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An experimental investigation of stratification characteristic of fire smoke in the corridor under the effect of outdoor wind

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A R T I C L E I N F O

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A B S T R A C T

An investigation of previously established correlations between gas temperature distribution and smoke stratification in corridors and tunnels has been carried out. The investigated correlations are based on excess gas temperature ratios and Froude number scaling. A set of experiments were carried out in a scale-modelled "room-corridor" to investigate the stratification characteristic of smoke induced by fire and outdoor wind. The smoke flow pattern was visualized and the wind speed, the heat release rate and area of the window were investigated. The dimensionless parameter Froude number (Fr) was used to describe the stratification characteristics. The results show that when $Fr \leq 0.29$, the smoke stratification is extremely strong; when $0.29 < Fr \leq 0.58$, the stratification intensity remains high and the smoke stratification is still strong; when $0.58 < Fr < 0.92$, the stratification strength decreased significantly; when $0.92 \leq Fr$, the fire smoke mixed completely with the lower air and the smoke stratification failed. This can provide reference for the study of smoke stratification in corridor.

1. Introduction

A fire can be defined as undesirable burning of materials with release of heat and toxic gases, causing hazards to people and structures. It has been shown that human causalities are much more due to smoke exposure than burns by flames (Stec and Hull, 2010). So much efforts have been made to explore fire safety engineering issues, particularly those relating the smoke dynamics. Smoke stratification induced by thermal buoyancy is a common phenomenon in building fires (Cooper et al., 1982a). When the fire smoke enters the corridor through the door, it should be maintained as stratified for safe egress. It has been found that the thermal buoyancy is beneficial to the stratification of the smoke. However, the forced ventilation may reduce the stability of smoke layer which can be harmful to occupant evacuation.

Outdoor wind was one of the important driving forces of fire smoke, which blows into the fireroom and increases the smoke production and the mass flow rate of smoke. The outdoor wind velocity increases exponentially with increasing building height, which has significant influences on the fire smoke spread in high-rise building (Li et al., 2017). If the outdoor wind was strong enough, the natural smoke exhaust may be degraded or even invalidated (Yi et al., 2013; Chen et al., 2011). Wind blow into the fire room from windows and carry a large amount of smoke into the corridor, which can affect the stratification of the smoke and threat the evacuation and firefighting (Yi et al., 2013; Chen et al., 2011). Therefore, it is necessary to study the smoke stratification characteristic in the corridor under the effect of outdoor wind. The current paper investigates the effects of outdoor wind on the stratification stability of smoke in the building corridor using a set of medium scale experiments. A criterion of smoke stratified stability in the corridor was proposed which can benefit the smoke control and firefighting of buildings.

Previous research investigated the fire smoke flow in the corridor or tunnel focusing on the distribution of smoke temperature, the forward velocity (He, 1999; Hu et al., 2005) and the stratification characteristics (Brahim et al., 2016). Stratified flow was extensively studied but is still a hot topic in the field of hydrodynamics (Zhao et al., 2015; Wei, 2017; Tang et al., 2017). J. G. Quintiere (Quintiere et al., 1978) studied the smoke and flow field in a corridor subject to a room fire using a scale model and visualized the smoke flow in the corridor. Myung Bae Kim (Kim et al., 1998) conducted large-scale experiments in which the visualization technique with a laser sheet were firstly used to observe the variations of the smoke layers along a corridor. Small size salt water experiments were carried out by Ellison and Turner to study the surface jet and inclined plume which indicating that the entrainment coefficient of stratified flow was determined by an overall Ri number (Ellison and

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Turner, 1959). The zone model was studied by Hinkley and the distinction between the two extreme situations was controlled by the Richardson number and the criterion for determining the stability of smoke by using Ri: when Ri > 0.8, it was completely stratified and when Ri < 0.8, it was mixed (Hinkley, 1970). P.H.E. Vandeleur researched smoke stratification through numerical simulation and pointed out that stratification was critical for the spread of smoke. In the five simulation scenarios, the corridor area of Ri < 0.8 appeared, but the smoke layer did not lose stability; when the temperature of the smoke layer decreased along the longitudinal direction, the Ri number did not decrease, but increased. Therefore, it is not appropriate to simply and coarsely use Ri = 0.8 as the criterion of smoke stratification and stability as stratification has an important influence on fire and smoke spread (Vandeleur et al., 1989).

D. Yang (Yang et al., 2010) carried out a lot of experiments in a reduced-scale horizontal channel to investigate the fire-induced buoyant flow stratification behavior. It was found that under the effect of forced ventilation, the stratification pattern fall into three regimes as the result of the comparison of two factors: buoyancy force and inertia force. The criterion for judgement was: at Region I (Ri > 0.9 or Fr < 1.2), the buoyant flow stratification was stable, where a distinct interface existed between the upper smoke layer and the lower air layer; at Region II (0.3 < Ri < 0.9 or 1.2 < Fr < 2.4), the buoyant flow stratification was stable but with interfacial instability; at Range III (Ri < 0.3 or Fr > 2.4), the buoyant flow stratification becomes unstable, with a strong mixing between the buoyant flow and the air flow and then a thickened smoke layer. The dimensionless Froude number (represents the ratio of inertia force to buoyancy force) or Richardson number (the ratio of buoyancy force to inertia force) was calculated by Eq. (1) and Eq. (2):

$$Fr = \frac{\Delta U}{[(\Delta\rho/\rho)gh]^{1/2}} = \frac{\Delta U}{[(\Delta T/T_a)gh]^{1/2}} \tag{1}$$

$$Ri = g\beta H \frac{T_t - T_b}{(U_t - U_b)^2} \tag{2}$$

where Δ represents difference between variables, U represents horizontal velocity, ρ represents density, g represents the gravitational acceleration, h represents thickness of the hot layer, T represents temperature and the subscript a represents the ambient, the subscripts t and b represent the top and the bottom of the measurement tree respectively, H represents the height from the bottom thermocouple to the top thermocouple, β represents thermal expansion coefficient.

A significant amount of experiments were carried out by Newman to study the stratification characteristic of smoke in mine tunnel with longitudinal wind (Newman, 1984). The experiments were done in a T-type underground mine tunnel with a dimension of 2.4 m × 2.4 m × 61 m. Newman studied both the temperature and species distributions in the smoke layer and proposed another Froude number (Fr) as shown in Eq. (3). The calculation of Fr does not require the velocities of smoke and air layers but used the average velocity u_{avg} of the whole cross section. Meanwhile, Newman also proposed that the smoke stratification can be determined by Fr, as shown in Eq. (4).

$$Fr = \frac{u_{avg}}{\sqrt{gH\Delta T_{cf}/T_{avg}}} \tag{3}$$

$$\frac{\Delta T_{cf}}{\Delta T_{avg}} = f(Fr) \tag{4}$$

where u_{avg} is the average velocity of the whole cross section of tunnel, g is the gravitational acceleration, H is the clear height of tunnel, ΔT_{cf} is the temperature difference of ceiling (at 0.88H) and floor (at 0.12H), ΔT_{avg} is the temperature difference between the average temperature of cross section and ambient temperature. The experimental data show that the stratification characteristic of smoke can be divided into three regions using the Froude number as shown in Fig. 1.

Region Ⅰ, $Fr < 0.9$, smoke stratification is strong and the layer is clear.

Region Ⅱ, $0.9 < Fr < 10$, smoke stratification is in the transition and the smoke layer is not obvious.

Region Ⅲ, $Fr > 10$, there is no stratification and the smoke is completely mixed.

The Froude number of region Ⅰ is low indicating that the buoyancy is dominant in smoke stratification. The hot smoke flows near the ceiling and the smoke temperature near the floor is close to the ambient temperature. Region Ⅱ is the transition stage in which there is an interaction between the longitudinal wind and smoke although the temperature stratification has been weakened, there still exists large temperature gradient in the vertical direction. The stratification in region Ⅲ is no longer existing, which leads to a uniform temperature distribution.

Newman (1984) found that $\Delta T_{cf}/\Delta T_{avg}$ and Froude number have a reciprocal correlation:

$$\frac{\Delta T_{cf}}{\Delta T_{avg}} = 1.5Fr^{-1} \tag{6}$$

In region Ⅰ:

$$\Delta T_h = \frac{2.25gH}{T_{avg}}\left[\frac{\Delta T_{avg}}{u_{avg}^2}\right]^2 \tag{7}$$

In region Ⅱ:

$$\Delta T_h = 1.8\left[\frac{gH}{T_{avg}u_{avg}^2}\right]^{0.23}\Delta T_{avg}^{1.23} \tag{8}$$

where ΔT_h is the temperature difference of ceiling and ambient temperature. Ingason (2007) verified Newman's theory and proposed that the gas species and temperature show the same distribution in the vertical direction. According to full-scale and 1/20 small-scale experimental data, Nyman and Ingason. (2012) confirmed Newman's temperature stratification theory. Nevertheless, when studying the relationship between $\Delta T_{cf}/\Delta T_{avg}$ and Froude number, Nyman found that $\Delta T_{cf}/\Delta T_{avg} = 0.62Fr^{-1.58}$ and the critical value to divide the region Ⅰ and region Ⅱ was Fr = 0.55 which was different from the critical criteria of Newman's Fr = 0.9. The difference was confusing, but Nyman collected both full-scale and 1/20 small-scale experimental data from multiple researchers (including Newman's data) and it was thought that his conclusion was more reliable.

Corridor is a typical long and narrow confined space, similar as tunnel. However, the smoke stratification characteristics and theories in tunnels can not be directly used for corridor owing to the different geometry and ventilation conditions. Therefore, the tunnel researches can only act as references to the stratification characteristic in corridors. New experiments are demanded. This study aims to investigate the stratification characteristic of smoke in corridor under outdoor wind. Then, theoretical analysis is carried out to identify the mechanism of smoke stratification.

Smoke layer height or interface height is an important parameter in the zone fire modelling and in the fire safety calculations in general. Hot smoke generated in the fire plume tends to move along the upper part of

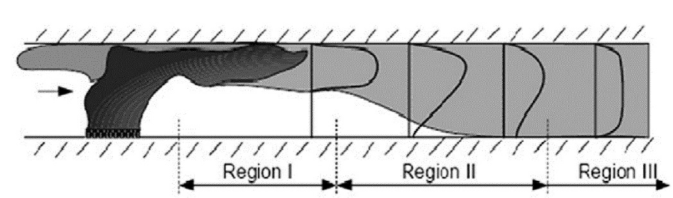

Fig. 1. Three types of smoke flow patterns in the tunnels proposed by Newman.