Applied Thermal Engineering 89 (2015) 526–533

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

Experiment investigation on the influence of low pressure on ceiling temperature profile in aircraft cargo compartment fires

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HIGHLIGHTS

- Ceiling thermal characteristics of aircraft cargo compartment at various pressures.
- Air entrainment ratio has been proposed for the ceiling temperature correlations.
- Ceiling maximum temperature has been predicted for low pressure conditions.
- Ceiling temperature decay profile has been correlated for low pressure conditions.

ARTICLE INFO

Article history:
Received 3 February 2015
Accepted 11 June 2015
Available online 20 June 2015

Keywords:
Ceiling thermal flow
Low pressure
Ceiling temperature profile
Aircraft cargo compartment
Ceiling jet

ABSTRACT

The objective of the present study is to evaluate the low pressure effects on ceiling temperature profile in aircraft cargo compartment fires, which will affect the activation of fire detectors. A Series of fire tests were carried out in a full scale simulated aircraft cargo compartment at four atmospheric pressures (100 kPa, 90 kPa, 80 kPa and 70 kPa) corresponding to the pressure within an actual aircraft cargo compartment from the sea level to the cruising altitude (about 10,000 m). Results show that the maximum ceiling temperature increases and the ceiling temperature decays faster as ambient pressure reduces. The air entrainment ratio C_α is proposed in the correlation to predict the maximum ceiling temperature based on previous plume theory, considering the low pressure effect and entrainment coefficient. Meanwhile, modified by the air entrainment ratio C_α, the previous classic correlations established by Alpert, Heskestad and Delichatsios for the ceiling temperature decay profile are further extended to low pressure conditions. The results based on Heskestad and Delichatsios method are more accurate than that of Alpert method in the experiments. All these findings would provide theoretical basis for the design of fire detection system in the aircraft cargo compartment.

1. Introduction

An inflight fire may cause catastrophic casualties and loss of property if not detected before growing into an uncontrollable size [1]. Early and accurate detection is of significance, especially for the inaccessible areas of the aircraft, such as cargo compartments, where a direct visual inspection is not possible during flight [2]. For the selection of multi-sensor detection methods [3], it is particularly critical to identify the ceiling temperature profile especially for small fires. It should be noted that the aircraft cargo compartment is a flat long and narrow closed compartment and the atmosphere pressure inside changes from 100 kPa to 70 kPa corresponding to the sea level and cruising altitude respectively. Therefore, it is worthwhile from a practical perspective to investigate the low pressure effects on fire ceiling jet temperature profiles which would provide theoretical basis in the design of fire detection systems for the aircraft cargo compartment or other similar compartments at high altitude.

The characteristics of ceiling jet, such as heat transfer and temperature profile etc., have received extensive attention in certain thermal engineering research for large industrial or commercial storage facilities and tunnels [4–20]. Studies quantifying the flow of hot gases under a ceiling resulting from the impingement of a fire plume have been conducted since 1950s, in which the theoretical models came from the work carried out by Alpert [10] and by Heskestad and Delichatsios [11]. Alpert [10] developed a

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http://dx.doi.org/10.1016/j.applthermaleng.2015.06.021
1359-4311/

generalized theory to predict gas velocities, gas temperatures, and the thickness (or depth) of a steady fire-driven ceiling jet flow for a weak plume under an unconfined ceiling when the height of the ceiling above the fuel source is much higher than flame height. Later on, Heskestad and Delichatsios [11] proposed new correlations of non-dimensional velocity and temperature applicable to a much wider range of conditions. Additionally, some studies about the strong plume-driven ceiling jet [12–14] have been carried out to build empirical formulas to predict the flame extension length beneath the ceiling, ceiling jet temperature and thickness. More recently, a series of sidewall fires was performed in a small-scale tunnel model to investigate the influence of sidewall restriction on the maximum ceiling temperature, and thus the correlation was modified [15,16].

Some studies [21-25] have been reported on fires under reduced pressure conditions and investigated such low pressure effects. Rectangular source fuel jet fire tests were carried out by Zhang [21] at two atmospheric pressures to modify the correlation for axial temperature profiles based on Quintiere formula. Niu [22] and Yao [23] conducted cardboard box fires in Hefei and Lhasa, showing that mass burning rate and radiative heat flux decrease while plume temperature increases under lower pressure conditions. Furthermore, Zhou [24] analyzed the data from circular n-Heptane fires with serial sizes and obtained that the flame height and the plume temperature increase as a power function of pressure. However, they are mainly concerned about the pressure effects on fire flame, and it seems that there are very limited researches about the ceiling temperature profiles under low pressure conditions. The pressure effects on the ceiling temperature decay profiles have not been involved in previous studies. Meanwhile the correlations of predicting the ceiling temperature profiles have not yet been verified under low pressure conditions.

Therefore, this paper focuses on the influence of low pressure on the ceiling temperature profiles driven by weak plume and the verification of the classic correlations in reduced ambient pressure to propose modified predictive formulas for the maximum ceiling temperature and the ceiling temperature decay profiles under different low pressure conditions. The work is of significance to improve the understanding on ceiling jet of the aircraft cargo compartment fires in the reduced air pressure and provide the basis for fire detection system design.

2. Experiment setup

Experiments were conducted in a long rectangular prism with curved sidewalls, as shown in Fig. 1. The full scale simulated aircraft cargo compartment consists of the compartment, pressure controlling system, forced ventilation controlling system and other auxiliary systems (e.g. illumination and surveillance systems). The compartment is made of 8 mm thick stainless steel with inner dimensions of 467.0 cm long (L) and 112.0 cm high (H), and the width of top and bottom is 300 cm and 122 cm respectively, which are very close to the actual Boeing 737-700 forward cargo compartment. The pressure in the simulated aircraft cargo compartment ranging from 60 kPa to 100 kPa can be controlled by a vacuum pump with a controlling system. For fire tests, the compartment pressure is maintained at the specified value with measurement uncertainty ±2% throughout the entire testing process. In this study, four static pressures, i.e.100 kPa, 90 kPa, 80 kPa and 70 kPa were examined, which is equivalent to the pressure in an actual aircraft cargo compartment from the sea level to the cruising altitude (about 10000 m).

N-heptane was chosen as the ignition source according to the standard fire sensitivity tests [26,27]. N-heptane (C_7H_{16}) pool fires of 12 cm × 12 cm (D12), 10 cm × 10 cm (D10), 8 cm × 8 cm (D8) and 6 cm × 6 cm (D6) were conducted at the position of coordinates (3435 mm, 0) (see Fig. 1(b)). All pans were made of 3 mm thickness steel plates with 30 mm in depth, and filled with 10 mm depth of fuel before ignition. A digital electronic balance with an accuracy of 0.01 g was applied to measure the fuel mass loss at 1 s intervals during combustion. The pan was initially elevated 7 cm from the floor by the balance. The ceiling temperature profile was measured by 12 K-type thermocouples of 1 mm (TC-1 - TC-12) with measurement uncertainty ±1% installed along the ceiling. The horizontal interval between the thermocouples (TC-2 – TC-12) was 0.275 m and the thermocouple TC-1 was right above the fire location. The initial environmental temperature and relative humidity were ranging in 23–25 °C and 67–69%.

3. Results and discussion

3.1. Mass loss rate

Fig. 2 plots the variation of mass loss rate (MLR) acquired by the electronic balance for D10, and shows the steady burning stage occurs after a short pre-burning, which is the one with the shorter steady state. The average MLRs $\dot{m}$(g/s) at the steady stage for all cases are plotted in Fig. 3, showing the MLR is lower when the atmospheric pressure is 70 kPa and is proportional to the atmospheric pressure, as $\dot{m} \propto A \cdot P^{\chi}$, in consistent with previous studies [28,29]. The heat release rate $\dot{Q}$, controlling to a considerable extent fire plume flows and hot gas temperature, can be further calculated by $\dot{Q} = \varphi \cdot \dot{m} \cdot \Delta H$, where φ is combustion efficiency (about 1 for n-heptane) [30], and ΔH is combustion heat of fuel (4806.6 kJ/mol for n-heptane). Then, for example, $\dot{Q}$ for D12 at 100 kPa is 8.78 kW.

3.2. Maximum ceiling temperature

The maximum ceiling temperatures in the impingement area where the upward flow of gas in the plume turns to flow out beneath the ceiling horizontally, were obtained by averaging the values within the steady stage of 350–450 s. Fig. 4 shows the maximum ceiling temperature under different pressure conditions. The maximum ceiling temperature for low pressure is higher than that in normal pressure, showing an opposite tendency with that of MLR. This is because the combustion zone may be prolonged as the flame height is higher under lower pressure [22,23].

Previously, McCaffrey [31] divided the plume into three regions, i.e. the continuous flame region, the intermittent region, and the plume. The centerline temperature distribution of the plume relationships had been established:

$$\Delta T_0 = \left(\frac{\kappa}{0.9 \cdot \sqrt{2g}}\right)^2 \left(\frac{Z}{\dot{Q}^{2/5}}\right)^{2\eta-1} \cdot T_\infty \quad (1)$$

where Z is the height above the point source; T_∞ is the ambient air temperature; g is the gravity acceleration; the constants η and κ vary depending on the three regions. For the weak buoyant plume impingement condition discussed in this paper, the coefficient of centerline temperature at Z = H (which is also the maximum ceiling temperature. H is the height from the fuel source to the ceiling) has been given as $\eta = -1/3$, $\kappa = 1.1(m^{4/4}/(kW^{1/3}s))$, thus: $\Delta T_0 \propto \left(\frac{Z}{\dot{Q}^{2/5}}\right)^{-5/3}$ or $\Delta T_0 \propto \dot{Q}^{2/3} \cdot Z^{-5/3}$.