Experimental und numerical investigations on cooling efficiency of Air-Mist nozzles on steel during continuous casting

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Abstract. Cooling strategies in continuous casting of steel can vary from rapid cooling to slow cooling, mainly controlled by adjusting the amount of water sprayed onto the surface of the product. Inadequate adjustment however can lead to local surface undercooling or reheating, leading to surface and inner defects. This paper focuses on cooling efficiency of Air-Mist nozzles on casted steel and the experimental and numerical prediction of surface temperature distributions over the product width. The first part explains the determination of heat transfer coefficients (HTC) on laboratory scale, using a so called nozzle measuring stand (NMS). Based on measured water distributions and determined HTC’s for air-mist nozzles using the NMS, surface temperatures are calculated by a transient 2D-model on a simple steel plate, explained in the second part of this paper. Simulations are carried out varying water impact density and spray water distribution, consequently influencing the local HTC distribution over the plate width. Furthermore, these results will be interpreted with regard to their consequence for surface and internal quality of the cast product. The results reveal the difficulty of correct adjustment of the amount of sprayed water, concurrent influencing water distribution and thus changing HTC distribution and surface temperature.

1. Introduction
Secondary cooling strategies of continuous casting processes can vary from rapid to slow cooling. Water or air-mist nozzles with a wide range of possible spray water distributions and/or impact densities aim on uniform heat removal during the casting process. High effort is done in research in homogeneous water distribution over a wide range of operation parameters (varying water flow rate, air pressure e.g.) [1–3], nevertheless heat transfer coefficients (HTC) can still differ over spray width, leading to uneven heat removal during casting. [4–7]
Mean heat transfer coefficients based on adjusted water impact densities [8–11] are commonly used to describe the heat removal in the secondary cooling zone in continuous casting process simulations, aiming on simplicity and calculation speed. More complex approaches separate these mean values into local mean HTC values over spray width [12–14] to reach a more detailed look on temperature.
distribution below the nozzle. However, different researchers illustrate beside surface temperature parameters like spray water temperature [15], water/air ratios [16], casting speed [7,17], droplet size and velocity [5,7,9,11,18,19], and more [2,17,19–25] as important influence factors on heat removal. The demand on more detailed information on heat removal thus lead to the development of several test assemblies on laboratory scale to measure local heat transfer coefficients. [10,26–28]

2. Experimental equipment
A so called nozzle-measuring-stand (NMS) was developed as prototype within the frame of a K1-MET-Phase1 project in cooperation with voestalpine Stahl Donawitz GmbH, at the Chair of Ferrous Metallurgy (CoFM), Montanuniversität Leoben (MUL). The NMS is used to determine local HTC’s with the option on variation of a number of nozzle- and casting parameters. Figure 1 presents a schematic drawing of the HTC measurement set-up. The NMS can be separated into 3 levels:
- Level 1 contains a cylindrical steel sample, the induction heating unit and the sample support stand (positioning unit on linear axes). Maximum casting speed currently tested is 6 m/min.
- Level 2 is called the “wet-zone”, where the spray nozzles are fixed in definite positions, spraying upwards for HTC measurements, spraying downwards to measure water distribution.
- Level 3 stores technical equipment like air and water supply and the cooling unit of the induction device.

2.1. Determination of local heat transfer coefficients
HTC’s measurements are carried out using a cylindrical sample made of scale resisting austenitic steel (1.4841) with diameter to height ratio of 1:1.8. Three thermocouples are positioned along the center axis of the steel sample at different distances to the cooled surface (bottom of the sample), where an additional thermocouple is fixed. The lateral and the top of the steel surface are insulated to ensure one-dimensional heat flow towards the bottom during cooling.

Figure 2 displays the principle to characterize a flat fan nozzle regarding local HTC values:
- i. The spray water distribution has to be known (or determined using the NMS) to identify the ideal positions for HTC measurement and to avoid incomplete nozzle characterization.
- ii. The first HTC measurement typically starts at the center of the nozzle. The sample is positioned at a certain distance to the water spray to ensure no contact between water and steel during heating.
iii. Heating of the cylindrical steel sample to the aimed surface temperature \( T_{\text{surface,max}} = 1100^\circ \text{C} \) is done by inductive heating under normal atmosphere.

iv. When reaching constant volumetric flow of water (or water-air mixture), inductive heating is switched off and the sample is moved at constant velocity (casting speed) through the water spray (“a” in figure 2).

v. Temperatures are measured inside the steel sample during this movement, using type S or type K thermocouples, depending on the desired maximum surface temperature.

vi. After this first measurement in the center of the spray water distribution, the water (water-air mixture) is switched off and the steel sample is moved to the next position \( (C+1/5L) \) in figure 2). The cycle continues at step “iii”.

Local HTC are computed by inverse calculation of measured temperatures inside the steel sample.

![Figure 2. Scheme of nozzle characterization of a flat fan nozzle by the NMS; No variation of temperature, velocity or water impact density](image)

2.2. Determination and results of spray water distribution

Water distribution is likewise measured using the NMS, details concerning the measurement assembly and the nozzle results can be taken out of [6].

2.3. Test schedule

Both investigated nozzles are typically used in parallel arrangement in a conventional slab casting machine. Table 1 presents the layout and mounting information; the test schedule with measurement parameters can be taken out of table 2.

HTC measurements were carried out for combinations of minimum water flow rate at minimum air pressure (further stated as “case a”), and maximum water flow rate and maximum air pressure (“case b”) for each nozzle.

| Table 1. Nozzle layout and mounting |
|-----------------------------------|
| Nozzle | Spray Angle \(^{[\circ]}\) | Distance to surface \([\text{mm}]\) |
|-------|-----------------|-----------------|
| A     | 90              | 396             |
| B     | 60              | 346             |
### Table 2. Testing parameters.

| Nozzle | \( H_2O_{\text{max}} \) [l/min] | \( H_2O_{\text{min}} \) [l/min] | \( A_{\text{min}} \) [bar] | \( A_{\text{max}} \) [bar] | \( T_{\text{surf}} \) [°C] | \( v_{\text{cast}} \) [m/min] |
|--------|-------------------------------|-------------------------------|-----------------|-----------------|----------------|----------------|
| A      | 7                             | 3.0                           | 2.5             | 1.1             | 900 ; 1100    | 0.8 ; 1.2     |
| B      | 3.5                           | 1.5                           | 2.5             | 1.1             | 900 ; 1000    | 0.8 ; 1.2     |

### 3. Results

#### 3.1. Simulation

Measured local heat transfer coefficients at definite positions, for case “a” and “b” of both nozzles, were used to describe the heat removal over the spray width (X-direction). Measurements of local HTC were only done at half length of the nozzle due to the clear symmetry of the spray pattern, thus the results were mirrored for the simulation of the plate cooling. Limits to heat removal in spray length (Y-direction) and width were defined according to the water distribution, a HTC value of 200 W/m²K was adjusted for radiation at the remaining regions on the surface. Plate width was fixed as 0.95m with adiabatic boundaries. The same steel grade that is used for HTC measurements was taken as plate material; the thickness of the plate was set as 40mm with adiabatic regime in the bottom. The plate was moved through the different HTC distributions at (casting) speed of 0.8 [6] and 1.2m/min. Simulation results are printed as contour plots with additional color bars for better imaging of the temperature distributions over product width and according to the initial temperature of the steel plate. Images of the results at a casting speed of 0.8m/min can be taken out of [6]. Details to these results are contemporary explained with the results of a casting speed of 1.2m/min for sake of comparability.

#### 3.1.1. Nozzle A:

Using a minimum amount of water with concurrent low air pressure (case “a”) leads to a uniform water distribution over roundabout 400mm spray width, see also [6]. The simulation also predicts a nearly uniform heat removal in this region, independent on 0.8 or 1.2/m/min casting speed (figure 3, top). Increasing the water impact density (case “b”) shifts the distribution to a more pyramidal appearance, leading to a higher heat transfer coefficient in the center of the nozzle with decreasing values towards the edge of the spray width (figure 3, bottom). Increasing the casting speed to 1.2/m/min results in a more uniform temperature distribution as for 0.8m/min.

This first example predicts a higher heat removal when increasing the water impact density, and is in good accordance to the literature. However, even if the homogeneous water distribution leads to the assumption of a uniform heat removal in the spray width (case “a”), the temperature contour plot in the top of figure 3 already reveals small differences and local temperature drops at the edges of ~10°C. These effects cannot directly be explained using only the determined spray water distribution. In case “b” of nozzle A, the heat transport from the bottom of the plate towards the top leads to a nearly homogeneous temperature distribution on the surface of the plate, after leaving the region of water impact. This example reveals the severity to detect local maxima of heat removal during casting, due to the surface reheating by heat transport from the inner side of the product. Nevertheless, temperature gradients were present while passing the water distribution, owing to the determined heat transfer distribution over the spray width.

Decreasing the initial surface temperature of the steel plate to 910°C, and applying the measured local heat transfer coefficients at a casting speed of 1.2/m/min, leads to results depicted in figure 4. Even if the water impact density was held constant during the tests, while varying only the initial surface temperature, the distribution differs to the simulations at 1110°C.

- For low but nearly uniform water impact densities (case “a”), the surface temperature distribution becomes more inhomogeneous at a casting speed of 0.8m/min [6].
• For case “b” a nearly uniform surface temperature can be achieved, in contrast to tests at 1100°C, casting with 0.8m/min, where high temperature drops were detected [6].
• At a casting speed of 1.2m/min the results at 910°C nearly mirror those of 1110°C.

Slight differences can be visualized using snapshots of the temperature distribution at the surface of the plate, depicted in figure 7 in chapter 4. Higher values of the local heat transfer coefficients can lead to temperature differences, reaching a maximum of 18°C for case “b” at $T_{\text{surface, start}} = 1110°C$. Decreasing the initial temperature to 910°C however predicts a difference of roughly 22°C.

At low water impact densities (case “a”) no considerable differences can be found, when changing the casting speed from 0.8m/min to 1.2m/min. Higher water impact densities (case “b”) on the other hand results at 1.2m/min in a minor temperature difference at 1110°C, and a higher value at 910°C.

Figure 3. Temperature distribution for case “a” (top) and case “b” (bottom), nozzle A; $v = 1.2m/min; T_{\text{init.}} = 1110°C$.
Figure 4. Temperature distribution for case “a” (top) and case “b” (bottom), nozzle A; $v = 1.2m/min; T_{\text{init.}} = 910°C$.

3.1.2. Nozzle B:
Independent on the water impact density of nozzle B (case “a” or “b”), two local maxima are present at the edges of the spray pattern, resulting in higher local heat transfer coefficients at these positions. Figure 5 and 6 present the contour plots of the simulations, carried out for nozzle B at different temperatures and constant casting speed of 1.2m/min.

Temperature profiles at $Y = 0.15m$ in cast direction are depicted in figure 8 for all parameter variations of nozzle B at 1.2m/min. At low water impact densities (case “a”), temperature differences already appear at the surface, reaching values of roughly 25°C. High water impact densities (case “b”) have a
tremendous effect on the heat removal, located mainly on the spray pattern edges, resulting in temperature differences up to 100°C at 1.2m/min. Heat transport towards the surface from the inside of the plate seems only to be sufficient for case “a” at 910°C and 1.2m/min, to nearly equalize the temperature distribution after leaving the area of water impact. Surface defect formation owing to thermal stresses in these areas for all other cases is thus highly probable.

**Figure 5.** Temperature distribution for case “a” (top) and case “b” (bottom), nozzle B; \( v = 1.2 \text{m/min}; T_{\text{init.}} = 1110^\circ \text{C} \).

**Figure 6.** Temperature distribution for case “a” (top) and case “b” (bottom), nozzle B; \( v = 1.2 \text{m/min}; T_{\text{init.}} = 910^\circ \text{C} \).

4. **Summary**

Measurements to determine local heat transfer coefficients were carried out at the Chair of Ferrous Metallurgy, Montanuniversität Leoben, using a so-called nozzle measuring stand. Spray parameters of two different nozzles as well as surface temperatures were varied; the determined local HTCs were used as input parameter for simulation. A steel plate was moved through the local HTC distribution at two different casting speeds. The results can be summarized as follows:

- Water impact density does not simply correspond to heat transfer coefficient. More detailed information about droplet size, velocity and impact distribution is required.
- The influence of casting speed on HTC seems to be dependent on water impact density.
- Uniform spray water distributions can lead to inhomogeneous heat withdrawal (case “a”, nozzle A) and vice versa (case “b”, nozzle A).
However, local maxima in water impact density can result in high temperature gradients (100°C, figure 8) over spray width, increasing the probability of surface defect formation during casting.

Detection of local undercooling of the surface may be difficult, if the heat transport from the inside of the product causes a reheating of the surface (figure 3, nozzle A, case “b”). Only the surface defects may remain, but the underlying phenomenon is no longer detectable at the end of the casting.

Figure 7. Temperature distribution nozzle A; v=1.2m/min; Y=0.17m.

Figure 8. Temperature distribution nozzle B; v=1.2m/min; Y=0.15m.

5. Conclusion
The measurement of local heat transfer coefficients for better characterization of the heat withdrawal during casting is vital. Using a mean value based on water impact density for simulation, in order to keep calculation times low, leads consequently to information losses and makes it difficult to reveal the origins of possible defects in the casted product.

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