Heat Transfer Study of Secondary Cooling in Continuous Casting

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INTRODUCTION

Secondary cooling is an essential part of the continuous casting (CC) technology. The method of secondary cooling can strongly influence the quality of billet, regarding primarily the formation of internal and surface cracks. Quickly solidified surface shall hinder internal layer shrinking and the conditions for initiation of crack arise. The new generation of mist nozzles allows controlling the cooling intensity in a wide range by setting a combination of water and air pressures. Cooling has to be controlled with respect to casting speed, type of steel and other technological demands. Best results in product quality are obtained with on-line control systems based on numerical models of temperature fields and solidification. The paper presents experimental method for measurement of heat transfer parameters of commonly used mist nozzles. The nozzles are tested for pressure setting, for influence of casting speed, for behaviour in the overlapping areas. The tests provide the description of heat transfer coefficient on the cooled steel surface. The knowledge of these parameters is necessary for any advanced control system.

TWIN FLUID NOZZLE TESTING

Air mist atomizers are available in many styles and design configurations. Two basic distinctions in operating class are internal or external mixing. Air mist nozzles deliver spray droplets within their own generated gas flow fields that have high velocities as compared with straight hydraulic systems. Pneumatic atomizers are capable of producing fine drop sizes with very narrow range of sizes. Drop size is generally much smaller than that produced by basic hydraulic atomizers. Flat jet air mist nozzles have been successfully applied for secondary cooling applications in continuous casting steel production for more than fifteen years.
Standard nozzle tests for characterization of flow rates, spray pattern, impact pressure distribution, droplet size and velocity are usually provided by nozzle producer. Of higher importance for these nozzles is a measuring technique to determine the heat removal capability, which cannot be correlated with the standard spray parameters in a simple and well-defined manner.

In the area of secondary cooling the heat flux removed from the billet surface can be expressed by

\[ q = HTC \left( T_S - T_W \right) + q_R. \]  

(1)

where \( q \) is total heat flux, \( HTC \) is heat transfer coefficient, \( T_S \) is surface temperature, \( T_W \) is cooling water temperature and \( q_R \) is radiation heat flux.

**Flow Rates Measurement**

Flow rates measurement is a standard procedure. An example of flow rate diagram is plotted in Figure 1. For three different levels of air pressure, flow rate of water and air was measured. Water pressure was an independent parameter.

**Liquid Distribution Measurement**

Liquid distribution is measured by taking mist spray into a set of water containers of certain width. This information gives an idea about homogeneity of spray typically in longitudinal nozzle axis. These characteristics should be known for the whole operating range of water and air combinations. An example of water distribution for water pressure 7 bar is plotted in Figure 2 and for water pressure 2 bar in Figure 3. Air pressure was constant for both cases 2 bar.

**Impact Pressure Measurement**

Sophisticated measuring instruments are necessary for precise information about impact pressure distribution of twin fluid nozzles. A simple, early method used for high pressure nozzles when a soft surface was sprayed, can not be used for air mist nozzles. It is important to determine the impact distribution of air mist nozzles on a special test rig. The impact of the spray on a surface is measured with a force transducer, which scans the spray impingement area and measures the impact pressure of the spray on a given surface. Photo 1 shows measurement of impact pressure in laboratory conditions. Figure 4 illustrates an example of measured data.

**Velocity and Droplet Size Measurement**

The Phase Doppler Anemometry (PDA) technique is the principal spray measurement technique used in the laboratory environment. The PDA system can be used to measure the spray at a matrix of positions and at each position drop velocity, diameter and arrival time for several thousands drops is stored. The PDA technique has restrictions, which are principally:

- Drops must be spherical between close limits
- Optical properties of the drops must be known and homogeneous
- It must be possible to set up the system in such a way that either the reflection or refraction modes of light scattering dominate
Heat Transfer Measurement

Two major methods of HTC determination exist: steady state and transient. In the steady state method the specimen is heated at a prescribed temperature and at the same time is cooled by spray. HTC is computed from heat balance established at a particular temperature. The process must be repeated to cover the whole temperature range. This system needs to be controlled carefully. For the smaller, electrically heated specimen, there are dangers of burnout when character of heat transfer is rapidly changed. The obtained results do not fit too well to the results measured on casting machines. A good agreement was obtained only for the nozzle axis area. The source of differences was obvious: jet droplets spraying on the hot surface evaporate, steam is generated and the character of flow and conditions for the impact of the droplets on the hot surface is much different from the flow on the cold plate. The method used in this study is a transient one\(^2\). Specimen is first heated to a required temperature and then cooled. The whole studied temperature range is covered during one experiment and a realistic distribution of HTC can be evaluated. The size of specimen has to be larger than the size of spray impact area. If overlapping problems are studied the size of a test specimen has to cover at least the impact area of two neighbouring nozzles. It was found that the stationary tests with no relative motion between the nozzle and the cooled surface do not provide the results suitable for precise cooling models. The casting velocity influences heat transfer. This influence is significant even if the casting velocity is of order of meters per minute.
Experimental Equipment
The general arrangement of the experimental stand is shown in Figure 7. The basic part is a test specimen, made of an austenitic plate, size 600x320x30 mm. A set of thermocouples is embedded into a test plate and indicates temperatures at a certain depth from cooled surface.

![Diagram of the experimental stand for HTC measurement](image)

Experimental procedure is done as follows:
- Test plate is heated at a prescribed temperature (typically 1250 °C) using an external electrical heater.
- The heater is replaced by moving trolley with nozzle. Driving system controls motion of this unit. The range of motion is from – 250 mm to +250 mm.
- When the unit is moving in the positive direction, nozzle sprays the surface. Spray is reflected from surface by a deflector when nozzle is moving in the opposite direction.
- The temperature traces and nozzle position trace are logged on PC controlled data logger.
- Experiment is finished when the test plate is cooled below certain temperature (commonly 500 °C).
- Logged data are used for subsequent evaluation.

Next step in data evaluation is inverse computation where from measured temperature record (temperature at the certain depth from cooled surface)³, surface temperature, heat transfer coefficient and heat flux is computed. An example of temperature record of one thermocouple is shown in Figure 8 and result of inverse computation (HTC record) is plotted in Figure 9.
The objective of the final mathematical procedure is to obtain the function $HTC = f(x,T)$, where $x$ represents the position and $T$ represents the surface temperature. It is required from the approximating function $f$ to provide a good approximation with a minimum number of coefficients and to make the meaning of the coefficient as transparent as possible or provide HTC data in a matrix form. Figure 10 shows an example of HTC curves gained from experiment and following evaluating procedures as a set of vectors for the position in nozzle axis, and distances 100, 200 and 300 mm from the nozzle axis. In case when heat transfer intensity should be specified only by one number, the mean integral value of HTC, specified at a certain integration length, can be computed (see Fig. 10).
HEAT TRANSFER AND SPRAY PARAMETERS

Water Density
The estimation of cooling intensity obtained from spray cooling density (l/m²s) is frequently used for simulation purposes. The heat transfer tests showed that there is no explicit link between coolant flow and cooling intensity. Heat transfer is not influenced only by water flow but also by droplet size and velocity. Simple estimation of the heat transfer coefficient from water impingement density can be affected by significant errors.

The following example, obtained from nozzle testing, is demonstrating the above mentioned.

Two heat transfer tests were done with the following spray parameters. The mist nozzle with spray angle of 80° was located at a height of 300 mm. The cooled surface velocity was 1 m/min. Initial temperature of the cooled steel plate was 1100°C. Both experiments used water flow of 10 l/min.

The only parameter different in these two tests was air flow. Experiment 1 uses 30 m³/hr. Experiment 2 uses 15 m³/hr. The change of this parameter caused the change of droplet size and velocity. Water and air flows were set by combination of water and air pressures.

The results of tests are plotted in Figure 11. There are two curves for heat transfer coefficient (HTC) for surface temperature in interval from 900 to 1100°C. It can be seen that the cooling intensity is significantly different even if the water flow is the same in both cases. The average value of heat transfer coefficient for Experiment 1 is 860 W/m²K and for Experiment 2 is 510 W/m²K. The difference is 40%.

![Figure 11 Heat transfer coefficient (HTC) in the sprayed area, two nozzles with identical water flow, identical spray pattern and different droplet sizes and velocities.](image)

Influence of Casting Velocity on Heat Transfer
Three measurements are compared when the only different parameter is the casting speed. Experiment 3 was stationary with no movement, Experiment 4 used a velocity of 2 m/min and Experiment 5 was done for a casting velocity of 5 m/min. These three experiments used the identical mist nozzle, and the same pressure setting was used in all experiments - water pressure of 2 bar, air pressure of 2 bar. Figure12 shows the distribution of heat transfer coefficient in experimental group with a variation of velocity. HTC for the stationary case (not possible in mill) is symmetrical and the peak is narrow. The cooling intensity decreases with the casting velocity. Heat transfer coefficient distribution is more non-symmetrical when casting speed increases. The observed effect is caused by the flow on the surface and different vapour forming conditions in front and behind the impinging jet.

Leidenfrost Temperature – Border in Heat Transfer
The theoretical term “Leidenfrost temperature” has very practical impact on the operation and design of CC mill. Spray cooling efficiency strongly depends on surface temperature. Stable vapour layer can be formed at the cooled surface. The stable vapour layer protects the surface from direct contact to the coolant and the cooling is of low intensity. Stability of the vapour layer is coupled to the surface temperature. When temperature decreases and the vapour layer collapses the cooling instantly grows. The cooling intensity can be ten times higher in low temperature region in comparison to the intensity in the high temperature region. The border between these two temperature areas is the Leidenfrost temperature.
Stationary Experiment
Experiment simulating no casting speed will show the importance of the phenomenon - Leidenfrost temperature. A nozzle sprays a hot test plate and the temperatures are recorded. The surface temperature is measured and the record is shown in Figure 13. The temperature falls down and approximately in a period of 80 seconds a sharp change in the curve slope is observed. The temperature just reached the Leidenfrost temperature. It should be mentioned that all the spray parameters are constant. Knowing the surface and coolant temperature then HTC was computed. The curve for HTC in Figure 13 is very instructive. The initial value of HTC is about 400 W/m²K. This value rapidly grows when Leidenfrost temperature is reached. The new value of heat transfer coefficient is over 4000 W/m²K. Heat transfer is changed ten times when the temperature crosses the Leidenfrost point.

![Figure 12](image-url)

Figure 12  Influence of casting velocity at heat transfer, Exp. 3 is stationary, Exp. 4 is for 2 m/min and Exp. 5 is for 5 m/min.

Leidenfrost Point for CC Conditions
The experiment originally with no casting speed was repeated for casting velocity of 2 m/min. The Leidenfrost temperature was found, it is 950°C. The data were divided into two groups. The first group is for heat transfer above the Leidenfrost temperature and the second group is for heat transfer below the Leidenfrost point. The results are shown in Figure 14. It can be seen that the cooling intensity is significantly dependent on the surface temperature.

![Figure 13](image-url)

Figure 13  Measured surface temperature history in cooling experiment. Steep change in heat transfer coefficient values when crossing the Leidenfrost temperature.
Cooling Distribution along Spray Angle

Cooling uniformity across a wide slab is demanded but in most cases is not achieved. The major problem is that constant water distribution does not result in constant cooling intensity. Droplet size and velocity, impact angle, and water impingement density have an important significance, and the situation is also complicated by different boiling regimes below and above the Leidenfrost temperature.

Figure 14  Heat transfer coefficient distribution between the rolls, for surface temperature below Leidenfrost temperature and above Leidenfrost temperature - for high temperature region of 1200-950°C.

An example of the heat transfer coefficient distribution along the spray width is in Figure 15. Figure 15 shows the transversal direction while the Figures 11, 12 and 14 show heat transfer in the longitudinal direction. Heat transfer coefficient between the supporting rolls

Figure 15 Heat transfer coefficient along spray angle for constant air pressure of 2 bar, spray height of 300 mm and three water pressures.

Figure 16 The Leidenfrost temperature along the spray angle, for constant air pressure of 2 bar, spray height of 300 mm, casting velocity of 1 m/min and three water pressures.
forms a 2D surface. The HTC values in Figure 15 are plotted only for transversal direction. The HTC value at each point represents the average value in the longitudinal direction. The measured heat transfer coefficient plotted in Figure 15 is for three water pressures. The other parameters are constant. It can be observed how the homogeneity of cooling depends on the setting of pressure parameters. The pressure parameters 7/2 bar (water / air) provide strong non-homogeneity in cooling with intensive heat transfer at the nozzle axis position. Here is the source of temperature stripes on the cast material and longitudinal defects.

The Leidenfrost temperature should be discussed to see the problem in its complexity. It was experimentally proven that the boiling mechanism at the hot surface is primarily influenced by the kinetic energy of droplets. There is no known method how to theoretically set the Leidenfrost temperature from the parameters of spray. The only reliable way is a measurement. The results of three measurements for three water pressures are shown in Figure 15. Each curve in Figure 15 divides the area into two parts. The part above the curve is for low cooling intensity where the impinging droplets are separated from the hot surface by the stable vapour layer. The area below the curve is for intensive cooling, below the Leidenfrost temperature, where the values of heat transfer coefficient are about ten times higher than the high temperature area.

Figure 15 is instructive when discussing a situation in the casting machine. Let us assume that the secondary cooling system uses the nozzle with parameters in Figure 15 and the water pressure is 7 bar. Slab at surface temperature (say) of 1000 °C moves under the spray. The curve marked by squares in Figure 15 is valid for this case. The sprayed surface close to the nozzle axis (position –100 mm, +100mm, see Figure 15) is at the temperature below the Leidenfrost temperature and we can estimate HTC in this example to be 4000 W/m²K. The temperature of 1000 °C for the outside area is above the Leidenfrost temperature and the HTC can be estimated to be 400 W/m²K. This is the problem. The cooling will cause dark, cold stripes on the surface at the position of nozzle axes.

Cooling Distribution along Spray Angle – Overlapping

Flat-jet nozzles with wide spray angle are used for secondary cooling. Production experience and measurements show that cooling is not uniform along the spray width.

To design properly the cooling in overlapping area is artistry. Measurements and plant observations confirmed that ensuring uniform water distribution along the slab width does not guarantee the uniformity in cooling. A proper nozzles spacing is difficult even for constant casting velocity and constant pressures of air and water. And the problem is much more complicated when heat transfer should be controlled from soft to hard cooling.

The following example shows the comparison of four measurements. All measurements were done for two mist nozzles in spray height of 200 mm, spray angle of 90° and distance between nozzles of 400 mm. These four experiments differ in the pressure setting. Air pressure of 1 bar and water pressure of 0.5 bar in the first experiment gives the soft cooling. The fourth experiment using air pressure of 2 bar and water pressure of 5 bar provides the most intensive cooling in the group. The result in overlapping area is shown in Figure 17. The distance between nozzles of 400 mm is too big for the soft cooling and the same distance is too short for the hard cooling. The only way how to ensure the cooling uniformity is controlling air and water pressures at the same time.

![Figure 17 Cooling intensity in the overlapping area for different combination of air and water pressures](image)
CORRELATION BETWEEN SPRAY CHARACTERISTICS AND HEAT TRANSFER

Figures 5 and 6 show that parameters of spray are not constant along the spray width. The first comment can be made based on simplified 2D approach. Figure 18 shows three parameters of a mist nozzle. All the plotted data in Figure 18 were obtained for identical pressure setting of the nozzle. The most common parameter accompanying nozzles is the liquid distribution. General effort of the nozzle producers is to design nozzles with constant cooling intensity along the spray angle. Measurement of the HTC distribution shows that constant liquid distribution does not provide constant HTC distribution. Literature shows some effort of research groups to find correlation between measurement of the impact pressure distribution and HTC. This is again a difficult way. A typical mean impact distribution is shown in the middle part of Figure 18. The real HTC distribution is much wider than the impact pressure distribution as shown in Fig. 18. The usage of mist nozzles in continuous casting does not allow to reduce the problem only to the direction across the slab. Comparison of results plotted in the Fig. 19 and 20 provide information about relation between impact pressure distribution and HTC distribution. Figures 19 and 20 were obtained for mist nozzle, air pressure of 2 bar, water pressure of 7 bar and casting speed 1 m/min. It can be seen that the nozzle cools effectively much bigger area than is the impact area. This is significant in the longitudinal direction (direction of movement). If the spray depth of a flat mist nozzle is 40 mm, the area significantly influenced by cooling is about 250 mm.
The results of the experimental program show an important aspect for secondary cooling design and control. It was shown that for the identical nozzle with constant water flow impingement density, the cooling intensity could be changed significantly by only altering the air pressure. This experiment confirms that the simple way, in which the water flow is often converted to the cooling intensity, must provide wrong results. The importance of actual measurement of the heat transfer coefficient distribution and the Leidenfrost temperature was stressed because there is no numerical or analytical method of accurately deriving these data from the parameters of spray. Experiments with variable casting speed showed that the cooling intensity is not constant. Velocity of motion of the cooled surface is another variable that must be used when CC is modelled for design or control purposes. Experiments with cooling uniformity showed frequent problems with dependence of uniformity on pressure. The situation with cooling uniformity is even more complicated for the overlapping area. Most of the systems with water-only nozzles or with constant air pressure do not allow accurate control of cooling and ensure cooling uniformity.

The major variable influencing the secondary cooling is the surface temperature. The actual surface temperature and the Leidenfrost temperature for the relevant casting and secondary cooling conditions can significantly change the intensity of cooling. The Leidenfrost temperature is a theoretical term, which has a very practical impact on continuous casting. There is no existing theoretical method to predict the Leidenfrost temperature. It can be obtained only by measurement. The measurements above and below the Leidenfrost temperature show heat transfer coefficient changing by a factor of ten. The Leidenfrost phenomenon can explain a lot of problems with temperature stripes and the problems with control of the process. The collapse of the stable vapour layer at the Leidenfrost temperature causes an immediate change in the cooling mechanism and in cooling intensity.

The paper can be concluded by the statement that most of the questions connected to secondary cooling can be precisely answered only with the help of experiments and measurements.

REFERENCES