UDK 621.74.047:536.2 ISSN 1580-2949
Professional article/Strokovni članek MTAEC9, 46(3)311(2012)

INFLUENCE OF THE WATER TEMPERATURE ON THE COOLING INTENSITY OF MIST NOZZLES IN CONTINUOUS CASTING

VPLIV TEMPERATURE VODE NA INTENZITETO OHLAJANJA Z MEGLIČNIMI ŠOBAMI PRI KONTINUIRNEM ULIVANJU

Miroslav Raudensky[1], Milan Hnizdil[1], Jong Yeon Hwang[2], Sang Hyeon Lee[2], Seong Yeon Kim[2]

[1]Brno University of Technology, Czech Republic
[2]POSCO, Korea
raudensky@fme.vutbr.cz

Prejem rokopisa – received: 2011-10-20; sprejem za objavo – accepted for publication: 2012-02-15

Small mist nozzles used in continuous casting were tested for heat-transfer intensity. These nozzles are used in the secondary cooling area of a steel slab casting machine. The impact pressure distribution was measured first. The laboratory measurements of the cooling intensity (the HTC distribution) were performed with a variable water temperature. A temperature range from 20 °C to 80 °C was used in the tests.
Surprisingly, the water temperature was found to have a strong influence. The most noticeable effect is a shift in the Leidenfrost temperature to low temperatures. Changing the water temperature from 20 °C to 80 °C caused a change in the Leidenfrost temperature of 130 °C. This can be significant and can change the cooling character of the continuous casting machine. It is interesting that with an increase in the cooling intensity, following an increase in the water temperature in a high-temperature region (above the Leidenfrost temperature), there is a small difference of about 30 W/(m^2 K).
Surprisingly, high differences in the Leidenfrost temperature were found for an intensive cooling, where a difference of only 20 °C in the coolant temperature makes a difference of about 100 °C in the Leidenfrost temperature.
The results of the experiments performed with an elevated water temperature showed a high sensitivity of the cooling intensity to this parameter. The decreasing effect of the cooling intensity related to the water temperature is more important for the spray cooling of high intensities.

Keywords: water temperature, cooling intensity, mist nozzles, continuous casting

Majhne meglične šobe, ki se uporabljajo pri kontiuirnem ulivanju jekla, so bile preizkušene na intenziteto prenosa toplote. Te šobe se uporabljajo v območju sekundarnega hlajenja kontinuirne naprave za ulivanje jekla. Najprej je bila izmerjena razporeditev tlaka pri njegovem udarcu. Laboratorijske meritve intenzitete ohlajanja (razporeditev koeficienta prenosa toplote) so bile izvršene s spreminjanjem temperature vode. Pri preizkusih je bila uporabljena voda s temperaturo od 20 °C do 80 °C. Presenetljivo je, da se je izkazalo, da ima temperatura vode močan vpliv. Najbolj opazen učinek je bil premik Leidenfrostove temperature k nižjim vrednostim. Sprememba temperature vode iz 20 °C na 80 °C je povzročila spremembo Leidenfrostove temperature za 130 °C. To je pomembno in lahko močno vpliva na ohlajevalne značilnosti naprave za kontinuirno ulivanje. Zanimivo je, da se z naraščanjem intenzitete ohlajanja z višanjem temperature vode v visokotemperaturnem režimu (nad Leidenfrostovo temperaturo) opazi le majhna sprememba HTC za okrog 30 W/(m^2 K).
Presenetljivo velike razlike v Leidenfrostovi temperaturi so bile dobljene pri intenzivnem ohlajanju, kjer je razlika v temperaturi vode 20 °C povzročila razliko v Leidenfrostovi temperaturi za okrog 100 °C.
Rezultati eksperimentov, izvršeni s povišano temperaturo vode, so pokazali veliko občutljivost intenzitete ohlajanja za temperaturo vode. Padajoči učinek intenzitete ohlajanja z naraščanjem temperature vode je bolj pomemben pri bolj intenzivnem ohlajanju z meglo.

Ključne besede: temperatura vode, intenziteta hlajenja, meglične šobe, kontinuirno ulivanje

1 INTRODUCTION

The heat flux extracted from a cooled surface can be expressed as a product of the heat-transfer coefficient (HTC) and a difference between the surface temperature and the coolant temperature. This paper discusses the question whether the HTC is influenced by the coolant temperature. The cooling-water temperature changes during the year in the steel plants and can be considered to be in the range from 10 °C to 45 °C. Can this change in the coolant temperature influence the cooling characteristics of the mist nozzles typically used in the secondary area of the continuous-casting machines.

A typical dependence of the HTC on the surface temperature is shown in **Figure 1**. The HTC is strongly variable with respect to the surface temperature. The border between the high intensity cooling for low surface temperatures and the low intensity cooling for high surface temperatures is the Leidenfrost temperature[1,2]. The measurements performed with the mist nozzles showed a strong dependence of the Leidenfrost temperature on the kinetic energy of the droplets and of the water impingement density[3,4].

The influence of the cooling medium on the cooling intensity is rarely described in the literature. The research of the University of British Columbia in Canada[5] showed interesting dependences of an increasing temper-

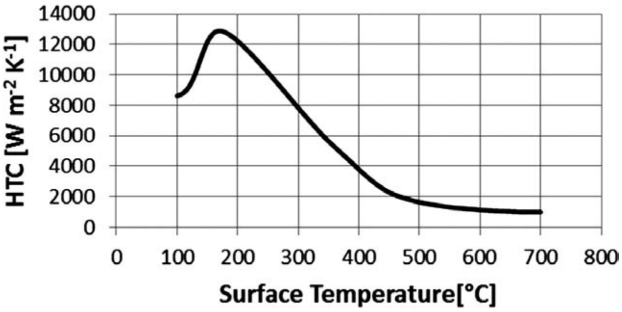

Figure 1: Typical dependence of the HTC on the surface temperature
Slika 1: Značilna odvisnost HTC od temperature površine

ature of the cooling medium. For the measurements, 7 mm thin carbon plates embedded by 16 thermocouples were used. One half of the thermocouples was positioned 1 mm under the surface. The second half was welded to the surface. The test plate was heated to the initial temperature between 700–900 °C, and then positioned under a full cone nozzle. A comparison of the results (**Figure 2**) showed that in the area between 50 °C and 70 °C, where the cooling is effective, the HTC reaches higher values for the water temperature T_w = 50 °C than for the water temperature T_w = 70 °C. On the other hand, the HTC difference between the water temperatures of 50 °C and 40 °C is not significant. The results described in[5] are very interesting showing a substantial dependence of the cooling-medium temperature on the spray cooling efficiency.

2 HTC-MEASUREMENT

2.1 Testing equipment

A laboratory stand (**Figure 4**) developed for testing the nozzles applied for continuous casting was used to test the cooling intensity with the water at elevated temperatures. The tested mist nozzles are located under a test plate. The steel frame holds three major parts of the stand: a test plate, a driving mechanism with a nozzle(s) and a heater.

The test plate is made of austenitic steel to prevent the surface from a significant oxidation. There are holes

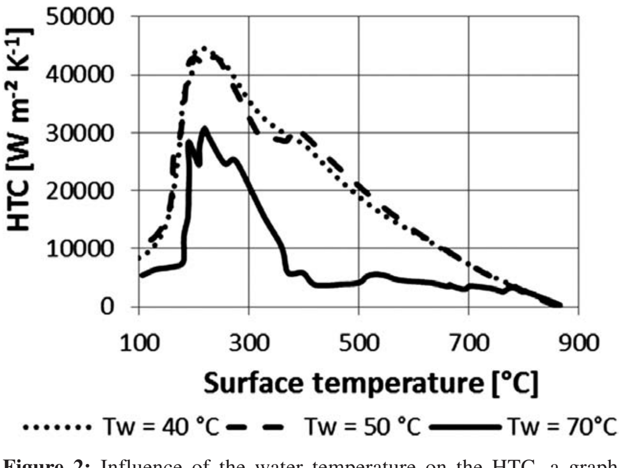

Figure 2: Influence of the water temperature on the HTC, a graph adapted from the paper[5]
Slika 2: Vpliv temperature vode na koeficient prenosa toplote; graf je povzet po viru[5]

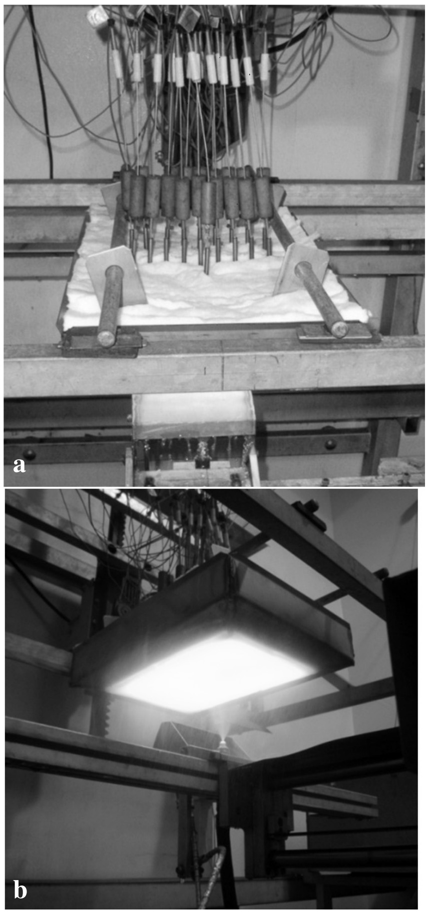

Figure 3: a) Insulated test plate and two rows of thermocouples, b) the test plate sprayed with nozzles
Slika 3: a) Izolirana preizkusna plošča in dve vrsti termoelementov, b) preizkusna plošča, brizgana s šobami

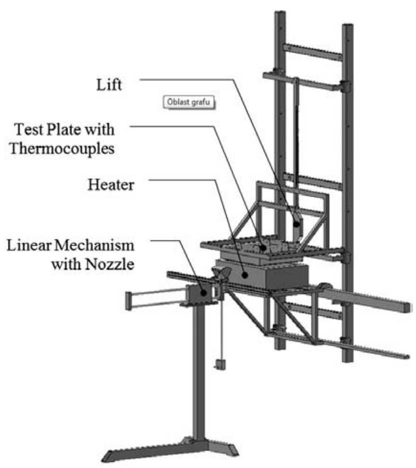

Figure 4: Basic parts of the experimental testing bench
Slika 4: Osnovni deli eksperimentalne klopi za preizkušanje

Figure 5: Initial stage of an experiment – the furnace is moving to the right, the pressure was set
Slika 5: Začetno stanje preizkusa – peč se odmakne na desno, vzpostavi se tlak

drilled into the plate, where the thermocouples are placed. Shielded thermocouples of type K with a diameter of 1.5 mm are used for temperature monitoring. The shape of the plate and the distribution of the thermocouples used in these tests can be seen in **Figure 3**. All of the 18 thermocouples in two rows and nine columns were used.

The driving mechanism moves the spraying nozzle(s) under the plate. The speed of the nozzle motion is controlled by a computer. A pneumatically driven deflector is placed between the nozzle and the cooled plate. The deflector opening and closing when the nozzle is spraying is controlled by the computer. The deflector is closed on the way back to its initial position.

The third major part of the test bench is an electric furnace used for the initial heating of the plate. The furnace moves on rails. It is placed under the test plate when the experiment is prepared and the gap between the furnace edges and the plate is filled with insulation. At the beginning of the experiment the plate is heated up to an initial temperature. The temperature of 1250 °C was set as the initial temperature. The test plate is placed into a jig. This allows the plate to move up, removing the furnace back and positioning the nozzle with the driving mechanism to the space under the plate. This stage of the experiment is shown in **Figure 5**.

A computer with a data-acquisition system is located outside the spray box in a control room. It monitors the heating process, controls the experiment and records the data from thermocouples and the position sensor.

2.2 Experimental process

The test plate is cleaned up, the holes for the thermocouples are cleaned and the thermocouples are tested before each experiment. The plate is positioned into the jig in the stand frame and the thermocouples are embedded. The data-acquisition system, the driving

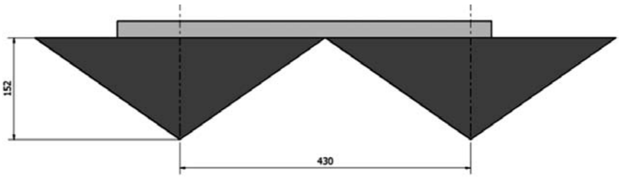

Figure 6: Scheme of a configuration of the air-mist nozzles
Slika 6: Shematičen prikaz razporeditve šob za ustvarjanje megle

mechanism and the deflector go through a cold preliminary test. The furnace is positioned under the plate. The heating control system is set up and the heating of the plate starts. After the plate reaches the initial temperature needed for the experiment, the control system keeps the adjusted temperature in the furnace and the temperature in the plate is homogenized.

The deflector on the driving mechanism is closed and a required pressure of the coolant is set up. The pressure of the coolant is measured in a manifold where the nozzles are mounted. The flow rate of the water is measured by an induction flow meter. The plate is moved up in the jig to adjust the cooling position and the furnace on rails is moved out. The driving mechanism with the spraying nozzle and the closed deflector are moved to a defined position under the hot plate. The data-acquisition system records the temperatures of all the thermocouples, the temperature of the coolant and the position of the nozzle. The nozzle moves in one direction with the open deflector and returns with the closed deflector. The experiment is finished when the temperature in all the measured points is below 500 °C. An inverse task is used to re-compute the internal temperatures to the surface temperatures in order to obtain the HTC[6].

2.3 Test configuration

Commercially available small mist nozzles used for cooling in continuous casting were used for the tests. The nozzles have a spray angle of 110°. A couple of nozzles with parallel main axes were used – see **Figure 6**.

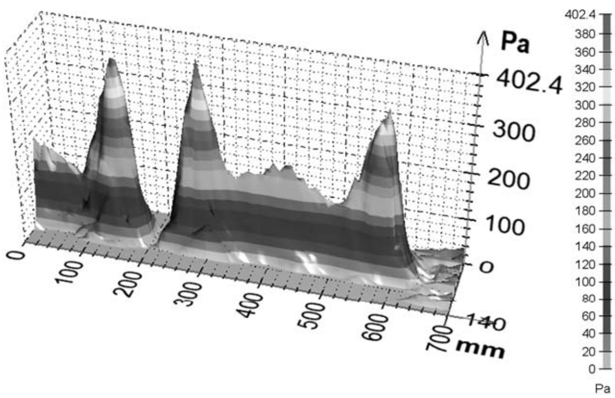

Figure 7: Impact pressure distribution, an example for the water pressure of 2.1 bar and the air pressure of 1.6 bar
Slika 7: Razporeditev udarnih tlakov – primer za tlak vode 2,1 bar in tlak zraka 1,6 bar

Table 1: Nozzle parameters
Tabela 1: Pregled parametrov šob

Experiment	Water Pressure (bar)	Air Pressure (bar)	Water Flow Rate (L/min)	Water Temperature (°C)	Air Flow Rate (m^3/h)	Spray Height (mm)	Pitch (mm)	Casting Velocity (m/min)
T35–41	2.1	1.6	4.5	20–80	8.1	239	430	1
T43	3.6	1.9	8	40 °C	6.3	239	430	1

The nozzles were tested for spray homogeneity prior to the heat-transfer tests. The result of the impact pressure measurement is shown in **Figure 7** (one complete footprint and one half of a footprint of the impacting jets is shown in the Figure). It is obvious that the tested nozzle is far from being ideal. The results published in this paper refer to the impacting area in the nozzle axis. The flow rate and the pressure conditions are described in **Table 1**. All the tests were carried out with a constant velocity of the sample: 1 m/min.

3 RESULTS

The results shown in this part are the average values of the heat-transfer coefficient in the impact area in the direction of the nozzle axis. The impacting area for –150 mm to +150 mm is considered both in longitudinal and transversal directions.

Figure 8 shows the results for seven experiments where the only variable parameter was the water temperature.

The experiments shown in **Figure 8** demonstrate a significant shift in the Leidenfrost temperature. Changing the water temperature from 20 °C to 80 °C causes a change in the Leidenfrost temperature of 130 °C. This

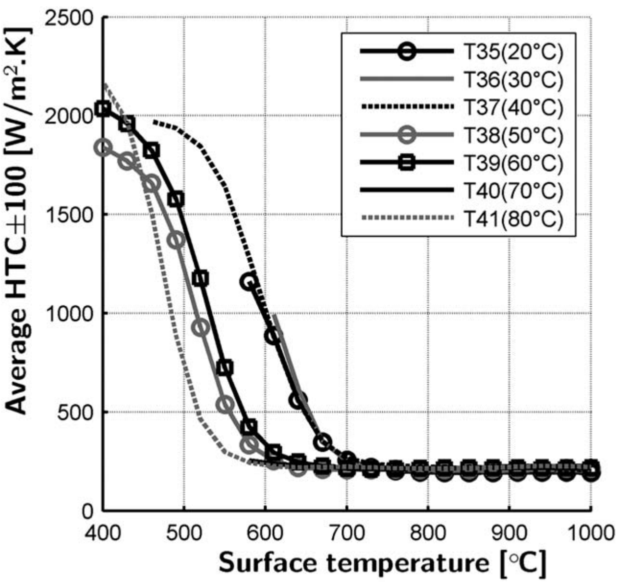

Figure 8: Seven experiments show an increase in the water temperature from 20 °C to 80 °C
Slika 8: Sedem preizkusov, ki kažejo povečanje temperature vode od 20 °C do 80 °C

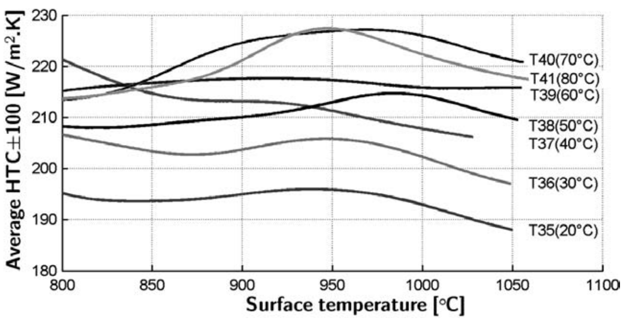

Figure 9: Influence of the water temperature in the high temperature region – a close-up of the right-hand part of **Figure 8**
Slika 9: Vpliv temperature vode v visokotemperaturnem področju – povečan desni del **slike 8**

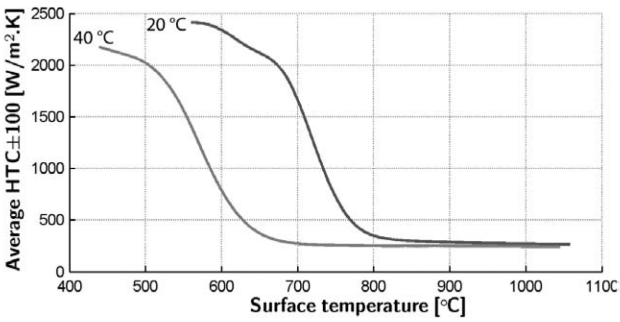

Figure 10: Changes in the cooling intensity for the experiment with a bigger flow rate, the water temperature of 20 °C and the experiment T43 with 40 °C
Slika 10: Sprememba intenzitete hlajenja pri preizkusu z večjim pretokom vode: voda s temperaturo 20 °C in preizkus T43 s 40 °C

can be significant and can change the character of the cooling in the continuous casting machine. It is interesting that there is an increase in the cooling intensity following the increase in the water temperature in the high-temperature region as shown in **Figure 9**. The difference is about 30 W/(m^2 K) (see the scale of the graph). **Figure 9** shows that hot water provides a higher cooling intensity above the Leidenfrost temperature. This finding can be explained with the positive effect between the water temperature and the boiling point that allows a faster setting of the boiling regime with high heat-transfer rates.

Surprisingly, high differences in the Leidenfrost temperature were found for the intensive cooling (**Figure 10**) where a difference of only 20 °C in the coolant temperature makes a difference of about 120 °C in the Leidenfrost temperature.

4 CONCLUSION

A high influence of the water temperature on the cooling intensity of the mist nozzles was found. The major effect is the shift in the Leidenfrost temperature to low temperatures. The effect is more significant in the case of intensive cooling. Even a temperature difference of 20 K (between 20 °C and 40 °C) makes a significant change in the Leidenfrost temperature. This finding can explain some of the problems of the continuous casting machines used in winter and summer when the temperature of the cooling water varies significantly.

Acknowledgement

The paper presented has been supported by an internal grant of the Brno University of Technology focused on specific research and development, No. FSI-S-11-20 - Heat Transfer Intensification.

5 REFERENCES

[1] M. Raudensky, J. Bohacek, Leidenfrost Phenomena at Hot Sprayed Surface, In the 7th ECI International Conference on Boiling Heat Transfer Boiling 2009, 3–7 May 2009, Florianopolis, Brazil

[2] M. Raudensky, J. Horsky, Secondary Cooling in Continuous Casting and Leidenfrost Temperature, Ironmaking and Steelmaking, 32 (**2005**) 2, 159–164

[3] M. Raudensky, A. Horak, P. Kotrbacek, Optimisation Of Controlled Cooling in Continuous Casting, 1st International Conference on Simulation and Modelling of Metalurgical Processes in Steelmaking, 25–27 October 2005, Brno, Czech Republic

[4] J. Horsky, M. Raudensky, A. A. Tseng, Heat Transfer Study of secondary cooling in Continuous Casting, AISTech 2005, Iron & Steel technology Conference and exposition, May 9–12, 2005, Charlotte, USA

[5] F. Xu, M. S. Gadala, Heat Transfer Behaviour in the Impingement Zone under Circular Water Jet, International Journal of Heat and Mass transfer, 49 (**2006**), 3785–3799

[6] M. Pohanka, H. Bellerova, M. Raudensky, Experimental Technique for Heat Transfer Measurements on Fast moving Sprayed Surfaces, Journal of ASTM International, 6 (**2009**) 4, 1–9