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Research Paper

Investigation of enclosure effect of pressure chamber on the burning behavior of a hydrocarbon fuel

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HIGHLIGHTS

- Small-scale pool fires were performed at two different altitudes and in an altitude chamber, and small to significant differences between them could be observed.
- Only for the 6~12 cm pool sizes, the burning intensity of chamber tests in quasi-steady stage could be approximate to that of field test.
- Flame in the chamber test exhibited a larger slenderness.
- Combined effects of the oxygen depletion and thermal stratification in the chamber resulted in a slightly M-shaped flame temperature.

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ABSTRACT

Although pressure chambers have been extensively employed to examine the pressure effect on fire behaviors at high altitudes, the results have not been carefully compared with that obtained by field tests for verification. In this paper, both the field tests at high altitude and chamber tests were performed to investigate whether the experimental conditions at high altitude can be faithfully replicated in a low pressure chamber and the limitations or restrictions on the use of the chamber in experimental study of fire behavior at high altitude. The n-heptane pool fires with different sizes were performed in current study. The differences in the burning intensity, flame envelop and axial temperature distribution were analyzed. It was found that only for 6~12 cm pool dimensions, the burning intensity in quasi-steady stage for chamber test can well simulate that for corresponding filed test. The difference in flame envelop appears for all the configurations, exhibiting a larger slenderness for chamber tests. The axial temperature distribution in quasi-steady stage can be well correlated with the classical theory of fire plume involving the pressure effect, while the exception of the 14 cm pool fires shows apparent distinction for field and chamber tests in plume region.

1. Introduction

Burning behaviors of liquid fuels under reduced pressures have been comprehensively explored in previous studies, all of which indicate that low air pressures have significant effects on the combustion characteristics of fuels [1–12]. Plenty of experiments have been performed to investigate these effects, primarily including field and simulative chamber tests. Field tests on pressure effects on burning behaviors of combustibles were initially conducted in a one-sixth of the volume of the European standard EN54 test room at four altitudes ranging from 420 m to 3000 m. Their results pointed out that the mass burning intensity $\dot{m}''$ shows a power law dependence on the pressure P, i.e. $\dot{m}'' \sim P^{\alpha}(\alpha = 1.3)$ [1]. Li et al. [2] initiated the experimental study on n-heptane pool fires and wood crib fires on plateau (Lhasa, 3650 m/64.3 kPa), in which related parameters were compared with the results of the experiment concluded at a much lower altitude (Hefei, 50 m/100.8 kPa) and the correlation of the former obtained by Wiser et al. was confirmed. Hu et al. [3] investigated burning characteristics of n-heptane pool fires at another altitude (Dangxiong, 4350 m/59.1 kPa) and compared the results with that obtained in Lhasa and Hefei. They found that the fuel burning intensity depends on the pressure and the pool diameter, i.e. $\dot{m}'' \sim f(D, P)$. A wider range of pool diameters ($D = 4\sim33$ cm) tested by Fang et al. [4] supported this finding and further indicated that α is determined by the thermal feedback from flames. Tu et al. [5] further stated that α should be equal to 1 under radiation-controlled pool fires.

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Due to the difficulties and expenditure of shipping experiment equipment to high altitudes, researchers tend to develop altitude chambers with adjustable inner pressures to simulate low-pressure environment. The result of the burning intensity scaled with pressure as $P^{2/3}$ was achieved in virtue of PMMA fire tests conducted in a 0.2 m^3 cylinder pressure vessel by De Ris et al. [6]. Recently, Zarzecki et al. [7] studied the flammability properties of PMMA in a 10 m^3 altitude chamber capable of reaching 0.1 atm, and Fereres et al. [8] explored the same phenomenon by the utilization of NASA's latest low-pressure cabin. The fuels used in the aforementioned studies [6–8] were regular solids with relatively smaller burning intensities, and the chamber pressure was instantaneously adjusted to maintain a fixed level with small deviations so that the simulated environment in the chamber was relatively stable during the whole tests.

A pressure chamber is an enclosed environment where no ventilation or air exchange with outside occurs. As such, the oxygen supply is finite and the combustion product is entrapped. The combined effect of oxygen depletion and accumulation of thermal energy in a closed chamber may yield different or even completely opposite results compared with experiment in the open space with the same pressure. For example, in the work by Zeng et al. [9], the small-scale pool fires with 4×4 cm^2 square burner were conducted in a 0.5 m^3 pressure cabin. Their experimental results indicated that the burning intensity, flame temperature of small-scale ethanol pool fires decreased with the decreasing pressure in chamber tests, while it increased with the decreasing pressure in field tests.

In a larger chamber of $3\times2\times2$ m with precise pressure controlling system to simulate both dynamic and static low-pressure environment, Yin et al. [10,11] studied the pressure effect on the burning intensities of n-heptane pool fires within a pressure range from 30 kPa to 101 kPa. They claimed that the largest pool size permissible in the chamber is 10-cm-diameter as constricted by the spatial dimension of the chamber and the oxygen content in the chamber. Employing the same pressure chamber, Liu et al. [12] also conducted pool fires with a number of pool diameters up to 10 cm. It was found that n-heptane pool fires with the tested diameters usually undergo four stages, namely, initial growth, quasi-steady, boiling and decay. After oxygen depletion analysis from the mass conservation and stoichiometric equations, the authors concluded that oxygen depletion in the finite chamber space during the boiling stage was quite significant and might affect the combustion process in addition to the influence of pressure. Thus, only the experimental results in the quasi-steady burning stage, including burning intensity and flame height, were quantitatively discussed.

In order to explore whether the experimental conditions at high altitude can be faithfully replicated in a low pressure chamber of finite volume, both the field tests at different altitudes and corresponding chamber tests were performed and compared carefully in current study. The enclosure effect resulting from the chamber test was examined to understand the limitations or restrictions on the use of the chamber in experimental studies of fire behavior at high altitude. The enclosure effect in the context of the chamber experiment to study pool fire behavior refers to the influence of the entrapped combustion product on the combustion process and the fire plume characteristics. It is manifested in oxygen depletion, thermal feedback and aerodynamic disturbance to the flame and fuel source. The study was carried out with the use of n-heptane fuel filled in pools of different sizes. Measurements on mass loss rate, plume axial temperature distribution and flame image were recorded and analyzed, and comparisons between field and chamber tests were made in detail. A numerical simulation was also conducted for a limited number of cases of the chamber experiment to further reveal the change of the enclosed environment during the experiment.

2. Influence of pressure and oxygen concentration on combustion

The burning intensity of pool fire is determined by the heat transfer from flame to fuel surface through conduction, convection and radiation [4,13,14],

$$\dot{m}'' \sim \dot{q}''_{cond} + \dot{q}''_{conv} + \dot{q}''_{rad} = \frac{4k(T_f - T_s)}{D} + h(T_f - T_s) + \sigma(1-\exp(-\kappa L_m))(T_f^4 - T_s^4) \quad (1)$$

where $\dot{q}''_{cond}$ refers to the conduction term from the rim of the oil pan to the fuel, $\dot{q}''_{conv}$ and $\dot{q}''_{rad}$ are the convective and radiative terms from the flame to fuel surface, respectively, k is the thermal conductivity related to the pool rim, T_f is the flame temperature near the fuel surface, T_s is the fuel surface temperature, h is the convective heat transfer coefficient, σ is Stefan-Boltzmann constant, κ is the soot absorption coefficient, and L_m is the mean beam length of the flame. Theoretically, the convective heat transfer coefficient h is generally expressed in Nusselt number, i.e. $\mathrm{Nu} = hD/k$, where k is the conductivity of the fluid. The dimensionless parameter Nu can be correlated with the Prandtl number Pr and Grashof number Gr as

$$\mathrm{Nu} = (\mathrm{Pr}\cdot\mathrm{Gr})^a \quad (2)$$

where Pr is independent of pressure and pool dimension and Gr can be correlated with pressure and the characteristic dimension as $\mathrm{Gr}\sim P^2D^3$ [15]. For laminar and turbulent fuel vapor layer flow, the exponential factor a in Eq. (2) is 1/4 and 1/3, respectively. Thus, the convective heat transfer coefficient can be approximated as $h \sim P^{1/2}D^{-1/4}$ for laminar flow and $h \sim P^{2/3}$ for turbulent flow [12,16,17]. With respect to the radiation term, it can be simplified as $\dot{q}''_{rad} \sim \kappa L_m \sim P^2D$ when employing an assumption of cylinder flame shape [7,13]. The three mechanisms compete with each other in determining the dominated heat feedback form as the pool dimension varies. For current study, the examined pool fires mainly belong to the convection-dominated ones, i.e. the power dependence on the ambient pressure should be in the range of 1/2~2/3.

The experimental findings by Zhou et al. [13] and summaries by Drysdale [14] on the fuel burning intensity of small-scale pool fires reveal that the dominated heat transfer mechanism is conduction when the burner diameter D is less than 7 cm, and then the transition follows at 7~10 cm, and convection dominates at 10~20 cm.

From the previous experimental studies, the relationship between burning intensity and ambient pressure has been concluded as $\dot{m}'' \sim P^\alpha$ for the same pool dimension [1–5,13]. As suggested by Zhou et al. [4,13], apart from the radiative term ($\alpha > 1$), dominated heat feedback terms for small-scale pool fires can be divided into three parts: conductive region ($\alpha < 0$); transition region ($0 < \alpha < 2/3$); and convective region ($2/3 < \alpha < 1$). However, it has been argued that the conduction trough the rim wall is eventually determined by the convection from flame to the wall and, therefore, can also be evaluated as a convection term [12,18,19]. Combining the convection terms, the heat feedback for a convection-dominated pool fire can be expressed as [14]

$$\dot{q}''_{conv} = h(T_f - T_s)\left(\frac{4\Delta}{D} + 1\right) \quad (3)$$

where h is the convective heat transfer coefficient related to the layer of fuel vapor, T_f and T_s are flame temperature and fuel surface temperature, respectively, $\triangle$ is the height of the rim exposed to flame, D is the pool diameter. For a convection-dominated pool fire with a larger pool diameter, the heat feedback is controlled by the heat transfer coefficient. The value of h exhibits a power law with

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