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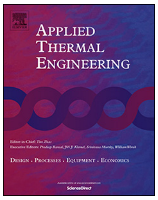

Low air pressure effects on burning rates of ethanol and *n*-heptane pool fires under various feedback mechanisms of heat

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HIGHLIGHTS

- Pressure effects on flame temperature of pool fire were analyzed.
- The coupling influences of pressure and heat feedback were studied theoretically.
- An overall correlation of pressure effects on burning rate was proposed.

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ABSTRACT

The present work is a theoretical investigation into the influence of reduced air pressure on pool fire burning rate with different domination of heat feedback mechanisms. The coupling effects of pressure and heat feedback on burning rate or other typical parameters, e.g., flame temperature and flame height, were discussed within 3 regions under conduction-controlled, convection-controlled and radiation-controlled, respectively. A comprehensive correlation of pressure effects on burning rate with increasing pool fire scale was formulated based on radiation fire modeling and classical fire dynamics theory, which was validated well by the previous experimental data (carried out in ~65 kPa and ~100 kPa atmospheric pressures). It was interesting that the influence of pressure on flame height was able to be predicted by combining the theoretical correlation established and the classical flame height equation. Also, pressure effects on burning rate and flame height with increasing pan diameter showed a similar trend.

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1. Introduction

One of the important reasons for interest in fire burning behavior under low air pressure was based on the fire science research of historic buildings located in high altitude area. Air pressure was proved to have significant influence on fire dynamic and burning characteristics [e.g. [1–21],] including flame temperature, burning rate, radiation, flame physical image, etc., causing new scientific issues on fire detection and protection.

Burning rate is one of the key parameters in pool fire burning, which is mainly determined by the heat feedback to the liquid fuel. As the dominant heat feedback mechanism transfers with increasing pool fire scale [22–26], the influence of air pressure on burning rate is prone to show some complex variation, which could be described as $\dot{m}'' \propto p^n$, where n was reported as shown in Table 1 for different scales of typical pool fires by experimental study [3,9,11,14,17,19]. In addition, most of the comparative tests listed were conducted in Hefei (100.0 ± 1.0 kPa) and Lhasa (65.0 ± 1.5 kPa), two representative locations with natural altitude difference in China.

Two theoretical models about ambient air pressure influences on burning were developed by De Ris et al., known as pressure modeling [1] and radiation fire modeling [4]. However, a systematic theoretical model of pressure effects on pool fire burning characteristics covering all kinds of heat feedback controlled mechanisms (from conduction to convection-controlled, and finally radiation-controlled, with increasing pool fire scale) was still absent. On the other hand, burning rate is strongly associated with other burning characteristics as a critical parameter, including flame temperature, flame height, radiation heat flux, puffing frequency and so on in diffusive combustion process. The influences of pressure on these characteristics were revealed by semi-empirical relationships of e.g., Fang et al., [9] Tang et al., [16,17] and Hu et al. [12,13], whereas for the lack of thorough understanding of pressure vs. burning rate, the relationships mentioned were usually applicable only within a certain or limited range.

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Table 1
Empirical value of index n with various heat feedback controlled mechanism.

Domination of heat feedback mechanisms	Pan diameter D/cm	Index n by experiments under different pressures	
Conduction-controlled	<7	–0.4 ~ 0	(D = 4.5 ~ 6.8) [9]
		0	(D = 6.8) [14]
Transition	7 ~ 10	0 ~ 1	(D = 7.9 ~ 9.0) [9,19]
Convection-controlled	10 ~ 20	1.3	(D = 17.2) [3]
		1 ~ 1.45	(D = 10.2 ~ 19.2) [9]
Radiation-controlled	>20	1	(D = 33.9) [11]
		1	(D = 23.1) [17]

In this short paper, the experimental data of our previous work [7,9,11] and other related work [e.g., 6, 14] are reused to provide an overall analysis of the complex pressure effects on pool fire burning rate $\dot{m}''$ and typical correlative parameters, e.g., flame temperature T_f and flame height H, under different domination of heat feedback mechanisms.

2. Experiments

Detailed information of experimental setup was described in Reference 9, which is introduced briefly here. All experiments were conducted in EN54 standard combustion rooms in Hefei and Lhasa, respectively. Ethanol (C_2H_6O) and n-heptane (C_7H_{16}) were selected as test fuels considering the good repeatability and different soot production abilities, with equivalent pan diameter from 4.5 to 37.2 cm. The primary burning characteristics recorded were burning rate, flame temperature and flame image information. Some former tests were repeated in this study to ensure a data set with higher accuracy, especially for the measurement of flame temperature, which was calibrated by Luo's method [27].

3. Results and analysis

3.1. Flame temperature

Flame temperature T_f is the pivotal factor for determination of pool fire burning rate by following simplified approximate equation [28,29]:

$$\begin{aligned}\dot{m}'' &\sim (\dot{q}''_{con} + \dot{q}''_{conv} + \dot{q}''_{rad})/\Delta H_g \\ &\sim \left[4\frac{\lambda(T_f - T_l)}{D} + h(T_f - T_l) + \sigma(T_f^4 - T_l^4)(1 - \exp(-\kappa_s L))\right]\Big/\Delta H_g\end{aligned} \tag{1}$$

The test result of flame temperature vs. pan size under two air pressures is shown in Fig. 1. The effect of pressure on T_f is observed to vary with pan diameter, i.e., the difference $T_{fd} - T_{f0}$ decreases gradually to ~0 K with the enlarged pan size as marked by the red solid line. For relative small scale pool fire, flame temperature appears obviously higher under low pressure, which was attributed to the weaker ambient entrainment cooling for laminar air flow with lower density. But the difference becomes inconspicuous for relative large scale pool fire, especially for radiation-controlled pool fires with pan diameter exceeding 20 cm. This phenomenon is suggested to be the strengthened effect of soot blockage [30] with increasing scale under normal pressure, which hinders radiation losses and leads to a certain increase of T_f. Instead, the effect of soot blockage is believed to be much smaller for low pressure due to the less soot formation [4].

3.2. Burning rate

Low pressure effects on burning rate of pool fire would be discussed within 3 regions in specific sequence, which are conduction-controlled for small size ($D < 7$ cm), radiation-controlled for large size ($D > 20$ cm), and convection-controlled ($D = 10 \sim 20$ cm) for medium size, respectively.

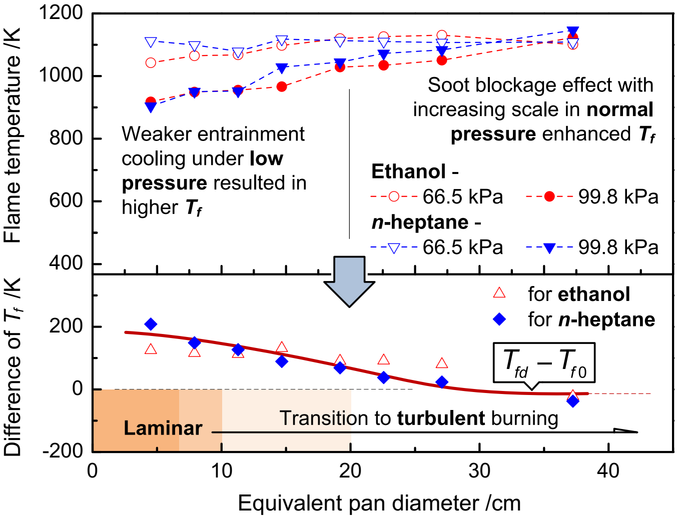

Fig. 1. Flame temperature and difference vs. pan diameter in Lhasa (~65 kPa) and Hefei (~100 kPa). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Firstly as expressed in Eq. (1), burning rate under conduction-controlled is:

$$\dot{m}'' \approx \dot{q}''_{con}/\Delta H_g = 4\frac{\lambda(T_f - T_l)}{D}\Big/\Delta H_g = 4\frac{\lambda\Delta T}{D}\Big/\Delta H_g \tag{2}$$

Since λ is nearly only dependent on burner material, i.e., $\dot{m}''$ is proportional to the temperature gradient $\frac{\Delta T}{D}$. The influence of pressure on burning rate for the same sized pool fire is substantially the influence of p on ΔT.

As shown above in Fig. 1, T_f is affected by pressure significantly in conduction-controlled region (with maximum difference ~200 K between Hefei and Lhasa for example). In addition, considering the decreased boiling point in low pressure, $\dot{m}''$ should be surly enhanced under low pressure for conduction-controlled pool fire as:

$$\dot{m}'' \propto p^n, n < 0 \text{ or } \dot{m}''_d/\dot{m}''_0 \sim \Delta T_d/\Delta T_0 > 1 \tag{3}$$

Secondly in radiation-controlled premise, a relationship of $\dot{m}'' \propto p$ was deduced in our previous study [11] with pan diameter ~30 cm based on the important assumption that flame temperature T_f should be insensitive to fire scale or ambient pressure [4] in radiation-controlled region, which was confirmed as shown in Fig. 1. Here, a supplementary theoretical analysis for larger scale pool fires is given below.

Considering $\dot{m}'' \approx \dot{q}''_{con}/\Delta H_g \sim \sigma T_f^4[1 - \exp(-\kappa_s L)]/\Delta H_g$ for radiation-controlled (by Eq. (1)) and the rapid decrease of $\kappa_s L$ with enlarged L [31], it could be simplified by expansion of exponential function as:

$$\dot{m}'' \sim 1 - (1 - \kappa_s L) \sim \kappa_s L \tag{4}$$

As $\kappa_s \sim m'''_s \sim p^2\left[\left(\frac{\rho_f}{\rho_\infty - \rho_f}\right)^3 \frac{\mu^2}{g^3\rho_f^2 L}\right]^{1/4}$ reported in the study of De Ris [e.g., 4] (approximately proportional to the ratio between Kolmogorov flow time and chemical time for soot formation), $\rho_\infty \sim p$, $\rho_f \sim p$ and $\mu \sim p^0$, κ_s is further presented as:

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