CONTROL OF PUSHER FURNACES FOR STEEL SLAB REHEATING USING A NUMERICAL MODEL

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Abstract **– Steel slabs are reheated in pusher-type furnaces up to a temperature of 1200°C in the steel sheet manufacturing process. In this article we describe a control system that uses an on-line numerical model to calculate the furnace setpoints in order to improve the heating quality. Examples of actual furnace operation with and without the system are presented to show the improvements that are obtained handling typical non-stationary situations.**

Keywords **-- Steel industry, Reheating furnaces, Furnace control**

I. INTRODUCTION

In the steel strip manufacturing process (Figure 1), steel slabs obtained from continuous casting are reheated up to temperatures of approximately 1200°C prior to the rolling process. The required temperature at the end of such process has to be comprehended within a narrow range determined by the subsequent on-line heat treatment process. Slab reheating in pusher furnaces is one of the sources of variability that produce departures from that narrow range.

In the case of SIDERAR's hot rolling facility in San Nicolás, Argentina, four pusher-type furnaces are used to reheat slabs that are approximately 6m long, between 0.65 and 1.53m wide, and from 0.18 to 0.20m thick. These furnaces are named after the way the slabs are pushed forward inside the furnace. Every time a hot slab has to be discharged to be rolled a new slab is introduced into the furnace and the intermediate slabs are pushed sideways towards the furnace outlet. In the first part of the furnace the slabs are supported by four refrigerated skids, while near the outlet they lie on a refractory hearth that is intended to diminish the temperature inhomogeneity generated by the skids The heating power is supplied by gas burners that use either natural gas or a mixture of natural and coke gases and are arranged in several zones. Typically one preheating zone, two heating zones (an upper and a lower one) and one soaking zone are present (Figure 2). The burners of each zone are controlled through thermocouple setpoints: a control loop regulates the air and gas flowrates to match the set value with the temperature measured by a properly placed zone thermocouple. Therefore, the problem of furnace temperature control is that of specifying the setpoints that produce an adequate slab outlet temperature distribution.

To monitor the slab outlet temperature there is an infrared pyrometer at the rougher exit (R4 in Figure 1), which measures the slab longitudinal temperature profile on the upper side of the slab. The mean temperature and the maximum temperature difference of this profile are the target variables of the furnace control and define the heating quality. Although it would be desirable to have a measurement point closer to the furnace outlet, the oxide layer that is formed during the heating process and that is removed by a descaler at the rougher inlet, prevents a reliable measurement prior to the rougher exit.

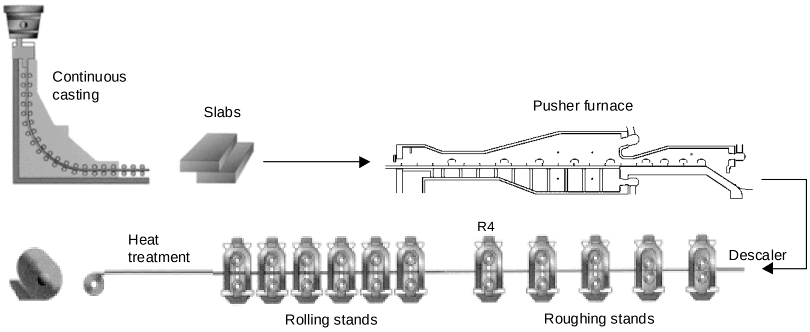

Figure 1. Schematic illustration of the steel strip manufacturing process

Traditionally the furnaces are operated manually, based on setpoint tables that correspond to steady state operation. There are also some automatic actions that are implemented in the Programmable Logic Controller (PLC) that is used to handle the signals from the process sensors and to regulate the process actuators. Although manual operation gives a reasonable heating quality when the furnace is in steady state, there usually are changes in the slab geometry, in the cycle time, in the inlet temperature, and there are downstream events that produce halts in the line. All these situations produce departures from stationary operation and generate variations in the slab mean temperature at the rougher outlet. For instance, to avoid slab overheating in manual operation, whenever a halt occurs, the gas and air flowrates are automatically decreased by the PLC. When operation is resumed, compensating for this effect is a delicate task that only experienced operators are able to carry out with relative success.

In this article we describe a control system based on a numerical model of the process that is used to automatically calculate zone temperature setpoints that are intended to minimize the departures of the slab mean temperature at the rougher exit from the corresponding process objectives.

II. NUMERICAL MODELS

The use of numerical models to improve the design of this process has been the objective of several analyses. A very complete steady state model was presented in (Barr, 1995). That model was used to study the influence of the skid configuration on the slab homogeneity.

Due to the fact that the models are used in a factory environment, the use of standard PC hardware is mandatory, thus restricting the model complexity. However, the continuous increase in the computing power has recently allowed the development of detailed numerical models capable of perform on-line.

(Correia *et al.*, 2002) investigate parametrically the use of 2-D zone models to predict the thermal behavior of a continuously operated metal reheating furnace. In (Boineau *et al.*, 2002) a CFD code with a module to calculate the radiative exchanges using a zone formulation was adapted to simulate transients eliminating the fluid dynamic calculation. Although a series of off-line analyses was presented, on-line results were not given. Also in (Honner *et al.*, 2002), a CFD model was used to calibrate a simpler one which uses adjustable coefficients to evaluate the radiative and convective heat fluxes. On-line results showed a good agreement between calculated and measured values.

In a previous paper (Marino *et al.*, 2002) we presented a detailed numerical model of the slab reheating in pusher-type furnaces and showed that the temperatures calculated by the model are in agreement with validation measurements made with instrumented slabs. Model results were also successfully compared with the pyrometer measurements at R4. The main model features are:

- 3-dimensional and spectral calculation of the radiative exchanges in the combustion chamber using the zone method (Hottel and Sarofim, 1967)
- Detailed description of the radiative properties of the combustion products from RADCAL (Grosshandler, 1993)
- The combustion product temperatures are calculated from thermocouple measurements
- 2-dimensional calculation of the slab temperature distribution (neglecting inhomogeneities in the slab width)

Similar features are present in models developed for different kind of furnaces (Marino and Pignotti, 1997; Altschuler *et al.*, 2000; Marino, 2000).

III. FURNACE CONTROL

In this section we describe the algorithm that is used along with the model to automatically calculate the zone temperature setpoints that are intended to minimize the departures of the mean slab temperature from the target value. This algorithm includes the evaluation of the effect of changes in the zone temperatures on the slab future thermal evolution. Due to the fact that both the model and the control algorithm have to perform in real time, and that this calculation has to be updated frequently in order to take into account possible changes in the load geometry, cycle time, thermocouple measurements, etc., there are bounds on the complexity of the algorithm used to calculate the temperature setpoints. The current practice is to perform this calculation every 30 seconds.

A. Control Algorithm

In the control algorithm a target average slab temperature at the rougher exit is defined for every slab in the furnace, according to the product and process requirements. It depends on the slab geometry and the strip final thickness. Intermediate target temperatures at the end of the preheating and heating zones are also defined.

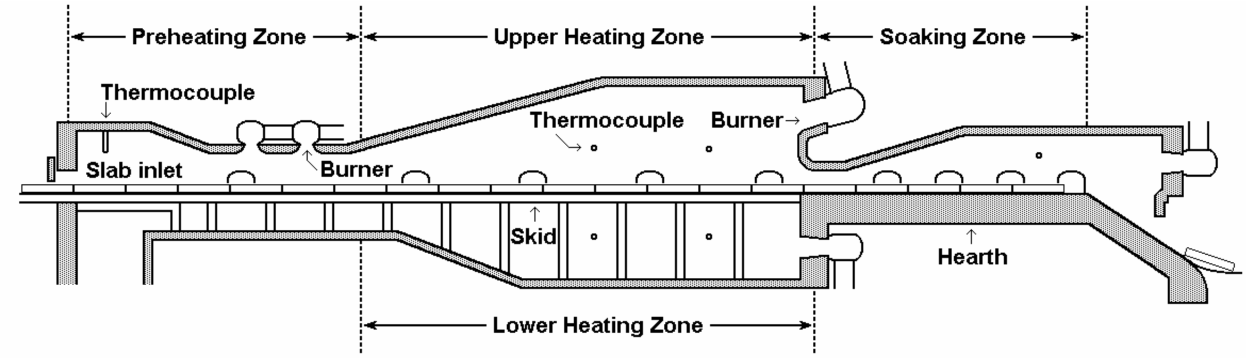

Figure 2. Longitudinal section of SIDERAR #3 pusher furnace

For each zone the updated setpoint temperature is determined by comparing the target temperature at the end of the zone, and the model predicted average slab temperature when it reaches the end of the zone. In practice, the following equation is solved:

$$\sum_i W_i.(Tc_i - Tobj_i) = 0$$

where

W_i : is a weighing factor that depends on the slab distance to the end of the zone and on the departure of the current slab temperature from its desired stationary value

Tc_i : is the calculated mean temperature that the slab *i* will have at the end of the zone under the assumption that the slab velocity remains constant. This value is a function of the updated zone setpoint temperature

$Tobj_i$: is the target temperature of slab *i* at the end of the zone

The summation comprises all the slabs of the zone and also part of those that are in the preceding zone. Both the obtained zone temperatures and their rates of change are limited in order to preserve the integrity of the refractories.

B. Target Offset

As the model calculates the mean slab temperature at the furnace outlet, but the heating process reference temperature is measured with a pyrometer on the slab upper surface after the rougher stand, there is a drop in the mean slab temperature between the furnace and the rougher exit. This drop may vary depending on the transference time, the performance of the descaler, and the refrigeration of the rolling cylinders. Thus, a correction term (offset) is introduced for the target temperature at the furnace outlet. This term is intended not only to compensate for departures from a constant temperature drop from the furnace outlet to the rougher exit, but also to correct deviations due to errors in the model input data such as errors in the thermocouple measurements.

The following deviation is calculated for each slab that is unloaded, assuming a constant change in the slab mean temperature from the furnace outlet to the measurement location:

$$\delta = \left(T_{obj} - T_{cal}\right) - \left(T_{obj}^{R4} - T_{meas}^{R4}\right)$$

where

T_{obj} : is the target temperature at the furnace outlet

T_{cal} : is the calculated mean temperature that the slab *i* will have at the furnace outlet

T_{obj}^{R4} : is the target temperature at the rougher exit

T_{meas}^{R4} : is the measured temperature at the rougher exit

Then, the target temperature at the furnace outlet is corrected using a standard PID control loop.

Another frequent cause of deviations is the lack of an accurate measurement of the slab inlet temperature. Until a final solution is found for this problem, the ambient temperature is assumed for the incoming slabs, avoiding the more dangerous alternative of supposing that an incoming slab is hot when it is actually cold. The target offset helps to manage these situations. It can also handle moderate departures caused by misleading readings of the zone thermocouples due to degradation or to the incorrect placement of the thermocouple inside the furnace. However the offset value is limited to a maximum value of 15°C and it has a small impact on the slab mean temperature.

IV. OFF-LINE ANALYSIS

The objective of the present work is to show how the control of this type of furnaces can be based on running on-line the above mentioned numerical model, and that this has definite advantages over the traditional manual operation. Henceforth we use the expression “model operation” to denote operation of the former type.

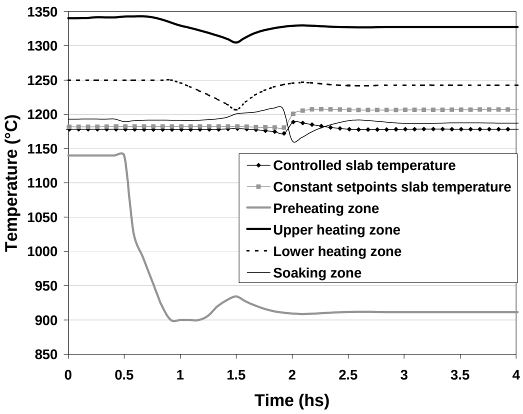

Figure 3. Control system response to an increase of 475°C in the inlet slab temperature

In order to show the response of the control system to the largest expected load perturbation, which is a change in the slab inlet temperature from ambient to 500°C, this case is simulated both with the calculated zone setpoints and keeping them constant. In the first case a ripple of ±8°C is observed in the outlet slab temperature in Fig. 3, whereas in the latter an increase of 27°C is produced.

Of course, also in manual operation there are changes to the zone temperature setpoints. Thus, in order to compare manual and model operation and determine the benefits of using the latter, the furnace operation corresponding to a period of 35 hours was analyzed. Figure 4 shows the slab mean temperature at the furnace outlet along with the corresponding target, and the temperatures measured by the zone control thermocouples. During this period the furnace was controlled by the operator, but some actions were carried out automatically when there were halts in the production (the air and gas flowrates were decreased to approximately 22% after 3 minutes of line halt, and to 13% after 7 minutes). When the line resumed the production after the halt, the zone temperatures were rapidly set to the values previous to the halt. The resulting high variations in the zone temperatures are apparent in the figure, and it can be observed that the slab mean temperature at the furnace outlet is biased towards higher values, mainly due to this manual control policy.

Figure 5 shows the results obtained simulating the same situation but assuming that the setpoint temperatures calculated by the control algorithm were actually measured by the zone thermocouples (allowing a maximum rate of change to take into account the air/gas control loop response). In this figure the calculated mean slab temperature at the furnace outlet is shown along with the values obtained previously for manual operation. It can be observed that the departures from the target curve are highly reduced if the zone temperature setpoints are calculated with the model-based control algorithm.

Also shown are the calculated zone temperatures, and it is apparent that the sudden zone temperature variations produced during halts in manual operation mode are not necessary. As in these off-line simulations there are no pyrometer readings, the target offsets do not apply.

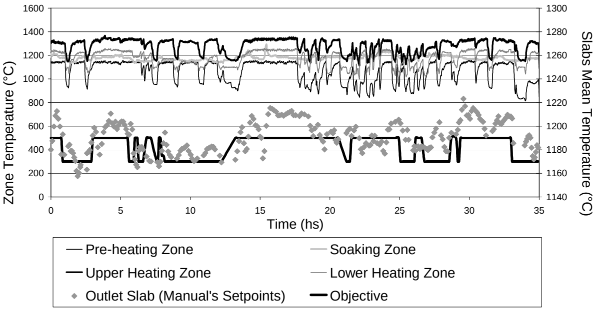

Figure 4. Mean slab temperature calculated by the model at the furnace outlet for a period of manual operation

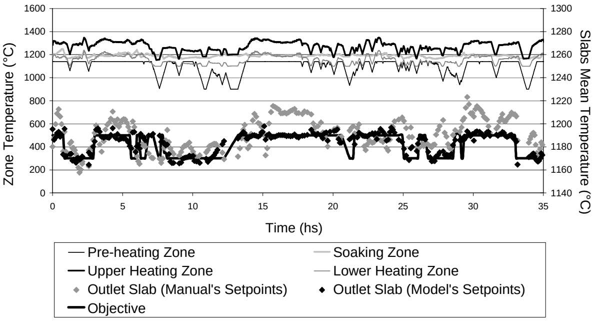

Figure 5. Mean slab temperature calculated by the model at the furnace outlet for the same period of Figure 4 using the zone temperatures calculated by the control algorithm. The outlet temperatures shown in Figure 4 are reproduced for comparison purposes

V. ON-LINE IMPLEMENTATION

Figure 6 shows a diagram of the system flow. The heavy line represents the slab flow from the unpiler through the furnace and to the rougher stand. The dashed lines show the data flow: initial slab temperature, zone temperatures and slab geometry and movement are input to the model. Likewise, the R4 pyrometer reading is input to calculate the target offset. The model returns the temperature setpoints.

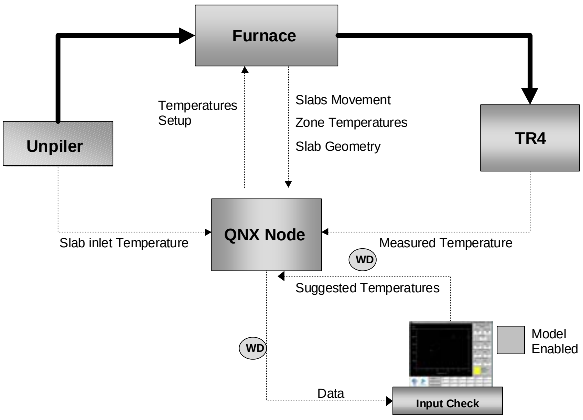

Figure 6. System architecture

VI. CONTROL RESULTS

Due to the promising results obtained with the off-line simulations the model was installed in furnace #3. After a period in which the model-based control was tested and the parameters associated with the control algorithm were adjusted, the performance of the control system was evaluated.

Due to the fact that furnace #4 is practically identical to furnace #3 it was possible to compare the actual performances of the model and the operators under the same circumstances. In the following subsections, for typical transient situations, these performances are compared with each other and with the specified reference band for the target temperature indicated by the “error bars” in Figures 7-10.

A. Halts

Although the control algorithm behavior during halts was discussed in section IV, it is interesting to verify those results comparing the temperatures measured in furnace #3 (model operation) and #4 (manual operation) for a several hours halt.

It can be observed that the R4 temperatures for manual operation were low for slabs 4-9, that were in the soaking zone during the halt, whereas the slabs that were in the heating zone during the halt had a temperature above the reference band (due to the sudden heating zone temperature increase after the halt). For the same situation the slabs reheated using model operation were within the reference band, except for the last two slabs that entered the furnace prior to the halt, that were slightly overheated in order not to underheat those that entered after the halt.

B. Residence time

Whenever there are slabs with very low residence time, there is the risk of underheating these slabs.

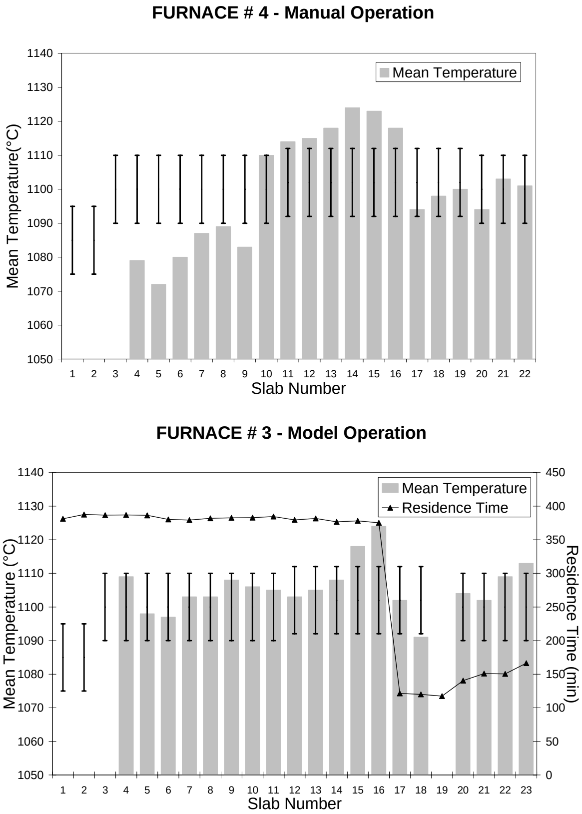

Figure 7. Outlet temperatures measured at the rougher exit for furnaces 3 and 4 after a halt that lasted approximately four hours. Furnace number 3 was model operated, while furnace number 4 was run in manual operation.

The situation illustrated in Figure 7 shows that in model operation the worst reheated slab almost remained inside the reference band, whereas in manual operation the slabs with low residence time were severely underheated in furnace #4. This improvement was obtained in model operation at the expense of a minor overheating of a few previous slabs.

C. Changes in the slab thickness

Departures of the measured temperatures from the target values are also produced by changes in the slab thickness. In Figure 8 two instances are shown in which some 200mm slabs are preceded and followed by 180mm slabs. In the first case, slabs 14-16 are severely underheated in manual operation, whereas they are only barely underheated in model operation. Similarly, at a later occurrence only slabs 84 and 85 are slightly underheated in model operation, whereas a much more severe underheating is present in the concurring episode in furnace 4.

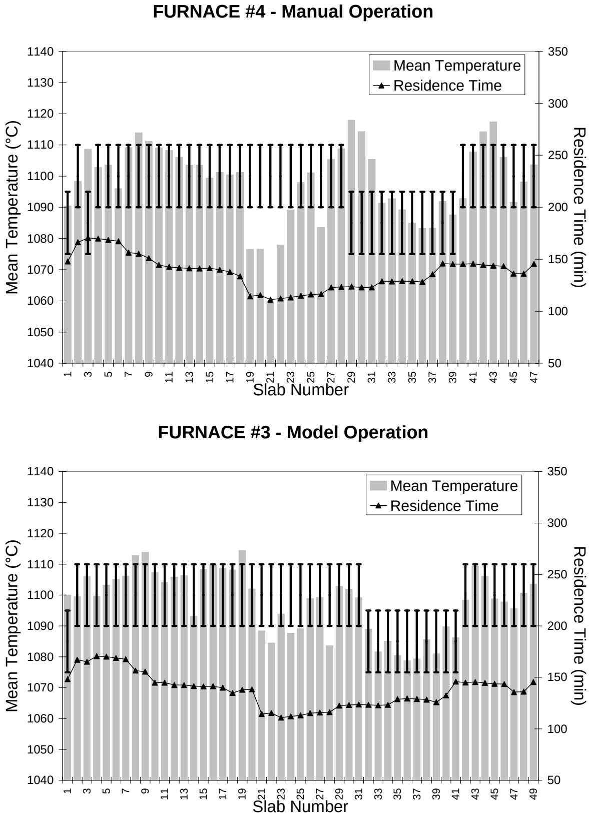

Figure 8. Comparison of the mean temperature measured on the slabs reheated in furnace #4 (manual operation) and #3 (model operation). The use of the model is shown to help in preventing slab underheating due to low residence time

VII. OVERALL RESULTS

The superior performance of the model operation in the cases presented in the previous section is evident. Since March 2003 the model is fully operational at furnace #3. The percentage of slabs that fall within the reference band and neighboring bins is shown in Figure 10 for both model and manual operation. The results correspond to a whole month of operation, and it can be observed that the use of the model improves the distribution of the slabs mean temperature at the rougher outlet. However, twenty percent of the slabs were overheated. This figure may appear excessive, but it should be realized that there are circumstances in which it is necessary to overheat some slabs in order not to underheat neighboring ones. This happens, for instance, after extended halts, when there is a large temperature difference between the slabs loaded into the furnace immediately before and after the halt. Occasionally, it is also inevitable to overheat 180mm slabs adjacent to 200mm slabs. Finally, it also occurs when slabs with higher initial temperature (because they are reheated shortly after they are produced by the continuous caster) are loaded into the furnace. Even though the model is prepared to take this fact into account, the tracking system is not yet able to provide this information, and the assumption is made that all slabs are loaded at room temperature, which is a "safe" assumption, inasmuch, from the rolling point of view, it is preferable to overheat than to underheat.

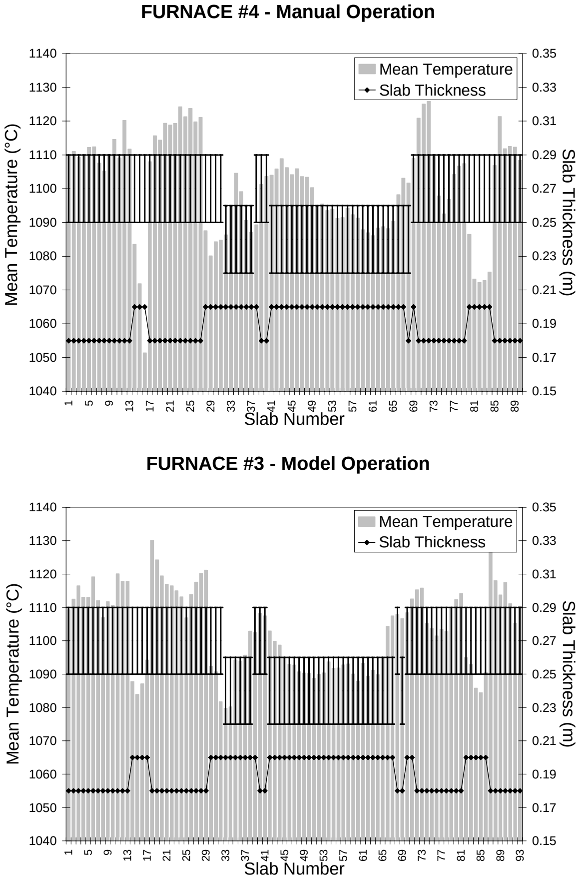

Figure 9. Temperatures measured at the rougher outlet for manual and model operation, along with the target reference band and the slab thickness.

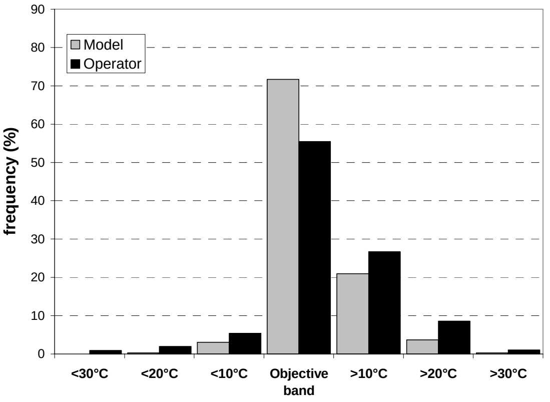

Figure 10. Distribution of the slab mean temperature corresponding to model and manual operation

VIII. CONCLUSIONS

It was shown that the use of a detailed numerical model along with a suitable control algorithm to determine the zone setpoints for a slab reheating furnace leads to a more consistent and reliable furnace operation and significantly improves the slab heating quality. Currently the model is being installed in the three additional furnaces of the same production line, with the objective of controlling concurrently the four furnaces and of determining possible decreases in the cycle time.

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