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Experimental measurements, integral modeling and smoke detection of early fire in thermally stratified environments

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Abstract

Building fires go through a series of stages. They start with a fire plume period during which buoyant fire smoke rises to the ceiling. A second stage is the following enclosure smoke-filling period. In this paper, the first stage is the subject, especially for the fire plume behavior in thermally stratified environments in large volume spaces. In NFPA 92B, Morton's integral equation was introduced for calculating the maximum plume rise, and beam smoke detectors were recommended for smoke detection design. In this work, experiments and CFD simulations were conducted in a small-scale enclosure and a large space to investigate early fire movements in temperature-stratified ambients. The results show that in a thermally stratified environment, the axial temperature and velocity of a fire plume decrease more quickly along the vertical axis than in uniform environment, and in some cases the fire plume ceases to rise. The previous integral equation was shown to underestimate the actual maximum height of a fire smoke plume, and also was unable to explain the differences of the maximum heights of low-density and high-density smoke plumes with the same stratification and outlet conditions. The integral equation was improved by introducing two correction factors, and extended for non-linear temperature stratified environments. A light section smoke detection method with three space-protected area was suggested and discussed.

Keywords: Fire smoke plume; Thermally stratified environments; Integral equation; Correction factors; Smoke detection

1. Introduction

In large space buildings such as enclosed shopping malls, arcades, sports arenas, exhibition halls and airplane hangars, the solar radiation, air conditioning system and the translucent glass structure tend to produce an increasing ambient temperature from floor to ceiling, which is called as a thermally stratified environment.

As a buoyant, turbulent fire plumes rises, it cools by entrainment of ambient air. In a temperature-stratified space, the ambient air increases in temperature with height. If the fire source is weak, the temperature difference between the plume and the ambient, which gives the plume buoyancy, may vanish and actually reverse sign. Eventually, the plume ceases to rise and plume fluid moves laterally to eventually form a more or less horizontal layer, fire detectors under the ceilings are unable to detect and fire loss may occur.

The objective of the work reported here was to develop general correlations for smoke distributions of low-intensity fires in temperature-stratified spaces to aid in assessing damage potentials and designing detector installations.

The previous work of fire smoke movements in large spaces mainly focused on smoke filling and settlement process of a large fire by experimental measurements or zone modeling for smoke exhaust or egress time analysis [1–3].

In NFPA 92B [4], for consideration of stratification, the maximum smoke rise equation, which only depends on the convective heat release rate and the ambient temperature variation in the space, was derived by Morton et al. in 1956 [5] using an integral model as

$$Z_{\max} = 5.54 Q_c^{1/4} \left(\mathrm{d}T_a/\mathrm{d}Z\right)^{-3/8}. \quad (1)$$

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Nomenclature

Z_{max}	plume maximum height (m)
Q_c	convective portion of the fire heat release rate (kW)
T_a	ambient air temperature (K, °C)
T	smoke temperature (K, °C)
Z, z	vertical coordinate, plume height (m)
B	thermal buoyant flux (m^4/s^3)
N	Brunt–Vaisälä buoyant frequency (Hz)
ρ_a	r air density (kg/m^3)
ρ	smoke density (kg/m^3)
C_p	heat capacity at constant pressure (J/(kg K))
P	constant atmospheric pressure (Pa)
r_0	radius of smoke outlet (m)
d_0	diameter of smoke outlet (m)
u	local mean vertical velocity of smoke (m/s)
A	sectional area of a plume (m^2)
k_1	smoke density correction factor
k_2	self-similarity correction factor
z^*	the characteristic length of the fire with reference to the source diameter
x	horizontal coordinate
R^*	resolution of simulation
δ	burner surface grid size (m)

Eq. (1) often takes the following form, which is usually used to analyze the bubble movements in the density-stratified water [6–8].

$$Z_{max} = 3.8 B_0^{1/4} N^{-3/4}, \tag{2}$$

where B_0 is the thermal buoyant flux (m^4/s^3), N is described as below

$$N = \left(-\frac{g}{\rho_{a0}} \frac{d\rho_a}{dZ} \right)^{1/2}, \tag{3}$$

where ρ_{a0} is the reference air density (kg/m^3), taken as the ambient air density near the fire source, g is the gravitational acceleration. It is easy to prove that the above Eqs. (1) and (2) are equivalent by substituting $B_0 = gQ_c/\rho_{a0} C_p T_{a0}$ and ideal gas law into (2), T_{a0} is the ambient air temperature near the fire source.

It can be seen that in the NFPA 92B Z_{max} equation, only fire power and ambient air temperature are related, smoke property especially smoke density effect is not considered, while for the same Q_c and dT_a/dZ, different fire materials may have different Z_{max} values when there are differences between smoke densities.

For fire plumes in thermally stratified environment, little work was done except Heskestad's experiments [9] about heptane fire in a temperature-stratified environment in a 3.66 m × 3.66 m × 2.44 m high-compartment room. The results showed that the centerline temperature rise and CO_2 concentration agreed well with the calculated values below the theoretical plume reach, but the experimental maximum height needed an incremental value. In his study, the measurement method of the maximum heights was mainly responsible for the shortcomings of the maximum rise equation without more reasonable interpretations.

In large volume spaces with thermally stratified environments, the temperature gradient dT_a/dZ is not always linear, and early fire detection is a difficult task. In NFPA 92B, detection schemes recommended are beam smoke detectors with enough units, which are located at various horizontal and upward positions, to detect the smoke at different levels and different angles regardless of the condition present at the time of fire initiation.

In this paper, to better understand fire smoke plume behaviors in temperature stratified environments, and evaluate NFPA 92B equation and conventional beam smoke detection method, experiments and numerical simulations were carried out in a small enclosure and a large volume space, later the previous integral equation was discussed, modified and extended for linear and non-linear stratification conditions, finally a light section image smoke detection method was proposed to detect the early fires in large volume spaces.

2. Experiments

2.1. Experimental thermally stratified room

The experimental room was a small-scale enclosure, which was 1.2 m long, 1.2 m wide and 2 m high enclosed by transparent thermoplastic materials, which thermal coefficient of conduction is 0.027 W/m K, and coated with black cloth materials, leaving a front face for observation and a vent for smoke exhaust as Fig. 1 shows. In the bottom of the experimental setup, there were small air gaps connected with the outer environment to keep a constant atmospheric pressure.

The stable linear thermally stratified air environments were accomplished by pre-heating the enclosure air with fifteen quartz heating pipes evenly spaced under the ceiling

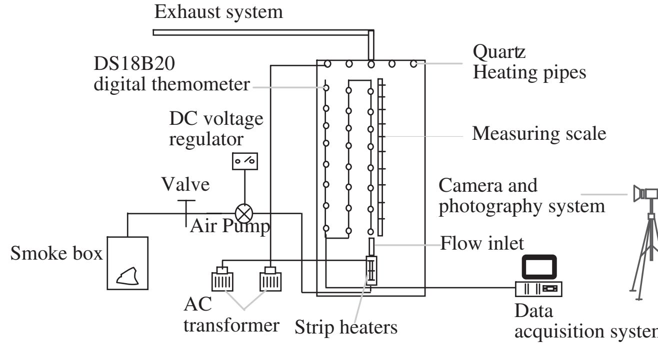

Fig. 1. Schematic plan of the experimental setup.