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Research Paper

Factors affecting the burning rate of pool fire in a depressurization aircraft cargo compartment

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HIGHLIGHTS

- The sudden ventilation activates the fire greatly at the beginning of the depressurization.
- The influence level of ventilation weakens gradually with the decrease of pressure.
- The dimensionless ventilation factor $\frac{Q\rho}{\dot{m}''_{p,\infty}S}$ has a linear relationship with burning rate.
- The faster depressurization rate causes a larger dimensionless ventilation factor and increases the burning rate peak.

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ABSTRACT

A full-scale below-floor cargo compartment with the size of 8.11 m × 4.16 m × 1.67 m was used to simulate a depressurized environment for an aircraft fire during flight. Pool fire experiments with 20 cm n-heptane at four depressurization rates of 6 kPa/min, 12 kPa/min, 17 kPa/min, and 20 kPa/min were carried out. The fuel mass, compartment pressure, vent flow rate, and oxygen concentration were measured. The results indicate that ventilation increases the burning rate drastically at the beginning of depressurization, and then its dominant role gradually weakens with a decrease in pressure. A dimensionless ventilation factor $\frac{q\rho}{\dot{m}''_{p,\infty}S}$ proved to have a linear relationship with the burning rate. In addition, a faster depressurization rate increases the peak of the burning rate. The above conclusions indicate that a fire in the compartment has the greatest risk when the ventilation begins, and the depressurization rate should be as low as possible to reduce the fire hazard.

1. Introduction

An aircraft fire is one of the most serious disasters in the aviation industry. When a fire takes place in an enclosed cargo compartment during a flight, the aircraft should climb (descend) to a specific altitude and equalize the compartment pressure with the exterior atmosphere to inhibit combustion [1,2]. The internal pressure decreases (increases) accordingly during this process. Therefore, the combustion condition is much more complicated because of the sharp variations in pressure. There is no doubt that it is essential to conduct an in-depth analysis.

Yin J. [3] and Ma Q. [4] carried out pool fire experiments under a pressurized environment in a pressure cabin of size 2 m × 3 m × 4.65 m. The fire behaviour was observed, and its change rules were concluded as preliminary research. Li C. [5] observed a n-heptane pool fire at varying depressurization rates and divided the entire process into five stages. Liu, J. [6] conducted small-scale pool fires in an altitude chamber and investigated the enclosure effect of the chamber on the burning behaviour. The fuel burning rate in a pressure chamber is similar or slightly lower than that for field tests when the pool size is smaller than 12 cm. X. Hu [7] and Z. Li [8] analysed the fire behaviour of liquid fire such as n-heptane and solid fire such as wood crib at high altitudes. The radiation heat flux for the same burning rate was compared with those at low altitude. A preliminary discussion was conducted on the mechanism of pressure influence on buoyancy-driven fire behaviour. The effects of the depressurization rate on the burning rate, flame height, and centreline temperature were compared with those under static pressure. However, the sizes of current pressure compartments are too small to conform that of an aircraft cargo compartment [9,10]. More experiments on the scale of an aircraft compartment need to be carried out.

It is important to note that when the pressure inside the compartment is higher than that on the outside, the air-flow will only leak out of the compartment unidirectionally. Therefore, the factors of ventilation and oxygen concentration are also changing and need to be taken into

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Nomenclature

D	pool fire diameter (m)	q	vent flow rate (m^3/min)
$\dot{m}''$	burning rate per unit area (g/s·m^2)	S	projected area of fuel (m^2)
$\dot{m}''_{p,\infty}$	burning rate in free atmosphere(g/s·m^2)	V_C	volume of compartment (m^3)
$\dot{m}''_0$	burning rate at 90 kPa (g/s·m^2)	X_0	initial oxygen concentration
p	pressure inside compartment (kPa)	X	oxygen concentration
		ρ	density of vent flow rate (g/L)

consideration [11,12]. To some extent, this condition is similar to an enclosed compartment under limited ventilation [13–17]. Pool fires were investigated in a 40 cm cubic compartment with a wall vent and ceiling vent by Utiskul Y. [18]. It was found that the wall vent had a more obvious increase in the burning rate than the ceiling vent because of the difference in vent flow rates. Bhisham Kumar [19] conducted crib fires in a compartment with interior dimensions of 4 m × 4 m × 4 m. The results indicated that the ventilation had a great influence on the fire behaviour. The mass loss rate could increase by 150% owing to sudden ventilation. Zhang J. [20] investigated the self-extinction phenomenon in two cabins. A linear relationship between the oxygen concentration and extinction time was observed. Fire self-extinction occurred when the local oxygen mole fraction descended to a level of 10.7–15.3%.

To combine the dynamic pressure with limited ventilation comprehensively, in this paper, a full-scale below-floor cargo compartment of a wide-body aircraft was used to simulate a depressurized environment with unidirectional air leakage. The pressure decreased from 90 kPa to 30 kPa at constant depressurization rates of 6 kPa/min, 12 kPa/min, 17 kPa/min and 20 kPa/min. An n-heptane pool fire with a diameter of 20 cm was observed. The fuel mass and environmental parameters such as pressure, vent flow rate, and oxygen concentration were measured. The evolution of the pool fire, and the major impact factors of the burning rate, were determined to provide a theoretical basis for aircraft compartment fire protection in the aviation industry.

2. Experimental apparatus and procedure

The compartment was located in Kangding, Sichuan Province (altitude 4250 m, atmospheric pressure 61 kPa, ambient oxygen concentration 19.6%). The interior dimensions were 8.11 m × 4.16 m × 1.67 m (length × width × height). The fan in the pressure control system was connected to both the inlet pipeline and the outlet pipeline. The flow direction was determined by four cutoff valves, as shown in Fig. 1. The outlet pipeline was connected by opening cutoff valves 2 and 4 to achieve depressurization. The vent flow rate was calculated according to the depressurization rate and was controlled by the valve opening. The compartment was equipped with pressure, oxygen concentration and vent flow rate sensors to monitor the parameters in real time during the experiment. An observation window made of glass was used to observe the flame (see Fig. 2.).

A steel pan with a diameter of 20 cm, a height of 15 cm and a wall thickness of 0.25 cm was used as the container. The fuel used was n-heptane with an industrial purity above 99% and a density of 0.684 g/ml. The initial depth was fixed at 2 cm to ensure a long enough duration. In addition, cold water at a depth of 10 cm was placed beneath the n-heptane to protect the experimental equipment below. An electronic balance with an accuracy of 0.1 g and a sampling rate of 5 Hz was used to record the fuel mass loss. An oxygen sensor with a measuring range of 0–30%, a sensitivity of 0.1% and a sample frequency of 1 Hz was used to measure the oxygen concentration near the flame. The distance between the sensor and the pan was 20 cm, which was the same height according to previous studies [17,20]. Each group of experiments was replicated at least three times to verify the reliability.

The experimental procedure was as follows: First, the compartment was sealed, and the internal pressure was adjusted to 90 kPa. Then, the fuel was ignited using an electronic ignitor. At 360 s after ignition, a target pressure of 30 kPa was set, along with depressurization rates of 6 kPa/min, 12 kPa/min, 17 kPa/min, and 20 kPa/min. Finally, when the pressure reached 30 kPa, the cutoff valves were closed and the compartment was sealed again until the flame was out.

3. Results and discussion

The burning rate of n-heptane was obtained via the derivative of mass data. The correspondence between the burning rate, pressure, vent flow rate, and oxygen concentration is shown in Fig. 3. The entire combustion process can be divided into three stages by the start time of depressurization $T = 360$ s and the end time of depressurization $p = 30$ kPa. The first stage is the enclosed combustion at 90 kPa before

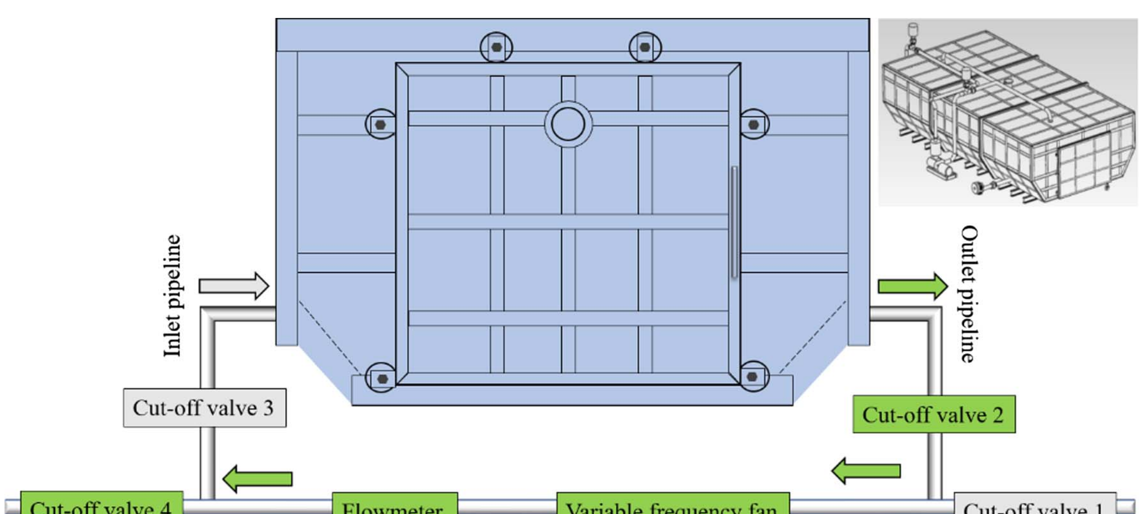

Fig. 1. Principle of pressure control system in compartment.