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NUMERICAL MODELING OF HEAT TRANSFER OF STEEL TUBE DURING QUENCHING PROCESS

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Abstract. *The evolution of the cooling curve during steel hardening process is essential to define the mechanical properties and quality of the final material. As these properties vary considerably depending on the cooling rate it is essential to monitor and control the temperature evolution in the metal. This paper presents the development of a mathematical modeling of heat transfer, whose purpose is to generate the temporal evolution of the temperature in a quenching process of steel tube in which water is used as cooling fluid. In this modeling the tube is divided into N control volumes. The heat conduction equation is applied to each control volume and conductive heat transfer rate at the tube surface is considered equal heat transfer rate between the tube and water by convection. The model equations are solved by implicit finite volume method. Comparisons between the cooling curves generated by the model are compared with the corresponding curves obtained experimentally in the industrial process. The results show that the model reproduces well the trend of the cooling curve during the process. The results also showed that the cooling curve obtained with the model is very sensitive to convection heat transfer values between the tube and water.*

Keywords: *Numerical Modeling, Quenching Process, Heat Transfer*

1 INTRODUCTION

Heat treatment of engineering components is an important process in which the final objective is to improve mechanical properties by variation of relative proportion of micro constituents.

Totten et. al. (1998) define that quenching is a process whose the main propose are to allow bainite or martensite formation and to prevent perlite and ferrite development. In general lines quenching of steel can be divided in three stages (boiling process): the vapour phase (first stage); nucleate boiling (second stage) and convective cooling (third stage). In the first stage a vapour blanket is formed immediately upon quenching in the interface at workpiece/quenchant. As a vapour has a low thermal conductive and acts as an insulating system, the heat transfer in this stage is low and is mostly done by radiation. As the temperature drops, the vapour blanket becomes unstable and collapses, initiating the nucleate boiling stage. Heat transfer is fastest and biggest in this stage, due to heat of vapourisation and continues until the surface temperature drops below the boiling point of the quenching medium. In the final and third stage the cooling takes place through convection.

Incropera et.al. (2007) describe the boiling process by four stages: film boiling, transition boiling, nucleate boiling (this stage is divided in two parts: isolated bubbles and jets or colums) and convective cooling. Each stage is separated of other by the value of parameter described as excess of temperature that is the difference between the temperature of material surface and quenching fluid boiling temperature. The heat transfer in each stage can be calculated by Newton’s law for cooling process. For the film boiling stage (excess temperature greater than 120°C), correlations are proposed by spheres and horizontal cylinders to determine the heat transfer coefficient. In transition boiling (excess temperature between 30°C and 120°C), correlations to determine the minimum heat flux are described to horizontal plates while the correlation for maximum heat flux is proposed to spheres, horizontal cylinders and large heat surfaces. For the nucleate boiling stage (excess of temperature between 5°C and 30°C) a correlation proposed by Rohsenow can be used to estimate the heat transfer coefficient and for the final stage correlations proposed by convection can be used to estimate the heat transfer coefficient.

Versteeg and Malalasekera (2007) in their development of computational fluid dynamics by finite volume method show that a one-dimensional model can be developed to estimate a cooling curve during quenching process. The analysis is based on transport equation that can be used with different schemes (explicit scheme, Crank-Nicholson scheme and fully implicit scheme). Schemes that have as a point of attention the criteria of computational stability. In term of stability is suggested to use the fully implicit method due to the fact that this scheme is unconditionally stable. Different situations of explicit and crank Nicholson scheme that has their stability conditioned to the time step.

Fernandes and Prabhu (2007) estimate the heat flux transients by inverse modeling of heat conduction of AISI 1040 steel for different quenching media (brine, water, palm oil and mineral oil). The study identified an effect of workpiece section size and agitation of quenchant media in the heat flux. Higher heat flux values was showed in workpieces with large sections immersed in stirring water.

Totten (2007) describes the results got of heat transfer coefficient during quenching process in water media at 30°C and oil media at 60°C for a cylindrical workpiece with diameter of 25mm and length of 100mm. The heat transfer appear as function of workpiece temperature and a maximum value between 15.000 W/m²K and 20.000W/m²K was got for water media and close to 5.000 W/m²K was got for oil media.

According Wallis (2010) the heat transfer coefficient to evaluate cooling curves or heat flux during quenching process can be determined by two methods. The first method is based in trial and error procedure and the second is based in inverse engineering techniques. Independently of the choice the main idea of both methods is use real data collected by thermocouples inserted in a workpiece as input information. In parallel, the mathematical model predicts the temperature and compares the result with real data collected. A precise heat transfer coefficient is obtained when the difference between predicted temperature and real data collected is small (less than 5°C).

Hassan et. al. (2011) develop a mathematical model by finite volume method to determine the cooling curve during quenching process based in a heat transfer coefficient as a function of surface temperature of the probe. As a result of the heat transfer coefficient a peak of 6000 W/m²K was obtained. The workpiece used in experimental tests to validate a mathematical model had three thermocouple of type k aligned through its radio and distributed in three different position (in the center of piece or radio equal zero, middle of radio or r/2 and close to surface of the piece). The cooling curve got from mathematical model showed good agreement with experimental data and revealed an intensification of cooling rates close to the surface comparing to the center of the piece.

Ramesh and Prabhu (2012) evaluated the effect of size section and heat transfer coefficient during quenching process by numerical simulation. For a body with constant section size an intensification of cooling rate is verified with the heat transfer coefficient enlargement. In the same way the results presented for a constant heat transfer coefficient when the section size was reduced showed an intensification of cooling curve and consequently an increase of cooling rate.

Devynck (2014) developed in conjuction with Vallourec Research Center in France a study in his doutoral thesis concerning of numerical study in quenching process that happens by water jet. As result were verified high thermal gradients in the wall thickness of the pipe.

Recently Singer (2014) calculated the heat transfer coefficient by finite volume method (implicit scheme) during quenching process in water and oil. Measured temperatures close to the workpiece’s surface were used as input data and by inverse engineering techniques, the heat transfer coefficient was calculated. As boundary condition used to calculate this parameter was established first a condition of symmetry in a position of radio equal zero (r=0) and second in the surface (r=R) a boundary condition of third type (heat flux by conduction is equal the heat flux by convection). The initial condition was the temperature of the surface before the immersion of workpiece in the quenching media.

As already described in the literature review the main point of attention in an analysis of heat transfer for quenching process are related to the heat transfer coefficients and the knowledge of this parameter in conjunction with a mathematical model well developed could result in a good agreement of simulation to predict a cooling curve or a rate of cooling during the quenching process. In many works the reliability of mathematical model with experimental tests has shown good results, but this has been just verified in laboratorial environment. This paper is dedicated to present and compare the results got by numerical simulation of cooling curves during quenching in water media of steel pipe with its real results got by an experimental test in an industrial process. Numerical and physical commitments of the model are presented and reveal that an agreement between simulation and tests in industrial environment are also possible.

2 MATHEMATICAL MODEL

The mathematical model developed in this work has as objective to define an unsteady thermal response for a steel pipe in industrial process of heat treatment by quenching in water media. The base of model development consisted in the finite volume method technique. The following considerations was adopted in the mathematical model: (1) Unsteady conduction; (2) One-dimensional heat transfer in radial direction; (3) The initial condition is the pipe temperature before the immersion in quenching process; (4) The heat transfer coefficient between the water and external and internal wall are equal and constant

"Equation (1)" represents the general equation used in each control volume. To use the transient scheme was necessary to use a temperature integration function described by "Eq. (2)," that leave a discretized equation described by "Eq. (3)," in the case of θ=1 (fully implicit scheme) for all the nodes presents in the system with exception of nodes present in boundaries. For this case "Eq. (4)," are applied to get a discretized equation.

$$\int_{t}^{t+\Delta t}\int_{CV}\frac{\partial(\rho T)}{\partial t}dvdt+\int_{t}^{t+\Delta t}\int_{CV}div(\rho UT)dvdt=\int_{t}^{t+\Delta t}\int_{CV}div(kgrad(T))dvdt+\int_{t}^{t+\Delta t}\int_{CV}Sdvdt \tag{1}$$

$$I_T=\int_{t}^{t+\Delta t}T_p\,dt=\Delta t\left[\theta T_p+(1-\theta)T_{p0}\right]. \tag{2}$$

$$a_pT_p=a_WT_W+a_ET_E+a_{p0}T_{P0}\,. \tag{3}$$

$$-k\frac{dt}{dr}=h(T_s-T_\infty) \tag{4}$$

In "Eq. (1)," *ρ, T, U, k,* and *S* represent respectively the steel density (kg/m³), temperature in control volume (°C), flow velocity (m/s), thermal conductivity of steel (W/m.k) and source term. The parameter *θ, Δt,* T_p and T_{P0} show in "Eq. (2) represent: scheme utilized, time step (s), temperature (°C) in the control volume at times t+i (s) and times t (s) respectively. In "Eq. (3) a_p , a_W , a_E and a_{p0} are coefficients of model described for each control volume. About the parameter h, T_s and T_∞ presented in "Eq. (4)," they are heat transfer coefficient (W/m².K) between pipe and water, surface temperature of the pipe (°C) and water temperature (°C) respectively.

3 NUMERICAL SIMULATION (MESH TEST)

The numerical simulation of cooling curve of steel pipe during quenching process was conducted in a pipe of outside diameter (OD) and wall of thickness (e) with four different heat transfer coefficient: 8000W/m².K; 7000W/m².K; 6000W/m²K and 5000W/m²K in a quenching process of water temperature (T∞) and time (t). To guarantee the reliability of simulation with less computational efforts, a mesh test based in this four heat transfer coefficient defined was done with the element as close as possible to the pipe surface. "Figure 1" and "Fig. 2" present the results of a mesh test for heat transfer coefficient of 8000W/m².K, and show that a mesh with 20 elements guarantees reliability of the model to a defined heat transfer coefficient with less possible computational efforts. For the others heat transfer coefficients the mesh test conducted showed the same behavior.

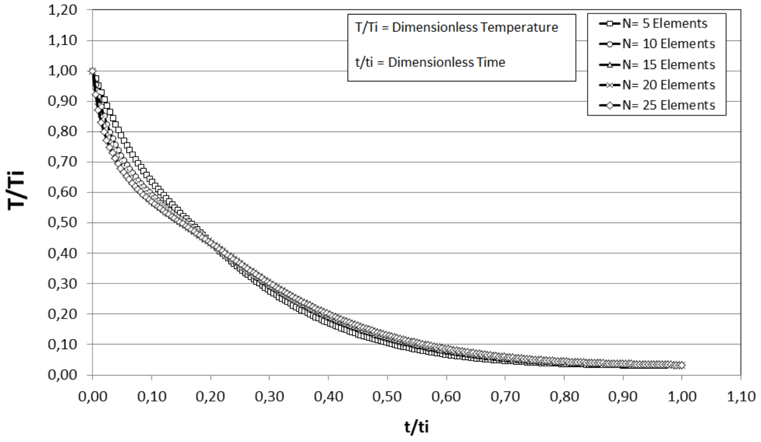


Figure 1. Mesh test of cooling curve (general)

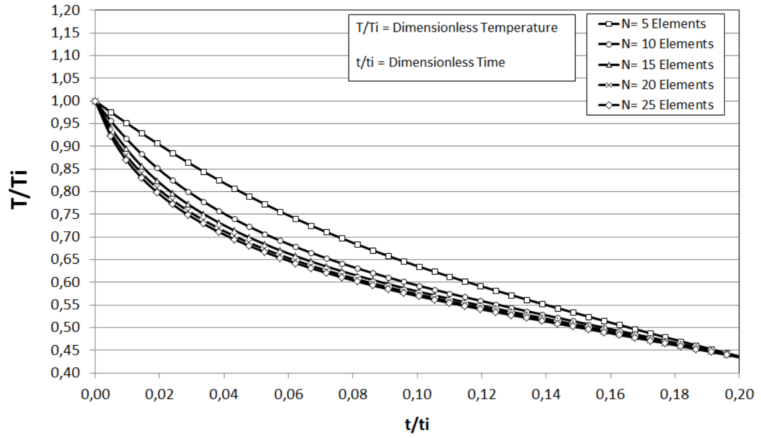


Figure 2. Mesh test of cooling curve (beginning)

4 EXPERIMENTAL TEST

Experimental tests done to compare the trend of cooling curve with the results got by numerical simulation was done in industrial environment (Heat treatment line). The “Fig. 3” shows a schematic of heat treatment line where the experimental tests was conducted. The quenching process happens in water tank when the pipe starts the immersion.

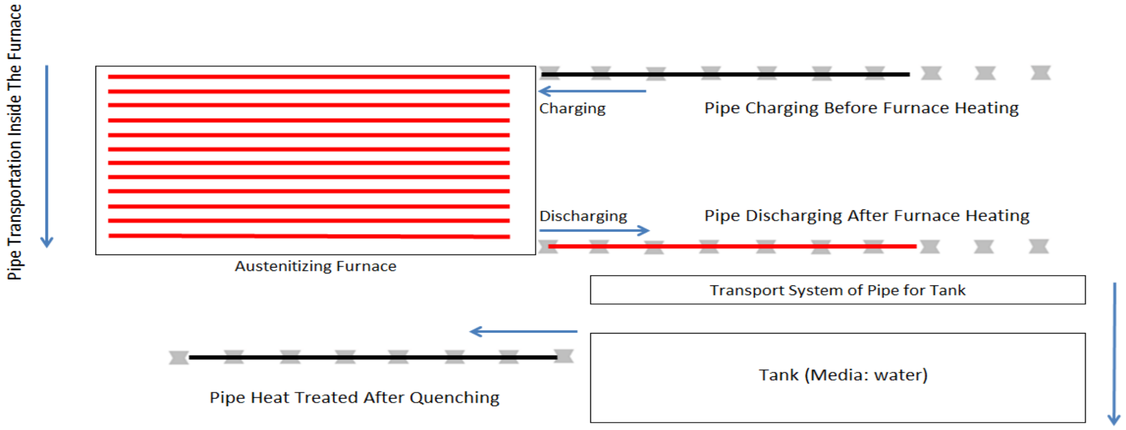
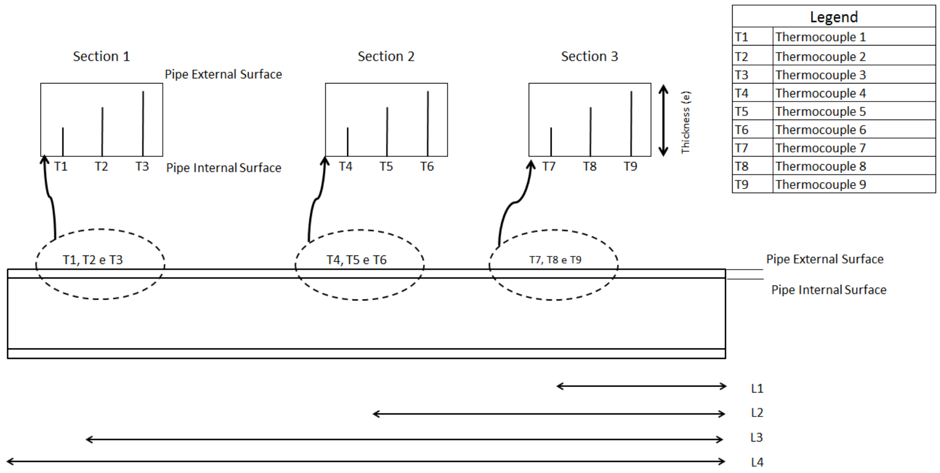


Figure 3. Schematic flow of production in a line of heat treatment (Plant view)

Concerning the experimental test assembly a pipe of outside diameter (OD), wall thickness (e) and length (L) wherein 9 thermocouples of k type, diameter of 1.5mm and mineral insulation were used. The “Fig. 4” presents a schematic assembly used in the experimental test.



Legend	
T1	Thermocouple 1
T2	Thermocouple 2
T3	Thermocouple 3
T4	Thermocouple 4
T5	Thermocouple 5
T6	Thermocouple 6
T7	Thermocouple 7
T8	Thermocouple 8
T9	Thermocouple 9

Figure 4. Schematic pipe assembly used in experimental test

The thermocouple distribution through the pipe occurs in three different length position (L1, L2 and L3) described as section 1, section 2 and section 3 respectively. Through the wall thickness the thermocouple distribution was done in three different positions (close to internal wall, middle of wall and external wall). The system of data acquisition was connected to the thermocouple and the frequency of data acquisition equal 0.2s was employed to got a good temporal response of the process.

"Figure 5" shows the results got (cooling curve): Average dimensionless temperature for each position in the wall thickness through the pipe as function of dimensionless time based in an experimental assembly of the pipe done.

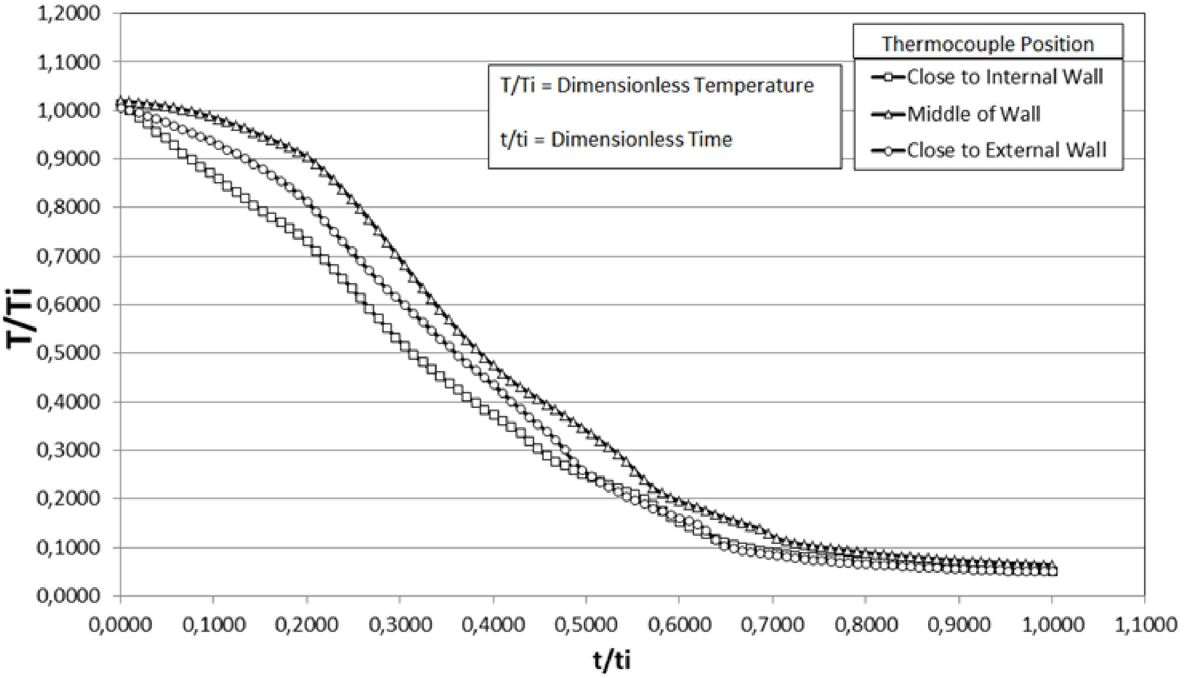


Figure 5. Average Cooling Curve in experimental test

(Thermocouple position: close to external wall, middle of wall and external wall)

5 RESULTS AND DISCUSSION

To compare the accuracy of mathematical model employed with the experimental results as well as the influence of heat transfer coefficient in the process, a numerical simulation of the cooling curve was done for each position of thermocouple located at the wall thickness of pipe (close to internal wall, middle of wall and external wall) in the experimental test. For this situation four values of heat transfer coefficient (8000 W/m²K, 7000 W/m²K, 6000 W/m²K and 5000 W/m².K) were used. The results for a simulated cooling curve in a position of the wall thickness and its respectively average cooling curve along the pipe length got in experimental test are presented in “Fig. 6”, “Fig. 7”and “Fig. 8”. The result shows a good stability of numerical model.

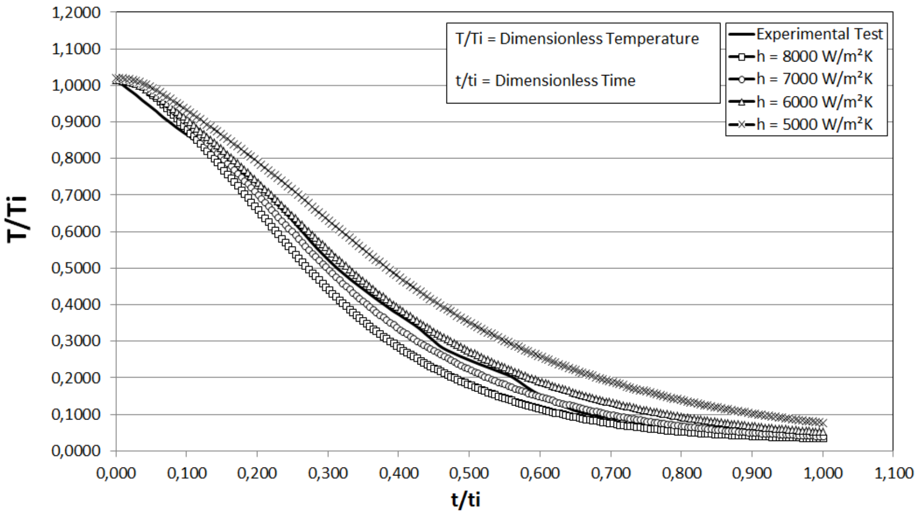


Figure 6. Cooling curve numerical simulation x experimental test (Internal wall)

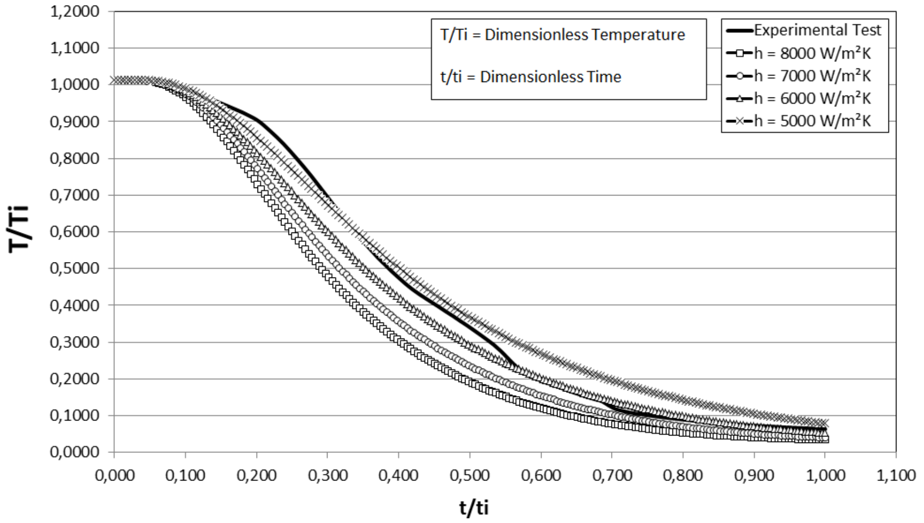


Figure 7. Cooling curve numerical simulation x experimental test (Middle of wall)

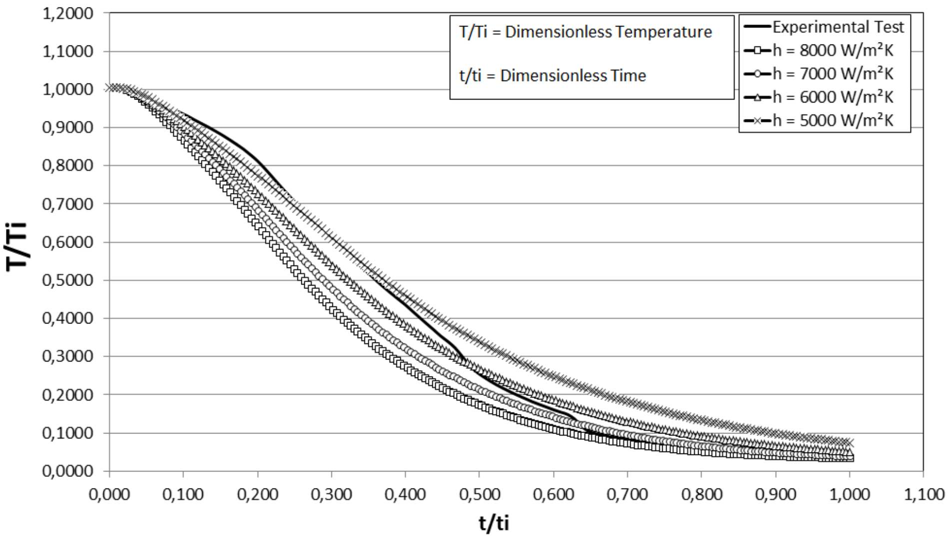


Figure 8. Cooling curve numerical simulation x experimental test (External wall)

According with "Fig. 6", "Fig. 7"and "Fig. 8", the place of cooling curve evaluation in the wall as well as the influence of heat transfer coefficient in the comparison between numerical simulation and experimental test are easily seen. The results showed that points closed to the internal wall and external wall presented a cooling curve or rate of cooling curve more intensified than a place located at the middle of pipe wall. In the other hand the choice of heat transfer coefficient in numerical simulation is correlated with the accuracy of model. Results showed that a heat transfer coefficient of 6000 W/m²k used in numerical simulation obtained the best fit when compared with experimental test. "Figure 9" shows that an absolute true error for a numerical simulation with this coefficient presenting an error less than 20% up to a dimensionless time equal to 0,6 when compared with experimental cooling curve obtained at points in internal, middle and external wall of steel pipe.

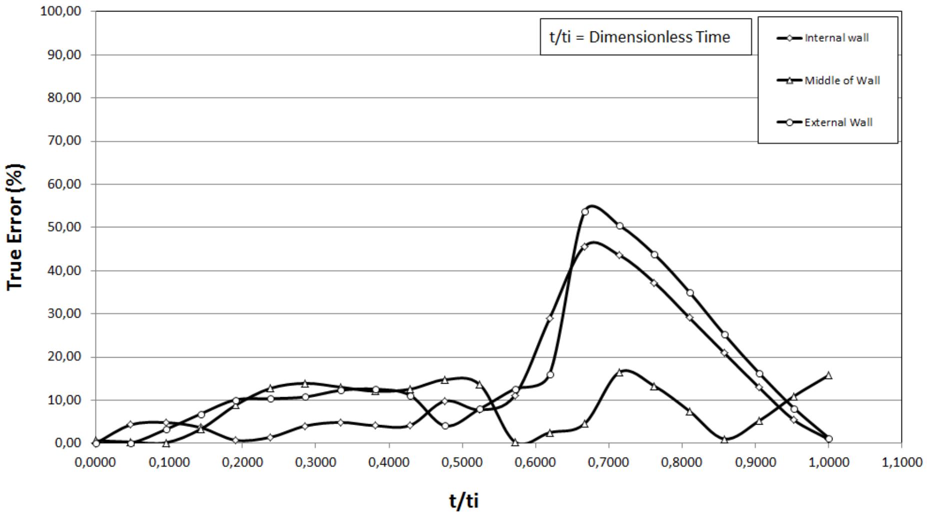


Figure 9. Relative true error - numerical simulation (6000 W/m²K) x experimental result

6 CONCLUSION

This work presented a mathematical model to predict a cooling curve of pipe in an industrial process of heat treatment more precisely a quenching process. With an objective to guarantee the accuracy of simulation with less computational efforts a mesh test was done. The number of 20 elements was verified as a good mesh to got accuracy in the model. The fully implicit scheme used in the mathematical model showed a good stability. A trend of cooling curve between numerical simulation and mathematical model was verified as well as the influence of the heat transfer coefficient in the process. Heat transfer coefficient equal to 6000 W/m²K has shown the best results between numerical simulation and experimental test. An absolute true error less than 20% was got to a dimensionless time up to 0,6 and an absolute error higher than 20% has been got for a dimensionless time in the range of 0,6 and 0,9.

In general lines, the mathematical model developed proved to be very consistent with the physics of the process although a constant heat transfer coefficient has been used. A definition of heat transfer coefficient as a function of quenching process variables could reveal an accuracy model to predict a cooling curve and the cooling rate present in the process extremely close to the real industrial process. As consequence a heat treatment engineer could simulate many situations avoiding experimental tests in order to save money and time.

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