Spray fire induced gas temperature characteristics and correlations in a ceiling ventilated compartment

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ABSTRACT

Spray fire, one of the common fires, often occurs in ship cabin and results in serious economic loss and casualties. However, there are few literatures [1–3] in terms of compartment spray fire, especially its gas temperature characteristics. Hence, a series of spray fire experiments were conducted in a $2 \, m \times 2 \, m \times 1.88 \, m$ ceiling ventilated compartment. It is found that the injecting pressure and ceiling vent size have significant effect on gas temperature. Gas temperature increases with the increase of injecting pressure and the increase in ceiling vent size results in a higher maximum gas temperature. The gas heat gain dominates the total heat transfer. The percentage of gas heat gain decreases with the ceiling vent size while the heat transfer through ceiling vent and compartment walls increases. For estimating the time-dependent average gas temperature in the combustion process, a simplified model was developed according to the thermal analyses, which shows good agreement with experimental data. Furthermore, based on M-Q-H method, a dimensionless analysis was performed for the total average gas temperature rise during the whole combustion process and the corresponding correlation was established, which can be applicable to estimate the gas temperature in ceiling ventilated compartment spray fire scenario.

1. Introduction

Compartments are very common in ships. Once compartment fire happens due to liquid fuel leakage, it possibly brings great hazards to personnel, equipment and structures, etc. Therefore, the study of compartment fire has attracted much more attentions and the related researches mainly focus on fire characteristics (including flame image, flame height and temperature etc.) [4,5], heat release rate [6–10], as well as heat transfer between fire source and surroundings (including convective and radiative heat transfers) [11–15]. It is worthy noting that gas temperature plays a great important role in determining whether the compartment is safe for the passengers or not, and evaluating the extent of damage to the equipments when the compartment catches fire.

On the gas temperature in compartment fire, McCaffrey et al. [14] conducted a series of pool fire tests in a compartment with vertical opening to study the gas temperature evolution and proposed a dimensionless correlation for gas temperature rise based on energy conservation, which has been a considerably accepted method (M-Q-H method) and widely applied. But the experimental data was obtained

from free-ventilated compartment fires, which made the gas temperature correlation only suitable for free-ventilated compartment fires. For gas temperature estimation in forced-ventilated compartment fires, Foote et al. [12] followed M-Q-H method and developed a new temperature correlation for forced-ventilated compartment fires. Peatross et al. [15] took into account the conductive boundaries and modified the two temperature correlations separately proposed by Deal and Beyler [16], and McCaffrey et al. [14], which made it possible to predict gas temperature in both natural ventilated and forced ventilated compartment fires.

In terms of compartment ventilation, there are two types: ceiling and vertical ventilations. Compared with compartment fire with ceiling ventilation, compartment fire with vertical ventilation attracts large numbers of researchers' attention because of its wide existence in most buildings and great effect on building safety. However, ceiling ventilation mechanism is completely different from vertical ventilation mechanism and hasn't been investigated in detail, especially in spray fire environment. Cooper [17] firstly paid attention to study on the gas flow induced by pool fire in a ceiling vented compartment. Utiskul et al. [18] studied the self-extinguishing behavior of compartment pool fire under

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Nomenclature		ρ_0	ambient gas density (kg/m³)
		$\dot{m}_v$	gas mass exchange rate through ceiling vent (kg/s)
p	injecting pressure (MPa)		ceiling vent area (m²)
t	time (s)	g	gravity acceleration (m/s2)
P	absolute pressure (Pa)	ΔT	average gas temperature (°C)
v	kerosene volume flow rate (L/min)	V	kerosene spray volume (L)
$\dot{Q}$	kerosene heat release rate (kW)	ΔT_a	total average gas temperature (°C)
$\dot{Q}_g$	gas heat gaining rate (kW)		
$\dot{Q}_v$	heat transfer rate through vertical or ceiling vent (kW)	*Greek*	
$\dot{Q}_h$	heat transfer rate through compartment walls (kW)		
c_p	specific heat of gas (J/(mol·K))	β	heat transfer percentage (%)
ρ_g	compartment gas density (kg/m³)		
V_c	compartment volume (m³)	*Subscript*	
h	effective heat transfer through compartment walls (W/(m²·°C))	*0*	ambient
A	compartment inner surface area (m2)	*G*	gas
T	compartment average gas temperature (°C)	*V*	vent
T_0	ambient gas temperature (°C)	*C*	compartment

limited ceiling ventilation. Ding et al. [19] focused on the gas temperature profiles of blended fuel pool fire in a ceiling ventilated compartment and pointed out that the composition of blended fuel had great influence on the peak gas temperature and the duration.

Since spray combustion is commonly used in engines and can improve combustion efficiency, it has been studied extensively [20–24]. However, from the standpoint of fire safety, when spray fire occurs in ship compartment, it can speed up the fire development and result in serious consequence. Moreover, spray fire behaviors are obviously different from those of compartment pool fire, which deserves our attentions. Currently, to address the details, a series of experiments were carried out to study the effects of spray fire on thermal performance in a compartment with various ceiling vent sizes. The purpose aims to develop a simple correlation to estimate the time-dependent average gas temperature in the burning process based on the experimental data and previous researches [12,14,15,18,25,26]. Furthermore, based on M-H-Q method, a dimensionless analysis for total average gas temperature rise was performed.

2. Experimental

By considering the size of real ship compartment and referring to experimental apparatus adopted in relevant literature [1–3], a compartment with the size of 2.0 m (L) × 2.0 m (W) × 1.88 m (H), as shown in Fig. 1 and Fig. 2, was employed for spray fire experiment. The front wall of the compartment was built with one piece of 20 mm thick fire-resistant glass for capturing the flame images. The other walls were made of 10 mm thick steel. For cleaning the glass, installing the igniter and changing the nozzle conveniently, a door with size of 0.6 m (W) × 1.2 m (H) was available on the right side wall of the compartment. Moreover, the vent was located at the compartment ceiling center.

Aviation kerosene, which was widely applied in ship industry, was chosen as the fuel in experiment. A spray nozzle was set in the center of the compartment floor and its operation parameters are shown in Table 1. An electronic spark for igniting kerosene spray was set 10–15 cm above the nozzle. Since such configuration can be considered to be symmetrical, only one thermocouple tree involving nine K-type thermocouples with 1 mm diameter, had the vertical space of 20 cm and the horizontal distance of 29 cm away from the left wall for measuring the gas temperature. The flame images were captured using a digital camera. A series of experiments were performed to investigate gas temperature evolution in the compartment with various injecting pressures (0.2 MPa, 0.4 MPa, 0.6 MPa, 0.8 MPa, 1.0 MPa) and ceiling vent sizes (40 × 40 cm², 60 × 60 cm², 80 × 80 cm²). The test cases are shown in Table 2.
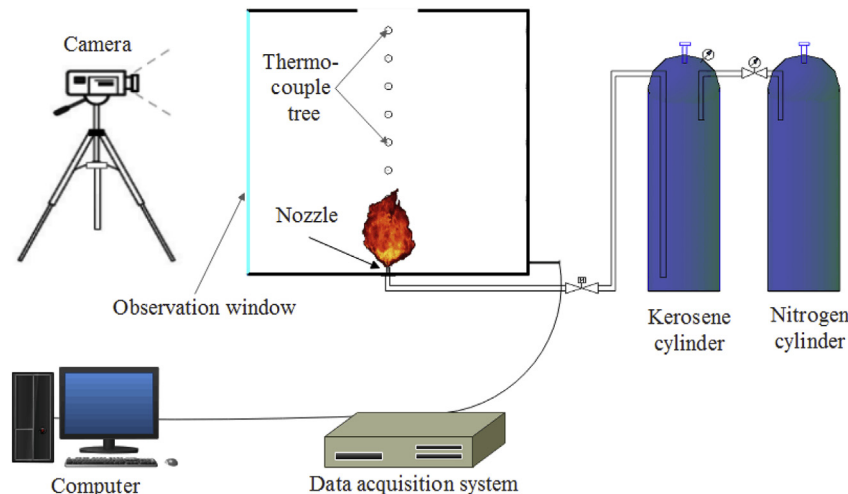

Fig. 1. Schematic of experimental setup.