CROSS-ZONE HEAT TRANSFER INTERACTION IN CONTROLLED COOLING ZONES

[1]Jan KOMINEK, [2]Petr KOTRBACEK, [3]Pepjin ADRIAEN

[1]BUT – Brno University of Technology, Faculty of mechanical engineering, Brno, Czech Republic, EU,
jan.kominek@vut.cz

[2]BUT – Brno University of Technology, Faculty of mechanical engineering, Brno, Czech Republic, EU,
petr.kotrbacek@vut.cz

[3]CRM Group, Ghent, Belgium, EU, Pepijn.ADRIAEN@crmgroup.be

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Abstract

This study presents the experimental investigation of Heat Transfer Coefficient (HTC) distributions conducted within the framework of the European RFCS SmartCool project. The SmartCool project focuses on the development and implementation of a smart-controlled actuator system designed to homogenize the temperature distribution across the width of the transfer bar in hot strip mills. The primary objective is to enhance product flatness and mechanical properties by minimizing temperature gradients, particularly in advanced high-strength steel (AHSS) production. A series of laboratory-scale measurements were performed using a custom-designed test bench equipped with a moving stainless-steel test plate and embedded thermocouples. The plate was subjected to intensive cooling by a segmented header equipped with solid jet nozzles, divided into seven zones. The cooling process occurred in a narrow gap, allowing for close-range, high-intensity water application. Measurements focused on quantifying the differential cooling capabilities and assessing the impact of water flow rate distribution across the nozzle sections. The results confirmed that the cooling intensity is naturally determined by whether the corresponding cooling zone is active. However, it was also observed that the influence of neighboring active zones is extremely strong—significantly altering the cooling intensity in the measured area. The presence or absence of cooling in adjacent zones considerably impacted the achieved HTC values, with isolated zones showing reduced cooling efficiency. The findings provide useful insights for optimizing the setup and control of selective cooling systems, contributing to a better understanding of how cooling strategies affect thermal profiles in industrial processes.

Keywords: Controlled cooling, Cross-zone interaction, temperature homogenization, HTC, experimental measurement

1. INTRODUCTION

The homogenization of temperature across the width of a transfer bar is a critical challenge in hot strip mills. Non-uniform temperature profiles, particularly the presence of hot shoulders and cold edges, negatively affect product flatness and mechanical properties, especially in the production of advanced high-strength steels (AHSS).

The effect of non-uniform cooling on plate flatness has been extensively studied both experimentally and numerically, for example by Hrabovsky et al. [1]. The link between cooling uniformity and strip flatness has also been addressed in industrial contexts such as continuous annealing lines [2].

The development builds on previous RFCS projects such as StrengthControl and ManCool, which demonstrated the feasibility of width-adaptable cooling concepts for strip products [3,4]. The European RFCS project SmartCool aims to address this issue by developing a smart-controlled actuator system that allows differential cooling along the width of the transfer bar.

This article presents the outcomes of a series of laboratory experiments focused on characterizing the heat transfer coefficient (HTC) distribution under various cooling configurations. The research investigates not only the performance of individual cooling zones but also the influence of neighboring zones, referred to as cross-zone interaction.

2. EXPERIMENTAL SETUP

The experiments were carried out at the Heat Transfer and Fluid Flow Laboratory at Brno University of Technology, which specializes in spray cooling research. Previous laboratory work includes for example cooling of fast-moving surfaces [5], quenching unit development [6], in-line heat treatment [7], and spray parameter studies [8, 9]. The experiments presented here were conducted using a custom-built test bench (see **Figure 1**).

The setup consisted of a moving stainless-steel test plate (see **Figure 2** for thermocouple layout), 25 mm thick, equipped with two rows of thermocouples (2×7), embedded approximately 0.6 mm below the surface. The exact depth of each thermocouple was determined indirectly during the calibration of the plate and estimated individually for each sensor.

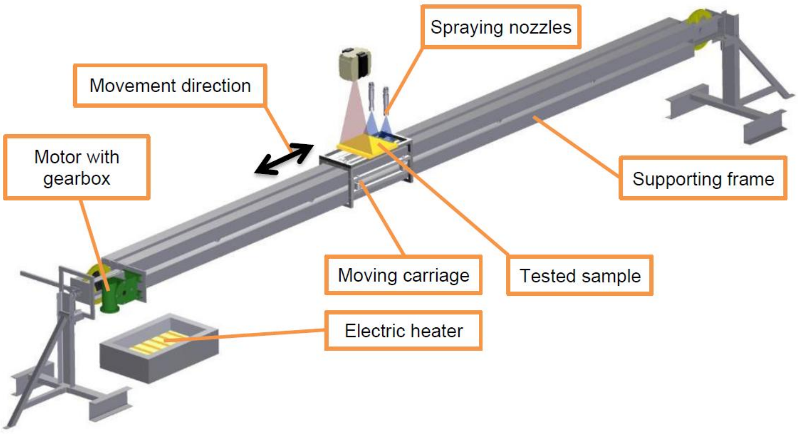

Figure 1 Experimental stand used for tests with moving samples

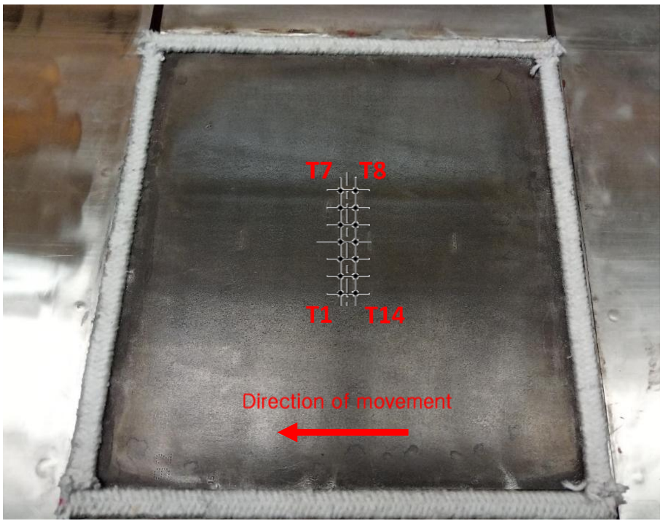

Figure 2 Test plate with expanding sheets, marked thermocouple positions in two rows

The plate was heated to 900 °C and then cooled by a segmented water header comprising seven independently controlled zones, each equipped with solid jet nozzles (see **Figure 3** for header segmentation). The plate moved above the cooling header at a constant velocity of 4 m/s, passing through a narrow cooling gap and simulating conditions typical of industrial hot rolling [10].

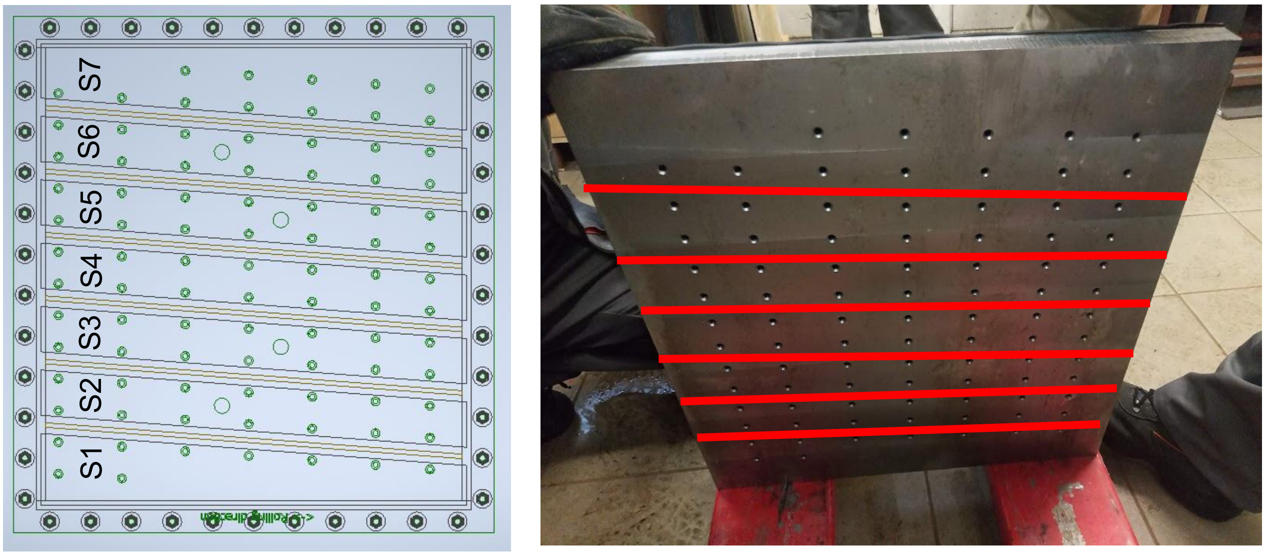

Figure 3 Header divided into 7 zones

Thermocouple signals were recorded at a frequency of 1000 Hz and later filtered and resampled to 250 Hz for use in inverse heat conduction calculations. Surface temperatures and corresponding boundary conditions (HTC) were determined using the sequential identification method, a standard approach in inverse thermal analysis. A detailed description of the method can be found in [11]. For theoretical background and classical formulation of the inverse problem, see Beck et al. [12]. The use of inverse heat conduction methods for HTC determination in spray-cooled plates has also been described in detail by Malinowski et al. [13]

For the purposes of this study, data from the two rows of thermocouples were averaged at corresponding lateral positions (across the width), yielding seven effective measurement points designated P1 through P7. These points are located relatively close to one another and describe thermal behavior only under a single cooling zone. The fact that there are seven points and seven zones is coincidental, and the measurement span does not cover multiple zones. To facilitate comparison across experiments, results are presented both as average HTC across width (P1–P7) and as a longitudinal average along the cooling path (from the beginning to the end of the cooling zone).

3. RESULTS AND DISCUSSION

This section highlights three key cooling phenomena observed during the experimental campaign. Each case is supported by a dedicated graph.

3.1 Single active section

In this configuration, only one cooling zone—corresponding to the measurement area—is active. The results clearly demonstrate that the cooling intensity is strongly dependent on the applied water flow rate. As illustrated in the corresponding graph, the HTC increases in an almost linear manner with flow rates set to 30 %, 60 %, and 100 %. This trend confirms the expected behavior of isolated cooling, where there is a direct and proportional relationship between water flow and heat transfer performance.

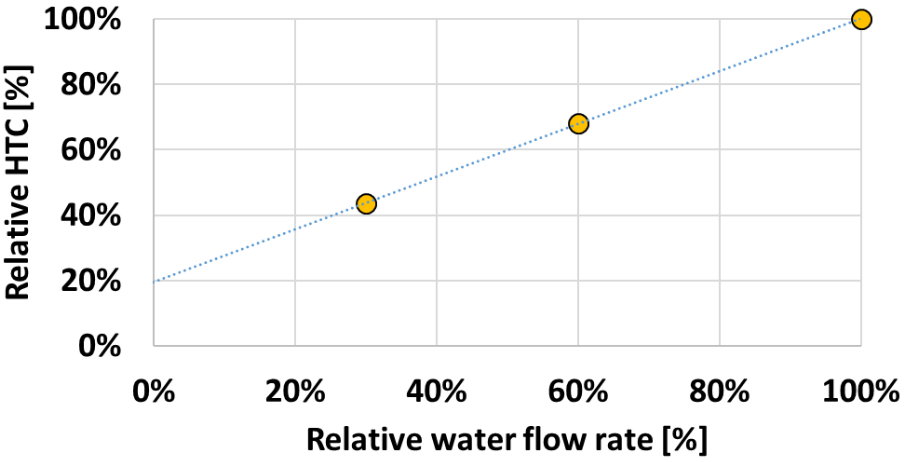

Figure 4 Relative HTC as a function of water flow rate for a single active section

3.2 Influence of Neighboring Zones

Beyond the direct effect of flow rate, the measurements revealed a significant dependence of HTC on the activation of adjacent zones. In this analysis, all measurements are taken at the center of the active zone while varying the number of surrounding zones that are also active. The x-axis in the accompanying graph represents the total number of active neighboring zones. For example, a value of 0 means no neighboring zones are active (only the center zone is on), while a value of 2 indicates one active zone on each side. All HTC values are expressed relative to the configuration where all seven zones are active. The trend confirms that effective cooling intensity can only be achieved when multiple neighboring zones are active, highlighting strong cross-zone interaction.

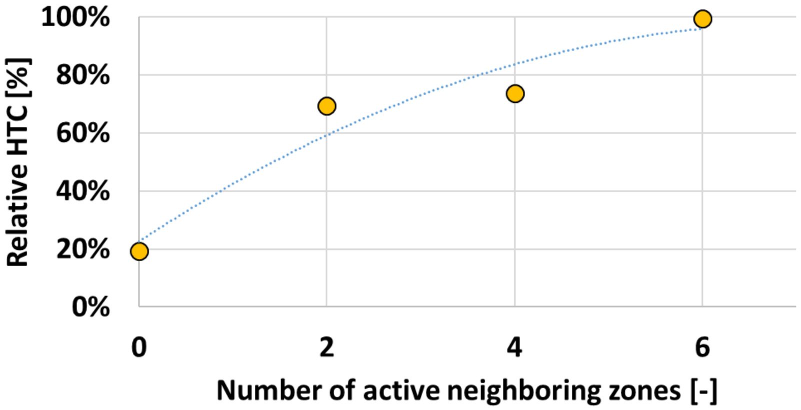

Figure 5 Relative HTC based on number of active neighboring zones

3.3 Uncooled Gap Behavior

In configurations where one zone is turned off while the others are active, the measured HTC in the inactive zone remains relatively high—about 52 % of the fully active case. A separate scenario with three adjacent inactive zones was also analyzed. In the corresponding graph, the x-axis shows the distance from the center of the middle inactive zone represented by whole numbers corresponding to the zone positions (e.g., 0 = center, 1 = adjacent zone, 2 = next, etc.). The y-axis shows the relative HTC compared to full activation. The results confirm that while isolated gaps retain some cooling due to cross-flow and lateral overspray, the intensity drops rapidly with increasing gap width and the relative position of the inactive zone.

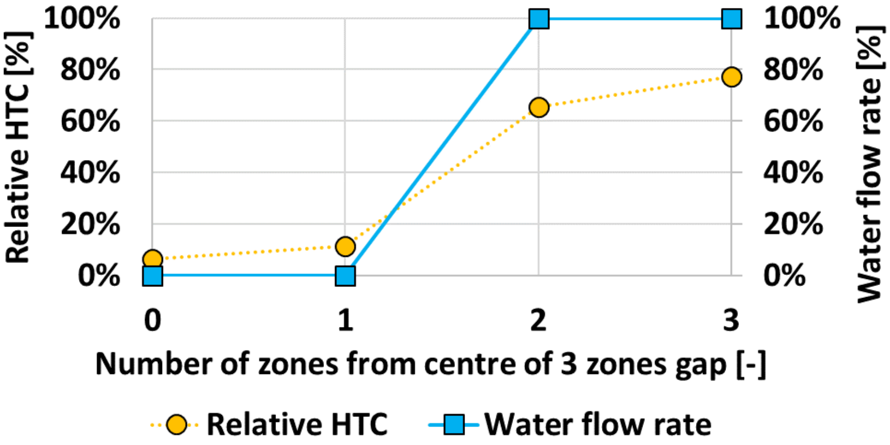

Figure 6 Relative HTC in and around a 3-zone gap (0 = middle of the gap)

4. CONCLUSION

The experimental results clearly demonstrate that in controlled cooling systems with segmented headers, the interaction between neighboring zones plays a key role in determining the local heat transfer coefficient. This cross-zone effect significantly influences the cooling intensity—not only in the targeted active zones but also in adjacent or even inactive ones.

Three phenomena were investigated in detail: (1) the near-linear dependence of HTC on local water flow in isolated zones, (2) the strong amplifying effect of active neighboring zones, and (3) the residual cooling observed in inactive gaps due to lateral overspray and flow.

These findings emphasize that to achieve effective and uniform cooling, especially in variable-width applications like the SmartCool actuator, the design and control of zone activation must take cross-zone interactions into account.

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