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A global model on temperature profile of buoyant ceiling gas flow in a channel with combining mass and heat loss due to ceiling extraction and longitudinal forced air flow

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ABSTRACT

This paper investigates temperature profiles of buoyancy-driven gas flow (both upstream and downstream) beneath a channel ceiling with combining heat and mass loss due to ceiling extraction (right above the buoyancy source) and longitudinal forced air flow. Experiments are conducted in a large scale model channel with dimensions of 72 m (length) × 1.5 m (width) × 1.3 m (height). The gas temperature profiles beneath the channel ceiling are measured by K-type thermocouples. Computational Fluid Dynamics (CFD) Large Eddy Simulations (LES) are carried out correspondingly by Fire Dynamics Simulator (FDS). It is found that: (a) with ceiling extraction only, the gas temperature profiles along the ceiling are symmetrically similar for upstream and downstream; and both decay faster longitudinally with increase in ceiling mass extraction velocity; however (b) with both ceiling extraction and longitudinal forced air flow, the gas temperature decays faster upstream than that downstream. A global model is theoretically proposed to describe the gas temperature profiles in both upstream and downstream direction with combination of mass and heat loss due to ceiling extraction and longitudinal forced air flow. Its predictions are in good agreement with measured values and CFD simulation results.

1. Introduction

The buoyancy-driven hot gas flows along the channel ceiling with its profiles varying with distance, which has attracted focused research attention in recent years [1–4]. Due to the special structure, the hot gases will spread to a long distance along the channel ceiling driven by the buoyancy (gravitational) force as well as by the longitudinal forced air flow [5–9]. So, the gas temperature profile along the channel ceiling is one of the key parameters in determination of its buoyancy driven strength during longitudinal spread, as well as in the maintenance of the buoyancy induced gas–air flow stratification.

Several models have been proposed to predict the decay of gas temperature beneath the ceiling in a channel [10–12]. Delichatsios [10] has studied the heat loss from ceiling flow to the ceiling and proposed following non-dimensional exponential function model, based on measured gas temperature profiles along a beamed ceiling in a corridor:

$$\frac{\Delta T_x}{\Delta T_0}\left(\frac{l}{H}\right)^{1/3} = 0.49\exp\left\{-6.67St\frac{x}{H}\left(\frac{l}{H}\right)^{1/3}\right\} \tag{1}$$

where ΔT_x is the average temperature rise at x meters from the reference position, K; ΔT_0 is the temperature rise near the ceiling over the buoyancy source, *K*; l is one half of the corridor width, m; H is the ceiling height and St is the Stanton number. Evers and Waterhouse [11] have also established similar exponential function based on experiments as follows:

$$\frac{\Delta T_x}{\Delta T_0} = K_1\exp(-K_2 x) \tag{2}$$

in which the parameter K_2 is defined as:

$$K_2 = \frac{K_1\alpha W}{\dot{m}C_p} \tag{3}$$

In Eqs. (2) and (3), K_1 is the empirical constant; α is the heat transfer coefficient, W/(m^2 K); W is the corridor width, m; $\dot{m}$ is the gas mass flow rate, kg/s and C_p is the specific heat of air at constant pressure, kJ/(kg K). It should be noted that the contribution to the ceiling gas flow temperature decay due to the turbulence mixing between the gas flow and fresh air (or entrainment of cool fresh air into the gas flow) is in fact negligible compared with that due to heat loss

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Nomenclature

l	one half of the channel width (m)	D	part of the perimeter of the gas flow contacting with channel surface (m)
A	channel cross-sectional area (m^2)	z	height from buoyancy source (m)
c_p	specific heat of air at constant pressure (kJ/kg K)	S	ceiling extraction outlet area (m^2)
g	gravitational acceleration (m/s^2)	T	hot smoke temperature (K)
H	ceiling height (m)	T_a	ambient air temperature (K)
H_d	height from buoyancy source to channel ceiling (m)	v	longitudinal forced air flow velocity (m/s)
ΔT_x	average temperature rise at x meters from the reference position (K)	V_c	critical velocity (m/s)
ΔT_0	temperature rise near the ceiling over the buoyancy source (K)	V	ceiling extraction velocity (m/s)
$\dot{m}$	mass flow rate of ceiling gas flow (kg/s)	St	dimensionless Stanton number
$\Delta\dot{m}$	mass flow rate of ceiling extraction (kg/s)	α	heat transfer coefficient (W/m^2 K)
Q	heat (buoyancy) release rate of source (kW)	ρ_a	ambient air density (kg/m^3)
Q_a	modified actual heat release rate (kW)	ρ	gas flow density (kg/m^3)
W	channel width (m)	K	gas flow temperature decay factor (m^{-1})

through the tunnel ceiling and walls [10–15]. This results in the exponential function based on the theoretical deducing of the heat loss process through the channel ceiling and walls.

Bailey [12] has carried out numerical simulation research with three-dimensional Computational Fluid Dynamics model by Large Eddy Simulation LES3D model, and proposed an empirical power law distribution for the temperature profile in the ceiling flow:

$$\Delta T_x = \Delta T_0 \left(\frac{1}{2}\right)^{x/16.7} \tag{4}$$

The longitudinal forced air flow along the channel makes the ceiling gas flow spread to be more complex. Recently, Hu [13] has studied the decrease of the gas flow temperature along the channel ceiling and, based on a theoretical analysis of heat loss, proposed similar exponential function as those by Delichatsios [10], Evers and Waterhouse [11]:

$$\frac{\Delta T_x}{\Delta T_0} = \frac{T_x - T_a}{T_0 - T_a} = e^{-K(x-x_0)} \tag{5}$$

in which,

$$K = \frac{\alpha D}{C_p \dot{m}} \tag{6}$$

where D is the part of the perimeter of the gas flow section that contacts the channel surface, m. This model has been validated by a series of full-scale experiments in large scale channels with longitudinal forced air flow (e.g., [14,15]). It is also found (e.g., [14,15]) that the decay factor K (Eq. (6)) is smaller when the longitudinal forced air flow speed is higher; and being higher in upstream direction than that in the downstream direction.

However, there is still few works in considering the ceiling gas flow temperature profile at combined condition of ceiling (mass) extraction and longitudinal forced air flow. Meanwhile, such kind of ventilation design strategy is going to be more and more common in channels in recent years, due to the inherent shortcoming of longitudinal forced air flow ventilation in destroying the hot-gas–air layer stratification at high flow speed [16,17]. With the additional effect of ceiling (mass) extraction, the gas flow movement is different from the situation with only longitudinal forced air flow. The combination of ceiling (mass) extraction with longitudinal forced air flow makes the problem even more complex, which has rarely been investigated. The goal of this work is to clarify and characterize the gas flow temperature profiles along channel ceiling with combination of mass and heat loss due to ceiling extraction and longitudinal forced air flow.

In this paper, a series of experiments are conducted in a large scale model channel with different buoyancy (heat) release rates, ceiling mass extraction velocities and longitudinal forced air flow velocities. Computational Fluid Dynamics (CFD) Fire Dynamics Simulator (FDS) Large Eddy Simulations (LES) have also been performed correspondingly. A new global model has been brought forward, through theoretical analysis based on the ceiling gas flow temperature decay model with longitudinal forced air flow only [13], with modified key parameters including effective heat release rate (buoyancy strength) and effective longitudinal air flow speed with additional ceiling (mass) extraction effect. Experimental measurements and numerical simulation results are used to compare with and validate the theoretical model.

2. A simplified theoretical analysis

A simple theoretical model is deduced to account for the gas flow temperature decay beneath the channel ceiling with combination of mass and heat loss due to ceiling extraction and longitudinal forced air flow, as shown in Fig. 1. The physical base is that in addition to Eqs. (5) and (6) for longitudinal forced air flow only, the effect of additional ceiling extraction will modify the following parameters: (a) the actual mass flow rate in the gas flow is to be deduced by the amount exhaust out by the ceiling extraction system; (b) the actual heat release rate (buoyancy strength) of the gas flow is to be deduced by the amount exhaust out by the ceiling extraction system; and (c) the actual longitudinal air flow speed (upstream and downstream) is to be modified by that amount induced by the ceiling extraction.

The mass flow rate without ceiling extraction can be estimated by the turbulent buoyant plume entrainment based on the classic Zukoski model [18]:

$$\dot{m} = 0.071\dot{Q}^{1/3}z^{5/3} \tag{7}$$

in which z is the height from buoyancy source, m. A part of the mass is exhausted out by the ceiling extraction outlet, the actual mass flow rate in the smoke flow can be expressed as:

$$\dot{m}_a = \dot{m} - \Delta\dot{m} \tag{8}$$

The mass flow rate of ceiling extraction $\Delta\dot{m}$ can be calculated by:

$$\Delta\dot{m} = \rho V S \tag{9}$$

where V is the ceiling extraction velocity, m/s; S is exhaust outlet area, m^2, with

$$\rho/\rho_a = T_a/T \tag{10}$$