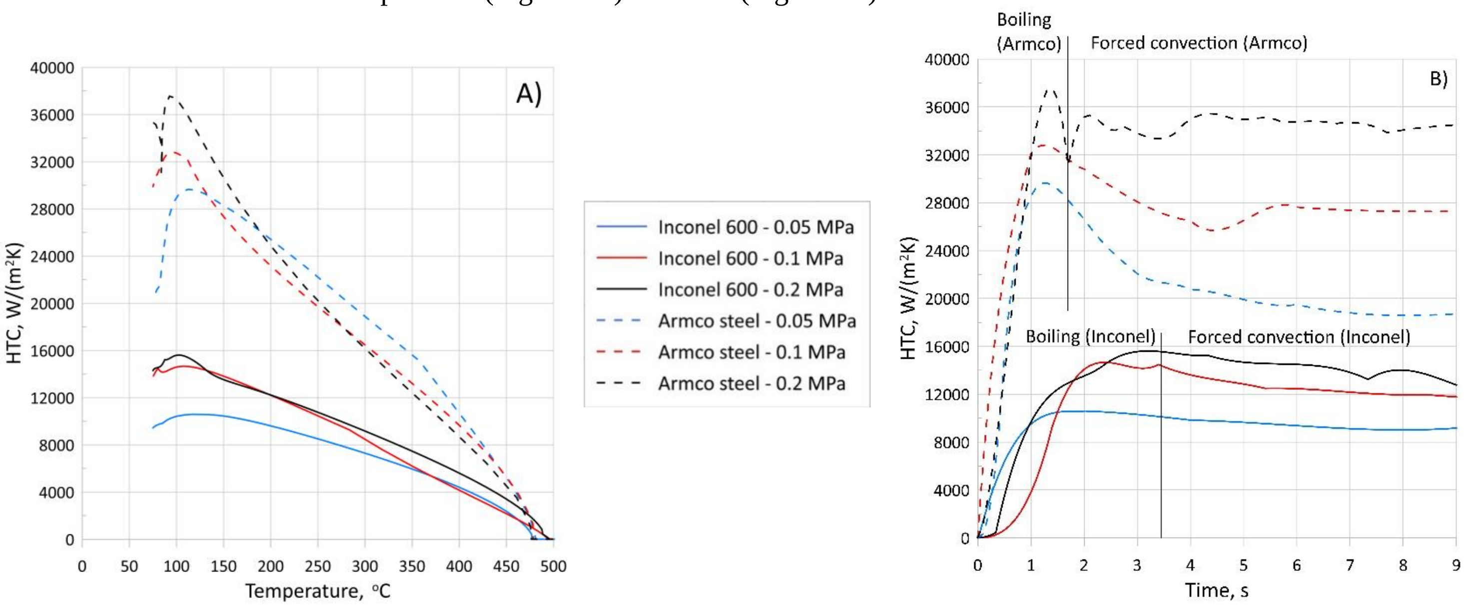

Figure 4: Average HTC value on the cooled surface as a function of surface temperature (A) and time (B).

The course of changes of the average HTC depending on the surface temperature (Figure 4A) and time (Figure 4B) allowed to notice significant differences occurring during the cooling of sensors made of Armco steel and Inconel 600. Higher values of the average HTC during the entire process were obtained during the cooling of Armco steel, regardless of the applied water pressure. The maximum values of the average HTC for Armco steel ranged from 30 000–38 000 $W/(m^2 \cdot K)$, while during the cooling of the sensor made of Inconel 600 alloy, these values ranged from about 11 000–16 000 $W/(m^2 \cdot K)$. One of the reasons for occurring the higher average HTC values during the cooling of Armco steel may be the higher thermal conductivity of the steel compared to Inconel 600. The higher thermal conductivity of steel is responsible for faster transport of thermal energy from the inside of the sensor to the cooled surface, thanks to which the intensity of heat reception can be at a higher level. The second reason for occurring higher average HTC values for steel may be the presence of a thin and heterogeneous layer of scale on the cooled surface. The oxidation changed the morphology of the cooled surface, and the scale fragments could be additional nucleation centres of the steam bubbles, which could increase the intensity of heat reception. The analysis of Figure 4A shows that the increase in water pressure caused an increase in the maximum average values of HTC during cooling of both the steel sensor and that made of Inconel 600 alloy. The increase in pressure caused also shift the maximum values of HTC towards lower temperatures when cooling the sensors, regardless of the material used. The analysis of Fig. 6 allowed to conclude that the boiling process, both in the case of cooling the sensor made of steel and Inconel, was very dynamic and the time of the boiling process itself was very short. During the cooling of the Armco steel sensor, the boiling time was approximately 1.5–2 s, while during the cooling of the Inconel sensor, the boiling time was in the range of 3–4 s. Shorter boiling time during cooling of the steel sensor indicates more intense heat reception from the surface of this sensor. The boiling curves presented in Figure 4A and Figure 4B also indicate the absence of a film boiling phase on the surface during jet cooling of both the steel and Inconel sensor, and a very short or no nucleate boiling period. During the measurements, the surface condition of the sensor made of Armco steel was also assessed. It was found that during the heating process, a layer of scale was formed, which was removed from the cooled surface under the influence of the water pressure.

Figure 5 shows a comparison of the temperature change measured at points T1 and T2 with the temperature determined from the solution of the inverse problem, obtained during the cooling of the Armco steel sensor, during which water is fed at a pressure of 0.2MPa. The presented curves show that the convergence between the measured and calculated temperature is high, which may indicate a high accuracy of the calculations performed. The accuracy of the inverse solution for all performed calculations is presented in Table 3. The values of the average temperature deviation measured experimentally from the numerically determined temperature in the case of cooling the steel sensor did not exceed 1.0 K, and the values obtained for cooling the sensor made of Inconel 600 alloy did not exceed 1.7 K, which may indicate a satisfactory accuracy of numerical calculations.

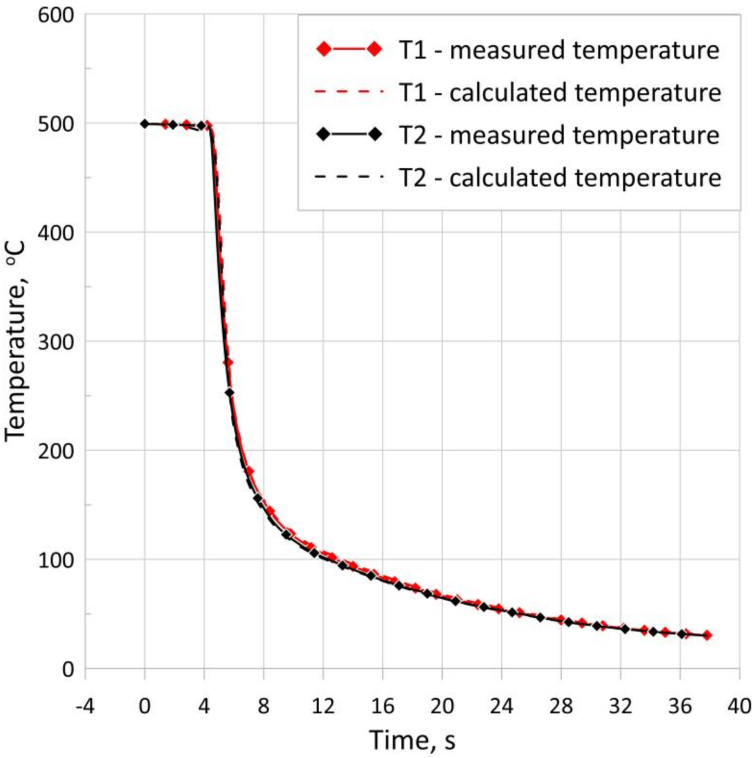

Figure 5: Comparison of the temperature change measured at points P1 and P2 with that calculated from the inverse solution, Armco steel, *p*=0.2 MPa

Table 3: The accuracy of the temperature field solution.

Sensor material	Pressure, MPa	The average deviation of the measured temperature from the calculated temperature, K
Armco steel	0.05	0.917
	0.1	0.674
	0.2	0.782
Inconel 600	0.05	1.686
	0.1	1.145
	0.2	1.191

6. Summary And Conclusions

In the paper the average values of HTC on cylindrical surfaces of sensors made of Armco steel and Inconel 600 during cooling with a water jet for three water pressure values: 0.05MPa, 0.1MPa and 0.2 MPa were identified. Thanks to the analysis of the conducted research, the following conclusions were formulated:

- The influence of material properties on the average values of HTC during water jet cooling is noticeable. The more than two-fold increase in the maximum average HTC value on the surface of the steel sensor, compared to the sensor made of Inconel, may be influenced by both the higher thermal conductivity of the steel and the presence of scale fragments on the steel surface, which may constitute additional centers of nucleation of steam bubbles, which improves heat reception intensity. This dependence persists later in the process, in terms of single-phase convection (Fig. 4).

- For the tested alloys, the increase in cooling water pressure contributed to an increase in the maximum average values of HTC by an average of 17.25% during cooling of steel, and by 30.76% during cooling of Inconel, and a shift of HTC maximums towards lower temperatures.
- The accuracy of the numerical calculations performed is satisfactory. The maximum value of the average temperature deviation measured experimentally from that determined from the inverse solution is 1.7 K, thanks to which the calculation results of the average HTC can be considered correct.

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