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An experimental and non-dimensional study on the vertical temperature distribution of a sealed ship engine room fire

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ABSTRACT

Fire in a sealed ship engine room is different from open fires, while its suppression is critically important to the emergency rescue and structure safety for a ship. This study focused on the vertical distribution of temperature rise during a sealed engine room fire. A series of experiments were carried out to investigate fire behaviors in a reduced-scale sealed ship engine room with a dimension of 3 m (length) × 3 m (width) × 3.5 m (height). The results suggested that there are vertical temperature gradients of smoke layer, showing a little lower than those of open fires. The experimental results demonstrated that the time to reach the maximum temperature is different for smoke layers at various heights, while a lower height showed a relatively long delay time. The vertical gradient of temperature rise was found increasing with pool diameter where the gradient of temperature rise of a 30 cm pool fire is about 9 times of that of a 10 cm pool fire. Furthermore, an empirical model was developed to predict the vertical temperature rise distribution along the height at the time of the maximum temperature for sealed engine room fires.

1. Introduction

One of the most disastrous situations threatening passengers/occupants in ships and related constructions is fire, which comes with high risk and uncertainty (Kang et al., 2017; Salem, 2016; Su and Wang, 2013). In fire emergency circumstances of a ship, to close the burning engine room is a final-taken and efficient means to extinguish the fire, especially when the ship is at sea without any help or support. For this case, ship engine room is completely closed, and the fire will be eventually extinguished due to the lack of oxygen. Sealed engine room fire is a special type as it is isolated from the ambient environment. Smoke and combustion products released from fire sources cannot be exhausted outside, and no fresh air is entrained into ship engine room as well. As a result, fire behaviors in a sealed engine room then is distinctly different from those of open fires (Zhang et al., 2013a, 2013b, 2015; Yuan et al., 2014; Tatem et al., 1986; Li et al., 2011; Yang et al., 2013).

Temperature or temperature rise is one of the critical parameters regarding the fire characteristics, which is essential to address the smoke movement and related suppression measures. Based on temperature, the initiation, development and extinguishment stages of sealed fires can be identified accordingly (Wang et al., 2017; Yao et al., 2017; Yoon et al., 2010). If a sealed engine room fire cannot be suppressed directly by fire extinguishing system, one of the alternative measures is to seal the engine room and wait for its self-extinguishment (Pu, 2009). After sealing the engine room, fire can be suppressed when the oxygen concentration drops to a certain value. After the fire is extinguished, the right time to reopen the ship engine room is very important. This is because the engine room is rich of fuel and also under high-temperature conditions, so re-ignition even backdraft may occur after sudden fresh-air entrance (Trouve and Wang, 2010). More importantly, the influences of hot smoke on the engine room structure are worthy of being studied, especially on accurately identifying or predicting the failure location of the engine room structure, which is significant to the structural risk assessment or fire emergency rescue (Kim et al., 2017; Jin et al., 2016; Jin and Jang, 2015). Therefore, the temperature distribution of sealed engine room fires is a practically important research topic.

Previous studies regarding the temperature rise in compartment fires, especially for a building fire, has been studied for several years,

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Nomenclature

$\propto$	proportional relationship
χ	combustion efficiency
$\dot{m}$	average mass loss rate, g/s
ΔH	heat of combustion, kJ/g
L	scale ratio
$\dot{Q}$	heat release rate, kW
$\bar{\dot{Q}}$	average heat release rate, kW
T_∞	ambient temperature, K
ρ_∞	density of ambient air, kg/m^3
c_p	specific heat capacity of ambient air, kJ/kg·K
g	gravitational acceleration, m/s^2
h	height of thermocouples, m
D	diameter of pool fire, m
H	height of ship engine room, m
S	floor area of ship engine room, m^2
$\Delta T(h)$	temperature rise at height of h, °C
$\dot{Q}^*$	non-dimensional heat release rate
$\bar{\dot{Q}}^*$	non-dimensional average heat release rate
$\Delta T(h)^*_{\max}$	non-dimensional temperature rise at the time of maximum temperature
k	slope obtained from regression
b	intercept obtained from regression

representative models such as M-Q-H method, F-P-A method, Beyler method, etc. (Walton et al., 2016). These models were developed based on the conservation of energy and mass for the gas phase inside the enclosure with openings or under well-ventilation. These models are typical zone models, including one-zone and two-zone models. The basic assumption of zone models is considered uniform for a one-zone model or the upper layer of the two-zone model. These models can predict the average temperatures which reflect the heat accumulation in the enclosure. Nevertheless, detailed temperature profiles are still a challenge of prediction. As we conduct the thermo-mechanical coupling analysis to assess the structural safety of ship engine room, the knowledge of the detailed temperature profiles is compulsory.

In the aspect of experimental study, Hu et al. conducted a series of fire experiments in a closed ship engine room and found that the temperature profile at the moment of self-extinction follows the Boltzmann distribution (Hu et al., 2010). Zhang et al. have investigated experimentally the vertical temperature distribution induced by an elevated fire in a ceiling vented ship compartment and found that the temperature of the upper layer was much higher than that of the lower layer (Zhang, 2014; Li et al., 2018). The stratification of the temperature was distinct including two regions of the hot upper layer and the cold lower layer according to the measured temperature. Additionally, Li and Chen have conducted experiments in a horizontally vented ship enclosure, smoke filled up the enclosure quickly after ignition and temperature seemed to increase gradually with height in most cases, which was quite similar to some forced-ventilation compartment fires (Li, 2010; Chen, 2011).

In numerical simulation studies, some studies focused on sealed engine room fires were based on numerical modeling (Su et al., 2012; Wang et al., 2013; Salem, 2013; Bonte et al., 2013; Jia et al., 1997; Sekret et al., 2013). The temperature distribution, volume fractions of gas species and thickness of smoke layer were investigated numerically. Another challenge is that the zone modeling, which divides the whole space into several vertical layers, may be no longer applicable to sealed engine room fires (Yuan et al., 2014).

In addition, some theoretical models have been developed regarding the prediction of temperatures in sealed engine rooms. A five-zone theoretical model (Tatem et al., 1986) was developed to predict the temperature in a gas-tight enclosure, which was based on the assumption that the combustion products and evaporated fuel are fully mixed. Another way of simplification is to consider a unified temperature for smoke layers (Li et al., 2011; Yang et al., 2013). Computational fluid dynamics models (Zhang et al., 2015) were also utilized to address the situation. However, there is still a gap between the prediction and experiments. Research efforts are especially needed from the experimental aspects.

Based upon the above analysis, previous studies have largely focused on the ship fires in ventilated or unsealed engine rooms, leaving very few studies on fully sealed engine room fire. The purpose of this study mainly focuses on the vertical distribution of temperature rise induced by fire in a sealed ship engine room. There are three main sections. The first section presents an introduction of a reduced-scale experimental rig. The second section focuses on experimental results and analysis including average mass loss rate, average heat release rate and vertical temperature rise. The third section conducts a dimensionless analysis of vertical temperature distribution at the time of maximum temperature and proposes a mathematical model.

2. Experimental methodology

A bench-scale ship engine room model was built to conduct a series of experiments, as shown in Fig. 1. In this figure, a transparent front-wall was used only to show the inside items, which does not mean that the wall of the testing engine room is transparent. To facilitate the observation of fire burning behaviors in a sealed ship engine room during experimental tests, several circular holes are set as experimental observation windows in the front and back walls, which are made of quartz glass and can stand for a high temperature of 600 °C. This ship engine room model consists of four parts, namely testing engine room, temperature measurement system, data collection system, and weighing device. The details of each part are introduced as follows:

(1) Testing engine room. Previous experimental studies were much focused on a relatively smaller engine room model than the one used in this study. For example, Zhang et al., 2013a, 2013b studied the characteristics of pool fire in two closed compartments, while one is 3 m (Length) × 3 m (Width) × 1.95 m (Height) and the other is 1 m (Length) × 1 m (Width) × 0.75 m (Height). The dimension of the current testing engine room is 3 m (Length) × 3 m (Width) × 3.5 m (Height), as shown in Fig. 1.

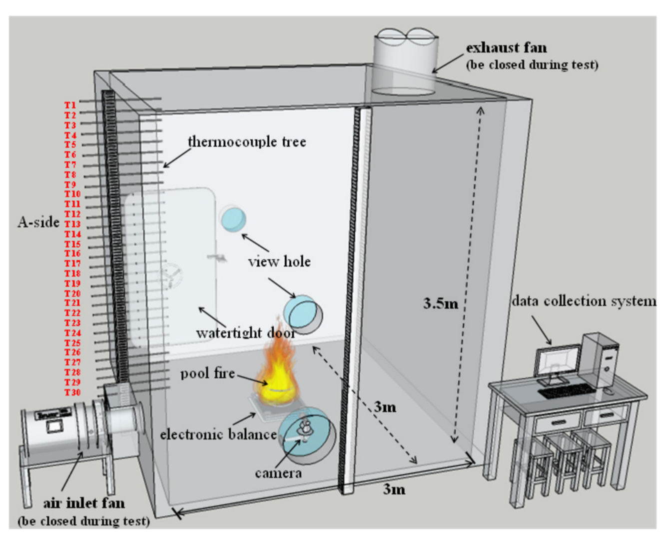

Fig. 1. Schematic diagram of the ship engine room test model.