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Validity evaluation on temperature correction methods by thermocouples with different bead diameters and application of corrected temperature

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ABSTRACT

Accurate measurement of flame temperature by using bare thermocouples is a traditional and still a challenging problem. Three measurement methods, including the double- and triple-thermocouple correction methods and extrapolation method, have been developed to seek accurate gas temperatures, but the validity of these methods has been rarely evaluated for application in fire experiments. All the three methods use the temperature readings of multiple thermocouples with different bead diameters. This paper presents a systematic evaluation of validity for these methods by conducting fire temperature measurements. A turbulent propane pool fire was used. The temperatures along the fire plume centreline were measured at ten vertical heights of 10–55 cm, for which four thermocouples with different bead diameters were used at each height. Analysis shows that the flame turbulence imposes a significantly negative effect on the double- and triple-thermocouple correction methods. However, the extrapolation method can correct the fire gas temperature regardless of temperature pulsation related to flame turbulence. In addition, a new radiation model that incorporates the corrected flame temperature is proposed well against the radiant heat flux measurement. Moreover, it is found that the flame pulsation frequency can be roughly estimated by the temporal derivation of the corrected flame temperature.

1. Introduction

Thermocouples of different types have been developed to measure the flame temperature. Brundage et al. [1] used a mineral-insulated metal sheathed thermocouple to measure the laminar premixed flame temperature for identifying the effect factors of thermocouple temperature readings. The aspirated thermocouple or suction pyrometer also has been used for reducing the radiation error in fire temperature measurement [2,3], but with a significant sacrifice in spatial resolution. Krishnan et al. [4] recently designed a rotating thermocouple to achieve accurate flame temperature measurements and also a spatial resolution better than that of the sunction pyrometer, but with a complex structure. In comparison, the bare thermocouple is widely used to measure the fire temperature due to its simplicity, good spatial resolution and cost effectiveness [3,5–8].

A bare thermocouple immersed in hot fire plume frequently underestimates the true gas temperature mainly due to the radiation loss to the cold ambient surroundings [3,7]. Moreover, the measurement errors by a bare thermocouple may be also caused by the conduction to the main leads, but the conduction loss can be reduced to be negligible by increasing the thermocouple wire-flame contacting length [5,7]. Thus, several temperature correction methods [6,8] based on multiple thermocouples with different diameters have been developed based on the fundamental heat transfer theory, as follows:

$$mc\frac{\mathrm{d}T}{\mathrm{d}t} = hs(T_g - T) - \varepsilon\sigma s(T^4 - T_0^4) \tag{1}$$

where m, c and s are the mass, volumetric specific heat and surface area of thermocouple bead, respectively, T the thermocouple bead temperature, t the time, h the convection heat transfer coefficient between fire gas and thermocouple bead, T_g the fire gas temperature, T_0 the effective ambient temperature (represented as the sum of all the surrounding objects at temperatures T_{01}, T_{02}, $\cdots$, T_{0n}), ε the thermocouple bead emissivity, and σ the Stefan–Boltzmann constant.

If the quasi-steady-state temperature was achieved by a bare thermocouple placed inside fire and the flame temperature pulsation holds little effect on the transient heating term, Eq. (1) can be reduced to

$$T_g - T = \frac{\varepsilon\sigma}{h}(T^4 - T_0^4) \tag{2}$$

The convection heat transfer coefficient is usually calculated by the

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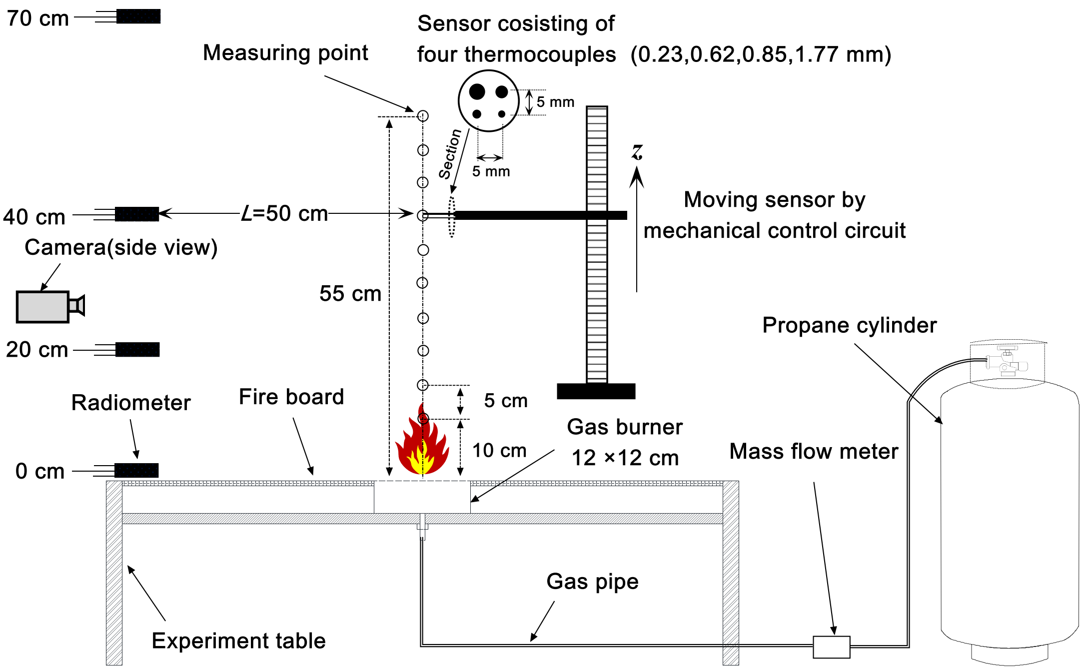

Fig. 1. Schematic for experimental setup.

empirical correlation of Nusselt number $Nu = hd/k_g$, where d is the bead diameter and k_g the fire gas conductivity. One commonly used expression from Zukauskas [9] is written as

$$Nu = 0.51Re^{0.5}Pr^{0.37} \tag{3}$$

where $Re = ud/v_g$ in which u and v_g are the upward velocity and kinematic viscosity of fire plume, respectively, and Pr the Prandtl number.

Several correction methods based on multiple thermocouples with different bead diameters have been developed based on Eqs. (2) and (3). One is the double-thermocouple correction method formulated by the following analytical correlation

$$T_g = T_s + \frac{T_s - T_b}{\left(\frac{T_b^4 - T_0^4}{T_s^4 - T_0^4}\right)\sqrt{\frac{d_b}{d_s}} - 1} \tag{4}$$

where the subscript s and b present thermocouples with small and big bead diameters, respectively. For use of Eq. (4) it is difficult to accurately determine the effective ambient temperature because of the temporally and spatially varying environment [10]. Therefore, a triple-thermocouple correction method was proposed, which was formulated as [8].

$$T_g = \frac{(T_s - \sqrt{d_s/d_b}\,T_b) - (T_s - \sqrt{d_s/d_m}\,T_m)\frac{T_s^4 - T_b^4}{T_s^4 - T_m^4}}{(1 - \sqrt{d_s/d_b}) - (1 - \sqrt{d_s/d_m})\frac{T_s^4 - T_b^4}{T_s^4 - T_m^4}} \tag{5}$$

where m presents the thermocouple of middle diameter. Eqs. (4) and (5) have been validated for considerable application in the temperature correction of thermocouples immersed in the burning flame of a furnace [8].

Besides the above two methods, there is also another method for which the gas temperature is evaluated by the extrapolation of the temperatures recorded by thermocouples with different bead sizes [1,5,6]. According to Eqs. (2) and (3), as the thermocouple bead diameter approaches zero, the h is infinite and then the thermocouple temperature reading approaches the true gas temperature. That is why the fine thermocouple can give the readings approaching the true gas temperature, and evenmore completely record the turbulent gas temperature pulsation. However the fine thermocouple is easy to break in the fire gas of relatively high flow speed and costs much. Thus it is of significant use to correct tempearature readings of thick thermocouples by the above three methods. For the extrapolation method, Daniels [6] suggested a second-degree equation to fit the air temperature data measured by thermocouples with different bead sizes (no improvement in the accuracy for high degree equations) as follows

$$T = A + Bd + Cd^2 \tag{6}$$

where A ($A = T_g$), B and C are constants determined by a least squares solution.

However, the validity of these methods has been rarely evaluated for application in fire experiments. Thus this paper presents a systematic evaluation on the validity of these methods by conducting turbulent pool fire temperature measurements. The temperatures along the fire plume centerline were measured at ten vertical heights, for which four thermocouples with different bead diameters were used at each position. The corrected temperatures were used for a new radiation model to calculate the radiant heat flux against experimental measurement and two other classical radiation model predictions. In addition, an analysis on the corrected temperatures was also conducted to estimate the flame pulsation frequency against experimental measurement and one classical model prediction.

2. Experimental

2.1. Experimental setup

Fig. 1 shows the schematic for the experimental setup. A square burner of 12 cm × 12 cm was designed and placed inside a piece of fire board. In the center of the fire board, a hole was dug to make the burner tip being flush with the board surface. The burner was fully filled with glass beads of 2.34 ± 0.12 mm in diameter, so that the propane gas from the pressure vessel could reach the burner exit at a nearly zero speed. A mass flow meter was used to monitor the mass flow rate. During test, the propane mass flow rate was controlled at 8.98 ± 0.09