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Ventilation limited extinction of fires in ceiling vented compartments

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ABSTRACT

Compartment fire behaviour under ceiling ventilation was experimentally investigated in a reduced-scale compartment. Different fuels, including methane, propane, N-heptane, ethanol and N-butanol, covering both gas and liquid phase fuels were used in the experiments. Measurements included gas fuel flow rate, pool fire Mass Loss Rate, gas temperature, and gas mole fraction. The fire development processes in ceiling vented compartments were described using energy and species balances. The influence of both the vent size and the fire size on energy and species transfer was examined. A ventilation limited extinction boundary was found for ceiling vented compartments and the general self-extinction processes were represented. The experimental results were plotted using a ventilation parameter $(A_v^{5/4}/\dot{Q}_f)$ derived from balance equations. It was found that this parameter can be used to identify the general ventilation condition in ceiling vented compartments. The oxygen concentration and gas temperature were shown to depend on the ventilation parameter.

1. Introduction

The compartment fire is one of the core elements of fire research. After decades of effort, our knowledge of normal compartment fires has greatly improved. Using a ventilation factor, $A\sqrt{H}$, (where A and H are the area and height of the ventilation opening), general vent flow problems involving vertical vents (e.g., typical windows and doors) can be analysed [1]. Additionally, due to the stratified thermal field, the fire behaviour in these compartments can be quasi-steady when the vent flows are appropriately balanced. However, when dealing with compartment fires under ceiling ventilation (e.g., fires in ships with deck hatches, fires in basements with stairway or burned out skylights, and fires in utility corridor with ceiling inspection outlets), the impact of stratification is that the hot smoke impedes the steady air inflow at the ceiling vent. Relatively little research has been conducted on modelling the transient fire development for such conditions.

The biggest difference between compartments with vertical wall ventilation and compartments with horizontal ceiling ventilation is the fire induced vent flow conditions at the openings. For fires in a vertically vented enclosure, a stratified two-way flow exists in which the combustion products flow out of the upper part of the vent and fresh air flows in from the lower part of it [2–4]. However, when the vent is at the ceiling, Jaluria et al. [5,6] found, for most cases with fire, that both density and pressure differences exist across the vent and lead to both buoyancy and pressure effects. The use of Bernoulli's equation, with a discharge coefficient, was no longer appropriate for these cases since the flow was bidirectional. Recently, the characteristics of buoyancy induced flow in ceiling vented compartments were numerically investigated by Venkatasubbaiah et al. [7–9]. The vent flow intensity was found to be strongly affected by the vent location and size as well as the flow turbulence, as characterised by the Grashof number, G_r. Other differences exist between the vertical and horizontal vent flows. Utiskul et al. [10] concluded that the horizontal ceiling vent flow rate is nearly 1/10th of the wall vent flow rate for comparable density difference and vent sizes according to theory of Cooper et al. [11–14].

In addition to Jaluria et al. [5,6], other researchers have examined fires in ceiling vented compartments. Tu [15] investigated ethanol pool fires in a $0.43 \times 0.43 \times 0.43\ \text{m}^3$ compartment varying ceiling vent size from 0 to $0.3048 \times 0.3048\ \text{m}^2$. He found that increasing the area of the ceiling vent size causes the fire behaviour to transition from initially being "choked and then extinguished" to becoming "erratic pulsating" and finally to becoming a "strong steady burning" state. Ventilation limited extinction takes place in the first regime of fires (i.e., "choked and then extinguished"). Wakatsuki [16] conducted experiments in a small cubic compartment with a central ceiling vent. "Extreme" fire behaviour such as ghosting flames and oscillating flames were observed in the

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research. The behaviour was observed to be similar to the three stages of fires classified by Tu [15]. More recently, Zhang [17,18] performed experiments in a $3.0 \times 3.0 \times 1.75\ \mathrm{m}^3$ ship model compartment considering the effect of an elevated fire source. Some other studies have focused on the ghosting flame analysis [19], flame pulsation behaviour [20], and vent flow oscillation [21–23]. Ventilation limited extinction occurred in many of the tests. These studies indicated that ceiling vented compartment fires are typically under-ventilated. The ventilation condition from the ceiling has a significant impact on the fire behaviour in such compartments and should control the self-extinction of the fire.

This study focuses on fire behaviour in ceiling vented compartments under limited ventilation conditions. Under some conditions, a ventilation-limited self-extinction phenomenon was observed in these experiments. Interestingly, despite differences in the type of ventilation, the fire phenomena from this study were similar to those observed by Utiskul et al. [10] in research on a small compartment fire with small upper wall and lower wall vents. Dimensionless variables were derived by Utiskul et al. [10] from quasi-steady balance equations to model the fire behaviours for their two-vent-wall scenario. Their findings are quite significant in understanding the fire behaviours under limited ventilation conditions. Since the horizontal ceiling vent flow rate is likely greatly reduced, the ventilation model for ceiling vented compartments should be quite different from that of wall-vented compartments.

In this paper, heat and mass transfer models through ceiling vented compartments were constructed. A dimensionless analysis method was used to analyse the ventilation parameters of the compartment fires under ceiling ventilation. Experiments with various fuel types were conducted and plotted using the dimensionless parameters to reveal the fire behaviour, and effort was made to describe the self-extinction phenomena in such conditions.

2. Experimental

The reduced scale experimental compartment was designed according a typical ship cabin as shown in Fig. 1. Its interior dimensions are 1.00 m (L) × 1.00 m (W) × 0.750 m (H), which is almost 1/4 scale of its original dimension. The compartment, except for the front wall, was constructed from 5 mm thick steel board, which simulates a ship cabin with relatively large heat loss from the walls. A large vitro-ceram window was installed at the front side of the compartment for visualisation. The only ventilation opening is located at the corner of the ceiling. The ceiling vent size can be adjusted from closed to $0.49 \times 0.49\ \mathrm{m}^2$.

Two types of cylindrical burners (Fig. 2), one for gas and one for liquid fuels, were used in the tests. Both burners have a diameter of 0.20 m and were elevated 0.10 m above the compartment floor. Different fuels, including methane, propane, N-heptane, ethanol and N-butanol, were burned. Fuel properties are included in Table 1. The gas supply rate of gas burner was measured by a digital multi-gas mass flow metre (Alicat Scientific® M20SLPM). The Mass Loss Rate (MLR) of the liquid burner was acquired by a load

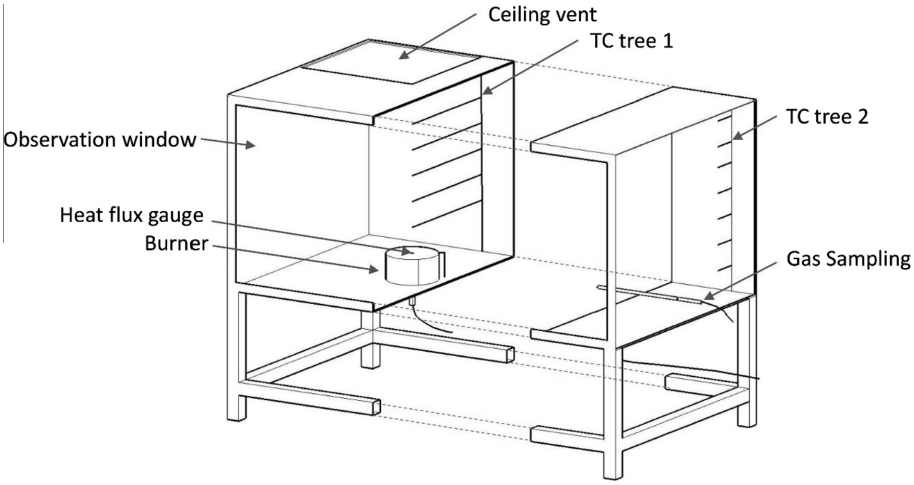

Fig. 1. Experimental apparatus.

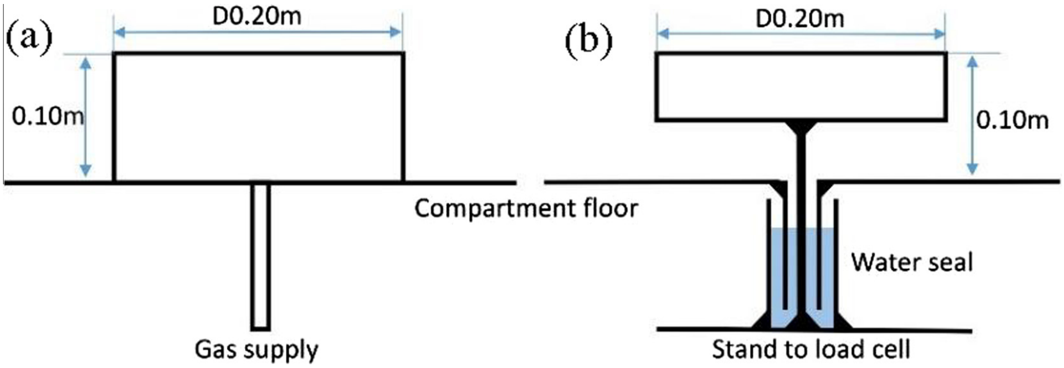

Fig. 2. Schematic of burners for gas and liquid fuels: (a) porous gas burner; (b) liquid burner.