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Influence of Air Cooling Jets on the Steady-State Shape of Strips in Hot Dip Galvanizing Lines ⋆

M. Saxinger * **A. Steinboeck** ** **M. Baumgart** *
P. Kerschbaummayr *** **A. Kugi** *

* *Christian Doppler Laboratory for Model-Based Process Control in the Steel Industry, Automation and Control Institute, Vienna University of Technology, Austria, (e-mail: {saxinger, baumgart, kugi} @acin.tuwien.ac.at).*
** *Automation and Control Institute, Vienna University of Technology, Austria (e-mail: steinboeck@acin.tuwien.ac.at)*
*** *voestalpine Stahl GmbH, Linz, Austria, (e-mail: peter.kerschbaummayr@voestalpine.com)*

Abstract: The influence of air cooling jets on the steady-state shape of the strip in hot dip galvanizing lines is investigated. For this purpose, the force characteristic of a single nozzle is measured by a laboratory flow simulator. This approach differs from conventional methods, where typically, CFD simulations are used. Based on the air cooler force characteristic the stability of the equilibrium points is investigated and the influence of different types of boundary conditions, tensile loads, strip thicknesses, and cooler fan speeds is examined.

Keywords: Mechanical system, Static models, Moving objects, Distributed-parameter system, Mathematical model, Stability analysis, Steel industry, Numerical simulation, Equilibrium.

1. INTRODUCTION

In hot dip galvanizing lines, like the one shown in Fig. 1, cold-rolled steel strip is coated in a bath of molten zinc. The strip is heated in an annealing furnace and guided by the sink roll. It leaves the zinc bath after passing both the correction and stabilization roll. Above the zinc pool, gas wiping dies are mounted across the width of the strip to reduce the thickness of the zinc layer to a certain value. Cooling arrays consisting of four cooling sections are located at the upper part of the galvanizing line. They guarantee a solidified zinc layer once the strip reaches the tower roll.

Experience over many years has shown that cooling jets can influence the stability of the strip motion, in particular when thinner and broader strips are processed. Moreover, in special cases even unwanted vibrations of the strip may be induced or the strip may collide with the nozzles of the cooling section. Many studies on the modeling of axially moving beams and membranes are available (Shin et al., 2006; Steinboeck et al., 2015; Pellicano and Vestroni, 2000; Antman, 2006; Chen, 2005; Marynowski and Kapitaniak, 2014), but up to the authors' knowledge no systematic investigations of the influence of the cooling array air jets on the stability of the strip in hot dip galvanizing lines can be found in the literature. The effect of the air cooling jets on the shape and on the stability of the strip is investigated in this paper.

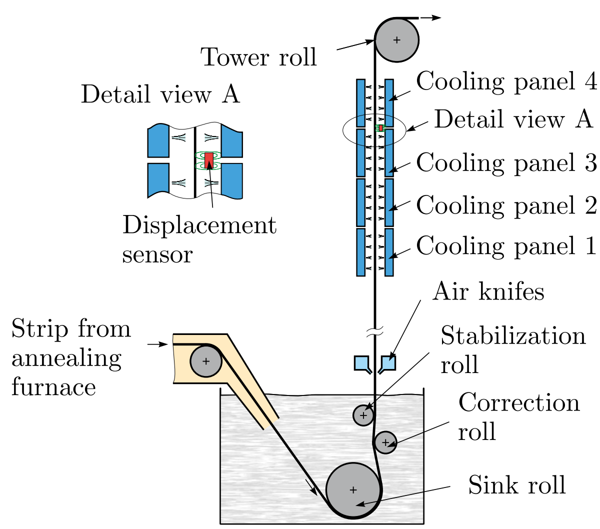

Fig. 1. A typical hot dip galvanizing line with a cooler array consisting of four panels.

For this, three eddy current sensors were used to examine the interaction between the cooler fan speed and the relative displacement of the strip. Two displacement sensors were assembled between the cooling sections 3 and 4 in order to measure the displacement at the outer edges of the strip: One at the drive side (DS), the other one at the operator side (OS). The third sensor was located in the middle of the strip (MI). The fan speed n_2 of cooler 2 was

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varied, all other fan speeds n_1, n_3 and n_4 and the most important parameters of the plant were held constant for this experiment. Fig. 2 shows the measured relationship between the fan speed n_2 and the displacement Δd of the strip for both increasing and decreasing fan speeds. The displacement Δd of each sensor is measured relative to its starting position. Displacements Δd for increasing fan speeds (up) are shown with bold lines and decreasing fan speeds are designated with thin lines. The fan speed was kept constant at a certain level for a few seconds and for this time interval the displacement measurements were averaged. The averaged data points are highlighted with markers. These measurement results clearly show that the strip displacement is influenced by the fan speed setting, although the absolute position of the strip is unknown. Additional measurements showed a clear correlation be-

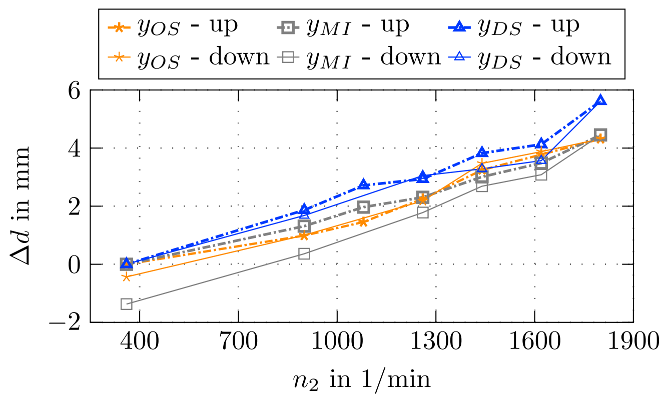

Fig. 2. Relative displacement Δd of the strip for different sensor positions.

tween the relative pressure p in the supply duct of the cooling jets (hereinafter denoted as pressure p) and the fan speed n of the respective blower. The pressure drop inside a cooling section can be considered as negligible. This simplification is supported by a cooler test run with twelve pressure sensors mounted at different positions in the cooling section. By means of a least-squares approximation the unknown parameters of the semi-empirical relation

$$p = c_1 n + c_2 n^2 \qquad (1)$$

are determined as $c_1 = 1.6785 \cdot 10^{-4}\,\text{mbar min}$ and $c_2 = 1.1847 \cdot 10^{-5}\,\text{mbar min}^2$. In order to study the pressure force of an impinging nozzle jet on the strip a flow simulator was developed.

2. FLOW SIMULATOR

A cooling section with the parameters in Table 1 is outlined in Fig. 3. All pipes are supplied by an air blower from the DS. With negligible pressure drop inside the pipes of one section, the air stream through all nozzles must be the same. Furthermore, the flow conditions after the fluid leaves the nozzle are similar. This assumption is supported by the geometry of the cooling section, where the fluid can only escape to the rear side. For a proper analysis of the force characteristic, a laboratory flow simulator with three nozzles was setup. The mechanism of an impinging jet force on a plate was analyzed for various distances h_s between the nozzle and the plate/strip and various relative

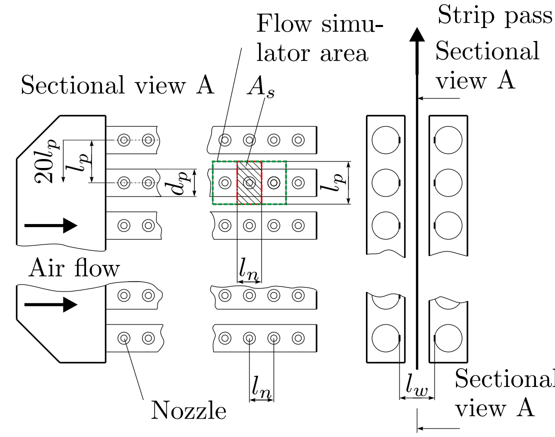

Fig. 3. Sketch of one cooling panel. The flow simulator area is marked with dashed lines. All nozzles have the same diameter d_n.

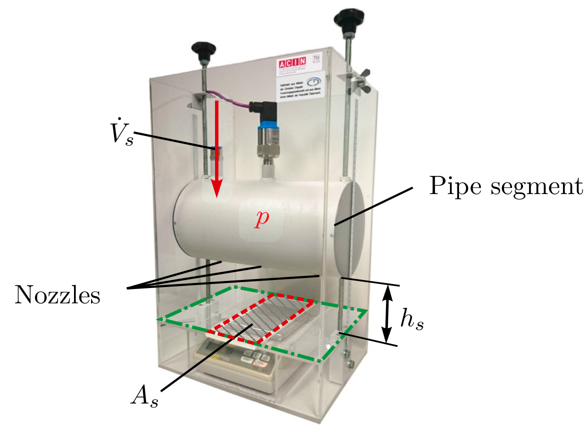

Fig. 4. Picture of flow simulator.

pipe pressures p. Several design aspects have been taken into account. First of all, the force application surface is in line with the associated area of the strip at the real cooling panel. Also, the diameter of the pipe is equal to the real cooling pipe and the lateral distance between neighboring nozzles is the same as in the real system. The vertical distance l_p between the single pipes equals the depth of the simulator. Thus the channel for the back-flow is also identical to the real cooling section. In order to account for the stream interactions between neighboring nozzles, at least three nozzles were used. Friction alongside the simulator wall can be neglected as a result of low fluid velocity at the wall. The flow simulator is shown in Fig. 4.

Fig. 5 shows the measured force F_s acting on the area A_s as a function of the pressure p depending on the distance h_s. An interesting feature can be seen in Fig. 6: In normal operating situations ($h_s > 1\,\text{cm}$), there is no influence of the distance h_s on the flow rate $\dot{V}_s$ of air. During the measurements, h_s was varied from 0 to l_w.

3. MODEL OF AXIALLY MOVING STRIP WITH COOLING PANELS

3.1 Cooling Sections

To transfer the results of the simulator to the nozzles of the plant, an offset displacement $w = h_s - l_w/2$ must