Fuel 111 (2013) 298–304

Contents lists available at SciVerse ScienceDirect

Fuel

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

Burning characteristics of conduction-controlled rectangular hydrocarbon pool fires in a reduced pressure atmosphere at high altitude in Tibet

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HIGHLIGHTS

- Conduction-controlled rectangular pool fire behaviors in a reduced pressure revealed.
- Unique experimental data achieved at a high altitude in Tibet.
- Burning rate increasing with aspect ratio and independent of pressure.
- A global factor for flame height accounting for both pressure and pool aspect ratio.
- Flame radiation fraction independent of both pool aspect ratio and pressure.

ARTICLE INFO

Article history:
Received 15 November 2012
Received in revised form 15 April 2013
Accepted 16 April 2013
Available online 1 May 2013

Keywords:
Rectangular conduction-controlled hydrocarbon pool fire
Burning rate
Flame height
Radiation heat flux
Reduced pressure atmosphere

ABSTRACT

The burning characteristics of conduction-controlled rectangular hydrocarbon pool fires in a reduced pressure atmosphere have not been revealed in the past. In this paper, rectangular pool fires with same area *S* (36 cm^2) but different aspect ratios (L/W = 1, 2, 3, 4) are burnt correspondingly in both normal (100 kPa; Hefei altitude 50 m) and reduced (64 kPa; Lhasa-altitude 3650 m) pressure atmosphere. Ethanol and n-heptane are used as fuel. Results show that the burning characteristics of conduction-controlled rectangular pool fires are quite different from those reported for radiation-controlled ones in the literatures. The burning rate of a conduction-controlled pool fire increases with aspect ratio, but does not change with pressure. The flame height in reduced pressure is higher than that in normal pressure. A global factor is developed for flame height correlation to account for both pressure and pool dimension aspect ratio effects. The flame radiation flux increases with increase in aspect ratio, being slightly lower in the reduced pressure than that in the normal pressure atmosphere. Meanwhile, the flame radiation fraction is nearly independent of both pool aspect ratio and pressure.

1. Introduction

Burning behaviors of a hydrocarbon pool fire have been studied for decades [e.g., 1–25] on its combustion characteristics, including thermal radiation [6–11], burning rate [12–16], flame shape and temperature [17–20], and heat transfer [21]. The pool scale effect on burning rate of a hydrocarbon pool fire can be characterized into three different regimes according to their different dominant heat feedback mechanisms at different pool sizes [1,2,4,5]. The burning rate of a pool fire is determined by the heat feedback from the rim walls or the flame to the fuel in different pool scale regimes [2,4]. The dominant heat feedback mechanism transfers from conduction to convection and finally radiation with increase in pool size. When pool size is less than 7 cm, the burning rate is dominated by conduction down through the pool rims. When pool size is between 7 and 10 cm, the burning rate is dominated by combination of conduction and convection. When pool size is between 10 and 20 cm, the burning rates is dominated by the convection. Thermal radiation feedback from flame to the fuel surface begins to be more and more important in the transition flame flow regime as pool fire beyond 0.2 m, where the burning rate is dominated by the radiation directly from the flame.

However, most of the previous works consider in default that the fire burns in the standard pressure atmosphere condition (100 kPa). In China, there is this wide range of plateaus, especially the Tibet (about 64 kPa) on the Qinghai-Tibet Plateau where the hydrocarbon fuel combustion behavior and fire safety is also a very important concern there. In such a reduced pressure atmosphere with lower absolute oxygen concentration in air, how the hydrocarbon fuel combustion behaviors change needs to be clarified, which should be different from those in standard pressure (100 kPa) or elevated pressures.

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http://dx.doi.org/10.1016/j.fuel.2013.04.032

Previous works [e.g., 22–27] have shown that the air pressure affects the burning behaviors of a hydrocarbon pool fire considerably. For example, de ris et al. [22] has studied the radiation characteristics by a series of model-scale pool-fire experiments (pan diameters of 0.15, 0.23, and 0.30 m) at elevated pressures, the proportionality of the ratio of burning rate to the pressure for radiation-controlled pool fires has been derived. Most et al. [23] have studied the effects of gravity and pressure (0.03–0.3 MPa) on the characteristics of diffusion flames produced by a 62 mm gaseous pool fire, which has indicated that the flame height decreases at lower pressure while the flame radiation fraction is independent of pressure. Li et al. [24] have carried out experiments on combustion characteristics of n-heptane and wood crib fires at two altitudes (Hefei city: 50 m, 100 kPa; Lhasa city: 3650 m, 64 kPa), which has revealed that the burning rate and radiation heat flux at higher altitude is lower. Hu et al. [26] have investigated experimentally the burning characteristics of n-heptane pool fire at higher altitude (Dangxiong city in Tibet: 4250 m, 59 kPa), their experimental results have confirmed the findings of previous studies at relatively lower altitudes and have showed that the burning rate per unit surface area, radiation heat flux and average flame axis temperature decrease when the altitude is increased. Fang et al. [25,27] have studied the effect of reduced air pressure (Lhasa city: 3650 m, 64 kPa), upon CO production and flame pulsation frequency of pool fires. It has been shown that in low air pressure, the pool fire flame has stronger periodic oscillation and puffing frequency.

However, all these works above consider the burning rate of a square or circular pool fire in the radiation-controlled regime. For the rectangular pool fires, Hasemi and Nishihata [28] have studied the effect of fire source shape (aspect ratio) on the flame height and fire plume temperature of turbulent diffusion flames. It has been revealed that McCaffrey classical correlation [29] on plume temperature is still applicable as aspect ratio (n = length/width) no more than 3. Meanwhile, the burning rate of a rectangular pool fire in a reduced pressure atmosphere has rarely been investigated. Recently, Tu et al. [30] has investigated the burning behaviors of radiation-controlled rectangular ethanol and n-heptane pool fires in a reduced pressure, showing the flame height Z_f is independent of pressure and decreases with increasing aspect ratio n ($n > 3$).

$$\frac{Z_f}{1.02D^* + H_0} \sim 0.149\left(\frac{1}{\sqrt{nS}}\right)^{2/5} \cdot \dot{Q}^{4/15}, \quad n > 3 \tag{1}$$

However, how a conduction-controlled hydrocarbon pool fire behaves in a reduced pressure atmosphere has never been revealed, a task undertaken in this work. Moreover, for a conduction-controlled hydrocarbon pool fire, as the conduction feedback through the pool rim is the dominant heat feedback, the pool dimension aspect ratio should be a very important factor to be considered and be included into the model.

In this paper, a series of experiments are carried out correspondingly both in Hefei city (altitude: 50 m, 100 kPa) and in Tibet Lhasa city (altitude: 3650 m, 64 kPa). The conduction-controlled rectangular pool fire characteristics (burning rate, flame height and radiation flux) are measured and compared for these two atmospheric pressures, and further compared with those for the radiation-controlled ones reported in the literature. There are three more sections following the introduction. The second section describes the experimental procedure, devices, equipment and conditions. The third section includes the analysis and results. The last section summarizes the major findings and conclusions of this paper.

2. Experiments

Ethanol and n-heptane are used as fuels producing representative flames with definitely different sootiness. The fuel is held within four rectangular pools of same area S (36 cm^2) but different aspect ratios n ($n = L/W$, long side divided by short side; n = 1,2,3,4.) as specified in Table 1. These pools are made by 4 mm thick steel board. Their depths are all 3 cm. In each test, the initial mass of the fuel is 20 g. The pool fires are burnt in a quiescent air in a large hall. A feature of the current study relative to previous ones investigating pressure effect on combustion behaviors is that the change of the ambient pressure is achieved naturally through the change of the altitude of experimental site, in which the possible complex boundary constraint effect and buoyancy induced inside-box (vessel) air flow condition in the previous works [e.g. 22,23] by using pressure vessel or box can be completely eliminated.

All the pools are placed on a horizontal insulation board with dimensions of 0.4 m (width) × 0.4 m (length) as shown in Fig. 1. An electronic balance is positioned below the insulation board to record the mass loss history of the burning pool fire with sampling intervals of 1 s. The mass resolution of the balance is 0.01 g. The uncertainty of the measured mass loss rate is estimated to be less than 3%. Typical time–variation curve of mass measured, for the 6 cm square n-heptane pool fire in Hefei city (100 kPa, attitude: 50 m), by the balance and the corresponding mass loss rate history derived are shown in Fig. 2. Before the burning reaches the steady period (150–330s), there is a preheating phase. The steady burning mass loss rate of the pool fire is deduced to be 0.623 g/s as averaged values in the steady burning period. There are two factors needed to be considered for the effect of the pool dimension configurations on the burning of the pool fires used here:

(1) The corner effect for such square/rectangular pools which will generate vortex in the corners of the pools. The generated vortex will enhance the convection (more importantly) and radiation feedback to the fuel surface. This will be more effective for large pool fire when the flame is turbulent. It is observed in our experiments that, as the pool size is small and conduction-controlled, the flame is laminar and no obvious vortex is observed to be generated at the corners as shown in Fig. 3.
(2) The transient effect of varying rim/lip height during the tests with descending of the fuel level surface. With the increase of the lip height, the radiation feedback from the hot rim to the liquid surface should be increased and air entrainment into the flame base center also be modified. However, for such small pool fires as conduction-controlled, the conduction heat feedback should be much larger than that directly from the flame radiation, which in turns should be higher than that from rim wall radiation. As the rim height of the pool fire is also small (3 cm), the effective radiation configuration view factor should also be small. As for the modification of the air entrainment into the flame base, this is also not important for such small pool fire with small rim height (3 cm) used in this work. When the rim wall height is large, this will certainly affect the air entrainment into the flame base center which is more important for the large pool fires. An evidence of the rim/lip effect is not so important for the small pool fires with small rim height in this experiments is that the burning of the fuel has reached and maintained for a quite long steady burning period (Fig. 2), although the fuel level descends with the increase in lip height during the burning period.