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Heating rate effect on the thermophysical properties of steel in fire

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ABSTRACT

Steel structures subject to fire require fire resistance design to protect the lives of occupants and reduce the structural damage and failures. The fire resistance design incorporates the estimation of the thermomechanical behaviours of the structures based on the development of temperatures of the structural elements subject to fire in which the structures are heated at varying rates. Thermal properties of steel, including the emissivity and specific heat capacity, are particularly required for predicting the temperatures of steel structures under fire condition. Since the heating rate under fire condition varies, it is uncertain how the heating rate may affect the thermal properties of steel as, to date, there is no such investigation carried out. In this study, the thermal properties of steel under the heating rate effect were investigated. The emissivity of steel was measured in experiments and found to be strongly dependent on the heating rate. A new emissivity model based on the kinetic theory was developed and provides an accurate estimation of the property at different temperatures under different heating rates. In addition, the specific heat capacity of steel during phase transformation was also found to be dependent on the heating rate and its formulation was proposed in kinetic modelling. This study provides new insights into the material properties of steel and new models for estimating the thermal properties used for achieving robust fire resistance designs.

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1. Introduction

Steel structures are required to have not only the capacity to carry design loads at room temperature but also the ability to maintain their strength in extreme events such as earthquake and fire in the structural design. Steel structures may be subject to fire. Under fire condition such as that defined by the ISO standard fire curve [1], the fire temperature increases with time at varying heating rates. In such fire, the temperatures of steel structures also increase at varying rates while the strength of steel drops significantly compared with that at room temperature [2–4]. Consequently, severe structural damage or structural failure may occur. Therefore, the fire resistance design for steel structures must be carried out to ensure that the steel structures can maintain sufficient strength at high temperatures within the fire resistance period. The fire resistance design of steel structures requires an accurate estimation of the structural mechanical properties for fire resistance assessments as the temperature of steel structures increases in fire. For such assessment, the increment of temperature of steel structures subject to fire needs to be estimated first, and can be obtained through heat transfer analysis based on parameters included in the convection and radiation heat transfer processes. In order to obtain a robust fire resistance design, the variation of the thermal properties of steel under fire condition needs to be clearly understood. In particular, the thermal properties essential for simulating such heat transfer processes are the emissivity and specific heat capacity of steel.

The emissivity of steel (ε_s) is related to the amount of heat absorbed in steel due to radiation heat transfer. It influences the prediction of temperatures of the steel structures in fire [5]. In design standards, the value of ε_s is given as 0.7 in Eurocode 3 [6] and 1.0 in ASCE [7], and is independent of temperature. Many researchers measured the values of ε_s under the isothermal condition at some specific temperatures while the specimens were exposed to air environment [8,9]. It was found that the values of ε_s varied at different temperatures and were significantly dependent on the growth of oxide layer on the surface at high temperatures. Sadiq and co-workers [10] measured the ε_s under continuous heating at a specific heating rate using specimens with exposure to air. In their study, it was found that the values of ε_s varied from about 0.29 at low temperatures below 380 °C to 0.7 at high temperatures above 500 °C. However, no study has been performed to determine the ε_s upon continuous heating at different rates. In addition, the existing models developed for estimating the variations of ε_s were generated through the curve fitting of the experimental results without considering the effect of the heating rate [10,11].

The specific heat capacity of steel (C_a) is the other key thermal property and is important in determining the increase in the temperature of steel structures according to the amount of total heat flux absorbed in fire. Curves of C_a are provided in standards [6,7] which show that the values of C_a are significantly influenced by the latent heat effect at high temperatures during phase transformation. The heating rates used to obtain the curves are not given in the standards. Li and the co-

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workers [12] measured the C_a of 4130 carbon steel at only one heating rate up to a temperature of 1300 °C. However, the effect of heating rate on the variation of C_a has not yet been investigated.

In this study, the effect of heating rate on the emissivity and specific heat capacity of steel was investigated. First, the emissivity of steel was measured experimentally at varying heating rates. A new emissivity model was developed to describe the effect of heating rate on the variation of the property. Further, the effect of heating rate on the specific heat capacity of steel was also investigated in kinetic modelling. In this work, the range of heating rates adopted in the tests is appropriate for fire resistance design of steel structures. This series of investigations give new insights into the dependence of the thermal properties of steel on the heating rate as well as new models for estimating the properties considering the heating rate effect, thus providing the basis to obtain efficient fire resistance design of steel structures.

2. Effect of heating rate on the emissivity of steel

2.1. Experimental details and results

2.1.1. Methodology

In this study, the indirect method introduced in Sadiq's study [10] was adopted to measure the emissivity of steel ε_s through a series of high temperature tests. During each high temperature test, both the specimen temperature and the furnace temperature were recorded and used for further analysis. This analysis was based on solving the energy equilibrium equation, Eq. (1), using the incremental method for temperature prediction to calculate the ε_s.

$$\Delta\theta_{s,t} = \frac{A_m / V}{C_a \rho_a} \dot{h}_{net} dt \tag{1}$$

where $\Delta\theta_{s,t}$ is the increase of the temperature of the steel specimen during a time interval dt, A_m/V is the section factor for unprotected steel, C_a is the specific heat capacity of steel, $\dot{h}_{net}$ is the net heat flux per unit area, and ρ_a is the unit mass of steel. The net heat flux ($\dot{h}_{net}$) is equal to the sum of heat flux due to convection ($\dot{q}_c$) and radiation ($\dot{q}_r$). The equations for calculating $\dot{q}_c$ and $\dot{q}_r$ are given as

$$\dot{q}_c = h_c(\theta_f - \theta_s) \tag{2}$$

$$\dot{q}_r = \varepsilon_s \sigma \left[(\theta_f + 273)^4 - (\theta_s + 273)^4 \right] \tag{3}$$

where h_c is the coefficient of convective heat transfer, θ_s is the steel specimen temperature, σ is the Stefan-Boltzmann constant ($5.67 * 10^{-8}$ W/m^2 K^4), and θ_f is the furnace temperature. Since the surface area of the object, i.e. the specimen, is much smaller than that of the enclosure, Eq. (3) is appropriate for estimating the radiation heat flux between the specimen and the furnace walls attached with the heating coils [13].

By substituting Eq. (2) and (3) into Eq. (1), Eq. (4) below can be obtained. By substituting the measured θ_s and θ_f and other parameters in Eq. (4), the ε_s can be obtained indirectly.

$$\varepsilon_s(T) = \frac{C_a \rho_a \frac{V}{A_m} \frac{\Delta\theta_{s,t}}{\Delta t} - h_c(\theta_f - \theta_s)}{\sigma\left[(\theta_f + 273)^4 - (\theta_s + 273)^4 \right]} \tag{4}$$

2.1.2. Experimental procedures

High temperature tests were conducted to obtain the temperatures-time history of both steel specimens and the furnace for the estimation of the emissivity of the material. The device used for each of the tests is an electrical furnace with 800 mm * 350 mm * 350 mm internal dimensions. The specimens were made up of 4130 carbon steel with dimensions of 10 mm in diameter and 200 mm in length. The 4130 steel specimens were chosen because the C_a of this material was measured by Li and the co-workers [12] and can be used as the input in Eq. (4) to obtain the values of ε_s. The values of C_a of 4130 steel at different temperatures are presented in Fig. 7. Each specimen was prepared by following the procedures below.

1. The specimen surface was first rinsed with acetone to get rid of the oils, grease, or dirt.
2. The surface roughness (R_a) of the specimen was measured by using a surface profilometer since the surface roughness is one of the key factors influencing ε_s [14,15].
3. A thermocouple was then attached on the surface of the 4130 steel specimen and used to measure the temperature of this specimen.

The prepared specimen was located in the furnace and supported by ceramic bricks, as shown in Fig. 1. The same location of the specimen inside the furnace was maintained for each high temperature test. A thermocouple was located next to the specimen to measure the environmental temperature inside the furnace.

Two transient high temperature tests, each at a different heating rate, were performed on a new specimen. During each test, the specimen was heated from room temperature up to a maximum of 700 °C. This maximum test temperature was chosen to complete the thermal oxidation process [10] which was considered to influence ε_s at high temperatures. Besides, the maximum temperature is below the start temperature (at about 780 °C) for phase transformation to austenite of 4130 steel. Therefore, the same values of specific heat capacity at the test temperatures provided by Li and the co-workers [12] for the material could be used in Eq. (4) to estimate ε_s based on the results of both specimen and furnace temperatures obtained in experiments under different heating rates. The target heating rates for raising the furnace temperature were 35 °C/min and 6 °C/min for tests 1 and 2 respectively. These two different heating rates were used in order to investigate the heating rate effect on the emissivity and are the values that may encounter in typical fires [1,5]. After each high temperature test, the R_a of the tested specimen was also measured and compared with that of the specimen measured before the test.

Fig. 1. Experimental setup.

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