Experimental Thermal and Fluid Science 82 (2017) 326–332

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Experimental study on ceiling temperature profile of sidewall fires at reduced pressure in an aircraft cargo compartment

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ARTICLE INFO

Article history:
Received 26 September 2016
Received in revised form 23 November 2016
Accepted 26 November 2016
Available online 28 November 2016

Keywords:
Ceiling jet
Ceiling temperature profile
Sidewall effect
Reduced pressure
Aircraft cargo compartment

ABSTRACT

Knowledge about the coupling effects of reduced pressure and sidewall restriction on ceiling temperature profile is crucial for the fire detection system of an aircraft cargo compartment. N-heptane fire tests at three places (floor center, flush with one sidewall, compartment corner) were conducted in a full scale simulated aircraft cargo compartment at 100 kPa, 90 kPa, 80 kPa and 70 kPa, since the pressure within an actual aircraft cargo compartment ranges from 100 kPa at the sea level to 70 kPa at the cruising altitude. Results show that due to the sidewall restriction and reduced pressure, less air entrainment into the flame results in higher maximum ceiling temperature. While ceiling temperature decay profile attenuates faster at reduced pressure and is little affected by sidewall restriction. A uniform correlation of maximum ceiling temperature considering reduced pressure and sidewall restriction is obtained by the introduction of air entrainment ratio C_α and modified mirror model coefficient. The classical correlations of Alpert, Heskestad and Delichatsios for the ceiling temperature decay profile are modified similarly to be extended to sidewall fires at reduced pressure and compared with results showing more accurate predicted results by Heskestad and Delichatsios' method.

1. Introduction

Temperature profile of a ceiling jet is an important parameter in the development of a multi-sensor detection system which is applied in the aircraft cargo compartment to detect the inflight fire before the fire size grows into an uncontrollable hazard [1,2]. Due to the confined space and the pressure change within the aircraft cargo compartment which ranges from 100 kPa at the sea level to 70 kPa at the cruising altitude, it is practically worthwhile to investigate the sidewall effect and pressure effect on ceiling temperature profile.

Ceiling jet characteristics, such as temperature distribution, gas flow velocity and heat transfer have been subjected to extensive and considerable amount of research [3–7]. Hereinto, the classical theory came from Alpert's [6] and by Heskestad and Delichatsios' [7] works. Alpert [6] proposed the basic model to descript the ceiling temperature profile and gas flow velocity beneath an unconfined ceiling. Further, Heskestad and Delichatsios [7] established non-dimensional correlations of the velocity and temperature of a ceiling jet applicable to a room. However, compared to a large amount of studies on the ceiling jet at normal pressure, the studies of pressure effect on ceiling jet properties are relatively less [8–10], and most work concerns the flame at reduced pressure [11–15]. Wang [8,9] conducted a set of measurements of temperature and CO concentration distribution of a ceiling jet from square burners at the floor center at reduced pressure and proposed the entrainment coefficient ratio in the correlations. Tang [10] simulated tunnel fires at two pressures with results showing ceiling temperature decayed faster than CO concentration.

Some works [16–19] have been reported to address the side wall effect on the plume characteristics. Zukoski [16] proposed the mirror model for fires adjacent to a wall, which assumes an imaginary fire source same to the original one exists on the other side of the wall, and then the flame height and temperature were calculated to in the same way as those of an unconfined fire. Ji [17] performed a set of sidewall fires in a small-scale tunnel model to investigate the effect of sidewall confinement on maximum ceiling temperature, and gave a simple calculation method. Gao

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http://dx.doi.org/10.1016/j.expthermflusci.2016.11.030
0894-1777/

Nomenclature

C_1	constant in Eq. (1)
C_2	constant in Eq. (2)
C_3	constant in Eqs. (6) and (8)
C_α	entrainment coefficient ratio
c_p	specific heat capacity (kJ/(kg K))
D	fuel source diameter (cm)
g	gravity acceleration (m^2/s)
H	height between fuel source and the ceiling (m)
M	molecular weight of the gas
$\dot{m}$	mass loss rate (g/s)
P	ambient pressure (kPa)
$\dot{Q}$	heat release rate (kW)
$\dot{Q}_c$	convective heat release rate (kW)
$\dot{Q}^*$	non-dimensional heat release rate
r	horizontal distance away from the plume centerline axis along the ceiling (m)
Z	height above the point source (m)
Z_0	virtual origin height (m)
T_∞	ambient air temperature (K)
$\Delta T_{\max,0}$	maximum ceiling temperature rise (K)
$\Delta T_{\max,r}$	temperature rise at horizontal distance r from the plume centerline axis (K)
ΔT^*	non-dimensional temperature rise
ΔT	temperature rise over ambient (K)
R	ideal gas constant (8.31 J/(K mol))

Greek symbols

α	entrainment coefficient at pressure atmosphere
α_{low}	entrainment coefficient in low pressures
β	mirror model coefficient
ρ_∞	ambient air density (kg/m^3)

[18,19] correlated maximum ceiling temperature and flame height from small-scale tunnel fire experiments. However, they mainly focus on the influence of sidewall restriction on maximum ceiling temperature, and it seems that the research on sidewall effect on ceiling temperature decay profile is very limited. Meanwhile, reduced pressure effect on ceiling temperature profile of sidewall fires has not been addressed in previous studies.

Therefore, this paper concerns on the coupling effects of reduced pressure and sidewall restriction on ceiling temperature profile driven by the weak plume. Attempts have been made to develop uniform correlation to predict maximum ceiling temperature and ceiling temperature decay profile of sidewall fires at reduced pressure. This work provides theoretical basis in the development of multi-sensor fire detection system for the aircraft cargo compartment or other similar compartments at high altitude.

2. Experiment setup

All tests are carried out in a full scale simulated aircraft cargo compartment in Fig. 1, which is made of 8 mm thick stainless steel plate and like a long rectangular prism with curved sidewalls. The size of the compartment is 467 cm long (*L*), 112 cm high (*H*), 300 cm top wide and 122 cm bottom wide, and is very close to the actual Boeing 737-700 forward cargo compartment. The inside pressure can be controlled at static value with measurement uncertainty ±2% throughout the entire test within the range of 60–100 kPa by controlling the vacuum pump systematically. According to the pressure change in an actual aircraft cargo compartment, 100 kPa, 90 kPa, 80 kPa and 70 kPa were set in this study.

N-heptane (C_7H_{16}) was chosen as fire fuel based on the standard fire sensitivity tests [20]. N-heptane pool fires were placed at the center of compartment floor (243.5 cm, 0), adjacent to one sidewall (0 + 1/2D cm, 0) and the corner of the compartment (0, 61 − 1/2D cm), which are called as center fires, wall fires and corner fires respectively hereinafter. Four square pools with side length of 12 cm (D12), 10 cm (D10), 8 cm (D8) and 6 cm (D6) with 30 mm in depth were adopted. A total of 48 experimental cases are listed in Table 1. All pans were made of 3 mm thickness steel plates and filled with 10 mm depth of fuel before ignition. A digital electronic balance was used to measure the fuel mass loss with an accuracy of 0.01 g at 1 s intervals during the experiment. Due to the balance, the pan has an initial elevation height of 7 cm above the floor. The ceiling temperatures were measured by 9 K-type thermocouples with diameter of 1 mm (TC-1–TC-9) with measurement uncertainty ±1% which were installed beneath the ceiling with the horizontal interval of 55 cm. The initial environmental temperatures were recorded before each experiment and ranging in 22–24 °C.

3. Results and discussion

3.1. Maximum ceiling temperature

Fig. 2 plots the maximum ceiling temperature of center fires, wall fires and corner fires under different pressure conditions against the heat release rate $\dot{Q}$. The maximum ceiling temperature is in the impingement area where fire plume impinges the ceiling and turns into a horizontal flow along the ceiling, and is gained by calculating the average values during the stable stage of 350–450 s. $\dot{Q}$ is calculated by $\dot{Q} = 48.0\dot{m}$ (kW) where $\dot{m}$ (g/s) is mass loss rate of fuel and increases with increasing fuel pool size and pressure [21,22]. Since the heat feedback from the sidewalls enhances the burning rate of fuel sources, $\dot{Q}$ of sidewall fires is higher than center fires. As shown in Fig. 2, for the same $\dot{Q}$, the maximum ceiling temperature of sidewall fires is higher than that of center fires and also increases when the pressure decreases, because the combustion region is lengthened as fire source is adjacent to walls as well as decreasing pressure, that is, the flame height is higher due to sidewall and reduced pressure effects. For center fires, air entrainment around the flame is basically the same and is like cone-shaped. When the fire is placed attaching the sidewall, air entrained into the flame near the sidewall is blocked and becomes limited. Thus, the unbalanced entrainment caused by the confinement effect of sidewalls results in that the flame leans to and expands along the sidewall. Similarly, due to the low air density at reduced pressure, less oxygen is entrained into the fire fuel loaded fire flames and the fire fuel must pass through a longer distance to get full combustion, which lead to the higher flame and further cause the higher maximum ceiling temperature.

McCaffrey [23] claimed that the fire plume includes the continuous flame zone, the intermittent zone and the plume zone, and established an empirical equation for the centerline temperature distribution of fire plumes. The maximum ceiling temperature in this paper is the point impinged by the weak buoyant plume and in the plume zone from the McCaffrey model, thus can be presented as: