Influence of temperature dependent properties on cooling behavior of cylindrical steels

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Abstract

Metallic materials, especially steels, are undertaken to different heat treatment processes in industry and cooling and heating times are of great importance. In this study, influence of variable physical properties of ANSI 1025 and AISI 304 steels and different boundary conditions namely forced convection, free convection and radiation on the calculation of cooling process was investigated. Governing differential equations were solved numerically for non-steady cases. It was found that variable properties should be taken into consideration for ANSI 1025, while the physical properties determined at an average temperature can be used for AISI 304. Another conclusion is that free convection can be neglected compared with radiation especially if forced convection coefficient is low.

Keywords: Cooling; Temperature dependent properties; Cylindrical steels; Heat treatment

1. Introduction

Cooling characteristics should be known for many heat treatment processes of steels. The non-steady state cooling problem can be approximately determined with the physical properties taken at an average temperature if the changes in physical properties with temperature are not too high and variations are linear. However, physical properties of different steels in a wide temperature range do not exhibit such behaviors. Therefore, one can make significant errors in calculating cooling processes of steels.
Cooling process with constant physical properties can be determined using the cooling charts given in [1] and the analytical expressions given in [1,2]. Phase transformation was taken into account in [3]; however, thermal diffusivity and density were considered to be constant. Variable specific heat and thermal diffusivity were used by [4] for St 45 steel. Heat transfer in cylindrical AISI 1015 steel was calculated by [5] assuming constant physical properties.

In this study, Fourier differential equation was solved numerically taking temperature dependent physical properties of two cylindrical steels (ANSI 1025 and AISI 304) into consideration to determine the influence of them. Influence of different boundary conditions was also investigated.

2. Differential equations

For an infinitely long cylinder that is subjected to constant boundary conditions at its surface, the following differential equation is valid [6]:

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

(1)

Fig. 1. Variation of thermal diffusivity of ANSI 1025 (a) and AISI 304 (b) steels with temperature.

Fig. 2. Variation of thermal conductivity of ANSI 1025 and AISI 304 steels with temperature.
in which $T$ is temperature, $t$ is time, $r$ is radial distance, $k$ is thermal conductivity and $a$ is thermal diffusivity of the cylinder.

Temperature of the cylinder is $T_i$ at the beginning of cooling:

$$t = 0 : t = T_i$$

Temperature is the maximum at the center and convective and radiative heat transfer take place at the surface of the cylinder:

$$r = 0 : \frac{\partial T}{\partial r} = 0$$

$$r = R : -k \frac{\partial T}{\partial r} \bigg|_{r = R} = h(T_s - T_f)$$

where $T_s$ and $T_f$ are surface temperature of the cylinder and surrounding fluid temperature, respectively. Free and forced convective, and radiative heat transfer were taken into account in calculating overall heat transfer coefficient $h$, if all the three modes of heat transfer are present.

Assuming turbulent flow, $h$ can approximately be calculated with:

$$h = (h_U^3 + h_F^3)^{1/3} + h_R$$

where $h_U$, $h_F$ and $h_R$ are mean forced convective, free convective and radiative heat transfer coefficient, respectively.

$h_F$ can approximately be determined with:

$$h_F = h_{OF}(T_s - T_f)^{1/3}$$

in which $h_{OF}$ is defined as:

$$h_{OF} = A_F k_f \left[ \frac{g \beta_f}{v^2} \right]^{1/3}$$

### Table 1

Physical properties at 20 °C, average temperature and 1000 °C for ANSI 1025 and AISI 304 steels

<table>
<thead>
<tr>
<th>Material</th>
<th>$a \times 10^6$ (m²/s)</th>
<th>$k$ (W/m K)</th>
<th>$\rho c \times 10^{-6}$ (J/m³ K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 °C Ave.</td>
<td>1000 °C Ave.</td>
<td>20 °C Ave.</td>
</tr>
<tr>
<td>ANSI 1025</td>
<td>16</td>
<td>35</td>
<td>3.5</td>
</tr>
<tr>
<td>AISI 304</td>
<td>39.5</td>
<td>5.05</td>
<td>3.8</td>
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### Table 2

Comparison of $T^*$ obtained in this work with those obtained from literature for $Bi = \infty$

<table>
<thead>
<tr>
<th>Dimensionless time ($t^*$)</th>
<th>Dimensionless center temperature ($T^*$)</th>
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<tr>
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<td>Yilmaz</td>
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<td>Martin</td>
<td>1</td>
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<tr>
<td>Soininen and Heikkila</td>
<td>1</td>
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</tbody>
</table>
can be considered to be constant at a mean fluid temperature. Similar to free convection at vertical surfaces, \( A_F \) can be taken 0.013 at moderate values of Rayleigh number.

The following equation can be written for \( h_R \):

\[
h_R = h_{oR} f_x
\]  
(8)

where \( h_{oR} \) and \( f_x \) can be calculated respectively with:

\[
h_{oR} = 4\varepsilon\sigma T_{Af}^3
\]  
(9)

\[
f_x (1 + T^* + T^{*2} + T^{*3}) / 4
\]  
(10)

\( T^* \) in Eq. (10) is defined as:

\[
T^* = T_{As} / T_{Af}
\]  
(11)

where \( T_{As} \) and \( T_{Af} \) are absolute surface and fluid temperature, respectively.

In this study, differential Eq. (1) was solved numerically using the initial and boundary conditions given by Eqs. (2)–(4). The implicit finite difference method was used in the solution. Since physical properties depend on temperature, the equations are nonlinear and, therefore, solution can only be obtained iteratively. A computer program using FORTRAN programming language was written for this purpose. Details of the solution procedure were given in [6].

### 3. Physical properties of ANSI 1025 and AISI 304 steels

Under normal conditions, governing differential equation (Eq. (1)) depends on thermal conductivity \( (k) \) and diffusivity \( (a) \). From definition, diffusivity is a function of density \( (\rho) \), specific heat \( (c) \) and conductivity. Figs. 1 and 2 show variation with temperature of diffusivity and conductivity of ANSI
1025 and AISI 304 steels, respectively [7]. In Fig. 1, four curves can be seen, one of which is for variable property, while the other three are for constant property. The constant averaged line was obtained by averaging the data from 20 °C to 1000 °C. For the other two cases, the $a$ values at 20 °C and 1000 °C were taken constant for entire temperature range.

The constant property values for $a$, $k$ and $q_c$ are also shown in Table 1 for ANSI 1025 and AISI 304 steels. For numerical calculations, equations were derived [6] to express the physical properties as a function of temperature using the data available in literature [7].

### 4. Results

The equations derived can be used to simulate cooling processes of steels. Physical properties were assumed constant and therefore, independent of temperature in the first stage of numerical calculations to validate the numerical procedure developed. The results can be compared with known values available in literature using only dimensionless quantities. Calculations were conducted for three different Biot numbers ($\infty$, 10 and 1) at different values of dimensionless time $t^*$, which was defined as:

$$t^* = \frac{a_o \cdot t}{R^2}$$  \hspace{1cm} (12)

where $a_o$ is thermal diffusivity of the material at a reference temperature $T_o$ and $R$ is the radius of the cylinder. Biot number was defined as:

$$Bi = \frac{h_U \cdot R}{k}$$  \hspace{1cm} (13)

In these calculations, free convective ($h_F$) and radiative ($h_R$) heat transfer coefficients were assumed to be zero. In Tables 2–6, dimensionless center and surface temperatures obtained from the calculations are compared with the

**Table 5**

<table>
<thead>
<tr>
<th>Dimensionless time ($t^*$)</th>
<th>Dimensionless center temperature ($T^*_c$)</th>
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**Table 6**

<table>
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<th>Dimensionless time ($t^*$)</th>
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<td>Martin</td>
<td>0.885</td>
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<tr>
<td>Soininen and Heikkila</td>
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</tbody>
</table>
equations given by [1,2] and with the diagrams given by [1] for $Bi = \infty$, 10 and 1. Dimensionless center ($T_c^*$) and surface temperature ($T_s^*$) were defined respectively as:

$$T_c^* = \frac{T_c - T_f}{T_i - T_f}$$

$$T_s^* = \frac{T_s - T_f}{T_s - T_f}.$$  (14)

From the tables, it is clear that the results of the numerical calculations compare very well with the results in the literature for constant physical properties.

5. ANSI 1025 steel

After validation of the computer code developed, temperature profiles were calculated for 20 mm diameter cylindrical ANSI 1025 and AISI 304 steels using variable physical properties and constant physical properties at 20 °C and 1000 °C and obtained by averaging the data over the entire temperature range (constant-averaged).

Variation of surface ($T_s$) and center ($T_c$) temperatures from an initial temperature of 1000 °C to 100 °C is respectively given for a very high forced convective heat transfer coefficient $h_U = 100,000$ (Fig. 3), which can be seen in bubbly evaporation, and for $h_U = 2000$ (Fig. 4), which can be encountered in cooling of steels with water. As expected, cooling time increases dramatically with decrease of $h_U$. $h_F$ and $h_R$ were taken zero for these cases.

Temperature profiles calculated using the averaged properties should lie between the results obtained with constant properties at 20 °C and 1000 °C. This behavior is only seen for center temperature in Fig. 3b that is obtained for a very high level of forced convection, for which both

![Fig. 3. Surface (a) and center (b) temperature profiles for ANSI 1025 steel for $h_U=100,000$, $h_F=0$, $h_R=0$.](image)
thermal diffusivity and conductivity are equally important. However, conductivity has much more influence on the center temperature than the other properties. $\rho c$ is the dominant parameter for the surface temperature even at high $h_U$ and its averaged value is higher than the values for 20 °C and 1000 °C as can be seen from Table 1. Therefore, surface temperature calculated with the averaged properties is higher than that calculated with the constant properties for 20 °C and 1000 °C (Fig. 3a).

For $h_U = 2000$, the surface and center temperatures calculated with the averaged properties are higher than that with the constant properties for 20 °C and 1000 °C (Fig. 4). This is again because averaged $\rho c$ is higher than the values at 20 °C and 1000 °C (Table 1).

The results obtained for ANSI 1025 steel clearly show that, it is necessary to calculate cooling and heating processes using variable physical properties.

Center temperature profiles for low convective heat transfer coefficients $h_U = 100$ and $h_U = 10$ are given in Fig. 5. The general behavior of the profiles is similar to that of high $h_U$ values. However,
because nearly uniform temperature profile in the cylinder can be assumed for low $h_U$ values, cooling time increases almost linearly with decreasing $h_U$, if $h_F$ and $h_R$ are neglected.

To see the influence of free convection and radiation heat transfer on the cooling process of cylindrical steels, center temperature is depicted in Fig. 6a for $h_U=0$, $h_F=10$, and $h_R=5$, and in Fig. 6b for $h_U=0$, $h_F=10$, and $h_R=0$. Comparison of these figures reveals that radiative heat transfer dominates free convective heat transfer especially at low forced convective heat transfer coefficients, so that free convection can be neglected under these circumstances.

6. AISI 304 steel

Physical properties of AISI 304 steel do not exhibit abnormalities as shown in Figs. 1 and 2. Therefore, temperature profiles obtained with the averaged properties locate between the profiles obtained with the constant properties at 20 °C and 1000 °C and they are very close to the profiles
obtained with variable profiles. Fig. 7 shows an example to the surface and center temperature profiles for AISI 304 steel with $h_U=2000$, $h_F=0$ and $h_R=0$.

7. Conclusions

Cooling and heating processes of ANSI 1025 steels should be calculated using variable properties. However, constant averaged values of physical properties that are calculated over the entire temperature range can be used only for high alloy stainless steels like AISI 304. Radiative heat transfer dominates free convective heat transfer especially at low forced convective heat transfer coefficients, so that free convection can be neglected under these circumstances.

References