M. PŘÍHODA, J. MOLÍNEK, R. PYSZKO, M. VELIČKA, M. VACULÍK, J. BURDA

ISSN 0543-5846
METABK 48(4) 235-238 (2009)
UDC-UDK 669.045:532.525:536.08=111

HEAT TRANSFER DURING COOLING OF HOT SURFACES BY WATER NOZZLES

Received – Prispjelo: 2008-02-28
Accepted – Prihvaćeno: 2009-01-20
Original Scientific Paper – Izvorni znanstveni rad

Method of cooling in a secondary zone of continuous casting of steel has a significant influence on a quality of continuously cast products mainly from the point of view of internal and surface defects as well as zonal segregations. At the department of thermal engineering, a physical model of the secondary zone has been developed, which enables testing of both water and water-air nozzles. During laboratory measurements cooling effects of a cone nozzle have been expressed by means of three parameters. Most commonly used parameter is an admission characteristic, infrequently heat transfer coefficient is determined and newly a measuring of dynamic impact of the cooling water has been introduced.

Key words: heat transfer coefficient, cooling of surface, nozzle, continuous casting of steel

Prijenos topline tijekom hlađenja vrućih površina pomoću vodenih sapnica. Tijekom kontinuiranog lijevanja čelika, hlađenje sekundarne zone od značajnog je utjecaja na kvalitetu odljevaka sa aspekta unutrašnjih i površinskih pogrešaka te u kontekstu zonske segregacije u materijalu. U odjelu za termoenergetiku razvijen je fizikalni model sekundarne zone, kojim je omogućeno ispitivanje vodenih sapnica i sapnica za hlađenje mješavinom vode i zraka. Tijekom laboratorijskih mjerenja, efekti hlađenja koničnom sapnicom izraženi su trima parametrima. Nejčešći je pritom parameter admisijske karakteristike, ponekad se određuje i koeficijent prijelaza topline a recentno je uvedeno mjerenje dinamičkog utjecaja rashladne vode.

Ključne riječi: koeficijent prijenosa topline, hlađenje površine, sapnica, kontinuirano lijevanje čelika

INTRODUCTION

A way of cooling in a secondary zone influences, to the considerable extent, the strand quality, especially from the point of view of surface defects, therefore for a compliance of required quality of the strand, knowledge of thermal processes during a solidification and cooling is necessary. For these reasons it is necessary to ensure a uniformity of strand cooling in the secondary zone by introducing new progressive systems of cooling. A certain cooling intensity is required for solidification of the steel shell and for preventing of shell tearing in the secondary zone. Ways of increasing heat removal efficiency at recent systems while reducing cooling water consumption are being explored.

One of efficient techniques of heat removal, which is characterized by high values of heat flux, is cooling of hot surfaces by heating and evaporating of water which is impacting the surface with high velocity. The cooling water is atomized and accelerated by means of water or water-air nozzles. This technique is used at many cooling processes in laboratories and industry, such as in engineering, electrical industry and mainly metallurgy.

M. Příhoda, J. Molínek, R. Pyszko, M. Velička, M. Vaculík, J. Burda, Faculty of Metallurgy and Materials Engineering, VŠB-TU Ostrava, Czech Republic

A considerable attention is given to the research of hot surface cooling at many research places worldwide. It follows from the literature sources [1-5], that research works are limited to concrete nozzles which often do not have an industrial utilization. Results obtained have usually a limited extent of validity. Each field of nozzles usage is worth of deeper research. An open question is an existence of the Leidenfrost's phenomena, its dependence on physical parameters and a position on the cooled surface according to the nozzle axis. Especially in case of nozzles with a grater admission pattern, the local conditions of heat removal are not measured in detail. Demands for realization of thermal models of admission lead to exploration of dependencies between heat transfer coefficient and cooling water rate, size and kinetic energy of water particles, therefore determination of correlation between results of hot model and cold model of admission.

PHYSICAL LABORATORY MODEL

Heat removal from solidifying and cooling material by means of water or water-air admission is a complex physical phenomenon. The whole process of cooling is hardly mathematically describable, that's why physical modelling is mostly used. A design of the physical model, mainly the model for simulation of cooling at high temperatures requires application of heat transfer theory as well as a theory of automatic control, knowledge from the field of physical measurements and computer science [6].

Cooling nozzles can be characterized by means of several parameters. The first one is an admission characteristic which is expressed by the intensity of admission according to the equation

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

where V / m^3 is water volume,
S / m^2 – surface,
t / s – time of admission.

Admission characteristics are measured at the model, which is based on a system of chambers in which water from the nozzle admission is collected for a predefined time. The system of chambers may have a shape of rectangular screen with total dimensions greater or equal to the admission pattern of the nozzle. The admission is run for a particular time interval and then the volumes of water in chambers are evaluated. Other method is based on relative movement of the nozzle and a system of chambers. By contrast to the real continuous casting, the nozzle is moving and the chambers are static. The nozzle velocity is optional and it is equal to the strand withdrawal velocity (casting speed) at the real caster. This arrangement gives information about water distribution incoming at the surface. The model in the direction of translation integrates the amount of incoming water. According to the movement of the strand against the nozzle, the water distribution in the longitudinal direction is irrelevant. The water distribution along the strand width is sufficient for a complete evaluation of the nozzle admission characteristic.

The admission characteristic expressed by the admission intensity usually does not enable to determine the real cooling effect as it does not always correspond with the heat flux which is being removed from the cooled surface. For this reason a technique for experimental determination of heat transfer coefficient during admission at hot surface by water nozzles has been developed. The method is based on measuring of electric input to a heated probe, which is necessary for keeping a constant temperature of the probe (Figure 1). The position of the probe is constant while the nozzle is moving in front of the probe in a plain along two perpendicular coordinates x, y. The limits of the coordinates x, y are determined from the shape of the cooled surface. The distance from the probe to the nozzle plain is constant [7].

The measured values of local heat transfer coefficient are saved into the matrix with elements $\alpha_{i,j}$. The dependence of the local and global intensity of cooling on water pressure and cooled surface temperature can be obtained.

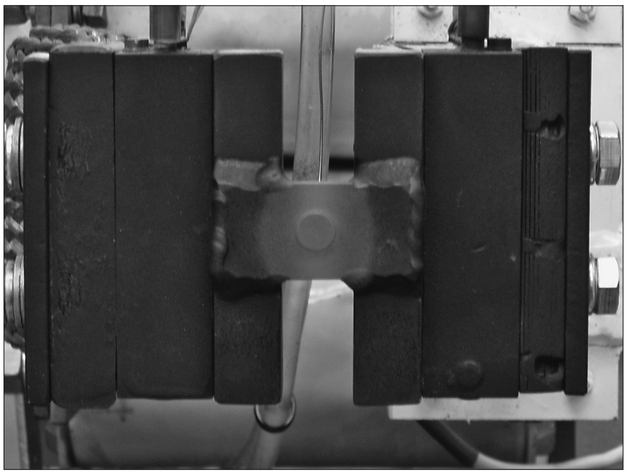

Figure 1. Measuring probe of physical model

The value of heat transfer coefficient α at the measured position i, j can be calculated from the formula

$$\alpha_{ij} = \frac{P_{ok} - P_z}{S_s \cdot (\vartheta_s - \vartheta_v)} \;/\; \mathrm{W/(m^2 \times K)} \qquad (2)$$

where i is index in the direction of coordinate x; $i = \langle 1, n \rangle$,
j – index in the direction of coordinate y; $j = \langle 1, m \rangle$,
P_{ok} / W – immediate electrical input to the probe at the position i, j,
P_z / W – the probe circuit heat loss,
S_s / m^2 – the probe area,
ϑ_s / °C – the probe temperature,
ϑ_v / °C – the water temperature.

It belongs to the advantages of the probe that the basic quantities needed for the calculation of the heat flow removal are electrical quantities, measuring of which is relatively simple and precise. The working part of the probe is heated by electric current and the electric input is measured. Electric input to the probe equals to the heat flow being removed from the probe. The measured electric input is used, after deduction of heat loses, for calculation of heat transfer coefficient α. The heat loses are determined by calibration at the beginning and at the end of the measurement.

An alternative way for obtaining an objective characteristic of the nozzle is a technique based on a research of dynamic effects of water admission of measured nozzles in dependence on the cooling water pressure and a distance of the nozzle from the cooled surface. The nozzle is moved in the plain, which is perpendicular to the nozzle axis, according to the coordinates x, y similarly as in case of measuring the heat transfer coefficient.

The circular shape of the probe measuring surface which is impacted by the cooling water from the nozzle has an area 2 cm2 and it is fixed on a tenzometric sensor of an electronic balance. The force caused by a dynamic impact of water particles is recorded by a measuring computer and then plotted in 3D charts in dependence on coordinates.

EXPERIMENTAL TESTING OF NOZZLES

Only testing of nozzles enables to evaluate in advance if a designed cooling system will ensure a correct uniformity and desired intensity of cooling. Uniform heat removal from the cooled surface is given first of all by distances and spacing of nozzles.

A cone water nozzle used in the technical praxis for cooling of the strand in the continuous casting machines (CCM) was experimentally tested on the physical model. Measuring was carried out while water pressure was set to 0,3 MPa, the distance from the nozzle to the probe was 102 mm, and surface temperature of the probe was 600 and 800 °C.

Firstly a measurement of the admission characteristic was carried out. It showed a uniform and symmetrical course according to the strand axis, which ensures symmetry of cooling and this way it prevents forming of shape defects. The nozzle admission characteristic is represented by a dashed curve in the Figure 4, in which results of particular testing methods are compared.

As mentioned above, an admission characteristic does not give a definite image about a cooling intensity. From this reason the research continued in measuring of cooling intensity on the hot model, where a matrix of local heat transfer coefficients was determined. An example of measured values of heat transfer coefficient for a temperature of the probe 800 °C is shown in Figure 2.

The reference value for determination of a relative heat transfer coefficient α was chosen as 70 % of the maximal value of α, measured at the nozzle with the highest flow rate of cooling water, which was 3 l/min at the reference pressure 0,28 MPa. The scanning step was 20 mm, thus heat transfer coefficient was measured at 81 positions. The real strand is moving against the nozzle uniformly in a straight line in a direction y, and so each surface element is cooled by a variable intensity of cooling during its passing in front of the nozzle. An average cooling intensity of a concrete place on the strand surface during its passing through the admission pattern was named as an average cooling intensity at a given coordinate x. Similarly the same method is applied for an average heat transfer coefficient determination at a concrete coordinate x along the strand width. Supposing constant velocity of the strand, average values α_i are arithmetic means of values $\alpha_{i,j}$ from columns i of the matrix.

While comparing values of heat transfer coefficients α_x measured just in the axis of the nozzle at two different temperatures of the probe, it was observed, that at the temperature 600 °C the value is about three times higher than in case of the probe temperature 800 °C. The significant drop of the intensity of cooling is a consequence of the Leidenfrost's phenomena. Similar results were obtained during measuring while different pressures of the cooling water were set.

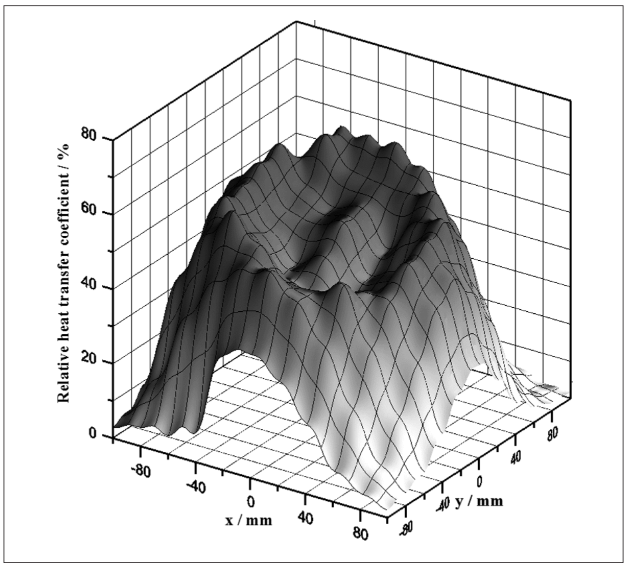

Figure 2. Relative values of α of a cone nozzle

The next part of the research was focused on measuring of a dynamic effect of cooling water in dependence on the cooling water pressure. The same type of nozzle was used and a pressure 0,3 MPa was set. In the Figure 3 a significant increase of the dynamic effect in the central part of the admission pattern can be observed in comparison with the chart of heat transfer coefficient (in the Figure 2).

It is probably caused by different angles of arrival of cooling water from the nozzle to the probe at different positions. The next work will be focused on determination of dependence of dynamic effect on the angle of arrival.

As heat transfer coefficient determination is more difficult, time demanding and expensive in comparison with the other methods, there is an effort to explore eventual dependences between the characteristics to enable substitution of one method by the other. A close relation between the intensity of cooling, the intensity of

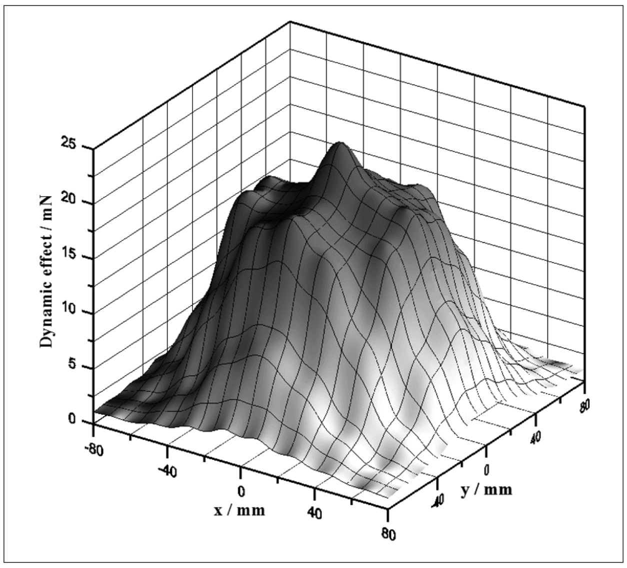

Figure 3. Dynamic effect of water

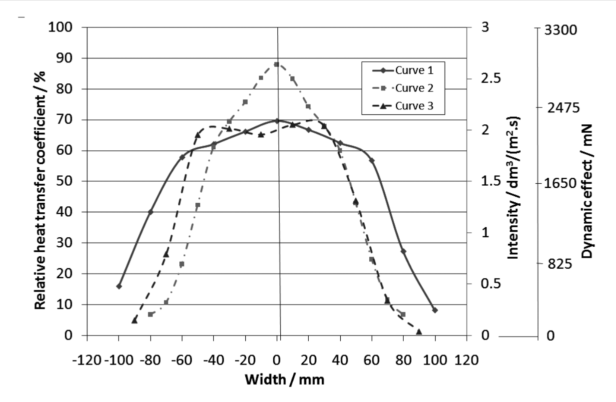

Figure 4. Cooling characteristics of nozzle

admission and the dynamic effect generally cannot be expected as heat transfer coefficient is dependent not only on the cooling water rate but also on size and velocity of water particles, surface temperature, angle of arrival etc.

Values of all three measured characteristics in dependence on the strand width are compared in the Figure 4. Heat transfer coefficient α is drawn by a continuous line (curve 1), the dynamic effect is drawn by dashed line (curve 2) and admission intensity is represented by dashed and dotted line (curve 3). Similar results were obtained for different nozzles and water pressures.

CONCLUSION

Heat removal from a hot surface by water admission is a complex physical phenomenon. The whole process of cooling is difficult to describe by a mathematical model and so most of all a physical modelling is used. Conditions of heat transport from a surface of a solid body by an admission of water by nozzles are being explored in a laboratory of physical modelling. For the reason of great demands and difficulties of the measuring on the hot models of admission, correlations between heat transfer coefficient, admission intensity and dynamic effects are being explored. Acquired knowledge can be used as boundary conditions for solving of heat transport tasks of the cooling processes both in a laboratory and industry.

The work was realised within the frame of solution of the grant project No. 106/07/0938 under financial support of the Czech Science Foundation.

REFERENCES

[1] Ya. V. Frolov, I. Mamuzić, V. N. Danchenko, The heat conditions of the cold pilger rolling. Metalurgija, 45 (2006) 179-184.

[2] Z. H. Liu, et al., Study on film bowling heat transfer for water jet impinging on high temperature flat plate. International Journal of Heat and Mass Transfer, 44 (2001), 2475-2481.

[3] G. P. Celata, et al., Heat flux and heat transfer coefficient in quenching of hot surfaces by drop impingement. 13th International Heat Transfer Conference, Sydney, 2006.

[4] J. Elfmark, Modelling and on line control of thermo mechanical rolling and cooling of micro-alloyed steel. Metalurgija, 36 (1997)1, 3-7.

[5] M. Raudenský, M. Čarnogurská, Effect of dynamic properties of thermocouples on the results of solving the inverse problems of calculating the boundary conditions. Transaction of the Technical University of Košice, Cambridge, England, 3 (1993), 363-369.

[6] M. Příhoda et al., Vodní a vodovzdušné trysky sekundární oblasti chlazení ZPO (Water and water-air nozzles of the secondary zone of continuous casting machine). Acta Metallurgica Slovaca, 7 (2001) 5, 444-449.

[7] J. Molínek et al., Porovnání studeného a teplého modelu sekundární oblasti chlazení ZPO (Comparison of hot and cold models of the secondary cooling zone of CCM). In.: Proceedings of X. International Scientific Conference Iron and Steelmaking, 2000, 156–159.

Note: The responsible translators for English language is R. Pyszko, Czech Republic.