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Fire spill plume from a compartment with dual symmetric openings under cross wind

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ABSTRACT

This paper presents a comprehensive theoretical and experimental study on the fire spill plume from a compartment with dual symmetric openings under cross wind. Experiments of spill plume were performed at the outlet of a wind tunnel using a bench-scale compartment with a leeward façade wall and dual symmetric openings. The experimental fire compartment was well-mixed. The effect of wind is theoretically elucidated by derivations on the pressure differences between inside and outside. The neutral planes for the two openings are theoretically formulated and compared with those in single-opening and no-wind case. The formulations of the neutral plane heights are verified by using video image analysis and velocity data regression analysis. Also a new method using the data of wind speed and neutral plane height in no-wind case is proposed to determine the neutral plane heights for higher wind speeds. The results suggest that the neutral plane heights vary monotonically with cross wind speed. Two new length scales with variable neutral plane heights are proposed by theoretical derivations to develop scaling models of spill plume. It is indicated that the new length scales are applicable to correlate the axial plume temperature and the total heat flux along the façade. The radial temperature profiles of spill plumes are well described by a Gaussian function normalized by the temperature radius, which is independent on the wind speed. It is found that wind enhances the air entrainment of spill plume in both the near and far fields, thereby the transition from continuous flame, intermittent flame to buoyant plume is accelerated. The data of total heat flux and temperature distribution along the façade indicate that cross-wind has two competitive effects on the heat transportation from the spill plume to the façade.

1. Introduction

Fire spill plume is an important phenomenon in compartment fires. In a post-flashover compartment fire, the smoke layer above the neutral plane (where the pressure difference between inside gas and outside air is zero) may flow out of the openings (windows, doors etc.) to form spill plume (Fig. 1). In high-rise building fires, fire spill plume often induces fire spread along the exterior façade, which may cause serious threat to the safety of building structure and human life.

During the past decades, spill plume has drawn wide attention in fire community, and some models have been developed based on experimental data analysis. Prahl and Emmons [1] pointed out that spill plume is driven by the pressure difference at the opening. Steckler et al. [2, 3] verified theoretically and experimentally that the mass flow rate of spill plume is proportioned to the so-called ventilation factor $A\sqrt{H}$, here A and H respectively denote the area and height of opening. This agrees with the pioneering work of Kawagoe [4]. In the classic work of Yokoi [5], dimensionless correlations of the excess temperature and the upward velocity were established by a length scale r_0 which represents the radius of a circle with half the area of the opening and equals to $\sqrt{W(H-H_N)/\pi}$, where W is the width of opening, and H_N, the neutral plane height, was assumed to be $0.5H$. In the work of Ohmiya et al. [6], the opening width W was used as a length scale to correlate the data of flame height with the heat release rate generated by external combustion ($\dot{Q}_{ext}$), and correlate the total heat flux of the plume on the façade wall, with the total convective heat flow rate $\dot{Q}_{conv}$. Himoto et al. [7] performed dimensional analysis of two-dimensional spill plume and used a dimensionless heat

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Nomenclature

A	area of the opening [m^2]
a	parameter of Gaussian function in Eq. (41) [dimensionless]
$b(z)$	effective temperature radius [m]
C_1	regression parameter in Eq. (40) [dimensionless]
C_2	regression parameter in Eq. (40) [dimensionless]
C_d	discharge coefficient at the opening [dimensionless]
C_p	specific capacity of gas [kJ/kg K]
$C_{P,L}$	pressure coefficient at leeward opening [dimensionless]
$C_{P,W}$	pressure coefficient at windward opening [dimensionless]
g	gravitational acceleration [m^2/s]
H	height of the opening [m]
H_N	neutral plane height in no-wind case [m]
$H^L_{N,w}$	neutral plane height under wind at the leeward opening [m]
$H^W_{N,w}$	neutral plane height under wind at the windward opening [m]
K	constant in effective temperature radius $b(z)$ [dimensionless]
l_1	characteristic length scale related to the thermal outflow at the opening [m]
l_2	characteristic length scale representing the length after which the flow turns from horizontal to vertical [m]
l_3	characteristic length scale representing the distance after which the flow turns from horizontal to vertical [m]
L_f	flame length [m]
$\dot{m}$	mass flow rate [kg/s]
P	pressure [Pa]
P_{a0}	reference static pressures at zero plane of ambient air [Pa]
P_{g0}	reference static pressures at zero plane of inside gases [Pa]
P_{gN}	static pressures of inside gases at the neutral plane [Pa]
$\dot{Q}$	heat release rate [kW]
$\dot{Q}_{conv}$	convective heat flow rate of spill plume [kW]
$\dot{Q}_{ex}$	excess heat release rate of spill plume [kW]
$\dot{Q}_{ext}$	external heat release rate of spill plume [kW]
$\dot{q}''_t$	total heat flux along the façade wall [kW/m^2]
r_0	radius of a circle with half the area of the opening [m]
Ri	Richardson number [dimensionless]
T	temperature [K]
T_r	temperature at radial distance r from the center line of the plume [K]
$T_{r,\max}$	centerline temperature of the plume [K]
T_x	temperature at the horizontal coordinate x [K]
$T_{x,max}$	the maximum temperature at $x = x_m$ [K]
$T_{x,z}$	temperature at the horizontal coordinate x and the height z [K]
$T_{0,z}$	parameter of Gaussian function representing the baseline of the peak in Eq. (41) [K]
V	velocity [m/s]
W	width of the opening [m]
w	parameter of Gaussian function in Eq. (41) [dimensionless]
x	horizontal distance relative to the façade [m]
x_m	horizontal coordinate of maximum temperature at the specific height [m]
z	vertical distance relative to the lower edge of opening [m]
z_n	height of virtual source [m]
z_0	height of neutral plane [m]

Greek symbols

α	constant in effective temperature radius $b(z)$ [dimensionless]
β	parameter of Gaussian function in Eq. (42) [dimensionless]
ξ	distance along the spill plume trajectory [m]
Θ	non-dimensional temperature [dimensionless]
ρ	density of gases [kg/m^3]
Δ	difference [dimensionless]

Subscripts

a	ambient air
$conv$	convective
ex	excess
ext	external
f	fuel gas inside the compartment
g	upper layer gas inside the compartment
max	maximum
r	radial
w	wind
x	horizontal distance relative to the façade [m]
z	vertical distance relative to the lower edge of opening [m]
0	origin of the coordinate

Superscripts

$*$	non-dimensional
L	leeward opening
W	windward opening
$'$	per unit length
$''$	per unit area

Overheads

.	per unit time

release rate $\dot{Q}'^* \equiv \dot{Q}'/(\rho_\infty C_p T_\infty g^{1/2}(H-H_N)^{3/2})$ to correlate the axial temperature data, where $\dot{Q}'$ was the heat release rate of the window flame per unit length.

Recently, Lee et al. [8] proposed two new length scales as the modifications of Yokoi's length scale [5]. One length scale is $l_1 \propto (A\sqrt{H})^{2/5}$, which is related to the thermal outflow at the opening, and the other is $l_2 \propto (AH^2)^{1/4}$, which represents the length after which the flow turns from horizontal to vertical owing to buoyancy. Lee et al. [9] also developed a new length scale $l_3 \propto (AH^{4/3})^{3/10}$ to correlate the flame height and the heat exposure to the façade wall and a parallel opposite wall under different opening geometries, fuel supply rates, and intervals between the two walls. The established correlations were recently further verified by Tang et al. [10] in reduced-scale experiments.

The developed correlations and length scales have allowed the researchers to simulate the spill plume and correlate the experimental data with different scales. Nevertheless, some problems remain unsolved.

First, the available experimental data and correlations of fire spill plume are mainly associated with single-opening compartment, however dual cross openings (i.e. two openings located on opposite walls) are very typical for buildings such as warehouses, schoolrooms, ship cabins and some high-rise buildings. So far, only a few experimental studies addressed the compartment with two