Interstand Cooling – Design, Control and Experience

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Interstand Cooling (ISC) can help to increase the productivity of the mill and improve the final mechanical properties of the strip. Constant Exit Rolling Temperature (ERT) can be ensured on the whole strip length eliminating temperature oscillations of the transfer bar caused by skid marks and other reasons. The paper presents experimental possibilities in investigation and design of ISC headers. Experimental stand is introduced and a complex approach – experiment and mathematical modeling – is shortly described. Further essential models of control system are introduced and basic functionality is explained. In conclusion practical experiences are discussed.

Keywords: INTERSTAND COOLING, TEMPERATURE, STRIP, MODELING

Introduction

The Interstand Cooling at wide strip hot mills partakes fundamentally in reaching and maintaining the required exit rolling temperature (ERT). Thus it enables to reach better and more homogeneous mechanical properties of a strip, particularly in microalloyed steels. ERT can be maintained constant on the whole strip length, even when transfer bar temperature oscillates due to skid marks in slab or other reasons. Very important is the possibility to increase the mill production so that it enables to roll at higher speed or speed up.

For the correct function of the Interstand Cooling it is necessary to fulfill two basic requirements – to keep at disposition an optimal hardware (cooling headers with sufficient cooling power including the possibility of fast and fluent regulation of cooling intensity) and the advanced control software, both for cooling setup, feed forward and feedback control.

The initial stage of the design of ISC is testing a variety of cooling headers at a laboratory test bench. These measurements provide a description of cooling intensity on a running hot steel surface. The studied parameters are as follows: type of nozzle, nozzle configuration, feeding pressure, spray height and impact angle.

A complex 3-D numerical model of temperature field in the rolled strip is used for the comparison of various configurations of the cooling headers and for the technological studies of the efficiency of ISC at a particular mill, measured by a maximum temperature drop for various materials cooled with various combinations of the cooling headers. The model is used in design stage of building or re-building the ISC.

Two different models used for the control, both empirical and physical, are used in the presented installations. The physical model uses a direct simplified temperature model as well as an inverse model to determinate the necessary cooling power for every coordinate of the strip (set up). Feed forward and feedback controls improve the accuracy of the control system.

Results and Discussion

Determination of ISC Headers Cooling Effects

In Heat Transfer and Fluid Flow Laboratory, Brno University of Technology, the methodology of determination of cooling effects during spraying hot surfaces was developed [1]. The basis is created by an experimental stand which enables study of cooling and mechanical effects of nozzles at linearly moving samples.

Structurally the stand is designed so that it enables progression of samples up to the weight of 50 kg with infinitely adjustable speed from 0 to 10m/s. On the supporting frame there is a carriage moving, on which the sample under examination with temperature sensors and measuring system – datalogger is fixed. The carriage's progression is provided by a hauling rope through a drive pulley and a motor with a gearbox. The motor is power supplied by a frequency converter with the possibility of a smooth change of rotation speed and changeovers. The direction of the carriage can be reversed and passages repeated in a requiring number. The whole cycle is programmed and controlled through the superior PC. There is a spraying section in the central sector where arbitrary jets configuration can be arranged (**Figure 1**). The optimal configuration of nozzles with known cooling intensity is used in plant (**Figure 2**).

There is wide group of cooling headers used in practice. **Figure 3** shows examples of the tested headers. It is difficult to find a general optimal design of interstand cooling because each rolling train has different space configuration and limitations.

Figure 1. Linear laboratory stand with test plate moving under group of full cone nozzles

Figure 2. Interstand cooling header with full cone nozzles

Figure 2. Various types of cooling headers (full cone nozzles, drilled holes, adjustable slit, cluster of solid jet nozzles)

Experimental Procedure of Cooling Effects Determination

The test plate is equipped with thermal sensors with thermocouples connected to the datalogger. The thermal sensors are calibrated before use and the results of calibration are used to eliminate dynamic error in measurement of highly transient thermal processes [článek Pohanka]. Before the actual experiment the carriage with the sample is positioned to the utmost position and it is heated to the required temperature using an external furnace. After temperature stabilization, the heating device is removed, the stand is turned to spraying position, the pump gets going and the carriage's travel gets started. The position of the cooled surface can be horizontal with spraying upper or bottom surfaces or vertical (for special cooling tests not for ISC). Signals from sensors are read by the datalogger which moves together along with the sample. At the same time, the signal indicating the actual carriage's position is sensed as well. After performing the required number of passes, datalogger's internal memory data are exported into the computer for further processing.

Information from temperature sensors (temperatures records in a particular depth under the surface) are used as entry parameters for the thermal conduction's inverse task [2]. Inverse task output are surface temperature history, heat flows and Heat Transfer Coefficients (HTC) on the heat transfer surface. Most often, in mathematical models the boundary condition of the 3rd type is used where heat flow is specified by the heat transfer coefficient value and the cooling water temperature. An example of the heat transfer coefficient distribution for cooling header with two rows of full cone nozzles is introduced in **Figure 4**. Geometry of spray jets is shown in **Figure 5**.

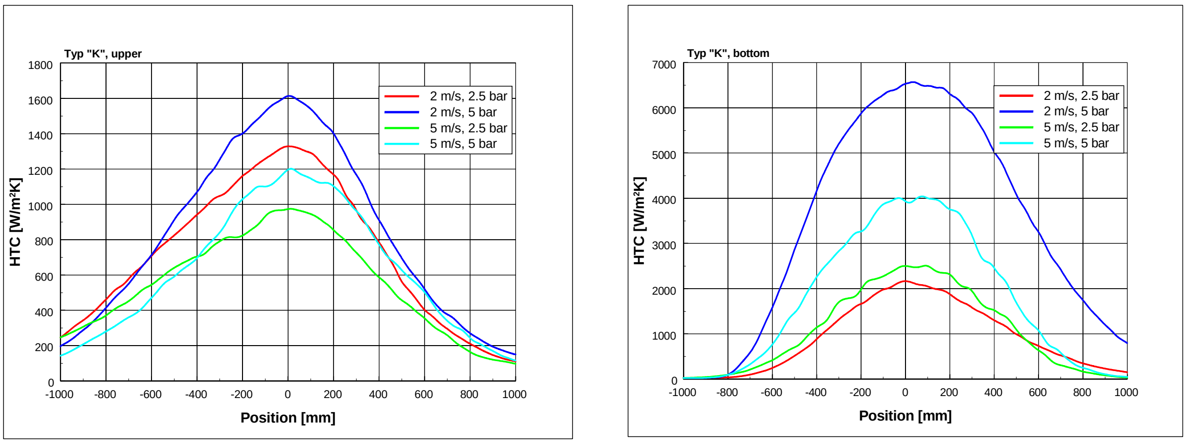


Figure 4. Distribution of heat transfer coefficient for experiments with two rows of conical nozzles, upper surface (left) and bottom surface (right), influence of pressure and velocity is shown

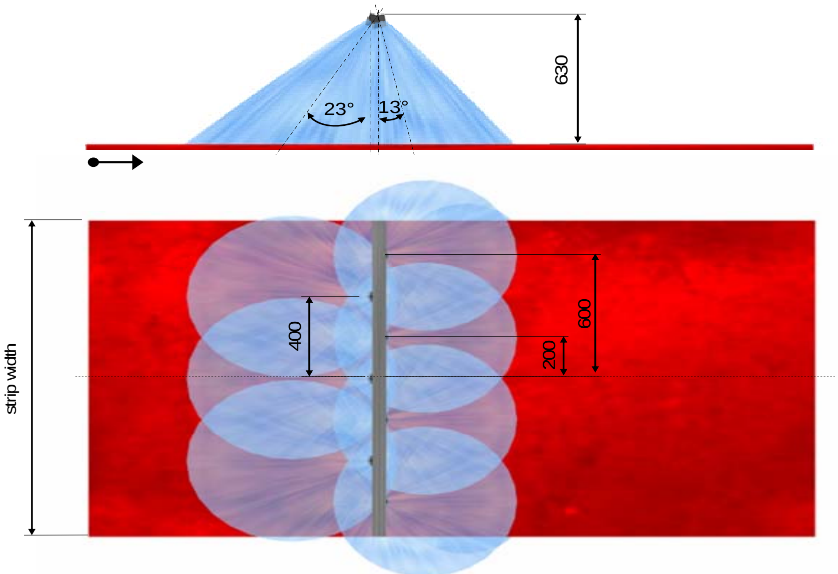


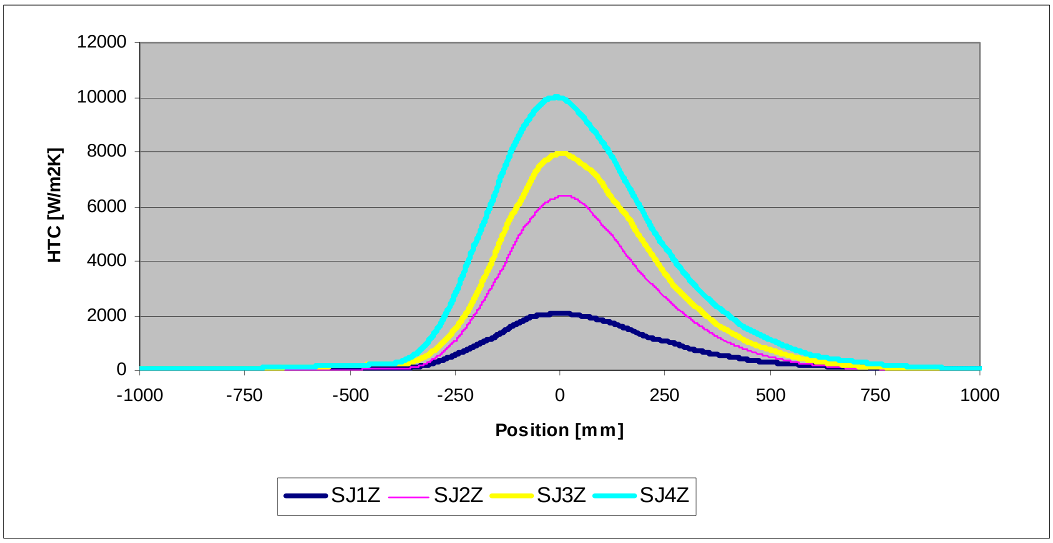
Figure 5. Designed upper header of ISC (width conical nozzles)

Results show influence of feeding pressure and strip velocity. Pressure increases from 2.5 bar to 5 bar and changes because of increasing velocity from 2 m/s to 5 m/s.

An example of cooling intensity of spray header with five rows of solid jet nozzles (see **Figure 3**) is shown in **Figure 6**. Results show influence of increasing flowrate (pressure) and two rolling velocities. Parameters of measurement are in **Table 1**.

Table 1. Parameters of tests with header with solid jet nozzles

Experiments with velocity 1 m/s	SJ1Z	SJ2Z	SJ3Z	SJ4Z
Experiments with velocity 5 m/s	SJ5Z	SJ6Z	SJ7Z	SJ8Z
Coolant flowrate l/s/m	11.0	17.3	24.5	31.7
Coolant pressure bar	1.0	2.5	5.0	8.0



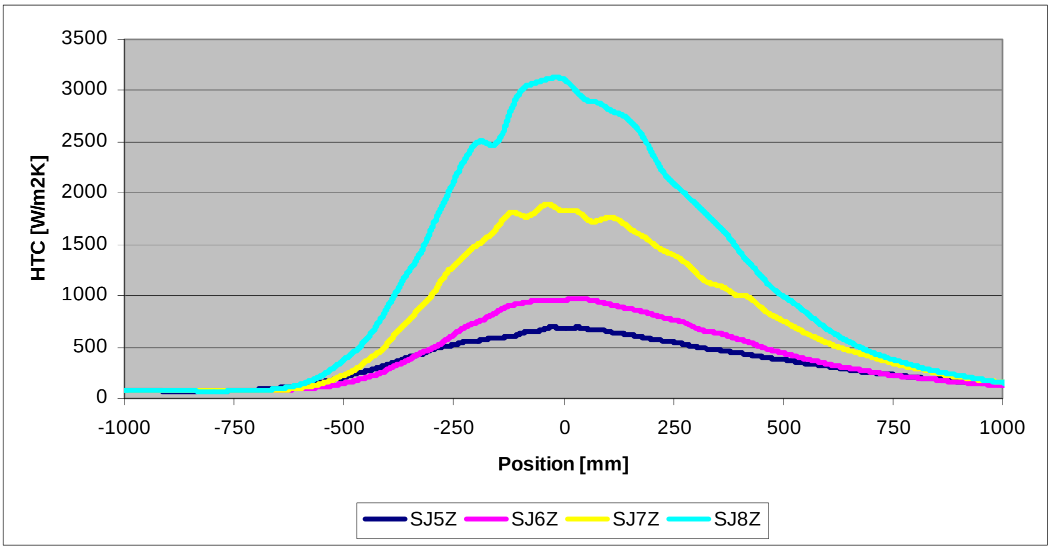


Figure 6. Heat transfer coefficient distribution for header with five rows of solid jet nozzles, rolling velocity 1 m/s (up) and 5 m/s (down)

Headers with slits and water curtains are frequent. Slits are usually used for cooling of bottom surface where free falling laminar layer cannot be used. An example of cooling intensity of slit 8 mm wide installed at spray height of 300 mm under bottom strip surface is shown in **Figure 7**. Result R14 is for flowrate of 4.7 l/s/m, R15 for 7.5 l/s/m and R16 for 10.5 l/s/m.

Verification of Interstand Cooling Effects with the Help of a Temperature Model

The Interstand Cooling detailed temperature model, which uses measured heat transfer boundary conditions, gives the answer whether the proposed method of cooling will meet the required parameters from the point of view of intensity and regulating range. This model is designed on the basis of knowledge of rolling mill conditions and simulates an actual rolling campaign. Various factors influence (header type, working pressure, rolled material thickness, rolling speed) on the cooling efficiency can be verified computationally. This procedure enables to design optimal ISC headers to measure for every hot mill or stand. **Figure 8** shows temperature field in the rolled material of final thickness of 3.4 mm. This detail numerical model is used for final headers selection and setting of spray parameters for various pressure and flowrate settings. The model is used for check of the system controllability. Finally this model is used for check and adjustment of simpler fast numerical control models.

Control System of ISC

Pesented control system of ISC has been designed to work either within existing Level 2 of the mill or to work rather independently of it. It consists of three basic parts – Setup (working within existing Level 2 or on separate computer), V-Controller and T-Controller (Level 1). Basis scheme of the system is shown in **Figure 9**.

The main task of the Setup is to calculate the number and power of cooling headers for reaching the temperature in the whole strip length. V-Controller is feed forward regulator respecting the influence of the strip speed changes. T-Controller is feedback temperature regulator.

The measured strip temperature is mostly available only at limited number of spots, at outlet from the roughing mill, before the finishing mill and at the finishing mill outlet. Nevertheless, the temperature measuring before the finishing mill entry is usually very unreliable because it is influenced by a thick scale layer, emissivity of which strongly depends also on the steel chemical composition. Temperature obtained from pyrometer at the outlet from roller table can be used to get more complex information but the control system can work without this information quite accurately.

As the transfer bar temperature oscillates, the number and cooling power of the headers must be calculated in several spots lengthwise (35 to 50 points). The points (coordinates) are situated in the local extremes of the temperature curve in the

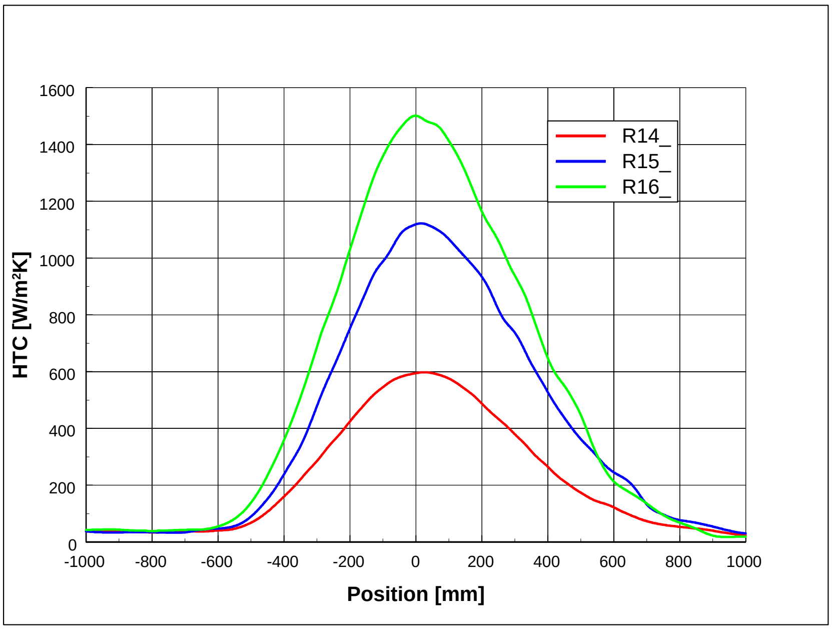


Figure 7. Heat trasfer coefficient distribution for cooling with slit header and increased flowrate.

transfer bar. Special filter is used to get rid of incorrect measurements, to smooth the temperature curve and to find local extremes of the temperature behind the roughing mill. Measured deviations of the transfer bar temperature at the outlet of roughing mill can be seen in **Figure 10**.

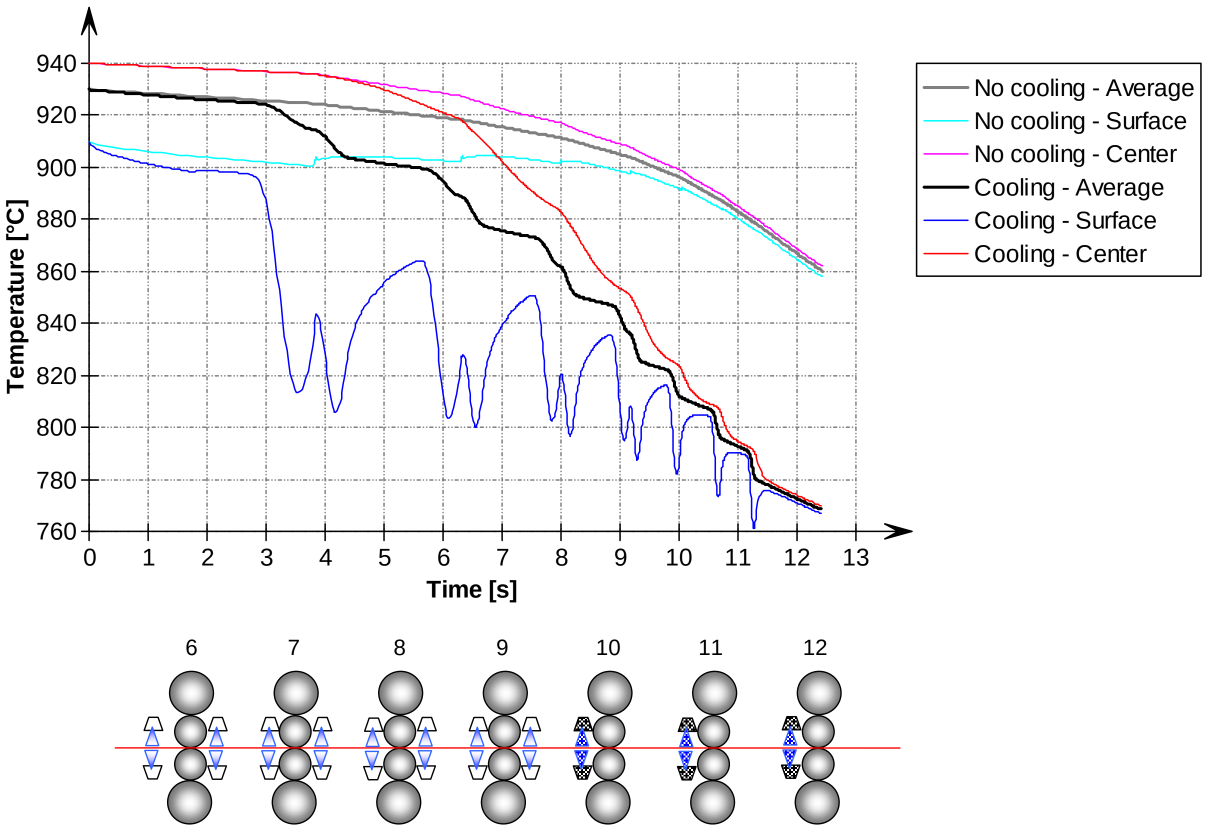


Figure 8. Computed temperature history in several points using 2D numerical off-line model in design stage of project

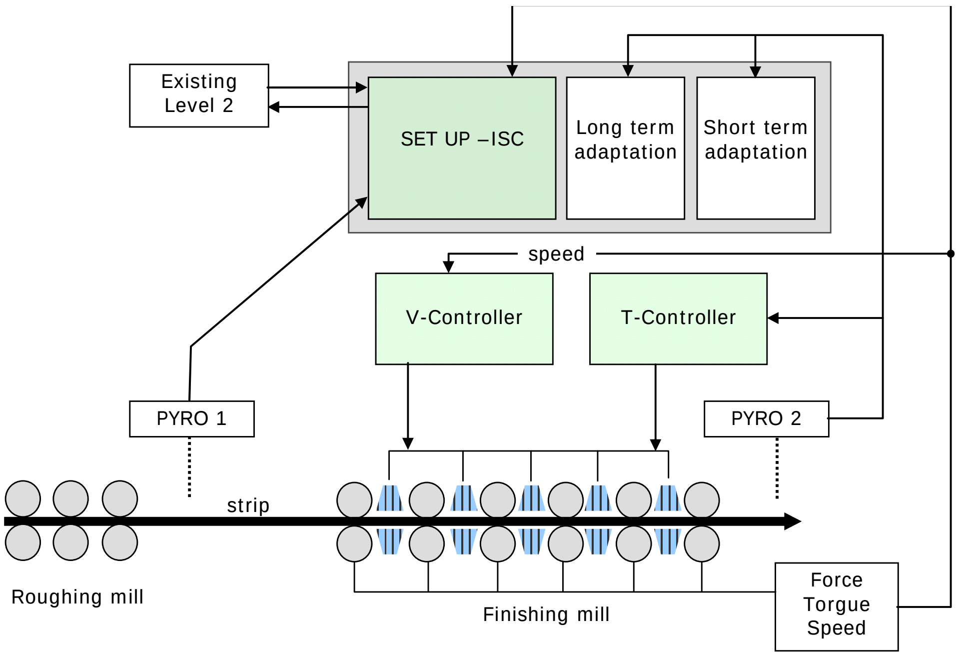


Figure 9. Basic scheme of the control system

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Using these data the setup of headers for every spot is performed and so called cooling matrix is assembled. An example of the cooling matrix – providing number, position and cooling power of headers (in terms of normed flow rates) in every spot lengthwise can be seen in **Figure 11** (see **Figure 14** for position of headers). It is obvious, that the total cooling power of ISC varies lengthwise.

Software Modules of ISC

Temperature Model

The temperature model has to describe the temperature field in the rolled strip for defined boundary conditions. Detailed multidimensional models can be used only in a limited way due to their demands for the processor's time. A compromise solution is 1-D physical model on the base of Finite Element Method which enables to calculate the temperature profile through the strip thickness in the given coordinate (point). The model neglects the heat conduction both across the width and along the length of the strip (**Figure 12**). However, understanding of the temperature along the length is very important and therefore it is necessary to calculate the temperature field in several points.

Boundary conditions cover:

- air cooling of a strip (heat radiation and convection),
- water cooling with the help of interstand headers, roll cooling, descaler,
- cooling in the rolling gap,
- heat generation due to deformation in the roll gap.

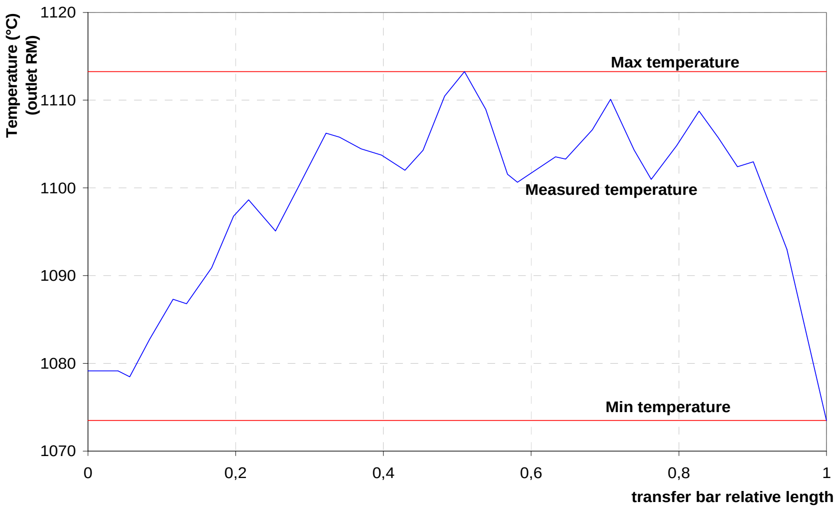


Figure 10. Measured transfer bar temperature lengthwise (example of an older furnace)

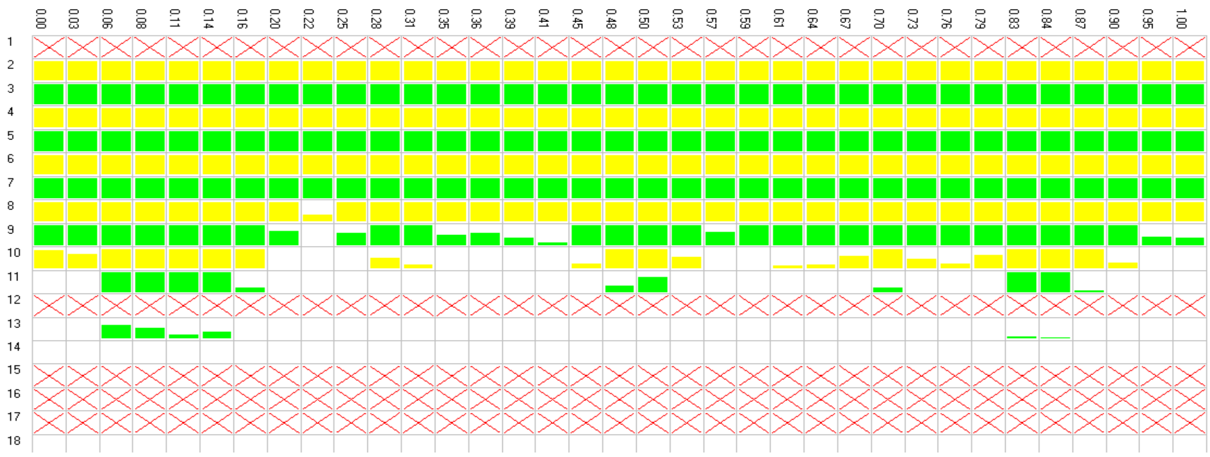


Figure 11. Cooling matrix, horizontal axis – relative strip length, vertical axis - active cooling headers (green-upper, yellow-bottom headers)

Model for the Headers Setup (inverse function)

The task of the model is a fast calculation of the cooling power and number of suitable headers so that the required exit rolling temperature is reached (for one examined point on the strip). For the calculation, the optimization method Merortha predictor corrector is applied.

Used constraints for the optimization calculation:

- Specific power of each of the headers must vary between 0 (off) up to 1 (max. power);
- The header's power must be higher than or equal the next header (along the rolling course);
- The headers' power should be distributed so that strip is being cooled most at the largest thicknesses (for some steel grades this criterion will not be applied);
- To give priority to condition off or set on the full power.

The algorithm scheme for one point with mutual relationship of both models is shown in **Figure 13.**

Cooling Possibilities of ISC

Interstand Cooling possibilities were determined by mathematical simulations and measurements at the hot strip mill 2000 mm. The scheme of finishing mill with headers is shown in **Figure 14**. The ultimate possible temperature drop due to ISC varies from 80°C for the thick strip (thickness > 8mm) up to 140°C for the thin strip (thickness < 2.7 mm). However, this value is limited in its application in thin strips because during intensive cooling in last stands flatness problems may occur.

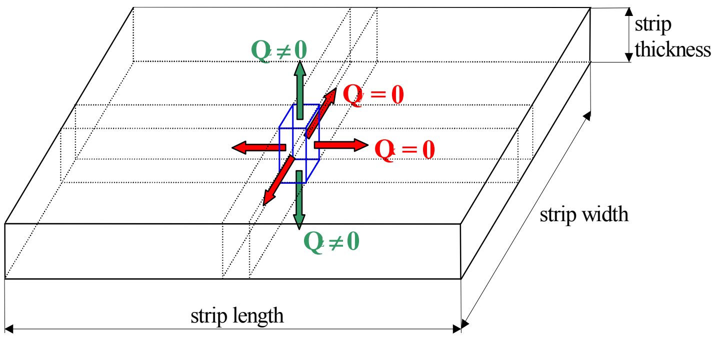


Figure 12. 1-D model scheme

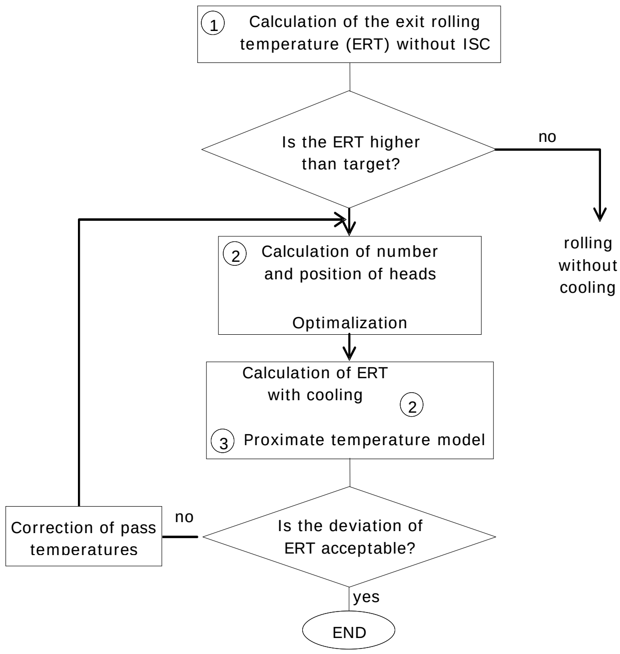


Figure 13. Headers setup algorithm for one point

Target Exit Rolling Temperature

Target temperature (ERT) can be kept lengthwise with a tolerance of ±10°C from the target temperature (see **Figure 16**). In thin strips (<5mm), the temperature deviations are less than ±5 °C. In thick strips (>10 mm) the tolerance ±10°C can be reached only if the temperature oscillation in transfer bar is less than 15°C. There are some problems in strip head and tail, because the temperature measurements at these parts are very unreliable.

Elimination of Skid Marks

ISC proved to be very effective tool to eliminate skid marks. If the slab is heated in older furnaces the temperature oscillation in transfer bar can be more than 30-40 °C. Those oscillations can be completely eliminated in thin strips (< 6 mm). In thick strips (more than 12 mm) temperature deviations up to 20 °C in transfer bar can be eliminated. Higher oscillations (30-40 °C) cannot be removed completely, but they can be considerably reduced.

In **Figure 17** there is ERT obtained with constant cooling power of ISC (constant number of headers and constant water flow rate). It is obvious, that the skid marks have not been eliminated in this case, temperature oscillation of measured temperature (green line) agrees with computed oscillations (red/blue line).

Enhancement of speed/speed up

Required exit rolling temperature is one of the limiting parameters for speed and speedup of the strip. Providing that ISC has enough cooling power and flow rate on headers and can be effectively controlled, limits of speed and speedup can be raised. There are several metallurgical and technological aspects prohibiting extensive cooling in special steels where this way of increasing productivity can be used only in limited manner. Nevertheless practical experience proved an increase of productivity due to ISC when compared with rolling without ISC or using ISC with constant cooling power (flow rate) lengthwise.

An example below demonstrates cooling matrices of thin strips rolled at 14 and 21 m/s. When rolling with low speed, the cooling is nearly off. When rolling with higher speed up (head velocity of both strips was the same), the ISC works with maximum power on the tail.

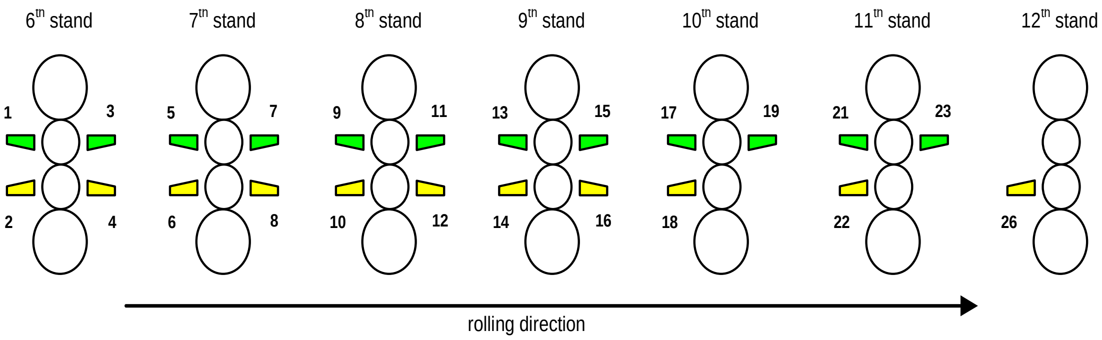
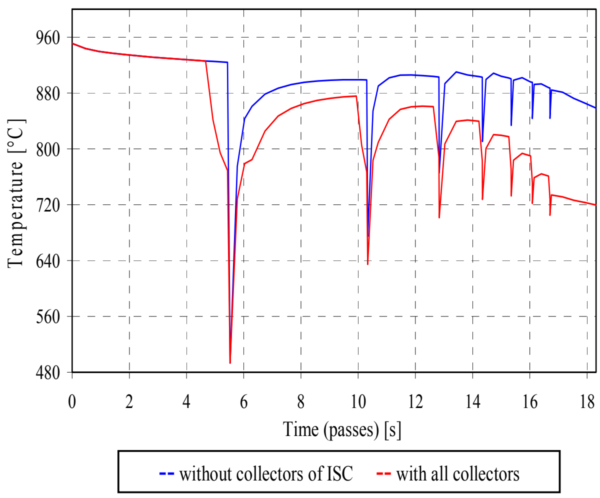


Figure 14. ISC headers position in finishing mill



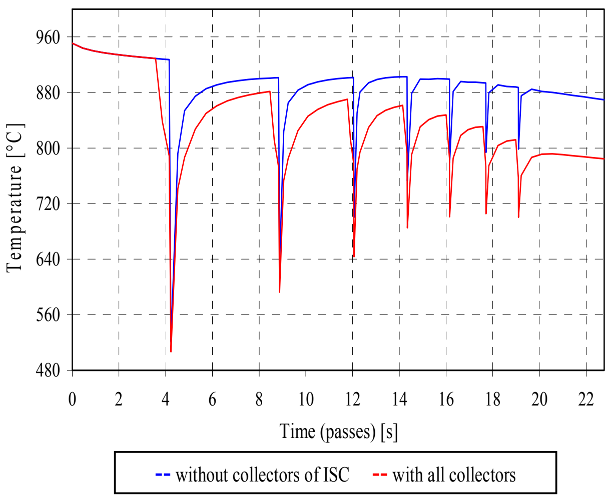


Figure 15. Efficiency of ISC in thin and thick strip

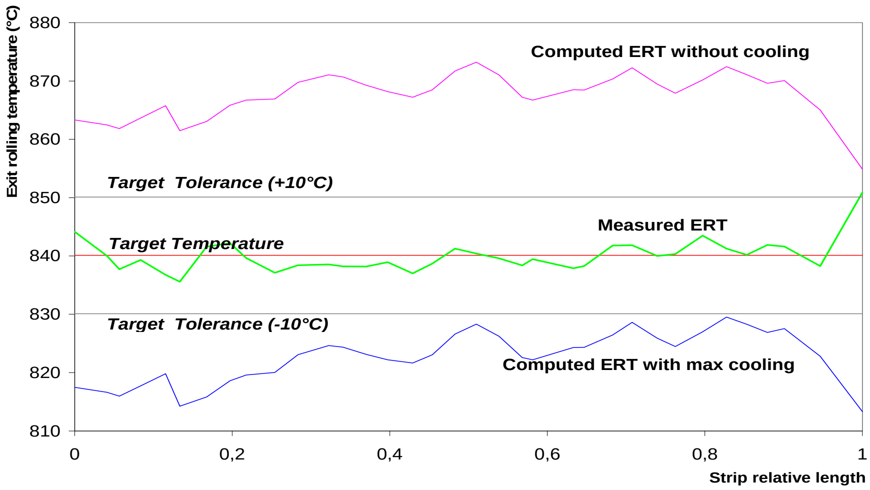


Figure 16. Measured and calculated ERT

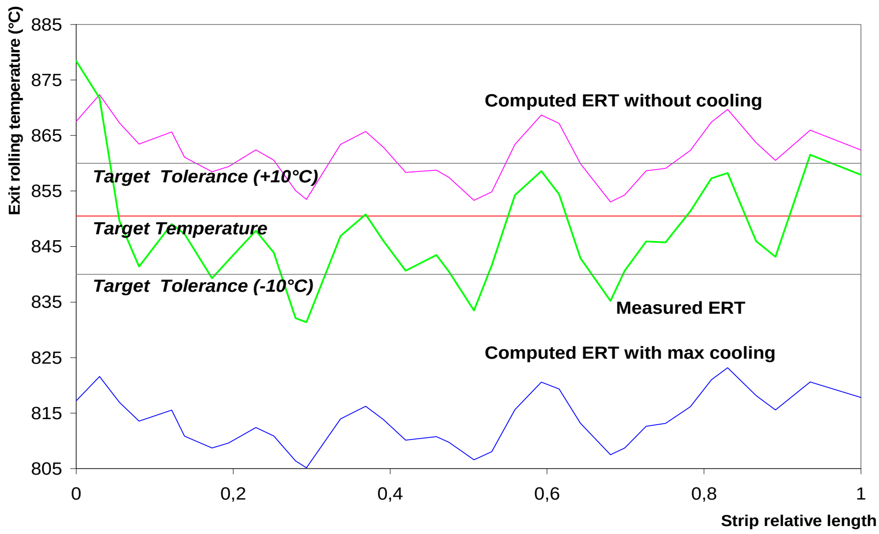


Figure 17. Measured ERT when rolled with constant header power lengthwise

Conclusions

The complex approach to the Interstand Cooling problems solution is briefly presented in this paper. There are possibilities of cooling headers experimental assessment and their cooling characteristics calculations are shown. In the next part the complex model for control of Interstand Cooling is presented, that can work quite separately from existing Level 2 control system. Some practical experience with ISC on wide strip mill is discussed. ISC helps to reach target exit rolling temperature and to ensure temperature homogeneity along the strip length. Temperature oscillations due to skid marks can be elliminated or considerably reduced. The productivity of the mill can be increased. Constant exit rolling temperature helps to reach target coiling temperature in laminar cooling section.

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