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Research Paper

Influence of heat release rate and wall heat-blocking effect on the thermal plume ejected from compartment fire

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HIGHLIGHTS

- Increasing HRR leads to plume getting closer to the wall.
- Wall heat-blocking effect causes quick attachment of plume trajectory.
- T-trajectory and V-trajectory are inconsistent in the near-wall region.

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ABSTRACT

High temperature and intensive radiation heat flux generated by ejecting flame are considered as the key factors causing fire spreading to the upper floors through building facade. Extensive effort has been devoted to study the plume temperature profile and trajectory. However, there are still obvious inconsistencies among the reported results. In this paper, both experimental and simulation methods were used to investigate the influence of heat release rate (HRR) and wall heat-blocking effect on the plume trajectory. A reduced scale compartment model was used. Cases with similar geometry were simulated with FDS6. Results suggested that in addition to the opening geometry, HRR and the wall heat-blocking effect also affected the plume trajectory. Increasing HRR would lead to the plume getting closer to the wall. Wall heat-blocking effect would cause deviation between temperature field and velocity field. In determining the plume trajectory in horizontal direction, (i) the induced pressure difference acted on the whole plume and pushed the plume towards the wall like a rigid body; (ii) the initial velocity dominated from the opening to the equilibrium point; (iii) the wall heat-blocking effect dominated in the region above the equilibrium point (only for attached plume).

1. Introduction

Window ejecting flame is a common phenomenon in compartment fire scenario, and usually occurs during the fully-developed stage caused by the combustion of excessive fuel outside the compartment. The high temperature [1,2] and the intensive radiation heat flux [3] generated by the external flame [4–8] are generally recognized as the key factors that lead to flame spread vertically to the upper floors through the building facade. Preventive facilities, like non-combustible spandrel (vertical) [9] and apron (horizontal) [10–14] have been proposed and studied. However, as glass facade is gaining popularity in modern commercial buildings, especially in high-rise buildings, those facilities are hardly implemented nowadays. Considering the glass facade is easy to crack [15–19], a detailed understanding of the ejecting plume trajectory is needed to improve the design of fire protection system in modern buildings. For fire safety concern, the plume trajectory is one of the main factors to investigate.

When there is a wall above the openings, the ejecting plume can be categorized into attaching plume and non-attaching plume [9]. The opening geometry is often believed to be the unique factor that determines the plume trajectory. The three existing criteria for evaluating plume attachment all used length scale related to the opening geometry [9,20,21]. The ejecting flame was found to attach to the vertical wall when the opening is of a large aspect ratio, W/H [9,12,20,21]. However, some reported results [12,22,23] show that even with the same opening geometry, the plume trajectory differs from each other. As shown in Fig. 1, although the openings in these three cases were of the same aspect ratio, the ejecting plume in Fig. 1(a) and (b) detached from the wall, while the plume in Fig. 1(c) attached to the wall.

The induced pressure difference between the two sides of the plume has always been regarded as the source driving the plume towards the wall and even making it finally attach to the wall, but this view needs to

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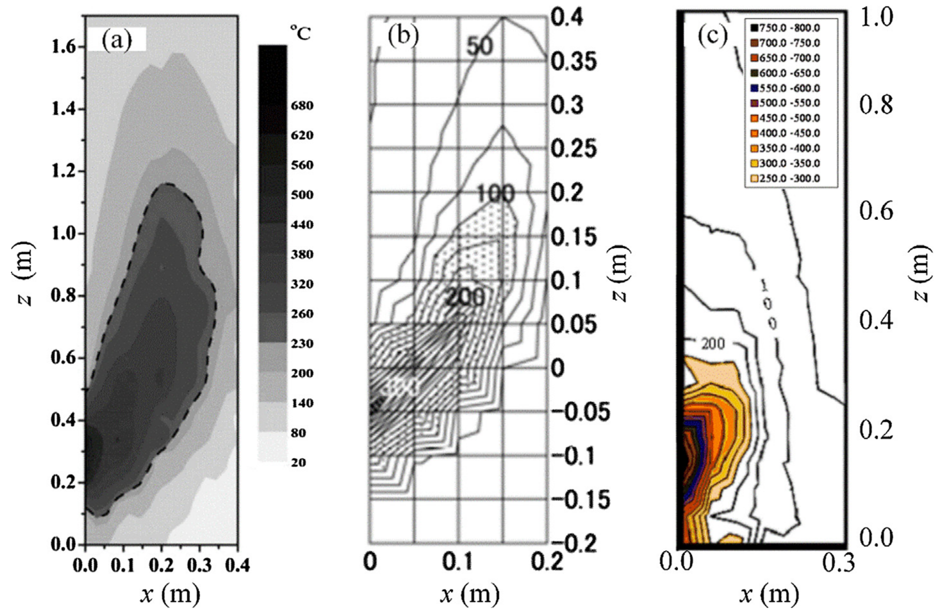

Fig. 1. Temperature contours of ejecting flame from openings with same aspect ratio. (a) reported by Cui et al. [23], opening geometry 0.2 × 0.4 (m), HRR ≈ 170 kW; (b) reported by Yamaguchi et al. [12], opening geometry 0.1 × 0.2 (m), HRR ≈ 2.2 kW; (c) reported by Yanagisawa et al. [22], opening geometry 0.1 × 0.2 (m), HRR ≈ 16.1 kW.

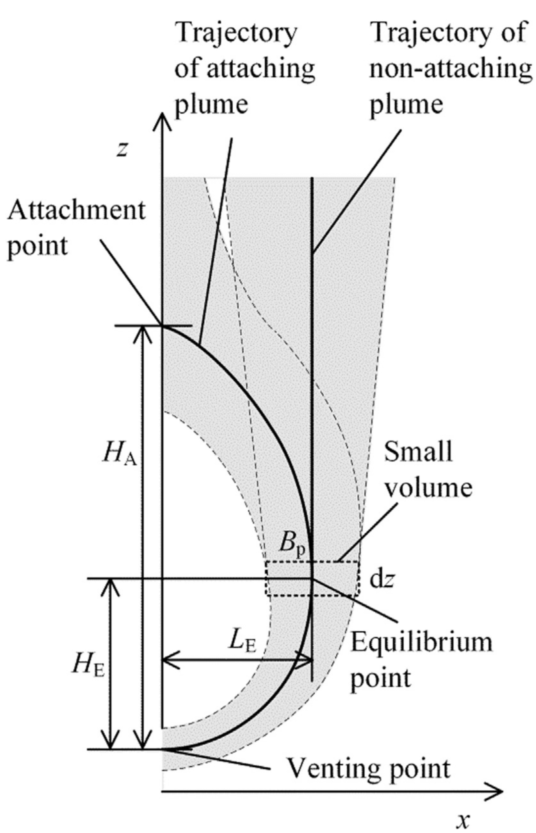

Fig. 2. Trajectory of ejecting plume.

be treated carefully. It is well known that when the plume moves upward, it entrains ambient air into the main stream. And when a wall exists near the plume, pressure difference exists between the two sides of the plume (by-wall region and the ambient region), considering that the air supply to the by-wall region is restricted by the wall [9,20,23,24]. This pressure difference was believed to "push" the plume towards the wall. However, referring to the reported plume trajectories [20] and the plume temperature contours [12,22,23], it was found that the plume trajectory soon attached to the wall after the equilibrium point. (In this paper, "equilibrium point" is defined as the position where the plume starts to move in the vertical direction as shown in Fig. 2, which is similar to the definition by Himoto [20]). In some cases, the vertical distance from the equilibrium point to the venting point (H_E) was nearly equal to (or even larger than) the vertical distance from the equilibrium point to the attachment point (H_A–H_E) [20]. It means that the horizontal velocity generated by the induced pressure difference was comparable to the initial horizontal velocity at the opening. It is doubtful whether the entrainment-induced pressure difference can generate such a large horizontal velocity.

The disagreements imply that there should be some unrecognized factors affecting the plume trajectory. In this paper, influence of the heat release rate (HRR) and the wall heat-blocking effect on plume trajectory was studied. Here the wall heat-blocking effect means the total effect that the wall reduces heat loss from the plume to the surroundings through the by-wall side. When there is a wall above the opening, plume temperature decreases relatively slower on the by-wall side, and thus the near wall region would become the high temperature region with the increase of height. This paper also aimed to explain the reason for the quick attachment of plume trajectory after the equilibrium point. Experiments using reduced scale compartment model with varying fuel supply rate were carried out to study the effect of HRR. Then, numerical simulations using Computational Fluid Dynamics (CFD) package FDS6 were conducted. The integrated trajectories based on velocity fields were compared with the trajectories based on temperature fields. Finally, the wall temperature was set to be constant and equal to ambient temperature in numerical simulation to study the influence of wall heat-blocking effect on plume trajectory.

2. Description of experimental facilities

2.1. Compartment-facade model

A reduced scale compartment-facade model as shown in Fig. 3 was used. The compartment was made of 5 cm-thick aluminosilicate board (bulk density 280–320 kg/m^3, conductivity (W/(m K)) 0.09 (400 °C), 0.12 (600 °C), 0.15 (800 °C), 0.20 (1000 °C), specific heat capacity 900