# INFLUENCE OF THE REMAINING WATER LAYER ON THE COOLING OF MOVING STEEL SURFACES

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**Abstract**

Steel is an integral part of today's life. To obtain the desired mechanical properties of hot rolled steel plates or strips, it is necessary to predict and control the cooling process. Cooling of a hot rolled strip on a run-out table or in a continuous annealing line is commonly realized by laminar and spray cooling, and involves a large amount of water, which impinges on the hot surface of the steel. Water is accumulated on the upper surface, which means the jets do not have a direct impact on the steel surface and the cooling intensity is changed. The cooling process is also affected by the remaining water layer that remains on the surface after cooling. This thin layer occurs both on the upper and the bottom surface, and also for light sprays. The remaining water can significantly influence the final temperature of the steel strip if the target temperature is below 500 °C. In this article, the effect of remaining water on cooling is experimentally investigated. A full cone spray nozzle is used for the measurements and the cooling in different areas (under the nozzle, outside the nozzle spray) is studied.

**Keywords:** Steel, remaining water, cooling, heat transfer coefficient

## 1. INTRODUCTION

Steel is a basic material in the machinery and construction industries, but it is also used for example in healthcare or in everyday life. Steel is processed by hot rolling, cold rolling, quenching or other methods into the required products. Hot rolling is one of the most common ways of processing steel. The output of hot rolling is semi-finished products or final products like steel sheets, plates, wires, rails, etc. After the steel leaves the last rolling mill, it is cooled to the required final temperature on a run-out table (ROT). To achieve quality steel products with the desired mechanical and physical properties while keeping costs low, the cooling must be controlled. Achieving the appropriate cooling settings is a complicated process, because the cooling is influenced by many parameters, such as nozzle type, water flow rate, water temperature, surface temperature of the steel, velocity of the steel strip [1-4], surface roughness, presence of oxide, and accumulated and remaining water [5-9]. Many researchers have already worked on improving the cooling process, but there are still problems, such as low cooling efficiency, poor cooling uniformity and in particular reaching the exact final temperature when the target temperature is below 500 °C. [9,10].

The cooling on the ROT (or in the continuous annealing line) is connected with the large amount of water that impinges on the hot surface of the steel strip. This leads to the accumulation of water on the upper surface of the steel strip in the cooling section. The accumulated water stops jets having a direct impact on the steel surface, and also causes overcooling of edges and influences the cooling intensity [11]. The situation where the single circular water jet does not impinge on the steel surface directly but instead impinges on a surface covered with water was investigated by Fujimoto et al. [12]. Cho et al. [13] studied the cooling on the ROT and they developed an equation to predict the height of accumulated water from the water flow rate, nozzle spacing, and strip width.

Cooling is also affected by the remaining water layer that remains on the surface after cooling. In contrast to accumulated water, the remaining water layer occurs not only on the upper surface, but also on the bottom surface (**Figure 1**). This thin layer can also be observed for light spray. In our previous research [9] (where the effect of the remaining water layer on the final temperature of the steel strip was investigated based on numerical simulations with experimentally obtained boundary conditions) it was found that the remaining water layer has a big influence on the final temperature when the target temperature is below 500 °C. These findings were also confirmed by a steel producer.

Almost no studies deal with the problematics of remaining water and therefore there is a lack of information about the influence of remaining water on cooling. In this study, the effect of remaining water on cooling is experimentally investigated.

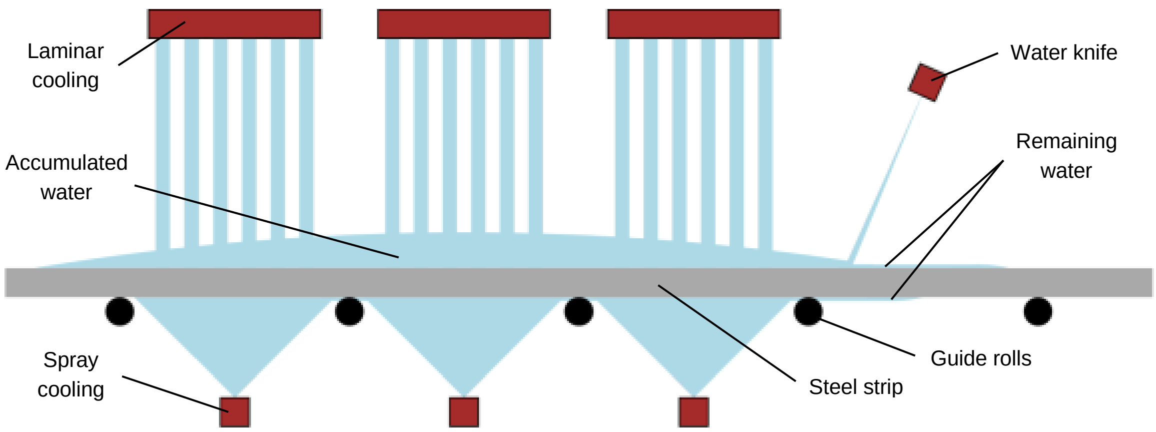


**Figure 1** Remaining water during cooling

## 2. EXPERIMENT DESCRIPTION AND EVALUATION

The measurements of the heat transfer coefficient (HTC) during water cooling were done in Heat Transfer and Fluid Flow Laboratory on a laboratory test bench with linear movement of the test plate. The scheme of this test bench can be seen in **Figure 2**. The velocity during measurements performed in this study was 5 m/s. A test plate made from austenitic steel (320x300x25 mm) was used for all measurements. The test plate was equipped with K-thermocouples located 0.8 mm under the cooled surface and attached to the carriage. Before each experiment, the test plate was placed in the electric heater and was heated to a temperature of 820 °C. After that, the test plate was placed in the upper position as shown in **Figure 2** and the carriage with the test plate moved repeatedly under the nozzle at a velocity of 5 m/s until the test plate temperature dropped to approx. 50 °C. Temperature history and position information were recorded throughout the experiment and at the end of the experiment these data were downloaded to the computer.

The inverse computation was done to obtain the time dependent HTC and the time dependent surface temperature from the measured temperature history [14]. Based on the inverse computation and information about the position of the test plate, HTC can be evaluated as a function of test plate position and surface temperature (**Figure 4**). The position 1940 mm on the x axis in **Figure 4** is the position directly under the nozzle. HTC as a function of position and surface temperature was used for analysis of the influence of the remaining water on cooling.

A full cone spray nozzle with the spray angle of 60° was used. The flow rate was 0.56 l/s at 0.25 MPa and 1.06 l/s at 1 MPa. The spray distance was 500 mm.

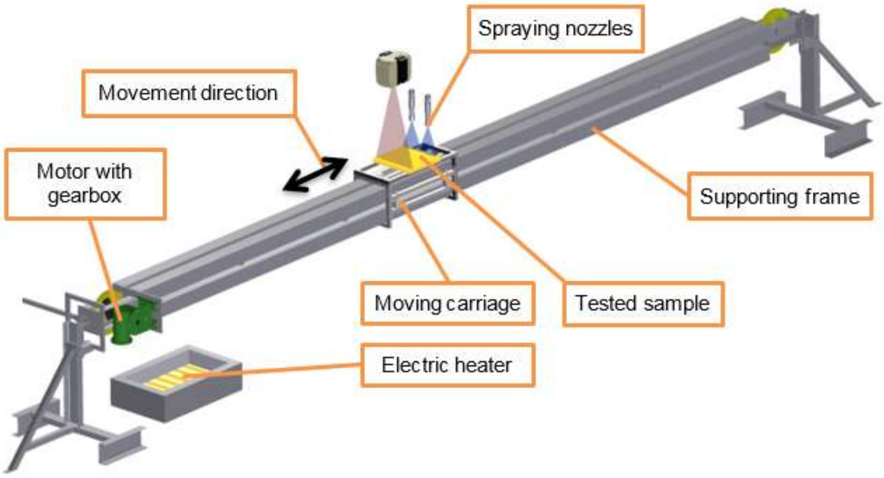


**Figure 2** Experimental test bench for HTC measurements

Cooling was investigated in four different cooling areas as shown in **Figure 3**. Area "A" represents the situation where part of the test plate enters under the water spray, but the area where thermocouples are installed is still out of the direct impact of the water spray (position 1510–1659 mm). Area "B" is a zone where the thermocouples are directly under the water spray (position 1660–2219 mm). Area "C" is similar to area "A", but the difference is that the test plate leaves the water spray (position 2220–2369 mm). The last cooling area is area "D". The whole test plate is out of the water spray here (position 2370–5620 mm). The thermocouples were placed on the axis of the test plate (centre of the test plate in the direction of movement).

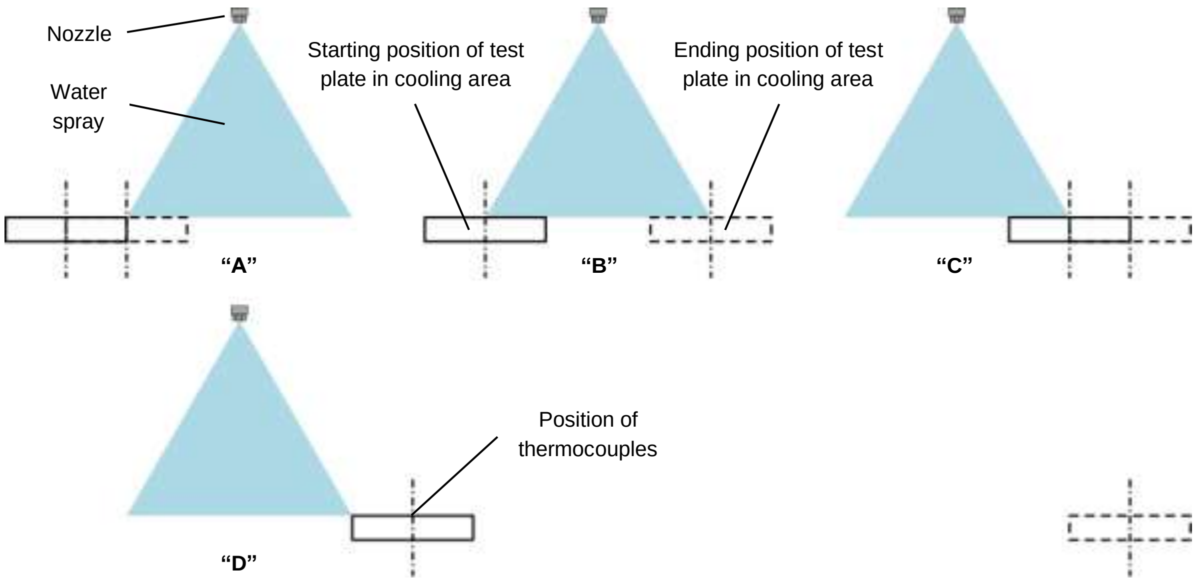


**Figure 3** Investigated cooling areas

## 3. RESULTS

Two measurements were conducted at different flow rates - experiment E1 (flow rate 0.56 l/s at 0.25 MPa) and experiment E2 (flow rate 1.06 l/s at 1 MPa). The obtained HTC functions are shown as a function of test plate position and surface temperature in **Figure 4**. Data from the thermocouple located in the center of the test plate was used.

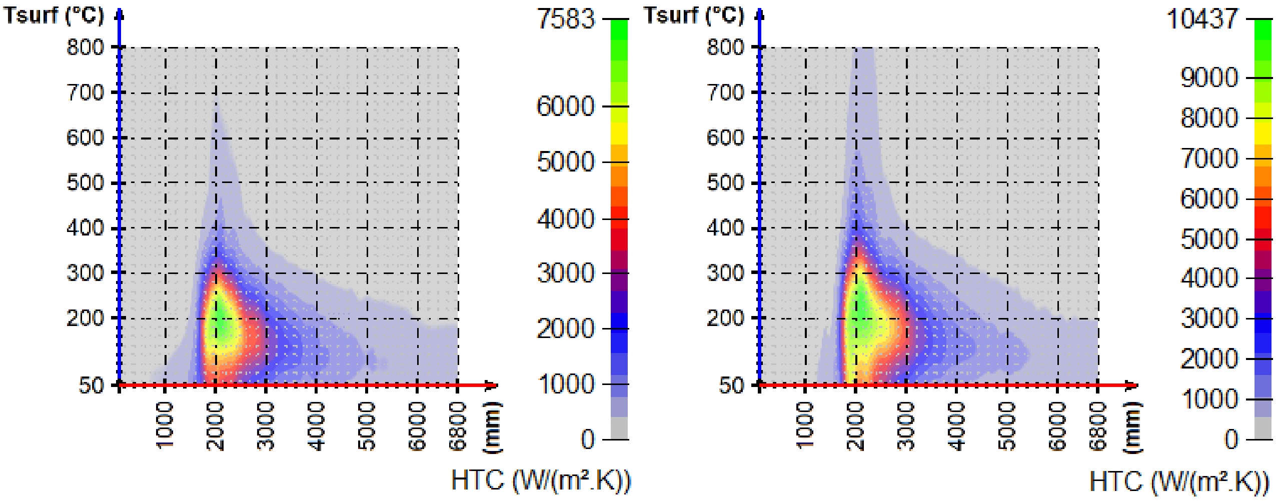


**Figure 4** HTC as a function of test plate position and surface temperature (left graph: experiment E1; right graph: experiment E2)

### 3.1. Cooling in all areas

The HTC and the heat flux are shown in **Figure 5** as a function of position. This dependence can be obtained from **Figure 4** for a specific surface temperature. In the case of **Figure 5**, the surface temperature was set to 150 °C. The cooling areas “A”–“D” are shown in **Figure 5** in the right graph. It can be seen that cooling is significant not only in area “B”, where the test plate is directly under the water spray, but also in areas “C” and “D”. In area “D” there is no spraying water on the surface and heat transfer is realized only by evaporation of remaining water and radiation.

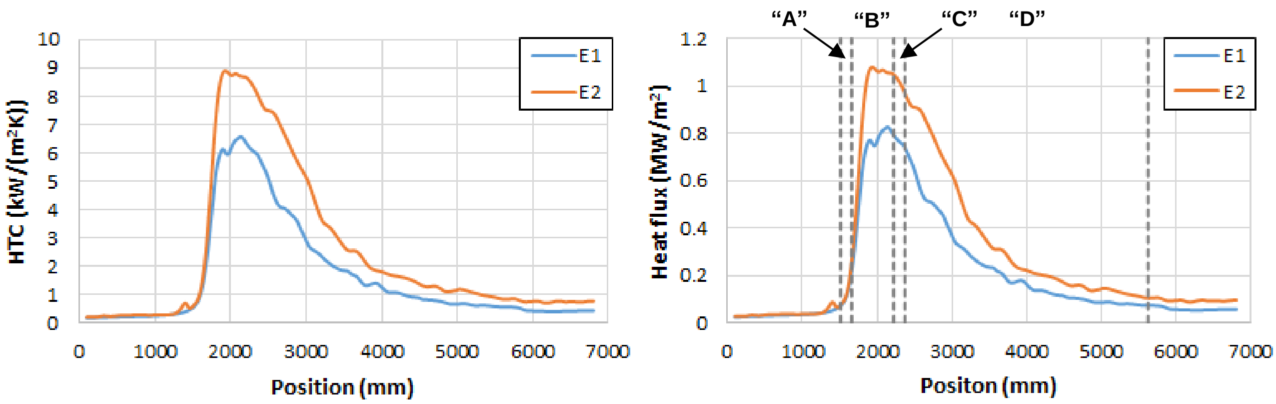


**Figure 5** HTC and heat flux dependent on the position for the surface temperature 150 °C

The heat removed from the steel plate was calculated in each area for a surface temperature in the range of 50–800 °C. The computed percentage share of the removed heat per unit time is shown in **Figure 6** for each area “A”–“D”. There is also information on how much heat is transferred to the surroundings by radiation. It is evident from **Figure 4** that the effect of the remaining water becomes significant for surface temperatures below 500 °C because HTC is also high in area “D” (above 2370 mm). Also it can be seen that the biggest influence of the remaining water is for a surface temperature of around 150 °C when intensive boiling occurs. Around this surface temperature, area “D” with the remaining water is responsible for almost 15 % of the removed heat from steel per unit time (**Figure 6**).

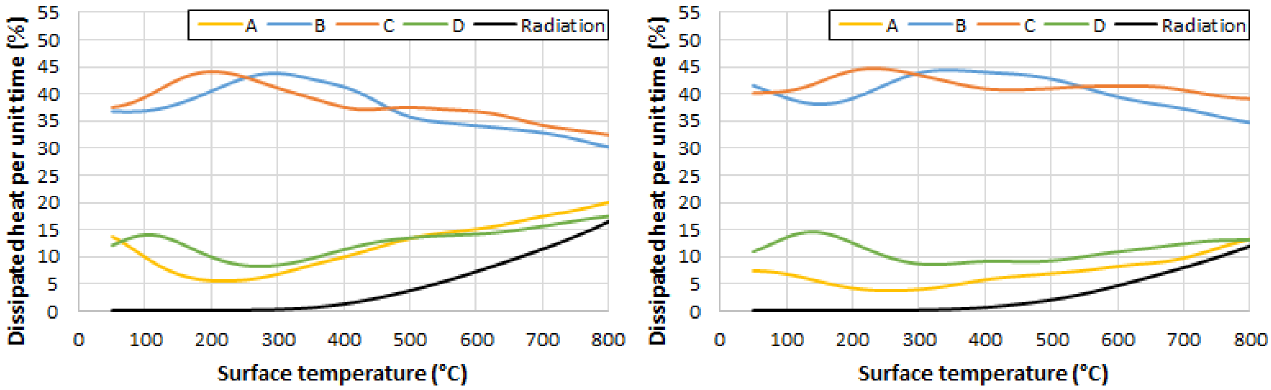


**Figure 6** The percentage share of the removed heat per unit time in each cooling area and amount of heat transferred to the surroundings by radiation (left graph: experiment E1; right graph: experiment E2)

### 3.2. Cooling in area "D"

The cooling in area "D" was investigated in more detail for a better understanding of the influence of the remaining water. The area was divided into four equally-sized sub-areas Q1, Q2, Q3 and Q4, where Q1 is the sub-area near the water cooling and Q4 is farthest from the water cooling. The average heat flux is shown in **Figure 7** for each sub-area Q1–Q4 as a function of the surface temperature. The temperature dependence was obtained by averaging on the position interval (according to the specific sub-area).

It is evident from **Figure 7** that cooling is mainly realized in the first half of area "D". The heat flux reaches a critical value for surface temperature at around 200 °C. The critical heat flux in Q1 is more than seven times higher than the critical heat flux in Q4. Also, it can be seen that in the case of the higher flow rate (1.06 l/s at 1 MPa), the heat flux reaches higher values than for the flow rate (0.56 l/s at 0.25 MPa) in all the sub-areas and the whole surface temperature range.

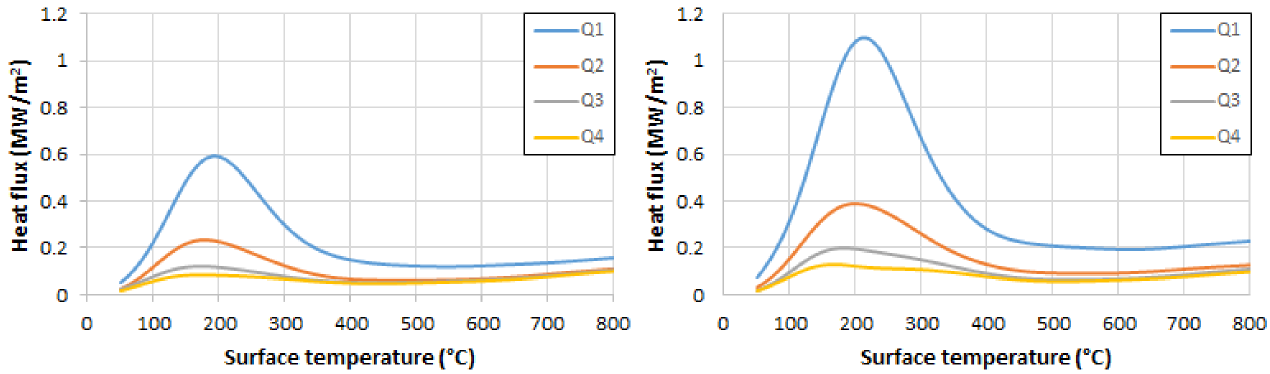


**Figure 7** The average heat flux dependent on the surface temperature in sub-areas (Q1 – Q4) of cooling area "D" (left graph: experiment E1; right graph: experiment E2)

## 4. CONCLUSION

The influence of the remaining water on cooling was experimentally investigated. Two measurements were conducted with a full cone spray nozzle at different flow rates and the top cooling in different cooling areas (under the nozzle, transition areas, and outside the nozzle spray) was studied. It was found that cooling is significant not only in the area with water spray cooling, but also in the area behind the water cooling, where heat transfer is realized only by the remaining water and radiation. The cooling effect of the remaining water was most significant for a surface temperature of around 150 °C. Almost 15 % of heat was removed in the area with no direct water spray (area with remaining water only). It was also found that the influence of the remaining water was most significant right behind the water spray cooling. The critical heat flux in the first quarter of area “D” (area with only remaining water) was more than seven times higher than the critical heat flux in the last quarter. Furthermore, the heat flux is growing with the flow rate increase.

It was shown that the remaining water influences cooling and has to be considered when the surface temperature is below 500 °C. Still, there is a lack of information about the behaviour of the remaining water and further research is needed to be done for a better understanding.

## ACKNOWLEDGEMENTS

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