INFLUENCE OF DIFFERENT BOUNDARY CONDITIONS AND VARIABLE PHYSICAL PROPERTIES ON METAL'S HEATING AND COOLING

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ABSTRACT

In the process of heat treatment of metals, generally, the dependency of physical properties of metals on the temperature is neglected. Besides this, very simple convective heat transfer boundary condition is assumed in performing the calculations.

In this work, Fourier differential equations are solved for heating and cooling using general boundary conditions which take forced convective, free convective and radiative heat transfer into account. The physical properties, namely, density, thermal conductivity and specific heat of pure iron are described as a function of temperature.

The results obtained with variable physical properties show significant deviations from the results which are obtained using constant material properties.

Keywords: metals, heating, cooling, convection, radiation, variable physical properties

METALLERİN ISITILMASI VE SOĞUTULMASINA ÇEŞİTLİ SINIR ŞARTLARI VE DEĞİŞKEN FİZİKSEL ÖZELLİKLERİN ETKİSİ

ÖZ

Isıl işlemlerde metallerin fiziksel özelliklerinin sıcaklığın fonksiyonu olduğu genelde göz önünde bulundurulmaz. Bunun yanında, hesapların yapılmasında çok basit konvektif ısı transferi sınır koşulu kabul edilir.

Bu çalışmada, zorlanmış ve serbest konveksiyonun yanı sıra, radyasyonla ısı transferini de içine alan genel sınır koşullarında Fourier diferansiyel denklemleri ısıtma ve soğutma için çözülmüştür. Yoğunluk, ısı iletim katsayısı ve özgül ısı gibi demirin fiziksel özellikleri sıcaklığın fonksiyonu olarak hesaplanmışlardır.

Demirin sıcaklığa bağlı fiziksel özellikleri göz önünde bulundurularak elde edilen sonuçlar ile sabit materyal özellikleri kabul edilerek bulunan sonuçlar arasında önemli farklılıkların olduğu gözlemlenmiştir.

Anahtar kelimeler: Metaller, ısıtma, soğutma, konveksiyon, radyasyon, değişken fiziksel özellikler

1. INTRODUCTION

Metals are still the most used material in industry. Metals and especially iron are undertaken to heat treatment such as quenching and hardening. For these purposes they should be heated up or cooled down. The heating and cooling processes should be correctly calculated.

Heating and cooling of bodies are calculated normally assuming constant physical properties and forced convection boundary conditions. For this case and simple regular bodies such as infinitely long cylinder, plain plate and sphere, diagrams are used to determine heat transferred and mean, surface and centre temperatures [1,2]. For arbitrary shaped bodies different methods are suggested. The method of Yılmaz [3,4] allows calculation of the temperature profile in the central part of the body, besides mean, surface and centre temperatures. In this work, heat transfer in a infinitely long cylinder was investigated with temperature dependent physical properties and different boundary conditions.

2. DIFFERENTIAL EQUATIONS AND BOUNDARY CONDITIONS

Fourier differential equation can be written for homogeneous cylinder in the following form:

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

where ρ, c and k are density, specific heat and thermal conductivity of the material, respectively. T is the temperature. t and r are time and radial coordinate, respectively. Eq. (1) can be rearranged as

$$\frac{1}{a}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial r^2} + \frac{\partial T}{\partial r}\left(\frac{1}{r} + \frac{1}{k}\frac{\partial k}{\partial r}\right) \tag{2}$$

Here, a is thermal diffusivity of the material.

Initial and boundary conditions are needed to solve differential equation (2). The initial condition is:

$$t = 0 \quad : \qquad T = T_i \tag{3}$$

One can assume homogeneous material and the same boundary condition is valid on the whole surface of the cylinder. Equation (4) can be written at the centre of the cylindrical material because of the uniform cooling from the cylindrical surface:

$$r = 0 \quad : \qquad \frac{\partial T}{\partial r} = 0 \tag{4}$$

At the cylinder surface, heat is transferred between the surface of the cylinder and the ambient. If h is designated as the total heat transfer coefficient including forced and free convective and radiative heat transfer, then one can write

$$r = R \quad : \qquad -k\left.\frac{\partial T}{\partial r}\right|_{r=R} = h\left(T_s - T_f\right) \tag{5}$$

where T_f is the ambient fluid temperature, T_s is the temperature at the cylinder surface. R is the radius and d is the diameter of the cylinder.

Total heat transfer coefficient can be written in the form of;

$$h = h_C + h_R \tag{6}$$

where h_C and h_R are mean convective and radiative heat transfer coefficients, respectively. Convective heat transfer coefficient can be found from [5],

$$h_C = \left(h_{FC}^3 + h_{NC}^3\right)^{1/3} \tag{7}$$

where h_{FC} and h_{NC} are mean forced and natural convective heat transfer coeffcients, respectively. Ambient fluid temperature is assumed constant, therefore h_{FC} is independent of temperature and can be determined easily. However natural convective and radiative heat transfer coefficients are

dependent on wall temperature and therefore, they should be calculated dependent on the temperature. Natural convective heat transfer coefficient can approximately be calculated by the equation below [6],

$$h_{NC} = 0.15 k_f \left(\frac{g/\nu^2 \beta_T (T_w - T_f)\mathrm{Pr}}{\left[1+(0.559/\mathrm{Pr})^{9/16}\right]^{16/9}} \right)^{1/3} \tag{8}$$

in which Pr number is constant and a physical property of the fluid. Radiative heat transfer coefficient is determined from the following equation [1],

$$h_R = 0.2268 \varepsilon_c (T_f/100)^3 f_T \tag{9}$$

In this equation, f_T is a temperature factor and it is defined as follows:

$$f_T = (1 + x + x^2 + x^3)/4 \tag{10}$$

where x is the temperature ratio and it is given below:

$$x = T_w / T_f \tag{11}$$

In equations (9) and (11), temperatures should be written in terms of Kelvin temperature scale.

3. TEMPERATURE DEPENDENCY OF THE PHYSICAL PROPERTIES OF PURE IRON

Pure iron is one of the commonly used materials in application and therefore, one needs the physical properties ρ, c and k of this material. Physical property data which are gathered from literature should be converted into equations to give specific values for any temperature for numerical calculations. Equations that relate specific data of pure iron were derived below from the data in literature [7,8,9].

3.1. Specific heat

Specific heats of pure iron can be described using the following equations:

$$c_{01} = 445 + 0.4(T - 20) \qquad T < 535 \tag{12}$$

$$c_{12} = 660 + 2(T - 535) \qquad 535 < T < 690 \tag{13}$$

$$c_{23} = c_2 = c_3 = 970 \qquad 690 < T < 765 \tag{14}$$

$$c_{34} = 970 - 2.5(T - 765) \qquad 765 < T < 915 \tag{15}$$

$$c_{4i} = 595 + 0.19(T - 915) \qquad T > 915 \tag{16}$$

3.2. Conductivity

Conductivity of pure iron can be determined through the equations below:

$$k = \left(k_{01}^{3.5} + k_{1i}^{3.5}\right)^{1/3.5} \tag{19}$$

3.3. Density

Density of iron can be calculated approximately by the equations below [10],

$$\rho = 7876 - 0.34T \qquad T < 910\,^{o}C \tag{20}$$

$$\rho = 8100 - 0.51T \qquad T > 910\,^{o}C \tag{21}$$

Because the temperature dependency of density is not very strong, one can use the same equations for other metals.

4. CALCULATION PROCEDURE

Discretization equations were written in the finite difference form for the governing differential equation (2) and the initial and boundary conditions (eqs. 3-5). Taylor series was utilized to calculate the terms in these equations. A Fortran computer program was developed to solve them iteratively for pure iron. The results from the numerical calculations are presented in the form of graphs for pure iron with and without neglecting variable physical properties.

5. RESULTS

In the calculations, fluid temperature T_f and reference temperature T_o were taken as $20\,^{o}C$, where as the cylindrical material has a uniform initial temperature of $1000\,^{o}C$. Emissivity and diameter of the cylinder material was assumed to be 0.8 and 20 mm, respectively. Variation of center and surface temperatures with time is given, respectively in Figures 1 and 2 for $h_{FC} = 100000$ (water under subcooled bubbly boiling). Forced convection and radiation were neglected in the calculations. Figures show both constant property and variable property results.

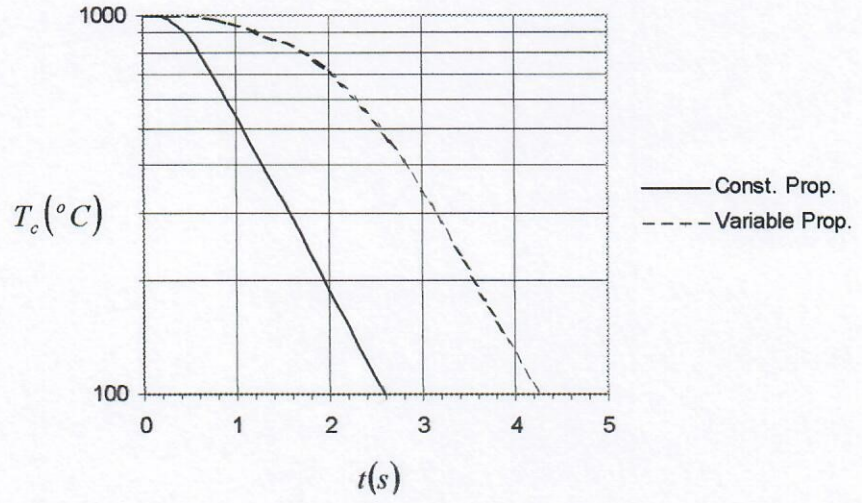


Fig. 1. Variation of center temperature with time for pure iron under forced convective heat transfer boundary condition (h_{FC} =100000)

As can be seen from Figure 1, the difference between the constant property and variable property results is significant. However, the difference is not so big in the case of surface temperature (Figure 2). The results obtained with constant properties should be used with caution.

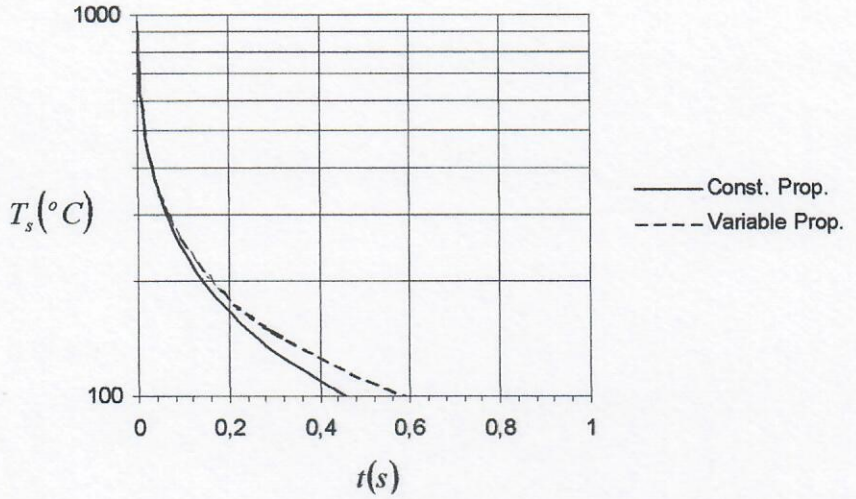


Fig. 2. Variation of surface temperature with time for pure iron under forced convective heat transfer boundary condition (h_{FC} =100000)

In figures 3 and 4, center and surface temperatures as a function of time for $h_{FC} = 2000$ (water, approximately with 1 m/s velocity) are demonstrated. In these figures, free convection and radiation were also neglected. Difference between the constant property and variable property results is again evident from the figures.

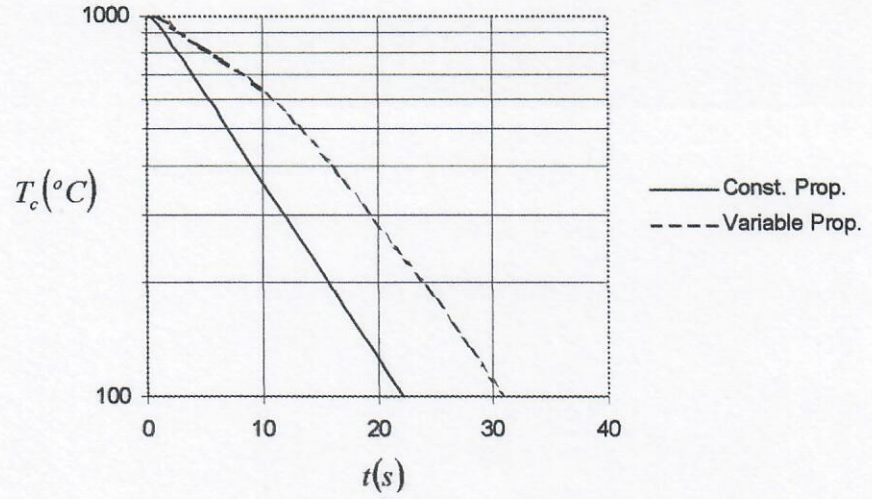


Fig. 3. Variation of center temperature with time for pure iron under forced convective heat transfer boundary condition (h_{FC} =2000)

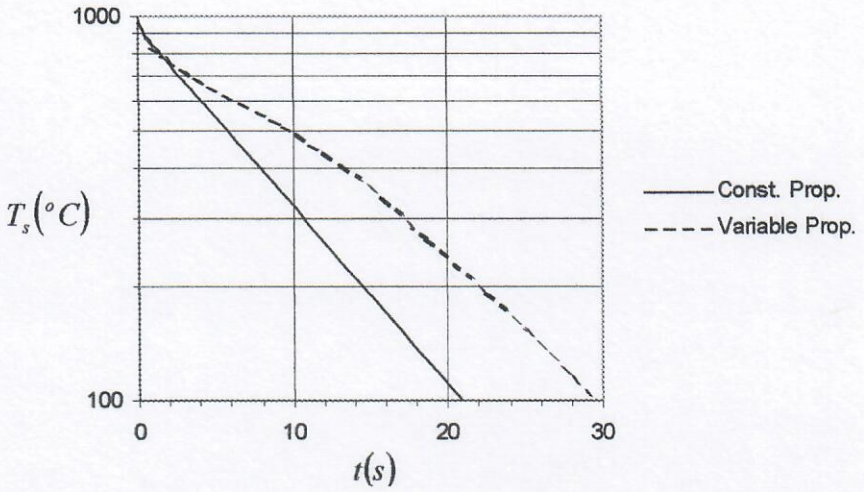


Fig. 4. Variation of surface temperature with time for pure iron under forced convective heat transfer boundary condition (h_{FC} =2000)

Center and surface temperatures of a cylinder with a forced convective heat transfer coefficient of $h_{FC} = 100$ (air, approximately with 10 m/s velocity) are sketched in figures 5 and 6 as a function of time, neglecting free convective and radiative heat transfer coefficients. One can see significant differences between the variable and constant physical property cases.

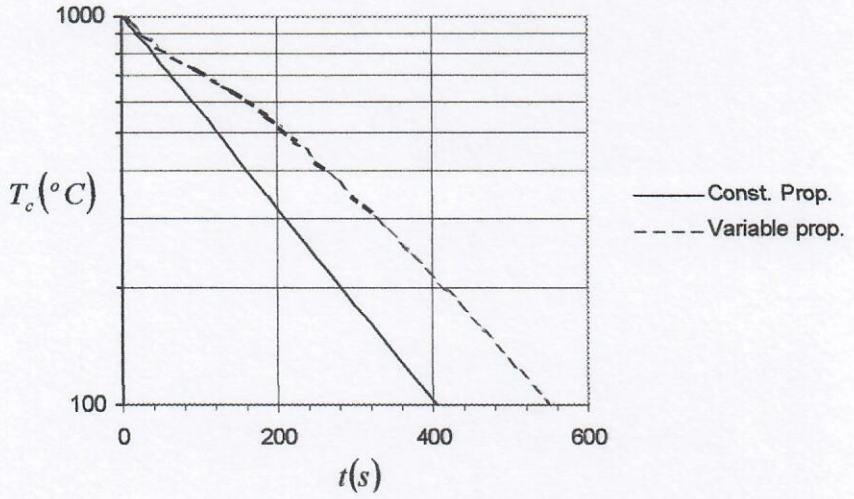


Fig. 5. Variation of center temperature with time for pure iron under forced convective heat transfer boundary condition (h_{FC} =100)

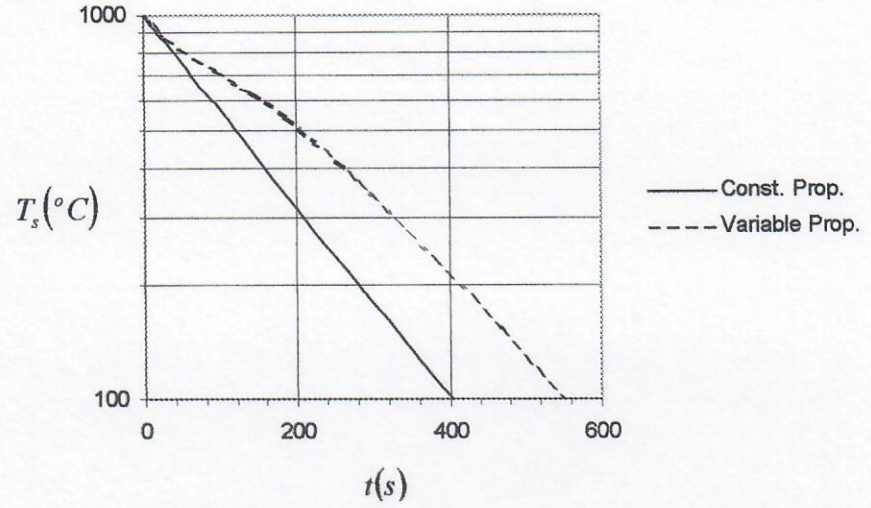


Fig. 6. Variation of surface temperature with time for pure iron under free convective heat transfer boundary condition (h_{FC} =100)

In figures 7 and 8, free convective boundary condition is taken into consideration neglecting the other transfer mechanisms (forced convection and radiation).

A clear difference between the results for center and surface temperatures obtained with constant and variable properties can be seen from figures 7 and 8. It is observed that cooling the pure iron from 1000 ^oC down to 100 ^oC needs more than 80 minutes under these conditions.

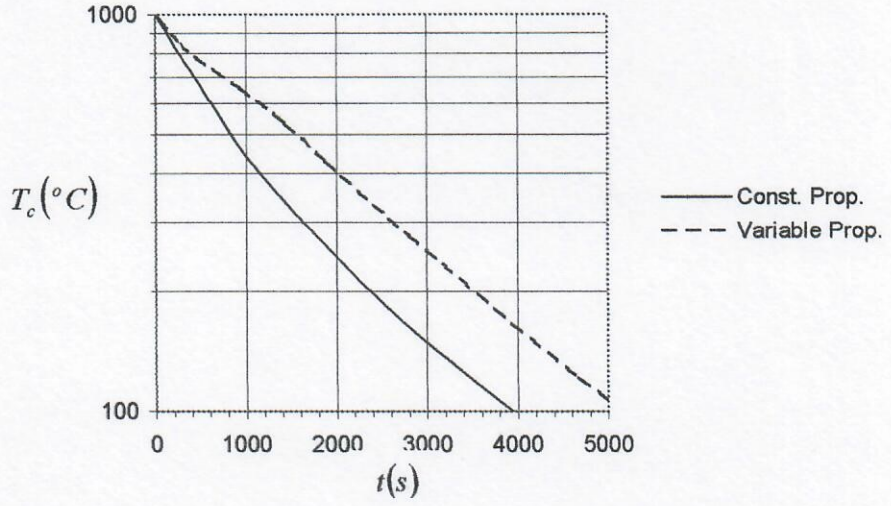


Fig. 7. Variation of center temperature with time for pure iron under free convective heat transfer boundary condition

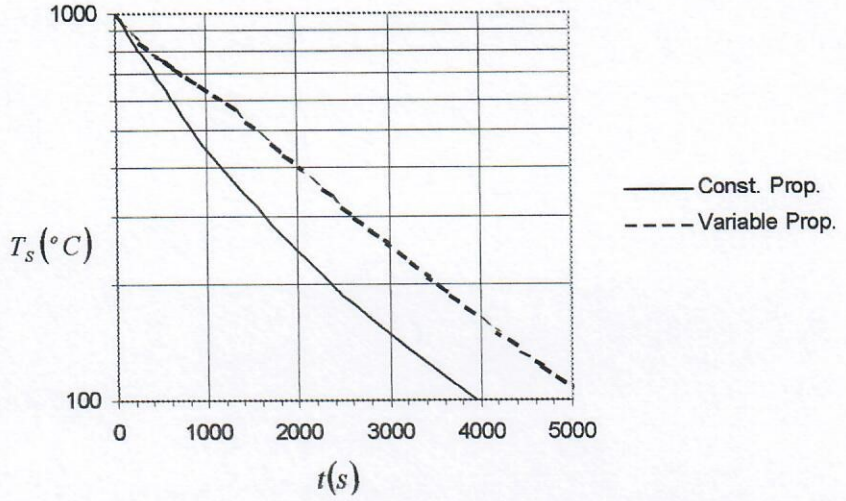


Fig. 8. Variation of surface temperature with time for pure iron under free convective heat transfer boundary condition

Variation of temperatures under radiative heat transfer boundary condition is depicted in figures 9 and 10. Although the differences between the temperature profiles for variable and constant property cases are not significant, pure iron with constant property needs slightly less time to cool down to the same temperature. One should wait for nearly a quarter hour to get the temperature around 100 $^\circ C$ under these conditions.

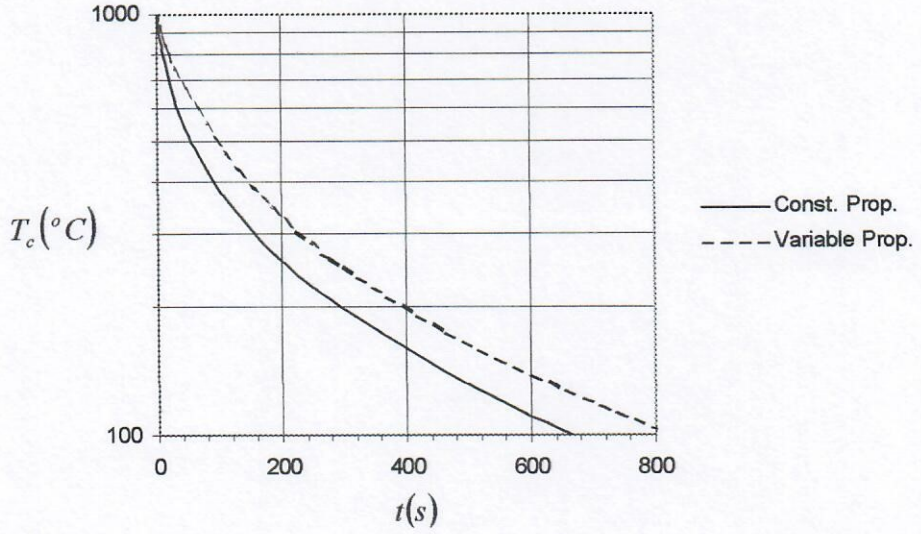


Fig. 9. Variation of center temperature with time for pure iron under radiative heat transfer boundary condition

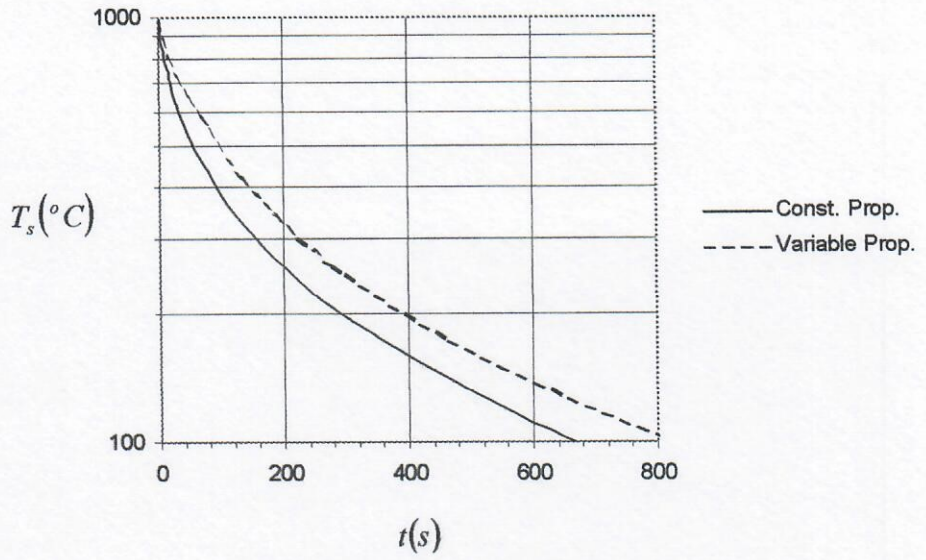


Fig. 10. Variation of surface temperature with time for pure iron under radiative heat transfer boundary condition

6. CONCLUSIONS

This work have shown that, temperature profiles of pure iron can not be predicted correctly by neglecting variable physical properties for cooling with water under convective and subcooled bubbly boiling conditions. For cooling with air at low velocities, free convective and especially radiative heat transfer boundary conditions should be taken into consideration.

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