An Experimental Study on the Influence of Low Air Pressure on the Flame Height of Wall Fire Plumes

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Abstracts

The combined effects of wall and low air pressure on flame height and mass loss rate of pool fires have not been reported in the past. A series of experiments were conducted to investigate the effect of low pressure on wall fire plume in aircraft cargo compartment in this work. It is found that the mass loss rate of fire plumes decrease as ambient pressure reduces, and mass loss rates of fire plumes against walls are smaller than that from the same size of the fire source in the open. In addition, at the same atmospheric pressure, the mean flame height increases slightly when the pool fire is against the wall. Compared to previous research, the effects of wall on the mass loss rate and the flame height are discussed. Based on previous plume theory, the Entrainment Factor directly affects the flame height, which is related to pressure. Therefore, the impact of pressure on EF is explored in this paper. These results may provide a theoretical basis for improving flame detection technology in low pressure environment.

Keywords: Flame height; burning rate; low air pressure; wall fire plumes; flame detection

Introduction

Effects of ambient pressure on pool fires burning characteristics have been explored by many scholars. It is important for fire safety design of low pressure area, e.g. aircraft in flight and high altitude area.

The burning behavior of pool fires is a subject of many recent studies, and low air pressure has been shown to affect pool fire mass loss rate and flame height. The burning rate was found to be $\dot{m}''{\sim}p^{1.3}$ in Wieser et al [1]. Fang et al. [2] showed the relationship between $\dot{m}''$ and p, the dependence of the burning rate exponent n ($\dot{m}''{\sim}p^{n}$) on the air pressure varying with the equivalent diameter D of the burner, with n <0 (D< 7 cm), (0–1) (7 cm < D< 10 cm), (1–1.45) (10 cm < D < 19 cm) and 1 (D > 19 cm). Hu et al. [3] found the non-dimensional flame height in the reduced pressure atmosphere was slightly higher than that in the normal pressure atmosphere for conduction-controlled rectangular pool fires.

Nomenclature

$\dot{m}''$	mass loss rate per unit area (g/m^2·s)
p	pressure (kPa)
D	equivalent burner diameter length (m)
L_f	the mean flame height (m)
$\dot{Q}^*$	dimensionless heat release rate
n	the exponents of pressure
h	convective heat transfer coefficient (W/m^2·K)
T_f	flame gas temperature
T_l	Liquid fuel boiling temperature
k^*	a coefficient in Eq. (3), dimensionless
EF	the Entrainment Factor

Subscripts

w	fire sources against wall
o	fire sources in open

The effects of wall on flame height have also been studied. Zukoski [4] developed a model named Mirror Model for wall fire plumes and corner fire plumes. Poreh et al. [5] proposed two simple models for predicting the effects of walls on the mean flame height.

However, the combined effects of wall and low air pressure on flame height and mass loss rate of pool fires have not been reported. Therefore, this paper investigates the pool fire burning characteristics in low pressure under the influence of the walls.

Experiments

Experimental facility is shown in Fig. 1. It shows the full scale simulated aircraft cargo compartment which is a long rectangular with curved sidewall on both sides. The compartment is 4.67 m long (L) and 1.12 m high (H). It is designed according to Boeing 737-700 forward cargo compartment. There are two rectangular sealed doors with quartz glass observation windows embedded for layout of experimental setup. On both sides of compartment, two observation windows are also embedded in curved sidewall. Quartz glass windows can be used to observe the progress of experiment inside the compartment. Pressure designed for the simulated aircraft cargo compartment can change from 101 kPa to 70 kPa, controlled by a pressure control system. Pressure control system can be adjusted according to the feedback of the pressure in the aircraft cargo compartment to achieve dynamic equilibrium of the air pressure.

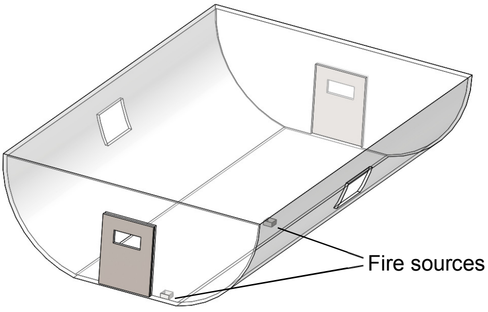

Fig. 1. Schematic of the simulated aircraft cargo compartment.

Anhydrous ethanol was used as fuel of fire source for its good experimental repeatability. The fuel was placed in square pans, which were made of 3mm stainless steel with 3cm depths, and the fuel depth was 1.5 cm under each experimental condition. The length of the square pans were 8 cm, 10 cm, 12 cm, 14 cm and 16 cm. Pool fires were tested in the full scale simulated aircraft cargo compartment at four atmospheric pressures, i.e. 101 kPa, 90 kPa, 80 kPa and 70 kPa, which is according to the pressure range of aircraft cargo compartment when aircraft is in flight. As shown in Fig. 1, the fire sources were placed in two locations, in the middle (in open) and against the wall of compartment respectively. All the experimental conditions are summarized in Table 1. The mass of the fuel was measured by an accuracy of 0.01 g electronic balance and recorded once per second. An insulation board was placed between electronic balance and pan to prevent the electronic balance overheating. Flame height was obtained by a digital camera, which can record 25 frames per second.

Table 1. Summary of experimental conditions.

Pool sizes (cm)	Fuel volume (mL)	Pressure (kPa)	Fire source location
8 × 8	96	101 90 80 70	In middle Against wall
10 × 10	150		
12 × 12	216		
14 × 14	294		
16 × 16	384		

Results and discussion

Mass loss rate

The mass loss rate has a direct relationship with the heat release rate. Fig. 2 plots mass loss as functions of time for 16 × 16 cm^2 free fires in 101 kPa. After ethanol is ignited, there is a phase that the mass loss rate has a rapid rise (0-160 s). Then, the ethanol pool reaches a steady burning phase (160-530 s). The average mass loss rate of the ethanol pool fire was 0.184 g/(s·m^2), which was obtained from steady burning phase.

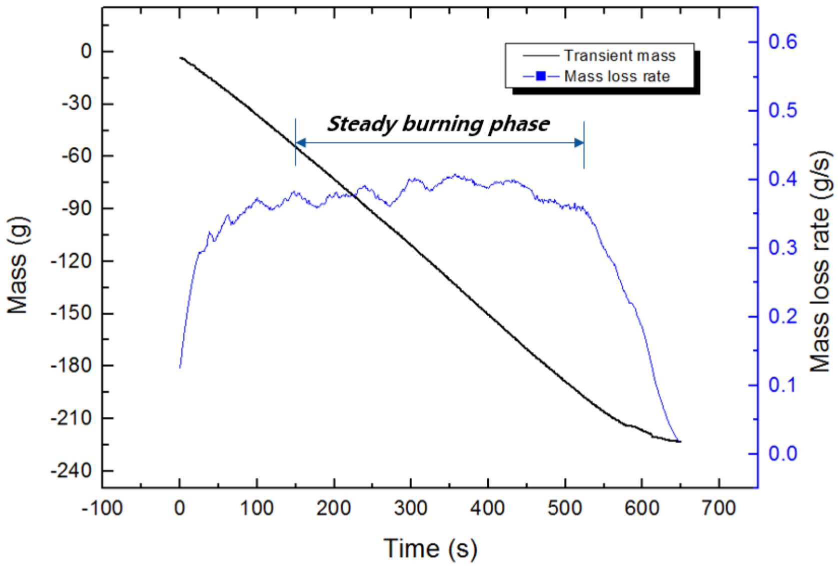

Fig. 2. Mass loss versus time of 16 × 16 cm^2 free fires in 101kPa.

The average mass loss rate in steady burning phase for all other experimental conditions are showed in Table 2.

Table 2. Summary of mass loss rate.

Fire source location	Pressure (kPa)	Mass loss rate (g/s·m^{-2})				
		8 cm	10 cm	12 cm	14 cm	16 cm
Against wall	101	0.110	0.134	0.129	0.158	0.162
	90	0.109	0.130	0.113	0.148	0.139
	80	0.086	0.106	0.096	0.123	0.118
	70	0.079	0.094	0.085	0.106	0.118
In open	101	0.112	0.152	0.147	0.165	0.184
	90	0.109	0.133	0.145	0.151	0.164
	80	0.087	0.125	0.118	0.133	0.133
	70	0.079	0.104	0.097	0.118	0.127

From the data in Table 2, the mass loss rates of fires burning against walls $\dot{m}''_w$ are smaller than mass loss rates of fires burning in the open $\dot{m}''_o$. Base on the data in Table 2, it can be seen that wall has a certain impact on mass loss rate.

The mass loss rate is determined by the heat feedback of the fire plume on the fuel surface. Heat transfer consists of three parts, conduction heat feedback, convection heat feedback and radiation heat feedback. It can be expressed in Eq. (1) [6].

$$\dot{m}'' \propto \frac{4\lambda\left(T_f - T_l\right)}{D} + h(T_f - T_l) + \sigma(T_f^4 - T_l^4)(1 - \exp\left(-\kappa_s D\right)) \qquad \text{(Eq. 1)}$$

where h is convective heat transfer coefficient, T_f is flame gas temperature and T_l is liquid boiling temperature. It can be seen that $\dot{m}''$ is mainly related to h and $\Delta\mathrm{T} = T_f - T_l$ when heat feedback is convective heat feedback dominant. It should be noted that the relationship between T_f and low pressure is not strong in Jean Most et al.'s work [7]. In addition, T_l changes slightly with the pressure, it can be ignored compared to other variables. Hence, $\dot{m}''$ mainly depends on the convective heat transfer coefficient, and it is closely related to ambient atmospheric pressure. Fig. 3 shows the ratio of $\dot{m}''_w$ to $\dot{m}''_o$ in all experimental conditions. By analyzing the ratio of $\dot{m}''_w$ to $\dot{m}''_o$, the ratio is close to 1 for the 8 cm square pan. It can be inferred that wall has little effect on the mass loss rate when square pan size is 8 cm. But for other pool sizes, the influence of wall on $\dot{m}''$ cannot be ignored. Therefore, wall has a certain impact on the convective heat transfer coefficient h. Since, pool sizes 10 cm, 12 cm, 14 cm and 16 cm are convection heat feedback dominant.

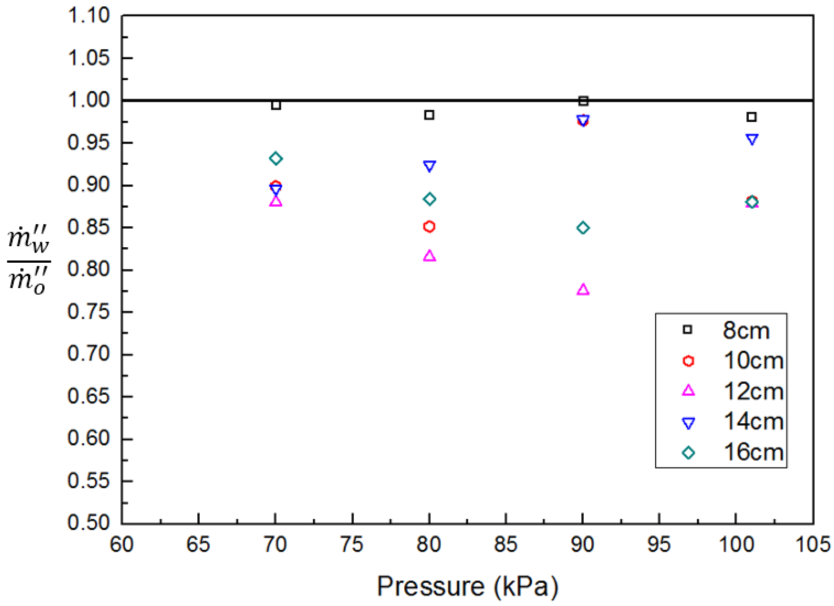

Fig. 3. The ratio of $\dot{m}''_w$ to $\dot{m}''_o$ in all experimental conditions.

By fitting $\dot{m}''$ with ambient pressure p, the exponents of pressure are showed in Table 3. By comparing n_w and n_o, it can be seen that n_w is larger than n_o. It is plausible to conclude that the effects of wall make mass loss rate more sensitive to atmospheric pressure.

Fang et al. [2] summed up the dependence relationship of the burning rate exponent n ($\dot{m}''{\sim}p^n$) on the air pressure varying with the equivalent diameter D of the burner, where n varied between 0 and 1 for equivalent diameter D was between 7 cm and 10 cm, 1 ~ 1.45 for 10 cm < D < 19 cm. According to the data in Table 3, it is consistent with Fang's conclusion.

Table 3. Exponents of pressure.

Pool sizes (cm)	Exponents of pressure	
	n_w (against wall)	n_o (in open)
8	0.947	0.945
10	1.043	0.992
12	1.205	1.177
14	1.149	1.052
16	1.200	1.148

Flame height

According to the flame height, Heskestad [8] suggested a simple equation, it can be expressed in Eq. (2)

$$\frac{L_f}{\mathrm{D}} = 3.7\dot{Q}^{*\frac{2}{5}} - 1.02 \qquad \text{(Eq. 2)}$$

which is based on a large number of experimental data, and it shows a linear correlation between dimensionless flame height and $\dot{Q}^{*2/5}$.

Fig. 4 shows dimensionless flame height versus $\dot{Q}^{*2/5}$. As seen from the figure, L_f/D varies proportionally with $\dot{Q}^{*2/5}$ in both locations of fire sources. R-square values are all great than 0.86. In the work, the mean flame heights of fires source against walls are higher than those from same fire source burning in the open. It is noted that the mass loss rates of fires source against walls are smaller than those fires in the open. Therefore, it can be inferred that wall has a significant effect on on flame height. The reason is that wall limits the air entrainment of the fire plume, fuel vapor needs to reach a higher position to burn completely. Hence, the flame height is related to Entrainment Factor.

Poreh et al. [5] researched the wall effects on the air entrainment and gave the general form of mean flame height as Eq. (3)

$$EF^{2/3}(\mathrm{L}/\mathrm{D}) = k^{*}\dot{Q}^{2/5}/\mathrm{D} \qquad \text{(Eq. 3)}$$

where EF is dimensionless entrainment factor, k^* is a dimensionless coefficient determined by the open fire data. The k^* can be obtained from experimental data of fire source burning in the open. In addition, for open fires, EF is 1. Then, the dimensionless entrainment factor EF can be calculated from measured flame height values of the wall fires. The values of EF is showed in Fig. 5. It can be seen that EF ranges from 0.7 to 0.83 in 101 kPa, and it decreases as pool size increases. With atmospheric pressure reducing, entrainment factor is decreasing. It is plausible to conclude that wall has stronger effect on air entrainment in low atmospheric pressure. It should be noted that the EF value of pool size 8 cm varies little in low air pressure, and the value is about a constant of 0.79.

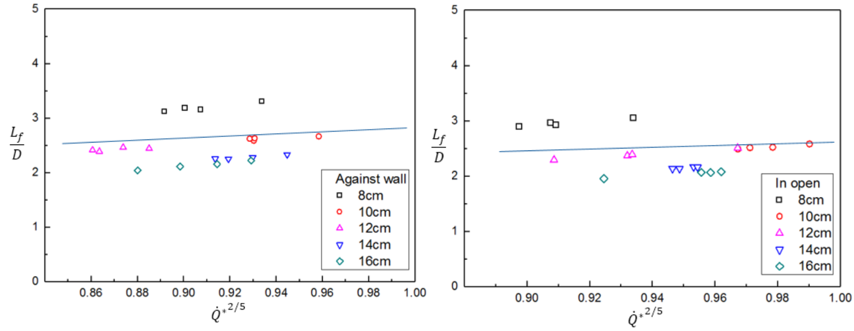

Fig. 4. Dimensionless flame height as a function of $\dot{Q}^{*2/5}$.

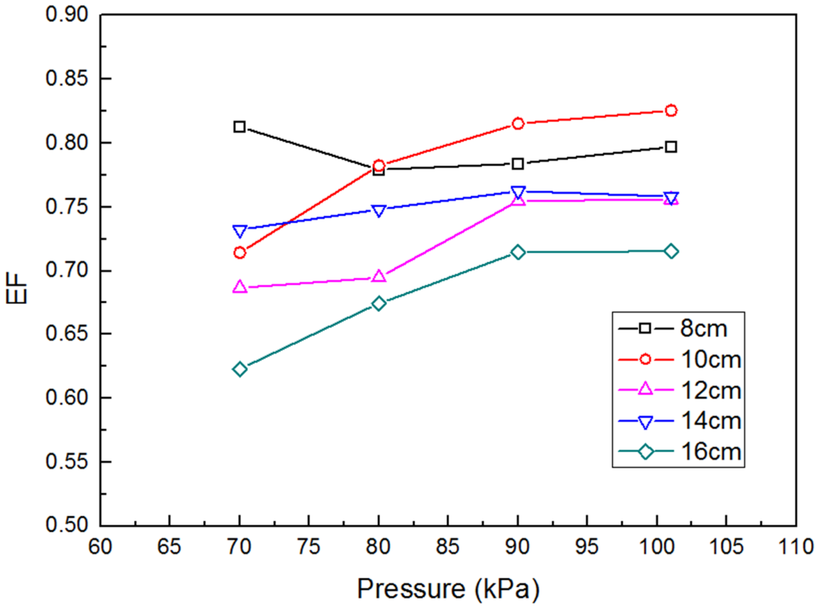

Fig. 5. Entrainment factor versus atmospheric pressure.

Conclusions

In full scale simulated aircraft cargo compartment, 5 pool fires of pan size from 8 cm to 16 cm were experimented to explore the low pressure effects on wall fire plumes. The main conclusions are summarized as follows:

(1) The mass loss rate has a strong relationship with atmospheric pressure, as $\dot{m}''\sim p^n$. $\mathrm{n} > 1$ when heat feedback is convective heat feedback dominant, and $\mathrm{n} < 1$ when heat feedback is conduction heat feedback dominant.

(2) When fire sources burning against wall, the powers of atmospheric pressure increase compared with same fire sources in the open. In addition, wall has a certain impact on the convective heat transfer coefficient h.

(3) Entrainment factor decreases with atmospheric pressure reducing. The flame height is larger of pool fires longer under the influence of wall. Wall has stronger effect on air entrainment in low atmospheric pressure.

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