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INFLUENCE OF DIFFERENT BOUNDARY CONDITIONS ON COOLING OF STEELS

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ABSTRACT

Metallic materials, especially steels, are undertaken to different heat treatment processes in industry. For these processes, cooling times should be determined. However, physical properties of these materials depend very strongly on temperature, and therefore, the dependence of physical properties should be taken into consideration while solving the governing differential equations for non-steady cases. In this study, the necessary physical properties of materials are gathered from literature and expressed as equations to use in the numerical calculations

ÖZET

Metalik malzemeler, özellikle çelikler endüstride farklı ısıl işlem proseslerine tabi olurlar. Bunlar için soğutma zamanlarının bilinmesi gerekir. Ancak bu malzemelerin fiziksel özellikleri sıcaklıkla değişmektedir ve bu yüzden diferansiyel denklemleri çözerken bu değişim göz önünde bulundurulmalıdır. Malzemelerin ilgili fiziksel özellikleri literatürden toplanmış ve sayısal hesaplamalarda kullanılmak üzere denklemler halinde ifade edilmiştir.

Bu çalışmada, çeliklerin soğutulmasındaki çeşitli sınır şartları ve bunların etkileri incelenmiştir. Diskretizasyon denklemleri iligili diferansiyel denklem ve sınır şartları için yazılmış ve iteratif olarak çözülmüştür. Sayısal hesaplamalardan elde edilen sonuçlar, çeşitli çelikler için, grafikler halinde verilmiş, çeşitli sınır şartları için elde edilen sonuçlar tartışılmıştır

1. INTRODUCTION

Even if the metallic materials have high thermal conductivity, it is not possible to assume constant temperature profile within the material especially for fast heat treatment processes like quenching. Therefore energy equation must be solved without the assumption of constant temperature profile within the material even for materials having very high thermal conductivity.

In recent years, the growing interest to low cost and better materials are well known. Therefore, theoretical calculation of thermal material processing with realistic assumptions, which means taking the different boundary conditions and temperature dependent properties into consideration and appropriate methods, has become a great need

2. THEORETICAL WORK

2.1. Differential equations

Fourier differential equation is written for the temperature distribution in the material as follows (Gebhart, 1993; Çengel, 1998; Yılmaz 1999);

$$\rho c \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r k \frac{\partial T}{\partial r} \right) \tag{1}$$

where ρ, c, k, respectively, are density, specific heat capacity and conductivity of the material. With the definitions of the parameters below,

$$\rho^* = \rho / \rho_o \tag{2}$$

$$c^* = c / c_o \tag{3}$$

$$k^* = k / k_o \tag{4}$$

$$r^* = r / R \tag{5}$$

$$t^* = \frac{a_o . t}{R^2} \tag{6}$$

$$a^* = \frac{a}{a_o} \tag{7}$$

$$\theta = \frac{T - T_f}{T_i - T_f} = \frac{T - T_f}{\Delta T_f} \tag{8}$$

where T_i and T_f are initial and fluid temperatures, respectively; differential equation (3.1) takes the form of equation (9).

$$\frac{\rho^* c^*}{k^*}\frac{\partial \theta}{\partial t^*} = \frac{\partial^2 \theta}{\partial r^{*2}} + \left(\frac{1}{r^*} + \frac{1}{k^*}\frac{\partial k^*}{\partial r^*} \right)\frac{\partial \theta}{\partial r^*} \tag{9}$$

In the equations given above, ρ_o, c_o, k_o and a_o are, respectively, density, specific heat, thermal conductivity and thermal diffusivity of the material at a reference temperature T_o. Equation (9) can also be written as follows:

$$\frac{1}{a^*}\frac{\partial\theta}{\partial t^*}=\frac{\partial^2\theta}{\partial r^{*2}}+\left(\frac{1}{r^*}+\frac{1}{k^*}\frac{\partial k^*}{\partial r^*}\right)\frac{\partial\theta}{\partial r^*} \quad (10)$$

2.2. Initial and boundary conditions

Initial and boundary conditions are needed to solve differential equation (10). The initial conditions are:

$$t=0 \;:\; T=T_i \quad (13)$$

$$t^*=0 \;:\; \theta=1 \quad (14)$$

Equations (15) and (16) can be written at the centre of the cylindrical material, because of the uniform cooling from the cylindrical surface:

$$r=0 \;:\; \frac{\partial T}{\partial r}=0 \quad (15)$$

$$r^*=0 \;:\; \frac{\partial\theta}{\partial r^*}=0 \;;\; \frac{\partial k^*}{\partial r^*}=0 \quad (16)$$

In addition, the conditions given by equations (17) and (18) can be written at the surface of the cylindrical material for convective cooling including radiation:

$$r=R \;:\; -k\left.\frac{\partial T}{\partial r}\right|_{r=R}=h\left(T_s-T_f\right) \quad (17)$$

$$r^*=1 \;:\; k^*\frac{\partial\theta}{\partial r^*}=-Bi\left(\theta-\theta_f\right) \quad (18)$$

In equations (17) and (18), h is convective heat transfer coefficient including radiation between the surface of the cylindrical material and ambient fluid at temperature T_f. T_s is the temperature at the cylinder surface. Bi is Biot number and, it is defined as:

$$Bi=\frac{h.R}{k_o} \quad (19)$$

2.3. Heat transfer coefficient *h*

Total heat transfer coefficient can be written in the form of (Yılmaz, 2004);

$$h=\left(h_U^3+h_F^3\right)^{1/3}+h_R \quad (20)$$

where h_U, h_F and h_R are mean forced convective, free convective and radiative heat transfer coefficients, respectively. Free convective heat transfer coefficient h_F can be calculated by the equations below, if Rayleigh number is not too low (Yılmaz, 2004):

$$h_F=A_F\,k\left[\frac{g}{\nu^2}\beta\left(T_s-T_f\right)\mathrm{Pr}\right]^{1/3} \quad (21)$$

$$h_F=A_F\,k\left[\frac{g}{\nu^2}\beta\Delta T_f\,\mathrm{Pr}\right]^{1/3}\left(\frac{T_s-T_f}{\Delta T_f}\right)^{1/3} \quad (22)$$

$$h_F=h_{oF}\,\theta_s^{1/3} \quad (23)$$

where h_{oF} and θ_s are defined as follows:

$$h_{oF}=A_F\,k\left[\frac{g}{\nu^2}\beta\Delta T_f\,\mathrm{Pr}\right]^{1/3} \quad (24)$$

$$\theta_s=\frac{T_s-T_f}{\Delta T_f} \quad (25)$$

In the above equations, the value of A_F is not constant. Instead, it changes between 0.1 and 0.2 at the moderate values of Ra, which would occur for the cylinders investigated. An appropriate A_F value of 0.13, which is similar to the value of turbulent free convection at vertical surfaces (Yılmaz, 1999), was used in the calculations.

Using the definition of h_{oF} given in eq. (24), one can write the following equation for Biot number for free convective heat transfer;

$$BIF=\frac{h_{oF}\,R}{k_o} \quad (26)$$

and similarly, Biot number for forced convective heat transfer is defined as follows:

$$BIU=\frac{h_U\,R}{k_o} \quad (27)$$

Forced convective heat transfer coefficient h_U was assumed constant. Heat transfer coefficient for radiative heat transfer can be written in the form of the equation below (Yılmaz, 1999);

$$h_R=4\,\varepsilon\,\sigma\,T_{Af}^3\,f_x \quad (28)$$

where ε and σ are emissivity of the cylinder and black body coefficient of the cylindrical material, respectively. T_{Af} is absolute fluid temperature. Equation (28) can be rewritten in a more general form as follows;

$$h_R=h_{oR}\,f_x \quad (29)$$

where h_{oR} and f_x are defined in the following equations, respectively;

$$h_{oR}=4\,\varepsilon\,\sigma\,T_{Af}^3 \quad (30)$$

$$f_x=\left(1+XT+XT^2+XT^3\right)/4 \quad (31)$$

where XT is defined as follows;

$$XT=\frac{T_{As}}{T_{Af}}=1+\theta_s\,\Delta T_f^* \quad (32)$$

where ΔT_f^* can be written in the form of the following equation.

$$\Delta T_f^*=\frac{\Delta T_f}{T_{Af}}=\frac{\Delta T_f}{T_f+273} \quad (33)$$

One can define a Biot number for radiaitve heat transfer with the definitions above:

$$BIR=\frac{h_{oR}\,R}{k_o} \quad (34)$$

From equations (19) and (20), it follows:

$$BIR = \frac{hR}{k_o} = \frac{\left|\left(h_U^3 + h_F^3\right)^{1/3} + h_R\right|R}{k_o} \quad (35)$$

Using equations (23), (26), (27), (29), (34) and (38), an overall Biot number is written as:

$$Bi = \left(BIU^3 + BIF^3\theta_s\right)^{1/3} + BIR\, f_x \quad (36)$$

3. RESULTS AND DISCUSSION

In figures 1, 2 and 3, variation of center temperature with time for ANSI 1025 steel at various forced convective heat transfer boundary conditions are given. In figures 4 and 5, it is seen that radiative heat transfer do have a much more influence than free convective heat transfer. Cylindrical material needs much more time to cool off when it is just exposed to free convection rather than it is exposed just to radiation. Cooling time is decreased a little bit if both free convective and radiative heat transfer are encountered which is shown in figure 6. Comparison among figures 1 and 5 shows that radiation heat transfer is also dominant over forced convection at low heat transfer coefficient (h_u=10).

In figure 7, variation of center temperature with time for ANSI 1025 steel at forced convective and radiative heat transfer boundary condition are given. In figure 8, all three modes of heat transfer, namely forced and free convection and radiation take place. It is seen that the decrease in cooling time of center temperatures is nearly the same decrease encountered in coupled forced convection and radiation (figure 7). This behaviour is well expected, because two other modes of heat transfer have a dominating influence over free convection.

Comparison of cooling curves of ANSI 1025 steel for center temperatures under various heat transfer boundary conditions with certain forced convective heat transfer coefficients are given for h_u=0, h_u=10 and h_u=100 in figures 8, 9 and 10, respectively.

In these figures, variation of center temperature as a function of time under various heat transfer boundary conditions at a certain hu are given. In these figures, all curves are drawn according to the calculations conducted for its particular boundary condition for ANSI 1025 steel with variable physical properties. Forced convective heat transfer coefficient (hu) is used as parameter and it is increased from 0 to 100 in order to thoroughly grasp the heat transfer process that takes place. To get a better insight to the process, free convective and radiative heat transfer boundary conditions are also coupled with forced convection.

In figure 8, there is no forced convection (h_u=0). Comparison of the curves in these figures shows the dominant influence of radiation over free convection. Cooling time is decreased by a factor of 4 with coupled radiation and free convection.

Curves can be grouped into two in figures 8 and 9 which are sketched for h_u=0 and h_u=10. These two groups can be categorized as "radiation involved" and "radiation not involved" groups. It is observed that when radiation is involved in heat transfer process, cooling time is decreased by a factor of 3 and free convection does have nearly no effect on cooling if forced convection and radiation occur in the same process, which can be seen from the rapidly cooled curves in these figures.

Comparison of figures 8 and 9 shows that forced convection does not have a big effect on cooling with h_u=10.

4. CONCLUSIONS AND RECOMMENDATIONS

Cooling of cylindrical iron and steel materials under various boundary conditions is investigated in this work. Although there have been several research in this field, these were either carried out for limited boundary conditions or did not account for the variations in physical properties of materials in interest.

Results of this study show that there is no effect of free convection on heat transfer mechanism if there is high forced convection h_u=100. Another thing that can be concluded from this study is that, free convection is nearly negligible compared to the other two heat transfer mechanisms, which is well expected.

Results obtained shows the importance of radiative heat transfer boundary condition which should not be neglected while making the calculations for ANSI 1025 steel as in the case for pure iron and various other steels (Yilmaz et. Al., 2005). One can conclude that free convective heat transfer boundary condition can be neglected if the other two modes are present in heat transfer process for cooling of steels.

5. NOMENCLATURE

Bi	Biot number
T	temperature
r	radius, radial direction
a	thermal diffusivity
c	specific heat
g	gravitational acceleration
h	convective heat transfer coefficient
k	thermal conductivity
t	time
R	radius
Pr	Prandtl number

Greek letters

ε	emissivity
ν	viscosity

σ	Stefan-Boltzman constant
∂	partial derivative
θ	dimensionless temperature
Δ	difference
β	constant in Grashof number
ρ	density

Subscripts

a	ambient
c	center
o	at 20 C; ambient
f	fluid
F	free convection
R	surface, radiation
s	surface
OF	at free convective heat transfer boundary condition
OR	at radiative heat transfer boundary condition
U	forced convection

Superscripts

*	dimensionless
o	degree
n	constant

Abbreviations

AISI	American iron and steel institute
ANSI	American national standards institute
XT	a term in differential eq. (3.31), defined by eq. (3.32)

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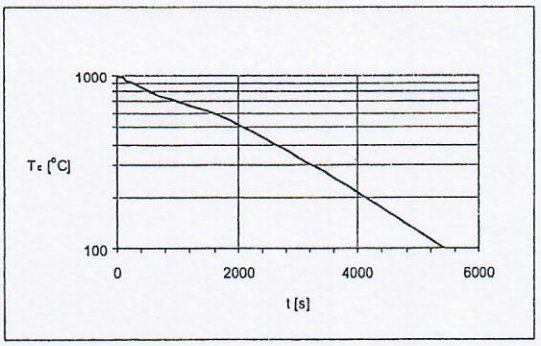


Fig. 1. Variation of center temperature with time for ANSI 1025 steel at forced convective heat transfer boundary condition (hU=10, hOF=0, hOR=0)

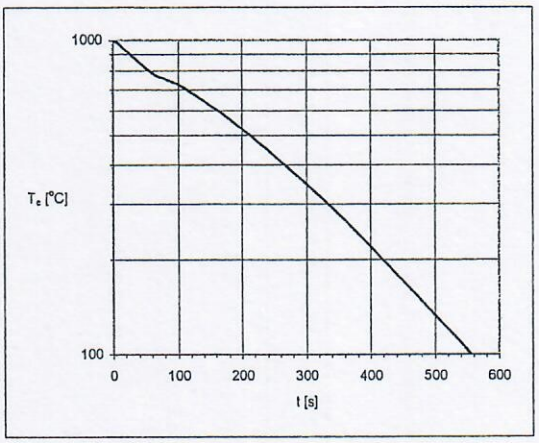


Fig. 2. Variation of center temperature with time for ANSI 1025 steel at forced convective heat transfer boundary condition (hU=100, hOF=0, hOR=0)

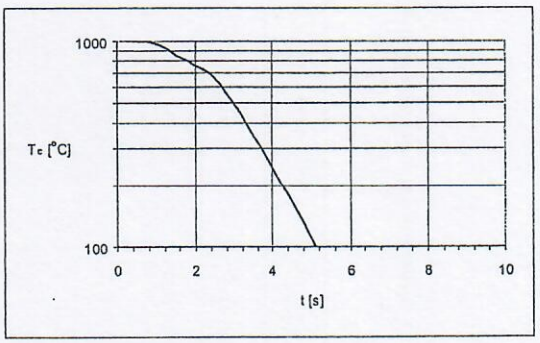


Fig. 3. Variation of center temperature with time for ANSI 1025 steel at forced convective heat transfer boundary condition (hU=100000, hOF=0, hOR=0)

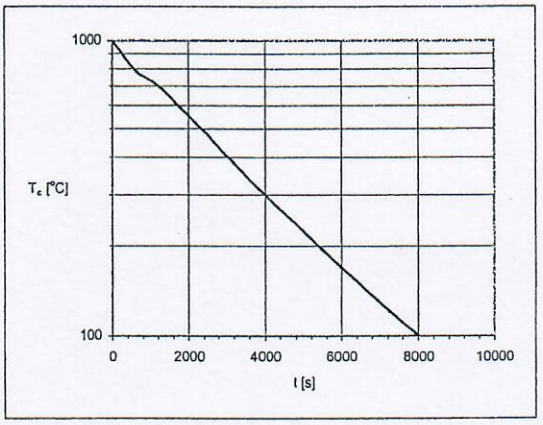


Fig. 4. Variation of center temperature with time for ANSI 1025 steel at free convective heat transfer boundary condition (hOF=10, hU=0, hOR=0)

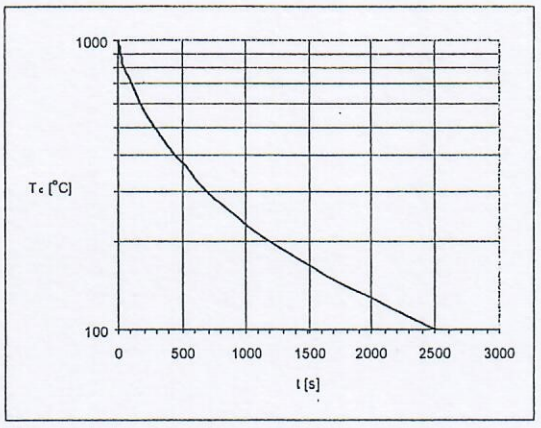


Fig. 5. Variation of center temperature with time for ANSI 1025 steel at radiative heat transfer boundary condition (hOR=5, hU=0, hOF=0)

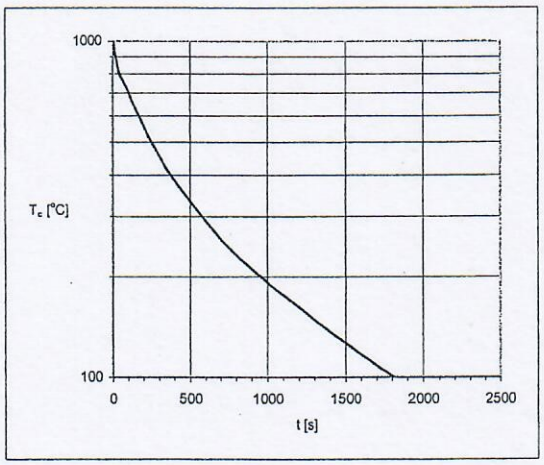


Fig. 6 Variation of center temperature with time for ANSI 1025 steel at free convective and radiative heat transfer boundary condition (hOF=10; hOR=5, hU=0)

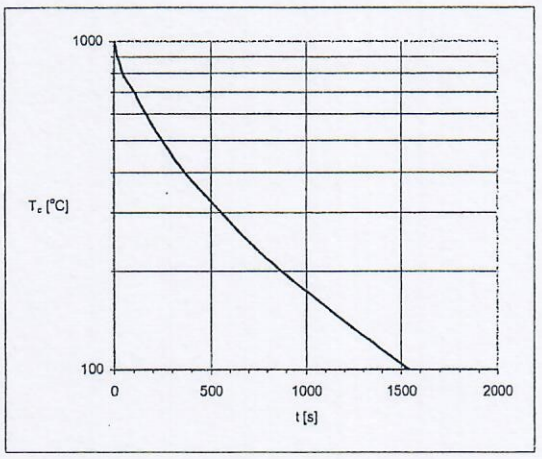


Fig. 7. Variation of center temperature with time for ANSI 1025 steel at forced convective and radiative heat transfer boundary condition (hU=10; hOR=5, hOF=0)

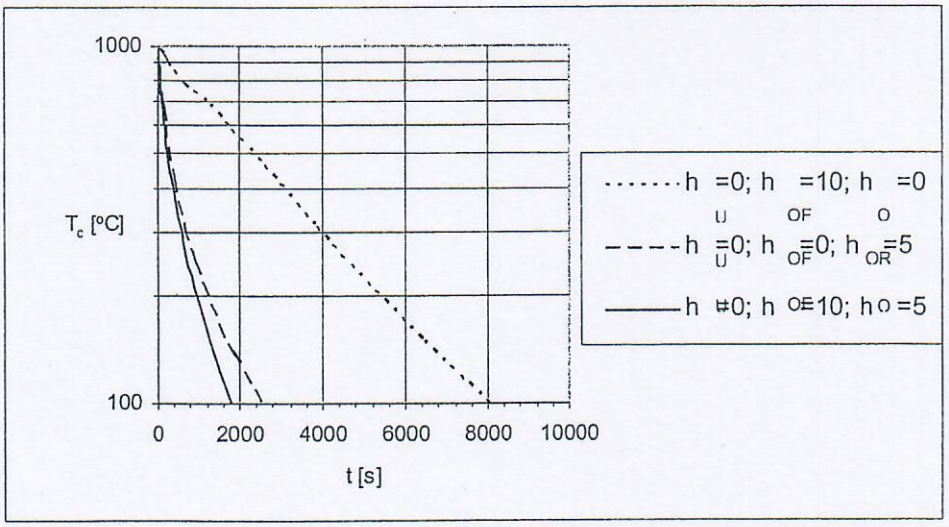


Fig. 8. Comparison of cooling curves of ANSI 1025 steel for center temperature under various heat transfer boundary conditions (hU=0)

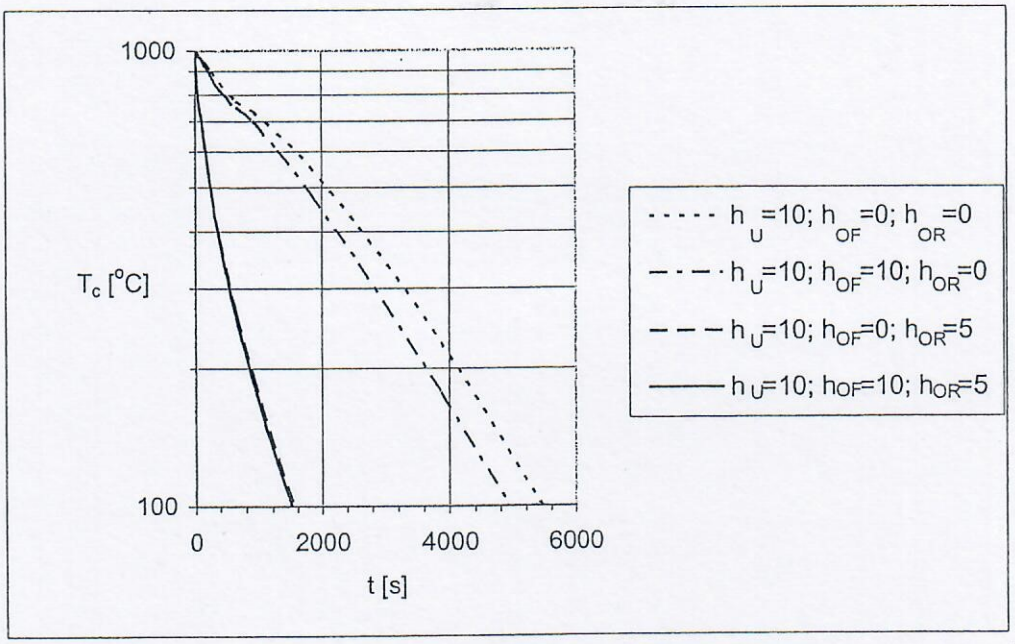


Fig. 9. Comparison of cooling curves of ANSI 1025 steel for center temperature under various heat transfer boundary conditions (hU=10)

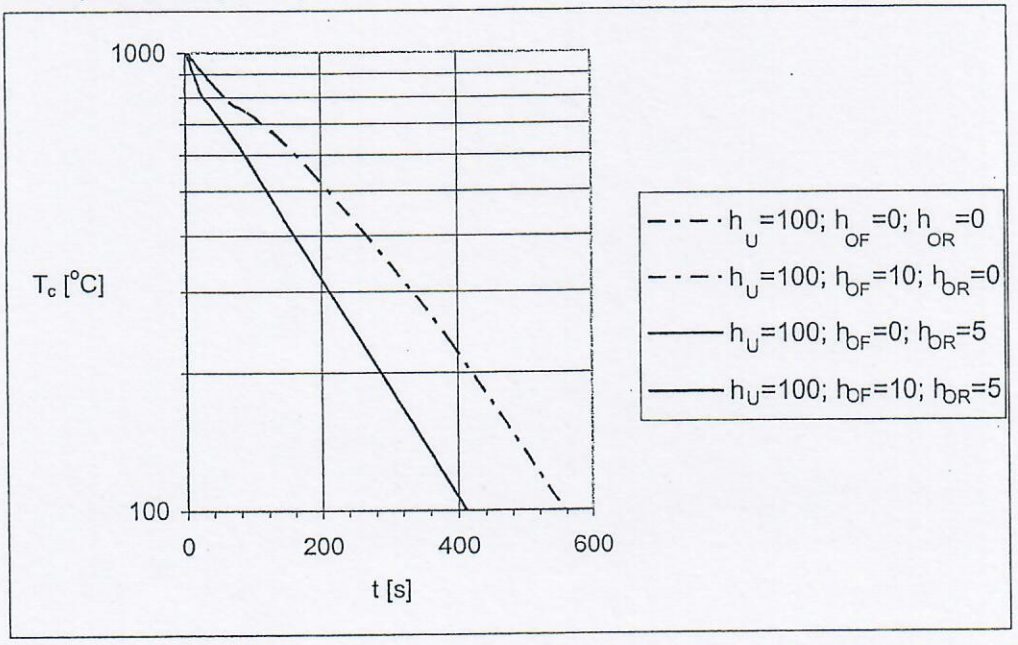


Fig. 10. Comparison of cooling curves of ANSI 1025 steel for center temperature under various heat transfer boundary conditions (hU=100)