International Journal of Heat and Mass Transfer 88 (2015) 91–100

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

The physical model and validation study of ceiling-jet flow in near-field of corridor fires

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ARTICLE INFO

Article history:
Received 19 January 2014
Received in revised form 26 December 2014
Accepted 9 January 2015
Available online 14 May 2015

Keywords:
Corridor fire
Temperature rise
Physical model
Ceiling-jet
Near field
Numerical simulation

ABSTRACT

In the corridors, combustion products of the fire are confined to spread in one or two directions, forming a ceiling-jet flow. For safety assessment and emergency treatment, it is important to investigate and understand the behavior of the ceiling-jet flow. In this paper, a simplified model has been developed and improved, which has been verified by the numerical calculation. It is worth mentioning that for the radial spreading region, we have simplified Alpert's equations, and obtained the simplified solution. Moreover, in this region, the mass entrainment has been got by linear fitting. And for the region of hydraulic jump, two sub regions of IV1 and IV2 have been established to analyze the conversion process. In order to validate the theoretical predictions, a series of small-scale experiments and numerical simulations have been conducted to validate the physical model of corridor fires. The predicted results, concerning exit position and flow state in near field, agree favorably with experimental data in different conditions.

1. Introduction

Tunnels or long corridor fires are nowadays greatly concerned in the research field of fire safety science. In tunnels or corridors, the fire smoke is hard to be exhausted because of the particularity of space structure, so high temperature and toxic gases are the major cause of death in the fire accident [1]. In order to provide the reliable design and safe operation of tunnels, the physics of ceiling jet flow should be well understood first.

In the confined corridor, the fire smoke flow is buoyancy driven. The buoyancy-driven hot gas flows below the ceiling has attracted focused research attention in recent years [2–5]. Meanwhile, between hot upper gas layer and lower cooler layer, there is an interaction mass entrainment occurred. A great deal of studies shows that mass entrainment, stability of stratified flow [6], and flow state [7–10] are closely related.

Some theoretical models have been proposed to study the dynamic characteristic and energy deduction process of the ceiling jet flow. Alpert [11] has developed a theory to predict the major characteristics of turbulent ceiling-jet flow in terms of the fire's heat release rate and distance under the ceiling. The governing equations were established to obtain the reduction of temperature and velocity, which was characterized by a dimensionless number, Richardson number (Ri). Cooper [12] briefly discussed the heat transfer to unconfined ceiling surfaces from buoyant plume driven ceiling jets. Based on Alpert's theory, the smoke spread under a beamed ceiling had been studied by Delichatsios [13]. The ceiling jet flow was divided into three regions according to Froude number, and an expression of the flow properties (temperature, velocity) agreed well with the experimental results. Combining the studies of Alpert and Delichatsios, Kunsch [14] proposed a model to predict the critical velocity of tunnel fire. In the model, the whole flow field has been divided into five regions by Kunsch, that is, (I) plume region; (II) turning region; (III) radial spreading region; (IV) transition region (Jump occurred in this phase); (V) one-dimensional flow region, but there is no predication and validation of the temperature field and velocity field. In terms of Richardson number and non-dimensional ceiling-jet thickness, Li [15] has presented a simple model to predict the temperature and the velocity of fire-induced ceiling-jet in a rectangular corridor.

However, the classical theories of fire plume and ceiling jet have been established for the common chamber fire or the flow under the ceiling, whether it is applicable to the corridor fire need to be validated further. For example, Alpert's model is applied to the unconfined ceiling flow within a certain distance, not to long-narrow space, in which smoke movement is restricted by

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.01.146
0017-9310/

Nomenclature

b	plume half-width defined by Eq. (1) (m)
B	width of corridor (m)
C_P	specific heat of gas (kJ/kg/K)
c_f	friction factor
E	entrainment function
E_p	entrainment function of plume
g	gravitation acceleration (m/s^2)
H	ceiling height (m)
H/B	height-wide ratio
h_c	convective heat transfer coefficient (kW/m^2/K)
h	thickness of smoke flow (m)
$\dot{Q}_c$	convective heat transfer (kW)
$\dot{Q}_{total}$	total of heat release rate (kW)
q''	heat flux (kW/m^2)
r	radial coordinate (m)
T_∞	ambient temperature (K)
∇T	gas temperature rise, time-mean (K)
∇T_e	gas temperature rise at the end of turning region, time-mean (K)
V	characteristic velocity (m/s)
x	longitudinal coordinate, origin at plume source
y	coordinate in width, origin at plume source
z	vertical coordinate, origin at plume source
∇	characteristic density (m/s^2)
β	plume profile parameter
ρ	gas density (kg/m^3)
ρ_∞	ambient density (kg/m^3)

Subscripts

c	turning region entrance
e	radial spreading region entrance, or turning region exit
o	radial spreading region exit, or transition region entrance
f	transition region exit
p	plume
∞	ambient condition

the wall. Other models focus on the radial spreading region, or one-dimensional flow region, theoretical analysis of the ceiling jet flow induced by a fire in the tunnels or long corridors has not been studied systematically.

In this paper, based on the theory of ceiling jet and stratified flow, the mathematical model of ceiling-jet flow in the corridor has been established. Simplified model can be obtained by means of the analysis of influence factors, and the relative parameters have also been discussed. Theoretically, for the region (I) and region (II), the smoke movement is just the same as the free fire plume, so we can follow the Yokoi model [16] and Alpert ceiling-jet theory. But for the radial spreading region, according to Alpert's theory, fraction coefficient and heat loss can be neglected. However, entrainment is the main governing factor in the confined corridor. Therefore, how to solve the mass flow becomes the main problem. And for the transition region, which is called 'Hydraulic Jump', previous studies have mainly focused on the position of hydraulic jump. But the temperature and velocity profile could not been predicted by the model, which is also the focus of this paper. At the same time, a small size test bench has been set up to study the flow characteristics in the near field of the corridor fire.

2. Physical model analysis

A fire plume in a tunnel or corridor is represented schematically in Fig. 1. The fire source can be idealized as a point source. Five regions can be divided for the complete flow region.

Region (**I**): from the surface of fire source to point c, plume region;
Region (**II**): from point c to e, turning region;
Region (**III**): from point e to o, radial spreading region, $Fr^2 > 1$;
Region (**IV**): from point o to f, transition region, where $Fr_o^2 > 1$ before hydraulic jump, $Fr^2 < 1$ after hydraulic jump and $Fr_f^2 = 1$ at f;
Region (**V**): from point o to f, one-dimensional flow region, where $Fr^2 = 1$.

The Froude number is defined as $F_r = \frac{u}{\sqrt{gh}}$ where g is the gravitational acceleration, and v and h are characteristic values of velocity and length, respectively.

In order to analyze the flow development from the source to the near field of the corridor fire, certain assumptions has been made as following:

1. Mass entrainment, frictional effect and heat loss can be neglected;
2. Mass entrainment law of Ellison and Turner [7] can be applied;
3. Alpert's ceiling-jet model can be applied in the turning region;
4. The temperature of near-field fits Gaussian distribution.

The physical model for the fire development from fire plume to the one-dimensional flow region will be established based on the study results of Apert [11], Delichatsios [13] and Kunsch [14]. The regions of radial spreading and transition will be corrected and recalculated especially (see Figs. 2 and 3).

2.1. Region (I): plume region

The smoke movement is just the same as the free fire plume. When the heat release rate is low, the flame height is far less than

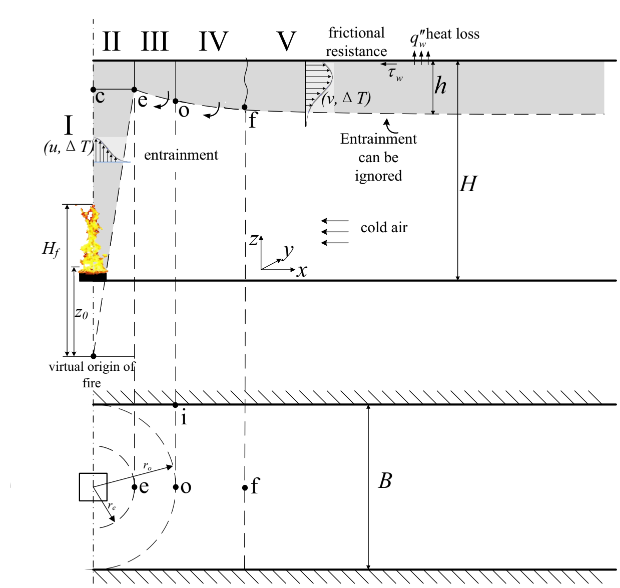

Fig. 1. Schematic diagram of the physical process of smoke movement in corridor.