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A mathematical model on lateral temperature profile of buoyant window spill plume from a compartment fire

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ABSTRACT

A Gaussian-based mathematical model is theoretically brought forward to describe the lateral temperature profile (in the direction normal to the façade wall) of a spill buoyant plume from window of a compartment fire. The model is built up physically based on that this buoyant plume is conceptually produced by a rectangular fire source with characteristic side dimensions of ℓ_1 (beside wall, physical length scale related to the effective area of the outflow) and ℓ_2 (normal to wall, physical length scale representing the length after which the outflow turns from horizontal to vertical due to buoyancy) sitting beside an adiabatic façade wall at the neutral plane height of the window. A deduced length scale, by accounting for the entrainment of air mass flow rate into the plume from the non-constrained sides, is brought forward to characterize the effective plume thickness in the direction normal to the façade wall, which will be used in the Gaussian profile function. Experiments are carried out in an experimental device to validate the model developed for six different windows. Results show that the length scale proposed for describing the effective plume thickness can successfully collapse the experimental data of different total heat release rates for various window geometries, and the proposed Gaussian-based model can predict the lateral temperature profile measurements. Furthermore, an exponential function is proposed for the parameter β in the Gaussian profile of such a spill plume in relation to the window aspect ratio (H/W).

1. Introduction

Buoyant fire plume characteristics have been studied for decades as an important aspect of fundamental fire research [1–8], which can be described as a vertically rising hot gas column driven by the combusting flame where the buoyancy-induced heat and mass transportation is the key mechanism. These characteristics include entrainment rate and mass flow rate, flame height, vertical variation of temperature and uprising velocity, as well as the radial (horizontal) profile of temperature and velocity. For a free-standing axis-symmetric fire plume, classical Gaussian profile approximation had been well used based on the measurements of Quintiere and Grove [2] and Rouse et al. [3], and is commonly deemed as an adequate description method for normalized radial temperature profile in the vertical center plane of the plume region above the flame

$$\frac{T - T_\infty}{T_{\max} - T_\infty} = \exp\left\{-\beta\left[\frac{r}{b(z)}\right]^2\right\} \quad (1)$$

where T is temperature at radial distance r from the center line of the plume, $T_{\max}$ implies maximum or centerline temperature, and the effective plume radius $b(z)$ is a function of z due to the entrainment of fresh ambient air into the buoyant plume by turbulence, resulting in an expansion of plume cross-sectional size with height. Morton et al. [4] and Steward [5] have established similarity solutions for an idealized axis-symmetric point source and two-dimensional strip fire plumes. Yokoi [6] have measured the vertical and radial temperature profile of free buoyant plume produced by point and line fire source.

This paper studies another special buoyant plume, which is issued from the window of an under-ventilated fire compartment, and attach to the outside façade wall [6,9,10]. It is the major cause of the floor-to-floor fire spread, which will result in big threaten to building and even urban fire safety. For such a spill plume issued from the window and attached to the façade wall, the entrainment from the wall side is constrained. And at the same time, it has initial horizontal momentum. These characteristics make it quite different from both the free-standing fire plume which has no wall constrain effect to the entrainment (nor initial horizontal momentum), and the wall plume which has wall constrain effect but no initial horizontal momentum. Yokoi [6] has carried out the first and most basic research on such spill buoyant plume

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Nomenclature

A	area of the window (m^2)
b	effective radius of free plume (m)
c_p	specific heat of air at constant pressure (kJ/(kg K))
H	height of the window (m)
J_0	buoyant convection strength of the spill plume (kW)
ℓ_1	characteristic length scale, $\ell_1 = (A\sqrt{H})^{2/5}$
ℓ_2	characteristic length scale, $\ell_2 = (AH^2)^{1/4}$
L	effective characteristic thickness of the spill plume (m)
$\dot{m}_a$	air mass inflow rate into the compartment through the window (kg/s)
$\dot{m}_e$	air entrainment mass flow rate into the plume (kg/s)
$\dot{Q}$	total convective buoyancy release rate outside the window (kW)
$\dot{Q}_{ex}$	excess heat release rate (kW)
$\dot{Q}^*$	dimensionless total heat release rate normalized by characteristic length scale $\ell_1 (\dot{Q}^*_{conv,\ell 1})$
$T_{\max}$	maximum or centerline temperature (K)
T_∞	ambient temperature (K)
ΔT	temperature rise above the ambient (K)
ΔT_{aw}	maximum temperature rise above the ambient at adiabatic wall surface (K)
u	uprising velocity of the plume (m/s)
W	width of the window (m)
z	vertical height (m)
z_n	neutral plane height of the window (m)
z_0	virtual origin (m)
Greek symbols	
ρ_∞	air density (kg/m^3)
ρ	density of plume gas at height z (kg/m^3)
ρ_F	density of hot gas when issuing out of the window (kg/m^3)
α	entrainment coefficient
β	Gaussian profile constant

characteristics for over-ventilated compartment fires. Dimensionless vertical temperature distribution along the trajectory axes of the plume is correlated experimentally. Himoto et al. [11,12], Ohmiya et al. [13,14] and Yamaguchi and Tanaka et al. [15] have developed a model to predict the trajectory of window flame ejected from a fire compartment, based on reduced scale experiments. Flame height has also been investigated with models developed by, e.g., Oleszkiewicz [16], Klopovic and Turan [17,18], Lee [19], and Lee et al. [20]. However, although there are already some earlier works on the quantitative vertical temperature distribution along the plume axes [6,9,17,18] and qualitative reports on two dimensional temperature distribution pattern outside the window [11,15], there is still no quantitative works reported on a model to describe the horizontally lateral temperature profile for such spill plumes. In contrast to the free fire plume, the function of $b(z)$ and the value of β in Eq. (1) should be re-found for such spill fire plume due to their inherent difference in entrainment and plume shape.

In this paper, a mathematical model is developed based on the Gaussian profile approximation to describe the lateral temperature distribution in the direction normal to the façade wall, for such buoyant plumes spilled out of the window of a compartment fire. In considering the Gaussian profile model, the variation of effective lateral thickness of the spill plume with height is deduced by accounting for the air entrainment mass flow rate contribution from the un-constrained sides. Experiments are further carried out to validate the model. The constant β in the Gaussian profile model for such spill plume is also discussed.

Following the introduction, the mathematical model development are described in Section 2, the experimental validation and discussion in Section 3 and the concluding remarks are summarized in Section 4.

2. A mathematical lateral temperature profile model based on Gaussian approximation

As shown in Fig. 1, the buoyant plume spilled out of the window can be physically deemed [20] as produced by a rectangular fire with side dimensions of ℓ_1 (beside wall, physically being length scale related to the effective area of the outflow) and ℓ_2 (normal to wall, physically being length scale represented the length after which the flow turns from horizontal to vertical due to buoyancy) sitting beside the façade wall at the neutral plane height of the window with a constant buoyancy convection of J_0. Here, it is assumed that the cross section area of the spill plume above the virtual fire source and flame (the plume stays attached or after re-attachment) can be reasonably approximated by a rectangular shape and that the aspect ratio of the rectangular is preserved. However, the horizontal width (in the lateral direction) of the fire source is determined by the characteristic length scale of ℓ_1, and its length (parallel to the façade wall) by the characteristic length scale of ℓ_2 [20].

$$\ell_1 = (AH^{1/2})^{2/5}, \quad \ell_2 = (AH^2)^{1/4} \tag{2}$$

With the rising of the plume, the air mass entrainment into the plume makes the horizontal plume size to increase with height. Thus, the correlation of ℓ_x with z needs to be established for determining parameter profiles across the thickness of the spill plume in the direction normal to the wall.

It is the buoyancy-induced turbulent entrainment transportation of fresh air mass flow into the buoyant plume that makes the value of ℓ_x to increase with z. The physical mechanism of such entrainment can be assumed to be similar to that of a free fire plume. The entrainment comes from all sides of the plume perimeter except that bounded by the façade wall:

Table 1
Summary of experimental scenarios.

Test series	Window (m)		Total heat release rate (HRR) / equivalent full-scale HRR (scale factor is 1:4) (kW)				
	Height	Width					
1	0.20	0.30	128.3/4106	140.5/4496	152.7/4886	165.0/5280	177.2/5670
2	0.25	0.25	146.6/4691	158.8/5082	171.1/5475	183.3/5866	195.5/6256
3	0.35	0.35	213.8/6842	226.1/7235	232.2/7430	238.3/7626	244.4/7821
4	0.40	0.20	177.2/5670	189.4/6061	201.6/6451	213.8/6842	220.0/7040
5	0.30	0.20	152.7/4886	165.0/5280	177.2/5670	189.4/6061	195.5/6256
6	0.20	0.40	165.0/5280	177.2/5670	183.3/5866	189.4/6061	195.5/6256