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Application of Radial Effective Thermal Conductivity for Heat Transfer Model of Steel Coils in HPH Furnace[1]

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The hot/cold rolled steel coil can be considered as a periodically laminated material composed of layers of steel strips and gas gaps in the radial direction. The conduction of steel, of gas, of contact points due to the surface roughness, as well as radiation have been included in a determination of the radial effective thermal conductivity. Based on the analysis of heat transfer mechanisms in radial coils, a new formula for the radial effective thermal conductivity has been derived, which depends not only on the temperature but also on the type of atmosphere gas, the surface characteristic of coils, strip thickness, and compressive stress. Using this effective conductivity, a detailed mathematical model has been developed to predict the temperature distribution of coils in a high performance hydrogen (HPH) furnace. The calculated annealing curves are in good agreement with experimental data.

KEY WORDS: effective thermal conductivity; HPH furnace; heat transfer; mathematical model.

1. INTRODUCTION

A high performance hydrogen (HPH) bell-type annealing furnace was developed and introduced into the steel industry in the late 1970s. Taking advantage of 100% hydrogen to replace the conventional nitrogen-hydrogen mixing atmosphere (95% N_2 and 5% H_2, in general), unprecedented temperature uniformity results from advantages of the pure hydrogen atmosphere

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heat treatment and the high convection technology [1]. Compared with the conventional annealing technology, the capacity may be increased by 40 to 60% and the product quality may be improved significantly [2].

The present work focuses on a mathematical model for heat transfer of coils in an HPH furnace. A rolled steel coil can be considered as a composite material, consisting of alternate layers of steel strips and gaps filled with atmosphere gas in the radial direction. Heat transfer through the gas gap is a complex phenomenon involving the combined mechanisms of gas conduction, contact point conduction due to the rough surface, and radiation. In order to overcome the difficulty of heterogeneity in the radial conductivity, the effective thermal conductivity, proposed by the method of thermal resistance analysis, is introduced in this model.

2. MATHEMATICAL MODEL

2.1. Heat Transfer Model

Since a coil can be assumed to be symmetric about the centric line, the tangential conduction is negligible, i.e., only the axial and radial conduction are to be considered. As shown in Fig. 1, consider the cross section of half a coil (width of 1250 mm and thickness of 620 mm). The center and bottom lines coincide with the z and r axes, respectively. Only half of the temperature field needs to be studied, the remainder will follow from symmetry. A two-dimensional transient heat conduction equation can be

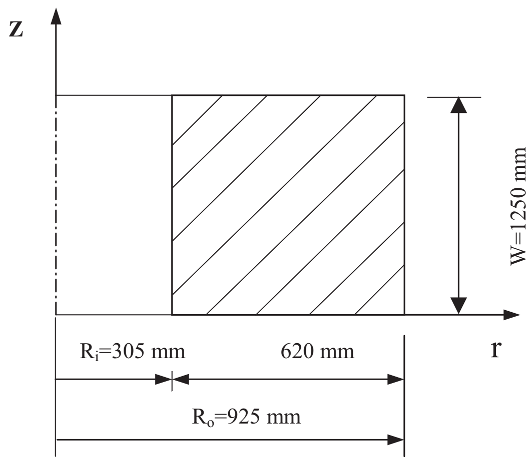

Fig. 1. Geometry and coordinate system.

written as follows to reflect the temperature distribution in the coil as a function of time;

$$\rho C_P \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda_r \frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda_s \frac{\partial T}{\partial z}\right) \tag{1}$$

where ρ is the density of steel; C_P is the specific heat of steel; λ_s is the thermal conductivity of the coil in the axial direction, namely that of steel; R_i, R_o, and W are the inner radius, the outer radius, and the width of the coil, respectively; and λ_r is the radial effective thermal conductivity which will be discussed in detail later in this paper.

2.2. Radial Effective Thermal Conductivity

Being alternately composed of layers of steel strips and hydrogen gaps, a coil can be considered as a composite material. As shown in Fig. 2, the heat transfer mechanism in the axial direction is the steel conduction while that in the radial direction is the combination of steel conduction, gas conduction, contact point conduction, and radiation. By virtue of the very small thickness of the gap (on the order of 10 to 100 μm), convection is negligible.

According to the foregoing discussion, the thermophysical properties of coils, especially the thermal conductivity, are not only anisotropic in two dimensions but also heterogeneous in the radial direction. In order to make the radial heat transfer more tractable, the radial effective thermal conductivity is introduced in the model.

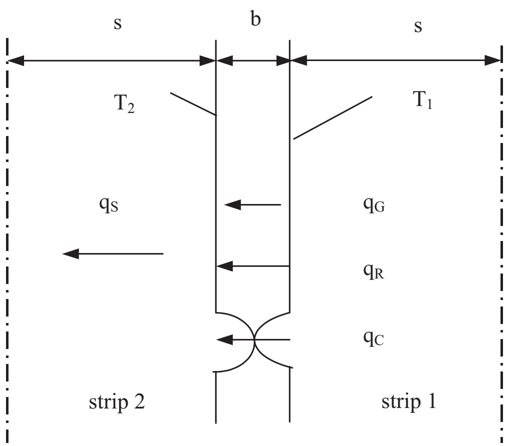

Fig. 2. Heat transfer occurring in the radial coil.

To derive the radial effective thermal conductivity, a coil is considered to be a lattice of identical control units whose conductivity can be calculated from a single representative control unit by using thermal resistance analysis. As illustrated in Fig. 1, there are about 1240 layers of strips in a coil corresponding to a strip 0.5 mm thick. In each control unit, the thermophysical properties are considered as constants and depend only on the mean temperature of the control unit. Based on the fact that either the thickness of the strip (on the order of 1 to 10 mm) or that of the gap is very small compared with the curvature of the coil (on the order of 100 to 1000 mm), the adjacent cylindrical strips can be considered as planes.

Considering a control unit which consists of one layer of steel strip and one layer of gas gap, the thermal resistance of conduction through a steel strip is R_S, and the thermal contact resistance for the gap is R_{CT}; therefore, the overall thermal resistance in a control unit can be expressed as

$$R_{\Sigma} = R_S + R_{CT} \tag{2}$$

where

$$R_S = s/\lambda_s \tag{3}$$

$$R_{CT} = (T_1 - T_2)/q \tag{4}$$

s is the thickness of the steel strip, T_1 and T_2 are surface temperatures of adjacent strips separated by a gap, and the heat flux q is given as

$$q = q_S = q_G + q_C + q_R \tag{5}$$

Substituting Eq. (5) into Eq. (4), we then obtain

$$R_{CT} = [1/R_G + 1/R_C + 1/R_R]^{-1} \tag{6}$$

where q_G, q_C, q_R are, respectively, heat fluxes of conduction through the hydrogen layer, of conduction through the contact points, and of radiation between the surfaces of two adjacent steel strips; R_G, R_C, R_R are the corresponding thermal resistances.

Pullen and Williamson [3] proposed an approximate factor of the actual contact area, φ, as

$$\varphi = P/(H + P) \tag{7}$$

Based on this factor, Mikic [4] proposed an equation of thermal resistance through direct contact points as follows:

$$R_C = \sigma_P/(1.13\lambda_s \tan\theta\varphi^{0.94}) \tag{8}$$

where P is the nominal compressive stress, H is the microhardness, σ_P is the standard deviation of profile height, and $\tan\theta$ is the mean of the absolute slope of a profile.

The other thermal resistances used in Eq. (6) can be expressed as

$$R_G = b/[(1-\varphi)\,\lambda_g] \tag{9}$$

$$R_R = (2-\varepsilon)/[\varepsilon\sigma_0(1-\varphi)\,4\bar{T}^3] \tag{10}$$

where λ_g is the thermal conductivity of hydrogen; b is the mean thickness of the gas layer; ε is the emissivity of steel; σ_0 is the Stefan–Boltzmann constant; and $\bar{T}$ is the mean temperature of the adjacent strips. The mean thickness of a gas layer was measured experimentally by Baik [5] as a function of compressive stress, which can be approximated by the following equation [6]:

$$b = 42.7\times 10^{-6}\exp(-5\times 10^{-2}P) \tag{11}$$

Substituting Eqs. (3) and (6) into Eq. (2), the thermal resistance in one control unit can be written as

$$R_\Sigma = \frac{s}{\lambda_s} + \left[\frac{(1-\varphi)\,\lambda_g}{b} + \frac{1.13\lambda_s\tan\theta}{\sigma_P}\varphi^{0.94} + \frac{4(1-\varphi)\,\varepsilon\sigma_0 T^3}{2-\varepsilon}\right]^{-1} \tag{12}$$

According to Eq. (12) and the definition of thermal resistance, we obtain the formula to calculate the radial effective thermal conductivity of a coil as

$$\begin{aligned}\lambda_r &= \frac{s+b}{R_\Sigma}\\ &= (s+b)\left\{\frac{s}{\lambda_s} + \left[\frac{(1-\varphi)\,\lambda_g}{b} + \frac{1.13\lambda_s\tan\theta}{\sigma_P}\varphi^{0.94} + \frac{4(1-\varphi)\,\varepsilon\sigma_0 T^3}{2-\varepsilon}\right]^{-1}\right\}^{-1}\end{aligned} \tag{13}$$

The parameters employed in Eq. (13) are given in Table I.

Table I. Parameters to Calculate the Radial Effective Thermal Conductivity

s (mm)	H (MPa)	P (MPa)	T_m (K)	λ_s	λ_g ($\mathrm{W\cdot m^{-1}\cdot K^{-1}}$)	ϵ	σ_P (μm)	$\tan\theta$	σ ($\mathrm{W\cdot m^{-2}\cdot K^{-4}}$)
0.806	1133.86	8	573	42.0	0.307	0.2	3.2215	0.08554	5.67×10^{-8}

3. RESULTS AND DISCUSSION

As mentioned above, the heat transfer of a coil in the radial direction is the total effect of the conduction of steel and heat transfer through the gap between two adjacent steel strips. According to Eq. (12), the radial thermal resistance is mainly affected by the mean temperature of a unit volume, T, and the nominal compressive press, P. Figure 3 shows the variations of the conduction resistance of a steel strip, R_S, and the contact resistance of a gap, R_{CT}, with T and P. It can be seen in Fig. 3b that $R_S < R_{CT}$ when $T < 500°C$, and the radial heat transfer of a coil is mainly affected by the heat transfer on the interface. It can be seen in Fig. 3a that $R_{CT} > R_S$ when $P < 13$ MPa, and $R_{CT} < R_S$ when $P > 13$ MPa. It's clear that, in the case of low compressive stress, the heat transfer on the interface is the main factor to influence the radial heat transfer of the coil, and the variation of R_{CT} with P is larger.

The thermal contact resistance on the interface is composed of R_R, R_G, R_C; the variations of these terms with T and P are shown in Fig. 4. As shown in Fig. 4a, R_R is larger than R_G and R_C by 3 to 4 orders of magnitude when T varies in the range 0 to 700°C; R_G decreases with increasing temperature; and R_C increases with increasing temperature and is always larger than R_G. In Fig. 4b, when P varies in the range 1 to 15 MPa, R_R is still larger than R_G and R_C by 3 to 4 orders of magnitude; both R_G and R_C decrease with increasing pressure, and R_C is always larger than R_G. Thus, according to the above analysis, it's found that the heat transfer in the gap mainly depends on the conduction of gas. So the radial effective thermal conductivity of a coil can be increased by increasing the conductivity of the atmosphere gas. The conductivity of hydrogen gas is about seven times as large as that of nitrogen gas, and Fig. 5 shows a comparison of the radial effective thermal conductivity of a coil under the conditions of either hydrogen or nitrogen atmosphere gas.

By means of the radial effective thermal conductivity, a mathematical model is developed for simulating the temperature distribution, as well as the annealing curves of steel coils in an HPH furnace. By simulation calculations, the annealing systems for rolled steel coils with different size and furnace condition can be established, and which would be useful to realize on-line control for furnace groups and the optimization of production management.

In order to validate the developed model and computation program, measurement tests have been performed for the annealing process of rolled steel coils with three different furnace loads. As shown in Figs. 6 and 7, the variations of the inside temperature and surface temperature with annealing time at different positions, 1 and 2, in the coils are measured and

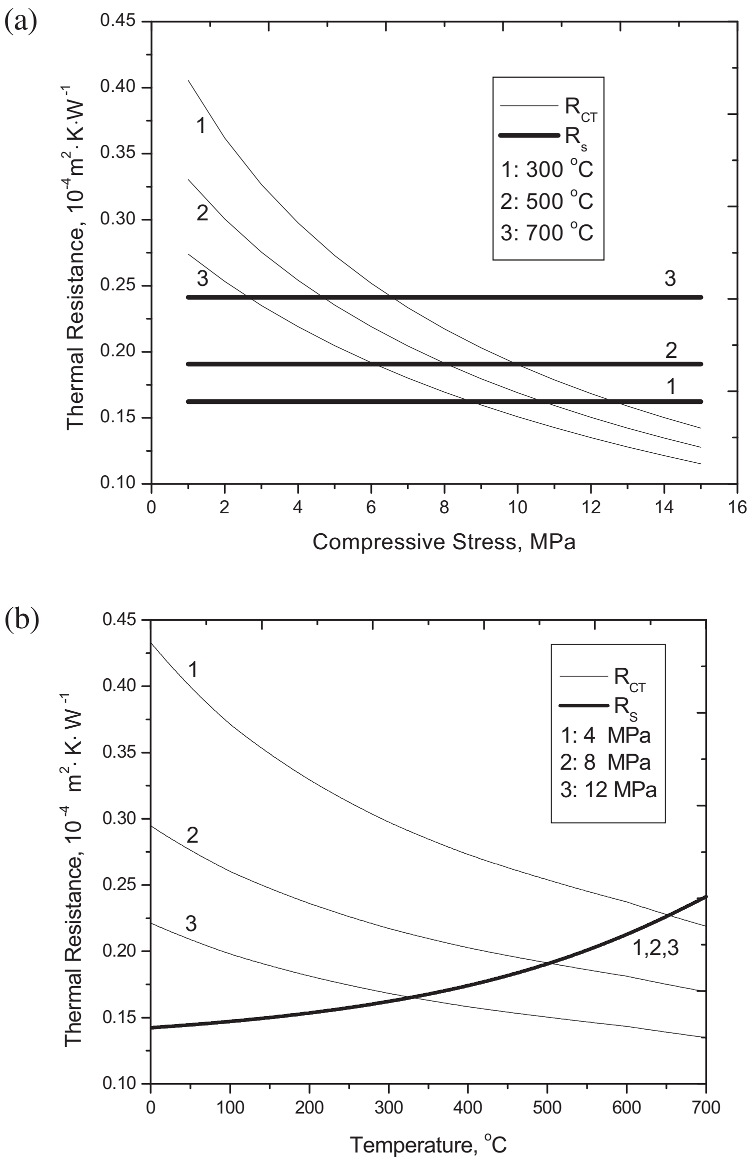

Fig. 3. Variations of the conduction resistance of steel and the contact resistance of gap. (a) R_S and R_{CT} with nominal compressive stress of coil. (b) R_S and R_{CT} with mean temperature of the unit volume.

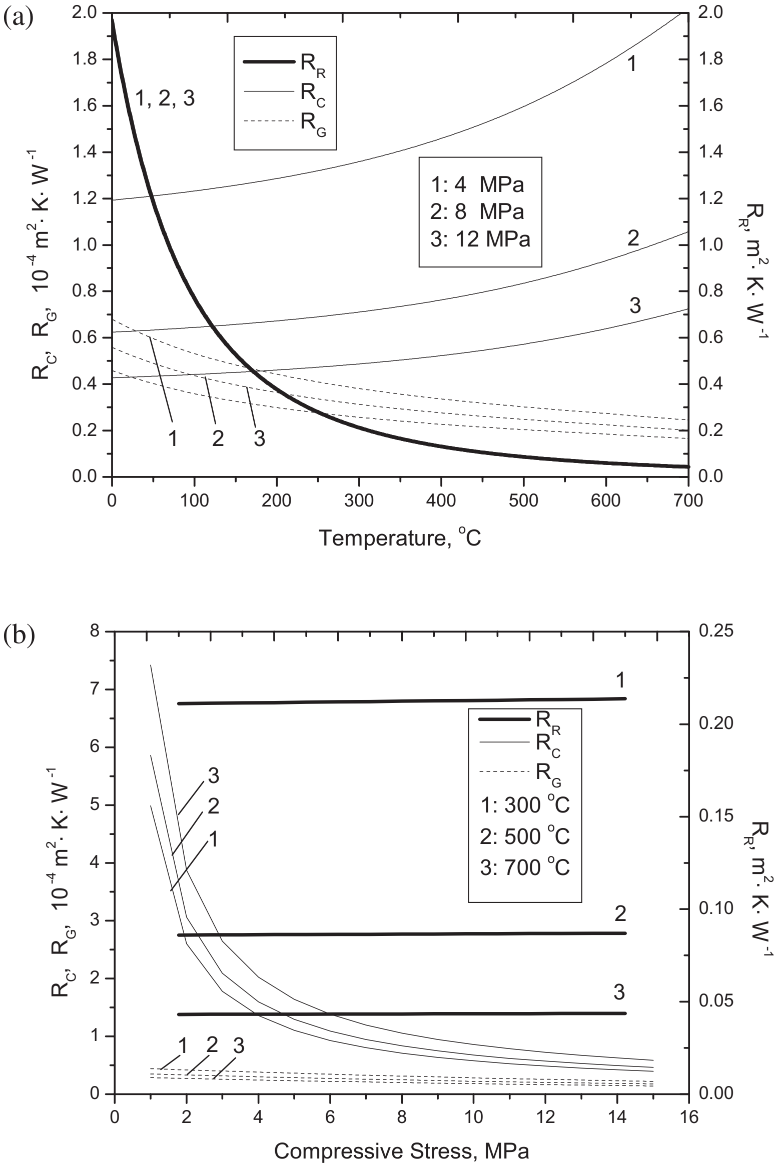

Fig. 4. Variations of thermal resistances in the gap. (a) R_R, R_G, R_C with mean temperature of the unit volume. (b) R_R, R_G, R_C with nominal compressive stress of coil.

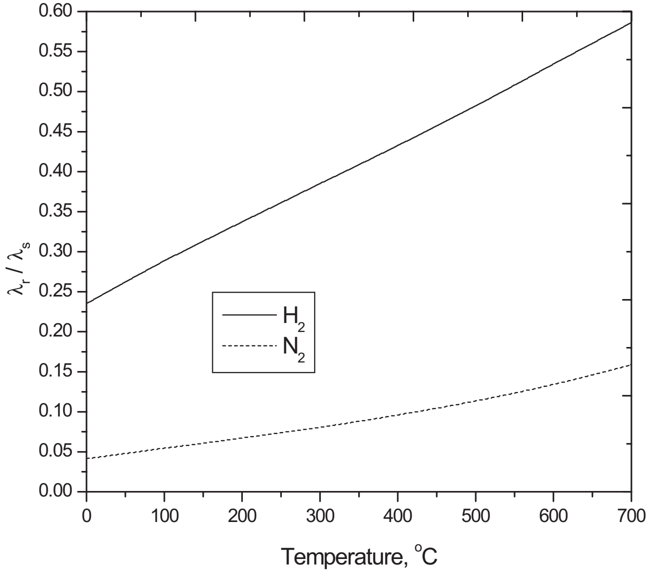

Fig. 5. Comparison of the radial effective thermal conductivity of coil under the conditions of either hydrogen or nitrogen gas.

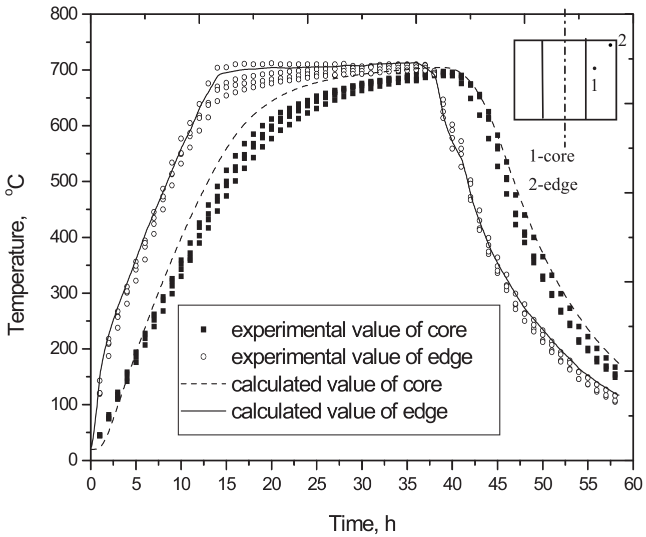

Fig. 6. Comparison of experimental and calculated results when furnace load is 122 and 120 kg.

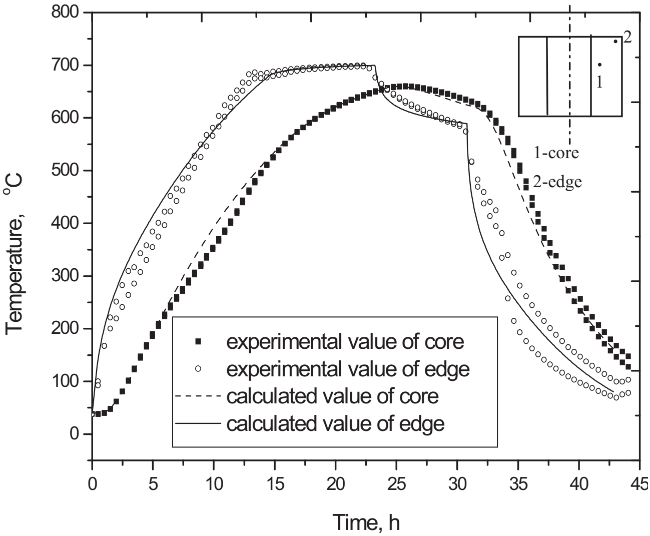

Fig. 7. Comparison of experimental and calculated results when furnace load is 74 and 160 kg.

compared with the results of the simulation calculations; the "core" point and "edge" point, or "cold" and "hot" points as sometimes called, are located approximately in the middle and at the top of the coil where the extremes of temperature occur. It can be seen that the numerical results are in good agreement with the experiment data.

4. CONCLUSIONS

According to the analysis of heat transfer mechanisms in the radial direction of a coil, a formulation for the radial effective thermal conductivity has been proposed to simplify the calculation of radial heat transfer. A mathematical model for the heat transfer of coils in an HPH furnace has been developed, and the annealing curves thus have been achieved. The numerical results are in good agreement with experimental data.

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