Experimental Study of Pool Fire Burning Behaviors in Ceiling Vented Ship Cabins

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Abstract

Experiments were carried out in a ceiling vented ship cabin, with its inner dimension of 3 m x 3 m x 1.95 m, in order to investigate the effect of ceiling vent size (0 ~ 0.3 m²) on the burning behaviors of a D30cm heptane pool fire. Boiling burning, self-extinction, flame oscillation and ghosting flame were observed during the experiments. Results show that ceiling vent size had great influence on the fire self-extinction. A ventilation factor of ceiling vented compartment $\Phi$ was defined to determine the ceiling vent size. According to this factor, the fires can be classified into three extinction modes: Self-extinction mode, transition mode and Burn-out mode. Fuel consumed ratio, burning time and fuel mass loss rate of different modes were also analyzed in the paper.

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Keywords: ceiling vent, pool fire, ghosting flame, self-extinction, ship cabin

Nomenclature

$A_s$ surface area of the compartment
$c_p$ air specific heat
$h$ convection coefficient
$\Delta h_{air}$ heat of combustion per kilogram air
$\dot{m}_{air}$ air inflow mass rate through the ceiling vent
$q_f$ heat release rate of fire
$T$ temperature
$Y_o$ oxygen mass fraction

Greek symbols

$\chi$ fuel consumption ratio
$\Phi$ ventilation factor

Subscripts

air air
e extinction
f fire
F fuel

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1. Introduction

Fire disaster was one of the most serious threats to maritime vessels. Fires onboard usually occur in the area such as cabins, staff lounges and kitchens. These cabins were located below the deck of the ship in most cases, and as a result, their vents for personnel access only locate horizontally at the top. When a fire occurs in such a ceiling vented ship cabin, hot smoke was driven to flow out of the cabin through the vent by buoyancy, restricting or reducing the fresh air inflowing the compartment. Fire development in such compartments presents great difference from the enclosures of ashore constructions.

Fire development in ceiling vented compartments had attracted researcher’s interests from 1980s. Jansson [1] did a wood crib fire experiment in an enclosure with a vent at the central ceiling. He found that the burning rate and flue gas temperature increased with the enlarging of opening size. Takeda [2] made a PMMA fire experiment in a cube cabin with the side of 0.4m. His study found that due to the limited ventilation, the fuel mass loss rate was decreased. Wakatsuki [3] studied the pool fires development in a compartment almost the same dimension with Takeda’s cabin, and found that the mass loss rate in such a ceiling vent compartment is smaller than that of free burning when the fuel pan is large.

In recent years, Li [5] and Chen [6] did a serious of pool fire experiments in a test cabin(1m ×1m ×0.75m). In their studies, it is found that the flame is extinguished due to the lack of oxygen when opening is smaller than a certain size. Self-extinction is defined as that fuel left after fire extinguished. With the increasing of the vent size, the flame extinguished due to the burn-out of the fuel. In addition, they also put forward the calculation method of the gas exchange flow rate through the vent.

It can be seen that previous studies are mostly carried out in small ceiling vented cabins (<1m³). Large-scale experiments were needed to verify the fire phenomenon found in small scale tests. In this study, tests were conducted in a full-scale ceiling vented ship cabin (3m ×3m ×1.95m). By changing the size of the top vents, we described the special fire phenomenon observed in the tests, and discussed the ceiling vent size effect on the pool fire burn time, fuel consumption rate and the mass loss rate.

2. Experimental

Figure 1 is a schematic view of ship cabin. The inner size is 3.000m (L) × 3.000m (W) × 1.950m (H). Windows were equipped in the front bulkhead, in order to observe the development of the cabin fire. An adjustable square ceiling vent is located at the ceiling corner. The opening size had a range of 0 ~ 0.3m². Heptane pool fire with its diameter of 0.3m was used as fire source located in the center bottom of compartment. We used the electronic balance with accuracy of 0.1 g to monitored fuel quality changes and a digital camera to record the development of the fire behaviors. The initial fuel mass is 1680.0g. The test conditions and some of the results are listed in Table 1.

Fig. 1. Schematic view of the experimental compartment
### Table 1. Summary of the Tests

| No. | Vent Size /m² | Vent area /m² | Burning Time /s | Consumed Fuel Mass /g | Fuel Consumed Ratio  |
|-----|---------------|---------------|-----------------|------------------------|----------------------|
| 1   | 0             | 0             | 388             | 627.8                  | 0.42                 |
| 2   | 0.25×0.25     | 0.06          | 457             | 695.1                  | 0.46                 |
| 3   | 0.30×0.30     | 0.09          | 469             | 716.5                  | 0.48                 |
| 4   | 0.35×0.35     | 0.12          | 464             | 756.8                  | 0.51                 |
| 5   | 0.40×0.40     | 0.16          | 430             | 747.0                  | 0.50                 |
| 6   | 0.45×0.45     | 0.20          | 461             | 825.8                  | 0.55                 |
| 7   | 0.48×0.48     | 0.23          | 830             | 1137.8                 | 0.76                 |
| 8   | 0.50×0.50     | 0.25          | 1290            | 1680.0                 | 1.12                 |
| 9   | 0.55×0.55     | 0.30          | 1314            | 1680.0                 | 1.12                 |

3. Results and Discussions

3.1. Burning Behaviors

The experiment shows that when the opening is small, the fire would extinguish by itself, and the fuel will be exhausted completely when the ceiling is large enough. In the limited space with the opening at its top, some special combustion phenomena of the pool fire, such as flame boiling, flame oscillation and ghosting flame, are observed during the tests. Boiling burning means the fire burns when the fuel boils. In this condition, the flame volume increases, and the flame presents bright color and irregular texture (As shown in figure 2). The flame oscillation refers to the phenomenon that the flame decreases, disappears suddenly or the burning only happen in the part of the fuel surface, and then restore the original size (As shown in figure 3). The ghosting flame refers to that the flame takes place out of the fuel surface and may wandering all around the compartment (As shown in figure 4).

Utiskul et al. [7] also observe the flame oscillation phenomenon in their small scale experiment of wall openings. But the flame oscillation cycle is about 1s, which is much smaller than the results observed during this research (5 ~ 10 s). It shows that the cycle, in the cabin with the opening at its top, will extend significantly.

Ghosting flames were also found in previous researches in wall vented compartments [7,8]. But in their tests, ghosting flame mainly occurs near the wall opening because of the oxygen inflow from the openings into the cabin. In this study, ghosting flame could happened at some region near the bottom. The experiments used heptane (C7H16) which owns larger vapor density than other gases in the cabin. So combustible gas released from the fire source will move downward and it was difficult to rise to the top vent.

![Boiling Burning](image1)

Fig. 2. Boiling Burning
3.2. Normalization of Ceiling Vent Size

The vent size within a ceiling vented compartment can be normalized from a single-zone model of the heat and mass transfer processes. From Chen’s research with a small ceiling vented compartment, most of the heat released by the fire was lost outward the compartment, and the heat for heating the compartment gas own a very small proportion of total calories. So the later part was neglected in the energy balance equation. Consider the quasi-steady-state heat and oxygen conservations as shown in Eq.(1) and Eq.(2).

\[
\dot{m}_{\text{air}} c_p (T - T_a) = \dot{Q} - h A (T - T_a)
\]  

\[
\dot{m}_{\text{air}} (Y_o - Y_{\infty}) = -\frac{\dot{Q}}{\Delta h_{\text{air}} / Y_{\infty}}
\]  

In which, \( \dot{m}_{\text{air}} \) is the air inflow mass rate through the ceiling vent, \( c_p \) is the air specific heat, \( T \) and \( T_a \) is the temperature in and out of the compartment, \( \dot{Q} \) is the fire heat release rate, \( h \) is the convection coefficient, \( A \) is the total
surface area of the compartment, \( Y_o \) and \( Y_{0.\infty} \) is the oxygen mass fraction in and out of the compartment, \( \Delta h_{aw} \) is the heat of combustion per kilogram air.

Epstein [11] shows that the steady air mass flow rate through horizontal vents can be calculated by Eq.(3) from salt water modeling method.

\[
m_{aw} = 0.068 \rho A^{	ext{1/4}} \sqrt{g} \left( \frac{2(1 - \theta)}{(1 + \theta)} \right)
\]

In which \( A_o \) is the ceiling vent size, \( \theta \) is the ratio of the temperature in and out of the compartment \( T_o / T_f \).

Substituting Eq.(3) for the inflow air mass rate, and normalizing them by \( \dot{m}_{F,\infty} A_F c_p T_o \) in both side of the equation, the Eq.(1) and Eq.(2) give Eq.(4) and Eq.(5).

\[
\frac{\rho A_o^{1/4} \sqrt{g}}{\dot{m}_{F,\infty} A_F} 0.068 \sqrt{2} \left( \frac{T}{T_o} - 1 \right) \sqrt{\frac{1 - (T_o / T)}{1 + (T_o / T)}} = \frac{\dot{Q}}{m_{F,\infty} A_F c_p T_o} - \frac{hA_o}{m_{F,\infty} A_F c_p T_o} \left( \frac{T}{T_o} - 1 \right)
\]

\[
\frac{\rho A_o^{1/4} \sqrt{g}}{\dot{m}_{F,\infty} A_F} 0.068 \sqrt{2} \Delta h_{aw} \left( \frac{1 - (T_o / T)}{1 + (T_o / T)} \right) \sqrt{\frac{1 - (T_o / T)}{1 + (T_o / T)}} (1 - Y_o / Y_{0.\infty}) = \frac{\dot{Q}}{m_{F,\infty} A_F c_p T_o}
\]

From Eq.(4) and Eq.(5), we can find that the following three parameters determine the temperature and oxygen within the ceiling vented compartment which represent the relative ceiling vent size, relative convection heat loss coefficient and the combustion efferency:

\[
\frac{\rho A_o^{1/4} \sqrt{g}}{\dot{m}_{F,\infty} A_F} \sim \text{ceiling vent size}
\]

\[
\frac{hA_o}{\dot{m}_{F,\infty} A_F c_p T_o} \sim \text{convection heat loss coefficient}
\]

\[
\frac{\dot{Q}}{m_{F,\infty} A_F c_p T_o} \sim \text{combustion efficiency}
\]

From all the analysis above, the parameter of \( \frac{\rho A_o^{1/4} \sqrt{g}}{\dot{m}_{F,\infty} A_F} \) could be introduced to analysis the effect of ceiling vent size on the burning behavior. We define it as the ventilation factor \( \Phi \) of the ceiling vent compartment.

3.3. Vent Size Effect on Self-extinction

Fig. 5 shows the values of \( A_o / A_F \) in the function of \( \dot{m}_{F,\infty} / \rho A_o^{1/4} \sqrt{g} \), and their ratios represent the ventilation factor \( \Phi \). Data from Wakatsuki(0.4m×0.4m×0.4m) [3] and Li(3m×3m×1.95m)[4] are also included in this plot. The filled symbols represent observed extinction, while open symbols mean burn-out when the liquid fuel was completely exhausted.

Although the data are obtained from cabins with different sizes, we can find that self-extinction takes place when \( \Phi \) is small (small slop) and the fire burns out when \( \Phi \) is large (large slop). Fires in different ceiling vented compartments had almost the same critical value of \( \Phi \).
3.4. Fuel Consumption Rate and Burning Time

Define theoretical mass loss of fuel $M_0$ as the necessary mass loss of fuel to burn up all the oxygen inside the compartment. So that the theoretical mass loss of fuel of this compartment $M_0$ is calculated to be 1495.7g. Define theoretical fuel consumption ratio $\chi$ as the ratio of consumption of fuel mass $M_f$ and theoretical consumption of fuel mass $M_0$, which can be represented as expression (6)

$$\chi = \frac{M_f}{M_0}$$  

The impacts of ventilation factor $\Phi$ has on theoretical fuel consumption rate $\chi$ and burning time $T_v$ is shown in Fig. 6. Theoretical fuel consumption rate and burning time have the same trend. When $\Phi$ is a small value, there is almost no variation of both Theoretical fuel consumption rate and burning time. When $\Phi$ increases to a certain value, there is a noticeable increase of Theoretical fuel consumption rate and burning time, however self-extinction can also be taken place. When $\Phi$ continuously increases to another certain value, combustion will last until the fuel completely exhausted. At this point, Theoretical fuel consumption rate and burning time are in great relationship with initial fuel mass. If keeping refueling, both Theoretical fuel consumption rate and burning time will become infinite.
According to the experiment result, extinction can be divided into three modes based on different value of ventilation factor $\Phi$:

1) For small size of opening, layer of hot smoke rapidly descends to the bottom. Because the amount of oxygen make-up in the compartment is small, so the compartment is lack of oxygen. Flame comes to be self-extinction after transient oscillation with plenty of fuel left. This combustion process is called self-extinction mode. 2) For large size of opening, oxygen coming from the top opening sustains the combustion so that self-extinction will not occur. Flame keeps table oscillation state until flame extinguish owing to exhaustion of fuel, and there is no fuel left. This combustion process is called fuel-exhaustion mode. 3) For the size in between, the little oxygen coming from the top opening makes self-extinction not occurring rapidly, but it is insufficient to maintain combustion until the fuel completely exhausted. Flame comes to be self-extinction after a period of oscillation with some fuel left. This combustion process is called transition mode.

Self-extinction process is under control of the ventilation factor $\Phi$ as well as is impacted by the heat radiation of bulkhead, the types of fuel, and so on. Therefore, the boundaries between three modes may not be unified at all. They varies in a certain range. In these three modes, fuel-exhaustion mode is much different from free burning in open spaces. In fuel-exhaustion mode, oxygen coming from the top opening is insufficient to maintain incomplete combustion, thus flame is repetitiously oscillatory and ghosting flame can be observed at the same time. We only discuss restricted combustion here (also most of the cases in reality), so only three modes are considered. When ventilation factor $\Phi$ increases to large enough, it becomes free burning.

3.5. Fuel Mass Loss Rate

Figure 7 is the curve of mass loss rate per unit area along with the change of time under different combustion mode. In different combustion mode. At the early stages of the combustion, the curves of mass loss rate are basically identical. Mass loss rate reaches maximum when the flame appears fluidized combustion, the flame oscillation and wander appear after fluidized combustion. This is mainly due to the boiling fuel will produce more of the combustible gas. The gas makes the combustion more intense and at the same time consumes large amounts of oxygen, which result in decreasing rapidly the oxygen content of the booth. At this moment, there is not quickly added oxygen from the top openings and the flame is unable to maintain normal combustion.

When the flame oscillation and migration occur, the mass decreasing rate decreases significantly, which emit less combustible gas, heat and radiation emitted by the drop in heat on the surface of the fuel. When the heat feedback by the heat of combustion of the combustible gas equals to the vaporizing heat, the amount of oxygen inside the cabin is in a dynamic balance to the amount consumed in the flam, then the burning procedure can continue until the fuel ran out.

![Fig. 7. Fuel Mass Loss Rate](image-url)
4. Conclusion

Theoretical and experimental analysis were carried out to investigate the effect of ceiling vent size on fire development, and the following conclusions can be drawn:

1. In ceiling vented ship cabins, special combustion phenomena of the pool fire, such as flame boiling, flame oscillation and ghosting flame, will occur.

2. The ventilation factor is an important dimensionless parameters which represent for the relative size of top opening of the cabin. The fire within such cabin is easier to go out when the ventilation factor is small. Depending on the ventilation factor, the fire extinguishing process can be divided into Self-extinction mode, transition mode and Burn-out mode.

3. The ventilation factor has the almost same influence on fuel consumed ratio and burning time. Under the self-extinction mode, burning time and fuel consumption rate increase rapidly and both controlled by the initial fuel amount when under burn-out mode.

4. The mass loss rate reaches maximum when the fuel boils, and keeps at a low level when flame oscillation and ghosting flame occurs.

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