24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-1248
ANALYSIS OF HEAT TRANSFER IN STEEL BILLETS DURING TRANSPORT

Kássio Nogueira Cançado
Centro Federal de Educação Tecnologica de Minas Gerais, Av. Amazonas, 7675 - Nova Gameleira, Belo Horizonte - MG, kancado@hotmail.com
Lis Nunes Soares
Vallourec Soluções Tubulares do Brasil, Av. Olinto Meireles, 65 – Billetreiro, Belo Horizonte - MG
Lis.soares@vallourec.com

Abstract. *The temperature decrease between the exit of the furnace and the rolling mill entrance is determinant factor in the rolling process and the quality of the tube. This study aims to model the cooling of the billets during transport in order to evaluate the minimum temperature required for the billet leaves the furnace and also the maximum transport time without compromising the rolling process, allowing a better setup of equipment and reducing the production costs. The results obtained with the cooling model were compared with real values of temperature measurements by thermocouples installed on the billet. Measurements with thermocouples were conducted in billets of 270, 230 and 180 mm diameter. The error relative to the real values for all cases was below than 2,5 % and the model is considered validated to use.*

Keywords: *Cooling, Transport, Rolling Mill, Heat Transfer, Cost*

1. INTRODUCTION

The seamless tube production process has as its first step the heating of steel billet at a temperature of about 1200 °C, after heating these billets are transported to the rolling mill. The temperature that the billet reaches the rolling mill is of great importance for the process quality. Thus, in order to understand and predict the cooling process of the billet during the transport, the heat transfer present in the cooling processes was studied and mathematically modelled. A tool was developed to simulate the cooling profile during transportation.

The cooling profile was determined using energy balances performed on the billet, these were solved numerically using the technique of successive substitutions (Chapra, 2004). To validate the results, measurements were made with thermocouples (billets of 270, 230 and 180 mm in diameter).

The knowledge of the cooling mechanism allows determining the cooling profile, a minimum unloading temperature and the maximum transportation time, it also allows a more efficient setup of the equipment generating a reduction in production costs.

2. EXPERIMENTAL AND COMPUTATIONAL PROCEDURE

2.1 Mathematical Model

In the mathematical model of cooling, the one-dimensional cooling (radial direction) was considered, and the central section of the billet was analyzed, so the corner effect present at the extremities was not considered. Once this was defined, the section was divided into n layers. The surface layer (layer 1) exchanges heat by radiation and natural convection with the external environment, and exchange heat by conduction with layer 2. The layers (2 to n-1) exchange heat through conduction. The inner layer n has very small area, close to zero, so it is considered that the temperature of this layer is equal to that of layer n-1. Figures 1 and 2 illustrate this modeling.

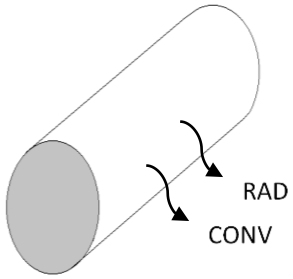

Figure 1. Heat Transfer Surface Layer

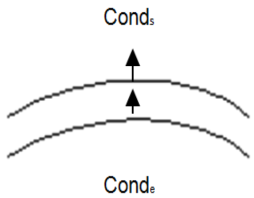

Figure 2. Heat Transfer Layer 2 to n-1

2.2 Energy Balances

According to (Incropera, 2003) the energy balance can be solved in a discrete way for each layer, approaching dT/dt by $\Delta T/\Delta t$. A time step, Δt, is equal to 1 minute, temperature and dependent properties were updated every iteration. The equation of the layer 1(surface layer) as in Eq. (1):

$$m.C_p.\frac{\Delta T}{\Delta t} = h_{conv}.A.(T - T_\infty) + h_{rad}.A.(T - T_\infty) + k.\frac{2\pi}{Ln\frac{re}{ri}}.(T_n - T_{n+1}) \quad (1)$$

Where: m is the mass of a layer, Cp is the specific heat of the steel, T is the layer temperature, t is time, h_{conv} is the convective heat transfer coefficient, A is the surface area of layer, h_{rad} is the coefficient of heat transfer by radiation, *re* is external radius, *ri* is internal radius, *n* is the layer index. The coefficient of heat transfer by radiation as in Eq. (2).

$$h_{rad} = \varepsilon.\sigma.(T + T_\infty) + ({T_n}^2 + {T_\infty}^2) \quad (2)$$

Where: ε is the emissivity of the surface of the steel billets (equal to 0.91), σ is the constant of Stefan Boltzmann whose value is $5{,}67.10^{-8}\ \frac{W}{m^2.K^4}$. The coefficient of convective heat transfer as in Eq. (3).

$$h_{conv} = \frac{\overline{NU}.K}{D} \quad (3)$$

Where: $\overline{NU}$ is the mean value of the Nusselt number of the billet, k is the thermal conductivity, D is the diameter. Nusselt along the surface, can be estimated for numbers of Rayleigth, *Ra*, less than 10^{12} as in Eq. (4).

$$\overline{NU} = \left\{0.60 + \frac{0.387 * Ra^{\frac{1}{6}}}{\left[1+\left(\frac{0.559}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}}\right\}^2 \quad (4)$$

Where: *Ra* is numbers of Rayleigth and *Pr* is number of Prandt.

The equation of the layers 2 to n-1 (inner layers) as in Eq. (5):

$$m.C_p.\frac{\Delta T}{\Delta t} = k.\frac{2\pi}{Ln\frac{re}{ri}}.(T_n - T_{n+1}) \quad (5)$$

The equation of the layer n (innermost layer) as in Eq. (6):

$$T_n = T_{n-1} \quad (6)$$

2.3 Numerical Method

In the energy balance equation Eq. (1), Temperature is function of h_{rad} and h_{conv} which are also function of temperature. In order to solve the equation was necessary an iterative method, in this case the technique of successive substitutions, where temperature is calculated in function of temperature, as in Eq. (8) (Chapra, 2004). To implement this method and solve the equations was written a code in c ++

$$T = f_{(T)} \quad (7)$$

To accelerate the convergence of the method, the value found in the previous iteration was arbitrated as the initial temperature value. The criterion of convergence of the method as in Eq. (9).

$$\left|\frac{T_p - T_{p-1}}{T_p}\right| \leq E \quad (8)$$

Where: E is equal to 0,001 and p is iteration index

Figure 3 illustrates the iteration process:

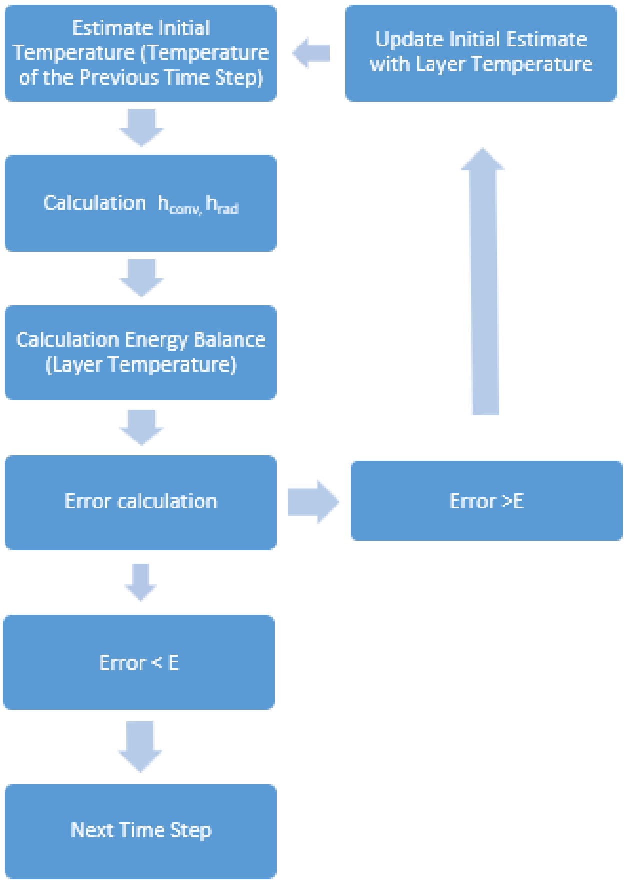

Figure 3 . Iteration Process

2.4 Measurement with thermocouples

Measurements with thermocouples consist of using pre-instrumented billets with thermocouples type k, these are connected to a logger that is housed inside a thermal barrier that has the function of protecting it from high temperatures. After being instrumented the billet is then load, heated, unload and transported to the entrance of the rolling mill.

The logger records the temperatures at predetermined time intervals which allows filtering only the range of interest, in this case the time between the furnace exit and the rolling mill entrance. Once this is done, is possible to compare the measured and calculated cooling profiles.

The billet is instrumented with 10 thermocouples. Those of numbers 1, 4, 7 are fixed to a depth of 10 mm from the upper face. Those of numbers 2, 5, 8 are fixed in the center. Those of numbers 3, 6, 9 are fixed to a depth of 10 mm from the lower face of the billet. The number 10 is not connected to the billet and works as an antenna, recording the ambient temperature. The thermocouples are distributed in groups of 3 as in Fig.4. In this way measurements are made of the upper, lower faces and center in three regions of the billet

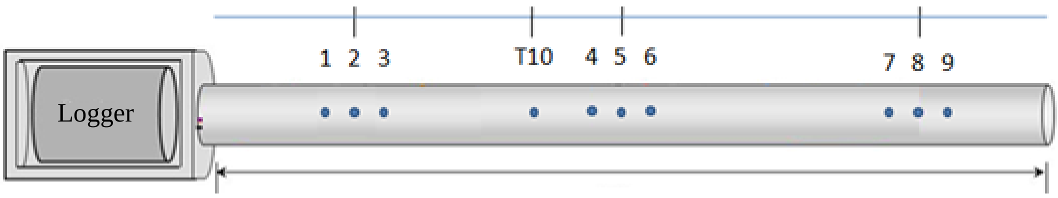

Figure 4. Instrumented Billets

3. RESULTS

All the equipment used in the data collection were calibrated, so the results obtained experimentally are valid.

The temperature profile of the billet during the cooling was simulated and can be compared to the profile measured with the thermocouples. The simulated temperature for the layer 2, which corresponds to the depth at which the thermocouple was fixed (10 mm), was used for analysis. The initial temperature value used in the simulation corresponds to the actual value of the thermocouple measurements at the start of the cooling. The cooling profile for the three measured diameters (270, 230, 180 mm) can be seen in Fig.5, Fig.6, Fig.7.

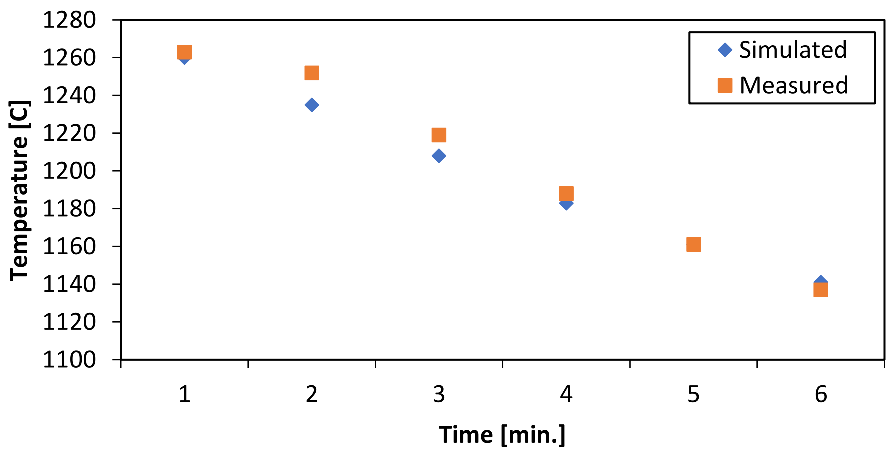

Figure 5. Cooling Profile Billet 270 mm

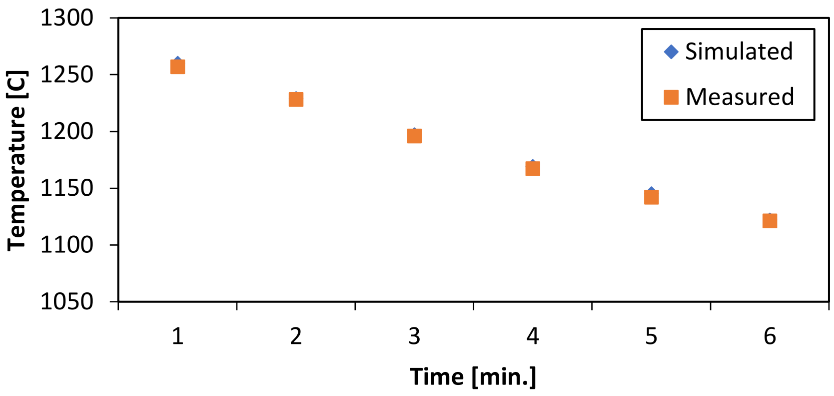

Figure 6. Cooling Profile Billet 230 mm

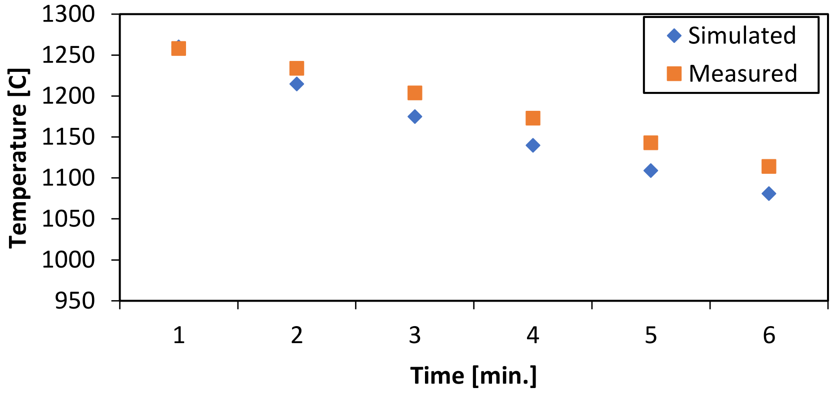

Figure 7. Cooling Profile Billet 180 mm

The temperature values of the measurements and simulations for the three diameters (270, 230, 180 mm) can be seen in Tab.1, Tab.2, Tab.3:

Table 1. Simulated and measured temperature values for 270 mm billets

	0 min.	1 min.	2 min.	3 min.	4 min.	5 min.
Simulated [°C]	1258	1215	1175	1140	1109	1081
Measured [°C]	1258	1234	1204	1173	1143	1114

Table 2. simulated and measured temperature values for 230 mm billets

	0 min.	1 min.	2 min.	3 min.	4 min.	5 min.
Simulated [°C]	1257	1229	1197	1169	1145	1122
Measured [°C]	1257	1228	1196	1167	1142	1121

Table 3. simulated and measured temperature values for 270 mm billets

	0 min.	1 min.	2 min.	3 min.	4 min.	5 min.
Simulated [°C]	1263	1235	1208	1183	1161	1141
Measured [°C]	1263	1252	1219	1188	1161	1137

The error between the simulation and the experimental data was calculated as in Eq. (9):

$$\text{Relative error} = \frac{\textit{Value measured} - \textit{Valor simulated}}{\textit{Valor measured}} * 100 \qquad (9)$$

The calculated error values for the three diameters analyzed as in Tab. 4.

Table 4. Simulation Error in Relation to Thermocouple Measurements

	0 min.	**1 min.**	**2 min.**	**3 min.**	**4 min.**	**5 min.**
270 mm	-	1,36%	0,90%	0,42%	0,00%	0,35%
230 mm	-	0,08%	0,08%	0,17%	0,26%	0,09%
180 mm	-	1,54%	2,41%	2,81%	2,97%	2,96%

Table 5 presents the calculated average error values for the three diameters analyzed.

Table 5. Average error between Thermocouple Measurements

	Average Error
270 mm	0,51%
230 mm	0,11%
180 mm	2,12%

4. CONCLUSION

This work achieved its objective of simulate simulate the cooling profile of the billets in the transport between the exit of the furnace and the entrance of the mill. The understanding of this cooling allows the correct setup of the equipment, improving the quality of the tubes and reducing the costs with:

- Rework;
- Energy in the unnecessary heating of the billets;
- Energy in the lamination of cold billets;
- Premature wear of tools;

In general, the cooling model showed good accuracy, obtaining an average error of less than 2.5%. In this way, it has satisfactorily achieved its objective, to help decision making in the industrial environment.

For billets of 270 and 230 mm presented a relative error lower than 0.5% indicating a good precision of the model.

For billets of 180 mm the simulation presented a real error of approximately 2,12%, being this, the worst result among the three types of billets studied.

The reason for this being observed only in the 180 mm billet is that the production line of this billet is different from the 230 and 270 mm billets.. Thus, the configuration of this equipments can influence the model boundary conditions, which were studied for the production line of billets 270 and 230 mm. A more detailed study is needed to refine the model for the production line of the 180 mm billets. However the error is within the operating limit accepted and the model can be considered validated for use in the three billet diameters.

5. ACKNOWLEDGEMENTS

To Vallourec Soluções Tubulares do Brasil for promoting research and development work.

6. REFERENCES

CHAPRA, S. C., Applied Numerical Methods With MATLAB, 3aed. Rio de Janeiro: MC Graw Hill, 2004, 384p.

INCROPERA, F. P., DeWITT, D. P., Fundamentos de transferência de calor e de massa, 5aed. Rio de Janeiro: LTC, 2003, 698p

7. RESPONSIBILITY NOTICE

Cançado Kássio, Soares Lis are the only responsible for the printed material included in this paper.