A Study on the Surface Emissivity of Oxidised Steel using a Three Layer Model

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ABSTRACT

A study was carried out to investigate the change in surface emissivity of oxidised steel using a 3-layer model. Plane electromagnetic wave theory was used to calculate the emissivity. In this paper, relationships between emissivity, wavelength of radiation and thickness of iron-oxide on the steel are discussed and some conclusions on the use of the model drawn.

1. INTRODUCTION

Temperature is one of the most important parameters to measure and control in the steel industry. The most commonly used technology for non-contact, on-line temperature measurement is Infrared (IR) pyrometry. Another useful technology is microwave radiometry which offers some unique advantages such as seeing through smoke and dust, measuring sub-surface temperature, etc. Both technologies are affected by the object's surface emissivity variation. The surface emissivity is dependent on several factors including the object's material composition, body temperature, surface structure and measurement frequency. It is important, therefore, to investigate the relationship between steel surface emissivity and the variables mentioned above. A cost-effective method of study is to simulate and analyse the surface emissivity of steel bodies based on appropriate mathematical models.

In the steel industry, the temperature of objects to be measured are often quite high, typically above 600^oC. Under such conditions, the surface of steel bodies are almost always covered by iron-oxide layers. Therefore the surface emissivity of the objects is in fact that of the iron-oxide layers instead of clean steel. Some research work has been reported on simulating the emissivity of an oxidised steel surface in the IR region using a model with a single iron-oxide layer on top of a pure steel [1]. However metallurgical studies indicated that a more appropriate model for an oxidised steel surface should be of three layers. Moreover, it is desirable to investigate the behaviour of the surface emissivity of oxidised steel over a broad spectral range from Near Infrared (NIR) through to microwave.

The growth rate of iron-oxide depends on time, temperature and oxygen potential. As an example consider that it takes $\simeq$ 2 min to grow a thickness of $10\mu m$ of FeO at 800^oC but only $\simeq$ 2 secs at 1000^oC (O_2 potential : $RTln(pO_2) \simeq -300$). This stresses that very little time is required for a layer of oxide to form on clean steel.

This paper presents results of a study on the emissivity of an oxidised steel surface using a 3-layer model over a wide spectral range.

2. METHOD

2.1 The Three Layer Model

Upon exposure to air, the surface of hot steel is quickly covered by layers of iron-oxide. Above 600^oC three different iron-oxide layers form on top of each other. The thickness of individual layers has the approximate ratios:

$$1_{(FeO)} : 0.04_{(Fe_3O_4)} : 0.009_{(Fe_2O_3)}$$

That is, Wustite (FeO) forms on clean steel having the thickest layer then followed by two layers : that of Magnetite (Fe_3O_4), the next thickest, and finally Hematite (Fe_2O_3), the thinnest topmost layer.

The previous study [1] dealt with the case of one layer of Fe_2O_3 on top of pure steel. In this paper, we use a 3-layer model to study the behaviour of the emissivity with respect to several variables.

2.2 Emissivity and Reflectivity

The spectral radiant excitance $M(\lambda, T)$ of a non-blackbody is given by the Planck radiation law [2]

$$M(\lambda, T)_{nbb} = \epsilon \frac{c_1}{\lambda^5 (e^{c_2/\lambda T} - 1)} W m^{-3} \quad (1)$$

where c_1 and c_2 are radiation constants ($c_1 = 3.7415 \times 10^{-16} W m^2, c_2 = 1.43879 \times 10^{-2} mK$), T the temperature of the steel surface in $^o K$, λ the wavelength and ϵ the emissivity. Emissivity is the ratio of the exitance of a smooth homogeneous body to that of a blackbody. The total energy falling on a body can be divided into three parts : the energy transmitted through the body, that reflected and that absorbed by the body. For an object with zero transmittance, Kirchoff's law [2] states that

$$\epsilon = 1 - r \quad (2)$$

where r is the surface reflectivity of the object taken at the same spot where the emissivity is measured. Equation (2) is used in the calculation of the surface emissivity in this paper.

2.3 Mathematics

Fig. 1 An EM wave incident upon 3 iron-oxide layers

To simplify the calculation, the following are assumed in the emissivity calculation (ref. Fig. 1) :

- The steel object is an infinitely large, specular surface with three iron-oxide layers on top of a steel substrate with infinite depth. The ratios of the three iron-oxide layers is given in section 2.1.
- A plane electromagnetic (EM) wave of wavelength λ is incident at the object's surface at an angle θ_{I1}.
- Equation (2) is applicable to the combined 3-layer/steel structure.

Under such assumptions, we first calculate the top surface reflectivity coefficient defined as $r = RR^*$ (* stands for complex conjugate), and then the emissivity $\epsilon = 1 - r$. The refractive indices of iron-oxide layers and steel are both complex with the imaginary part being the absorption coefficient. The angles of incidence, reflection and refraction at each interface of the model were obtained by Snell's law. Using the approach given in [3] we obtain the characteristic matrix of the three layer system $[m_{ij}]$. The reflectivity for both perpendicular ($\perp$) and parallel ($\|$) polarisation were obtained :

$$R_{\perp} = \frac{\gamma_1^{\perp} m_{11} + \gamma_1^{\perp} \gamma_5^{\perp} m_{12} - m_{21} - \gamma_5^{\perp} m_{22}}{\gamma_1^{\perp} m_{11} + \gamma_1^{\perp} \gamma_5^{\perp} m_{12} + m_{21} + \gamma_5^{\perp} m_{22}} \quad (3)$$

$$R_{\|} = -\left(\frac{\gamma_1^{\|} m_{11} + \gamma_1^{\|} \gamma_5^{\|} m_{12} - m_{21} - \gamma_5^{\|} m_{22}}{\gamma_1^{\|} m_{11} + \gamma_1^{\|} \gamma_5^{\|} m_{12} + m_{21} + \gamma_5^{\|} m_{22}} \right) \quad (4)$$

The total reflectivity is calculated as

$$r = \frac{r_{\|} + r_{\perp}}{2} \quad (5)$$

Where $\gamma_j^{\perp} = (n_j / c\mu_j) \cos\theta_{Ij}$, for perpendicular polarisation and $\gamma_j^{\|} = n_j / (c\mu_j \cos\theta_{Ij})$ for parallel polarisation, $k_0 h_j = n_j d_j \cos\theta_{Ij}$ is the phase change upon reflection from the various interfaces, n_j the refractive indices of each material, n_1 air, $n_{2,3,4}$ the iron-oxides and n_5 the steel substrate, k_0 the wave vector, d_j the thickness of each successive layer of iron-oxide, c the speed of light and μ_j the permeability of each of the materials. It is worthwhile pointing out that the refractive indices are functions of conductivity, permittivity, permeability and wavelength, ie. $n = n(\lambda, \sigma, \varepsilon, \mu)$, where the conductivity of steel decreases as temperature increases and vice versa for iron-oxides [4] as shown in Fig. 2.

Fig. 2 Conductivity vs temperature for iron-oxides

This was not considered by previous researchers where the imaginary part of the refractive index of the iron-oxides was set equal to zero. In addition, the previous study [1] only investigated the emissivity variation in the IR region where the refractive index of iron-oxide is nearly constant, although this is not strictly true at higher temperatures where the conductivity dependence with temperature takes effect.

3. RESULTS AND DISCUSSION

3.1 Comparison of 3-Layer and 1-Layer Models

We first reduced the 3-layer to a single layer model of FeO (on iron) and compared the calculated emissivity result to experimental results (carbon steel) in [1], Fig. 3. As can be seen there is reasonable agreement.

Fig. 3 Experimental and Calculated emissivity

Fig. 4 shows the calculated emissivity of the 3-layer and 1-layer models at a thickness of FeO of 0.2 mm. Note that when the wavelength is comparable with the thickness of Fe_2O_3 (the topmost layer) the emissivity fluctuates.

Fig. 4 3-Layer, 1-Layer Comparison

This indicates that when the wavelength of radiation is comparable to the thickness of a particular layer, interference within that layer causes the emissivity to vary. The same applies to both Fe_3O_4 and FeO. The highest contribution to the emissivity comes from the layer whose thickness is comparable to the wavelength used in the measurement.

As the wavelength increases beyond $\lambda \simeq 10\mu$m, ϵ decreases and converges to the 1-layer case. This implies that the 3-layer model can be reduced to a 1-layer model, of FeO, provided that the wavelength is much longer than the thickness of both Fe_2O_3 and Fe_3O_4.

It should be noted that for temperatures greater than 600^oC all three layers of oxide exist. Therefore we need to use a 3-layer model in general, whereas below 600^oC, Fe_2O_3 is the dominant layer and we may use a single-layer model as in [1].

3.2 Wavelength and Thickness

Fig. 5(a) shows the variation of emissivity with iron-oxide layer thickness in the IR range using a 3-layer model. It is seen that as the wavelength increases emissivity decreases.

Fig. 5(a) Emissivity variation with FeO thickness

In reality, an IR pyrometer operates at a fixed wavelength, but the thicknesses of iron-oxide layers increase with time.

Fig. 5(b) Emissivity fluctuations

Fig. 5(b) shows the transient behaviour of emissivity with oxide thickness at two wavelengths using a 1-layer model. Both curves oscillate over a certain thickness range but eventually stabilise. This implies that in order to obtain a reliable measurement, it is desirable to avoid the measurement being performed within this transient region.

Fig. 6(a) shows the emissivity variation with wavelength, of a 3-layer model, for different thicknesses of oxide. The case $d = 0$ represents a clean steel surface. Note that large differences exist between the emissivity of oxidised steel and clean steel. Due to the rapid build up of surface iron-oxide at high temperature, the widely used IR pyrometry actually measures the temperature of iron-oxide rather than steel.

Fig. 6(a) Emissivity variation with wavelength

Fig. 6(b) presents emissivity curves over an extended wavelength range into the centimetre region. The result agrees with the measured emissivity value ($\simeq 0.04$) obtained from a millimetre radiometer test.

Fig. 6(b) Emissivity behaviour at long wavelengths

It is important to note that the emissivity for thicknesses of iron-oxide layers in the range $d = 0$ to 0.1 mm are almost identical over the millimetre and microwave regions. This indicates that a microwave radiometer can "see" through the iron-oxide layers. The graphs in Fig. 6(b) also agree well with the known result :

$$\epsilon \propto \frac{1}{\sqrt{\lambda}} \tag{6}$$

The ability to penetrate the oxide provides the opportunity to measure steel temperature underneath the oxide layers. However due to the very low emissivity values (refer to (1)), the sensitivity of a microwave radiometer needs to be high to obtain a reliable measurement.

Fig. 7 shows how emissivity depends on temperature. This is due to the fact that the refractive indices are functions of temperature.

Fig. 7 Temperature dependence of emissivity

4. CONCLUSIONS

A three-layer model of iron-oxides on steel was used to investigate the relationship between emissivity, thickness of iron-oxide layers, and wavelength of radiation. The main conclusions are as follows :

- If the wavelength of measurement is larger than the thickness of FeO (95% of total layers) then the 3-layer model can be approximated by a 1-layer model.
- If the wavelength of measurement is significantly greater than the thickness of the combined oxide layers, eg. microwaves, the emissivity will be nearly that of pure steel. This implies that microwaves can penetrate iron-oxide layers.
- If the wavelength is less than the thickness of any of the oxide layers the 3-layer model must be used.

5. REFERENCES

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6. AUTHORS

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