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COOLING NOZZLES CHARACTERISTICS FOR NUMERICAL MODELS OF CONTINUOUS CASTING

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Modelling the temperature field of a continuously cast strand is an important tool for the process diagnostics. The main preconditions for numerical simulation of the temperature field of the solidifying strand are correct boundary conditions, especially the surface condition in the secondary zone of the caster. The paper deals with techniques of determining the surface condition under cooling nozzles as well as their approximation and implementation into the model algorithm. Techniques used for laboratory measurements of both cold and hot spraying characteristics of water or water-air cooling nozzles are described. The relationship between the cold and hot characteristics was found. Implementation of such a dependence into the model algorithm reduces the duration and cost of laboratory measurements.

Key words: cooling, nozzle, continuous casting of steel, numerical model, boundary condition

INTRODUCTION

The temperature field of the strand, the shell thickness and the metallurgical length are important quantities used for the continuous casting process control [1, 2] and quality prediction. Since the measurement of above mentioned quantities is either technically difficult or practically impossible, the numerical model can serve as a software sensor. Universal software packages are not suitable for operational use. Therefore, specialized programme codes have been developed (e.g. at the VŠB - Technical University of Ostrava [3] or Brno University of Technology [4]).

The problem in the numerical modelling is not the simulation algorithm itself, but determination of boundary conditions including thermo-physical parameters of the cast steel [5], surface conditions in the mould [6, 7] and in the secondary cooling zone [8-10].

Cooling nozzles are usually assessed through two types of characteristics. The first one, called "cold" or "isothermal", is the spraying intensity, the second, called "hot", is the heat transfer coefficient (HTC) between the cooled surface and surroundings, both defined as a function of the strand surface coordinates.

Various measurement techniques and devices for testing nozzle characteristics have been developed at the Department of Thermal Engineering of the Technical University of Ostrava, as in other laboratories [11-13].

NOZZLE CHARACTERISTICS

It was found that the cooling water pressure affects the characteristics of the nozzle both quantitatively and qualitatively.

The spraying intensity is measured at ambient temperature. It is defined as the amount of water V falling on a surface S per time τ

$$I = \frac{V}{S \cdot \tau} \qquad / \mathrm{m^3 \cdot m^{-2} \cdot s^{-1}} \qquad (1)$$

The spraying intensity is measured by means of water collecting chambers exposed to the spray for a defined period of time. The system of chambers is typically arranged as a row or in a grid. The new apparatus developed at the Department is equipped with a single collecting chamber with circular inlet. The tested nozzle is situated on the arm of an industrial robot opposite the chamber. The nozzle is moved through discrete positions where the measurements proceed. Step by step, the entire spraying pattern is scanned. Results are stored in form of matrix. An example of their graphic interpretation is shown in Figure 1.

The spraying intensity, however, cannot be directly used as a surface condition in a model. For this purpose, HTC distribution is measured using a similar scanning method. The appropriate measuring sensor was developed and verified at the Department. Two various measuring principles, steady state and transient, are used. The sensor is instrumented with an automatic heating system and thermocouples. From measured quantities, the HTC is then calculated by either direct or inverse method.

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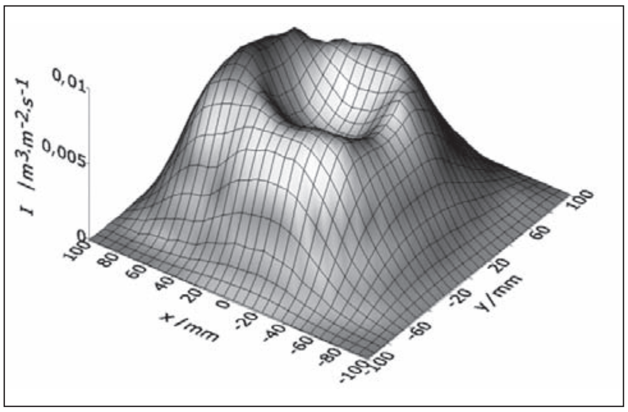

Figure 1 Spraying intensity distribution of the cone nozzle

RELATIONSCHIP BETWEEN HOT AND COLD CHARACTERISTICS

Determining the HTC is a considerably complex and demanding issue when compared to measuring the spraying intensity. Measuring spray characteristics on the cold model is faster and cheaper. At the Department, dozens of different types of water nozzles have been measured on the cold and hot physical models. Measurements were carried out for the pressure ranging from 0,1 to 1,5 MPa, different distances of nozzles from the cooled surface and surface temperatures from 300 to 1 000 °C. Thus, hundreds of different characteristics of nozzles have been obtained.

Efforts were directed towards finding a dependency between the cold and hot characteristics so that the HTC could be calculated from the measured intensity of spray instead of carrying out the demanding measurements on the hot model.

By means of correlation analysis, significant relationships between the hot and cold characteristics have been found in most cases. For most nozzles, the HTC correlates well with the spraying intensity, although this may not apply throughout the full range of the flow rates and the surface temperatures. It is known, that the HTC is also affected by impact energy and droplet size.

The dependence can be approximated by various functions e.g. logarithmic, polynomial or power function. In most cases the power function gives the best approximation. The approximation formula is the following

$$\alpha = a \cdot I^n \qquad / \mathrm{W \cdot m^{-2} \cdot K^{-1}} \tag{2}$$

where a and n are parameters of the model calculated by the linear regression using the logarithmic transformation

$$\ln\alpha = \ln a + n \cdot \ln I \tag{3}$$

The method fails for $I = 0$ and $\alpha = 0$. For this reason, zero spraying intensity at the edges of the characteristics shall be excluded from the data or replaced by a value close to zero. The second problem is that the method considers all data points as equally important. But in reality, at some positions, the HTC value affects the heat flow from the surface more intensively. Data points at these positions should be approximated more accurately or even exactly. For this reason a different approximation function has been brought in.

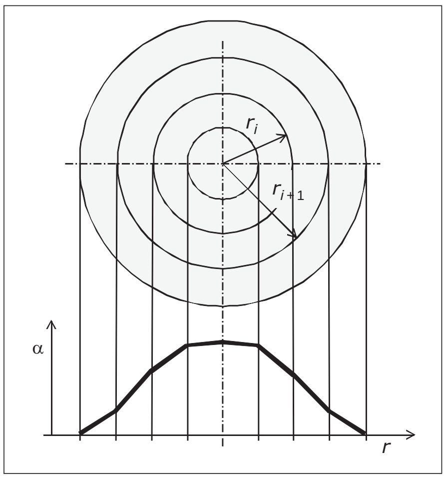

Figure 2 Schema of the spray pattern and the horizontal section of the hot characteristics

Either the spray intensity or the HTC are measured on a plane perpendicular to the nozzle axis at the discrete distances from the nozzle axis. Assuming a circular symmetrical spraying pattern, the area A_i belonging to the particular value of the measured spraying intensity or the HTC is a ring of the inner and outer radiuses r_i and r_{i+1}

$$A_i = \pi \cdot (r_{i+1}^2 - r_i^2) \qquad / \mathrm{m}^2 \tag{4}$$

An example of the spraying pattern with horizontal section through the hot characteristic is shown in Figure 2. The bigger is the distance from the nozzle axis, the greater area belongs to the value of the HTC. In case of symmetrical spraying characteristics, the partial heat flow P_i from the ring of the area A_i is obtained from

$$P_i = \frac{\alpha_i + \alpha_{i+1}}{2} \cdot A_i \cdot (t_\mathrm{s} - t_\mathrm{w}) \qquad / \mathrm{W} \tag{5}$$

where α_i is the HTC measured at the radius r_i, t_s is the strand surface temperature (°C) and t_w is temperature of the cooling water (°C). Total heat flow is a sum of partial heat flows P_i.

The chart of partial heat flows P_i from the rings in dependence on the distance from the nozzle axis r is shown in Figure 3 together with the measured values of

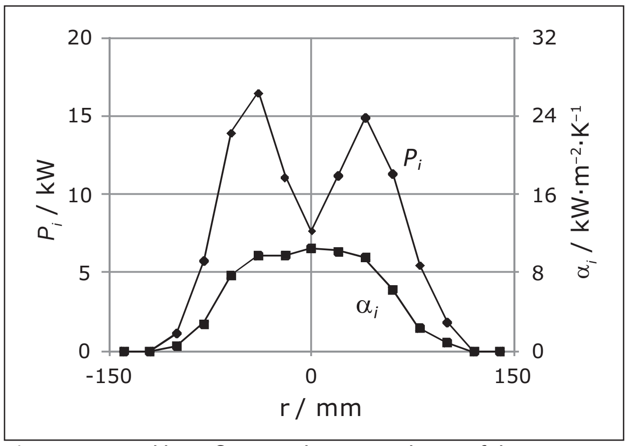

Figure 3 Partial heat flows and measured HTC of the cone nozzle of type 2565

the HTC (α). It is the characteristic of the cone nozzle of type 2565 for the water pressure 0,3 MPa, the distance 102 mm and the surface temperature 600 °C. The characteristic was not symmetrical. In this case, it is evident that, from the point of view of heat flow, the most important value of the HTC is not the highest value but the value at the distance of 40 mm from the axis.

The new approximation function has also a form of the power function

$$\frac{\alpha}{\alpha_{\mathrm{ref}}} = \left(\frac{I}{I_{\mathrm{ref}}}\right)^n \qquad /1 \qquad (6)$$

where the index "ref" means a reference value. This function has one degree of freedom less in comparison with the function (2). The model has only one parameter which is the exponent n. The curve is forced through zero point and the reference point which corresponds to the measured reference values I_{ref} and α_{ref}. For the best result, the reference values should be selected at the radius where the greatest partial heat flow is expected. The explicit formula for the predicted HTC is

$$\alpha = \frac{\alpha_{\mathrm{ref}}}{I_{\mathrm{ref}}^{\;n}} \cdot I^n \qquad / \mathrm{W \cdot m^{-2} \cdot K^{-1}} \qquad (7)$$

The unknown parameter n is calculated by an optimization algorithm which minimizes a sum of squared errors between the measured and predicted values of the HTC. The algorithm handles zero values of the spraying intensity and the HTC. Figure 4 shows both cold and hot characteristics as well as the predicted HTC of the nozzle of the type 2565 in dependence on the distance r from the nozzle axis.

The dependency between the HTC and the spraying intensity is shown in Figure 5. The single points are the measured values of the HTC. The value of the exponent n is 0,50.

Similar dependency was determined for the nozzle of double nominal flow rate as compared with the previous nozzle. The nozzle type is 5065, the water pressure 0,5 MPa, the distance 79 mm and the surface temperature 600 °C. Dependency of the HTC on the spraying intensity is shown in Figure 6. In this case, the exponent n was 0,21.

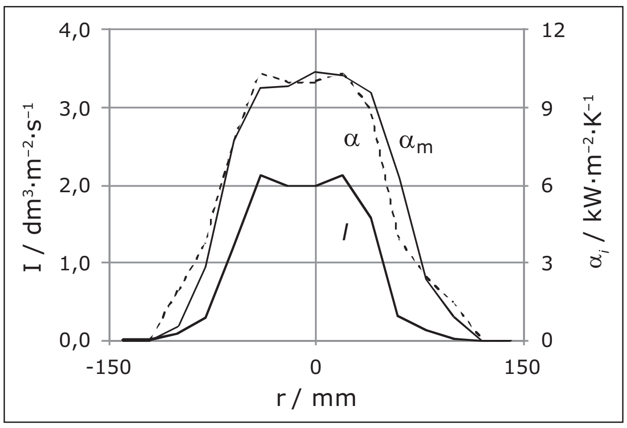

Figure 4 Spraying intensity I, measured (α_m) and predicted hot characteristic (α) of the cone nozzle of the type 2565

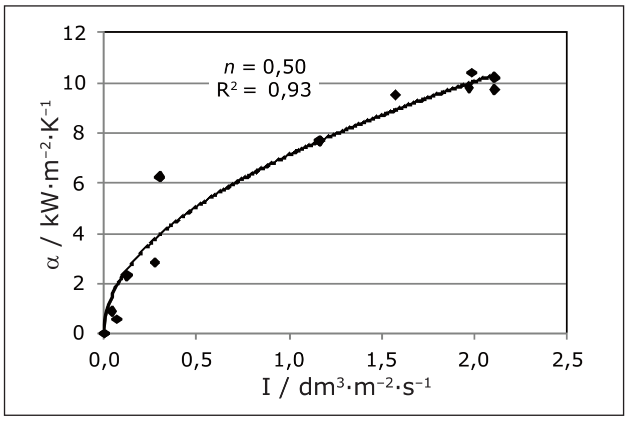

Figure 5 Points of measured values and the dependency curve of the HTC for the nozzle 2565

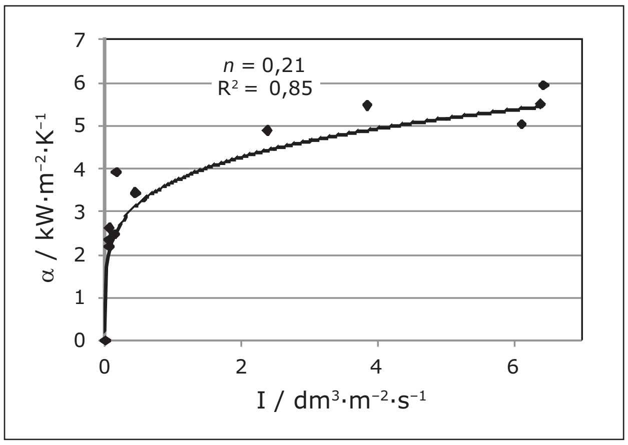

Figure 6 Points of measured values and the dependency curve of the HTC for the nozzle 5065

Theoretically the exponent n may vary from zero to infinity. The grater is the exponent, the narrower is the predicted hot characteristic.

DEFINING THE SURFACE CONDITION

To define surface conditions for the numerical model, cold characteristics of all types of nozzles being used in the casting machine were measured and approximated by cubic spline curves as functions of the position, flow rate and temperature. These characteristics were measured for pressures from 0,1 to 1,5 MPa. The HTC was then determined from the spraying intensity using the regression equation (7).

To do this, for individual types of nozzles and flow rates, the reference values α_{ref} of the HTC were measured using the hot model and the values of the exponent n were determined. It was found that the exponent varied from 0,2 to 1 according to the nozzle type, water flow rate and the surface temperature.

CONCLUSION

By measuring tens of nozzles of different types at various parameters, hundreds of cold and hot characteristics of the nozzles were obtained.

Significant relationships between hot and cold characteristics have been found for most nozzles. These relationships were approximated by the power function with an exponent ranging from 0,2 to 1.

For the purpose of numerical simulation of the strand temperature field, the user software procedure was created enabling to calculate the surface condition in the secondary cooling zone. The procedure allows determining the value of the HTC for different types of nozzles, strand surface positions, surface temperatures and cooling water flow rates.

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