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Mean flame height and radiative heat flux characteristic of medium scale rectangular thermal buoyancy source with different aspect ratios in a sub-atmospheric pressure

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ABSTRACT

The main objective of this work is to study the mean flame height and flame radiative heat flux of medium scale thermal buoyancy source with different aspect ratios in a sub-atmospheric pressure at high altitude, which has not been investigated before. Two series of radiative heat flux experiments of medium scale thermal buoyancy source were conducted separately in Hefei (altitude: 50 m, pressure: 100 kPa) and Lhasa (altitude: 3650 m, pressure: 64 kPa). The mean flame heights of rectangular heat sources burners were obtained by image processing method and the radiation flux was measured by a water cooled wide angle radiometer. Four medium scale rectangular thermal source burners with same surface area (about 420 cm^2) but different buoyancy source dimension aspect ratios n ($n = L/W$, long side divided by short side) were used to produced heat sources. It is found that the flame height in reduced pressure is higher than that in normal pressure, and the flame radiation flux increases with increase in source aspect ratios. Meanwhile, the flame radiation fraction of medium scale thermal buoyancy source with different aspect ratios in a reduced atmospheric pressure changes little with ambient pressure and theoretical demonstrate with expression $\chi_R \sim p^{0.45}\sigma T_F^4$.

1. Introduction

Flame radiative heat flux from large scale thermal buoyancy source (e.g. sooty hydrocarbon pool fires) can bring lots of thermal hazards to people and adjacent objects [1,2]. Combustion characteristics, including radiation heat flux, mean flame height characteristics, temperature and the flow field structure, as important thermal dynamic parameters of flame dynamics in buoyancy heat sources, has been investigated extensively by the experiment [3–6] and simulation [7–9] in recent decades. It was observed that the burning of sooty hydrocarbon heat sources can be divided into three different dominant heat feedback mechanisms based on the scale effect of different size [2]. If the diameter is more than 0.2 m, the heat feedback to fuel is mainly dominated by flame radiation. It is important to note that combustion characteristics of sooty hydrocarbon heat sources in reduced pressures has received increasing attention [10–17] in recent years, such as the mass burning rate [10,11], flame shape [12], temperature [14], thermal radiation [10,13], including fuel characteristics, such as fuel type with different soot emission (wood cribs [9], n-heptane [10], ethanol [14]) and the cross air flow effect [17]. It was shown that low ambient air pressure affects the flame radiation characteristics of a hydrocarbon heat sources considerably. Wang et al. [10,11] studied combustion characteristics of n-heptane fires at three altitudes (Location: Hefei city, altitude: 50 m, pressure: 100 kPa; Lhasa city, 3650 m, 64 kPa; Dangxiong city: 4250 m, 59 kPa), which reveals that the flame radiation heat flux at higher altitudes is lower. Most et al. [13] studied the effects of ambient pressure on the flame radiation characteristics of gas burner flames, which is shown that the flame radiation fraction is an about – 0.1 power law dependence on the ambient pressure.

All these works above, which studied the mean flame height and radiation characteristics of heat sources, are based on a square or circular thermal buoyant source shape. For the effect of considering heat source dimension aspect ratios [18–21], Hasemi et al. [19] have studied the effects of heat source shape with different aspect ratios on the axial thermal plume temperature profile of gaseous fuel source. The maximum excess temperature profile in the thermal buoyant plume were measured. It is also found recently that [20,21], based on rectangular heat sources experiments (pool fires experiments) in a sub-atmospheric pressure (Lhasa city: 3650 m, atmospheric pressure: 64 kPa). For the radiation-controlled

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Nomenclature

A_f	flame area (m^2)
C_p	specific heat of air at constant pressure (J/kgK)
D^*	characteristic diameter of sources (m)
g	gravitational acceleration (m/s^2)
ΔH	heat of combustion
I_R	the measured radiation flux
K_s	the soot absorption coefficient
L	long side length of rectangular source rim (m)
L_m	the beam length
ℓ_f	mean flame height (m)
$\ell_{f,Hefei}$	mean flame height in Hefei city (kPa)
$\ell_{f,Lhasa}$	mean flame height in Lhasa city (kPa)
$\dot{m}''$	mass burning rate per area (g/m^2s)
n	aspect ratio $n = L/W$
p	ambient air pressure (kPa)
P_{Hefei}	ambient air pressure in Hefei city (kPa)
P_{Lhasa}	ambient air pressure in Lhasa city (kPa)
$\dot{Q}$	heat release rate of the fire (kW)
Q_r	flame total radiation
$\dot{q}''_{f,rad}$	the flame radiant heat fluxes
R_f	the distance from the vertical flame mid-point height to the radiometer position
S	area of pool surface (m^2)
T_f	flame temperature (K)
u	characteristic upward velocity
V_f	flame volume
W	short side length of rectangular pool rim (m)

Greek symbols

ρ	ambient density (kg/m^3)
σ	the Stefan–Boltzmann constant
μ	dynamic viscosity
α	entrainment coefficient
α_{hefei}	entrainment coefficient in Hefei city
α_{lhasa}	entrainment coefficient in Lhasa city
τ_c	soot formation kinetic rates
τ_k	turbulent Kolmogorov times
χ_R	flame radiation fraction

rectangular ethanol heat sources experiments (the heat source aspect ratios range from 1 to 8, and the surface area is about 900 cm^2) [20], the ratio of radiative heat flux in Lhasa city (reduced pressure at high altitude) to that in Hefei city (normal pressure near sea level) is nearly proportional to ambient pressure. And the radiation heat flux decrease with increase in heat sources dimension aspect ratio. For the conduction-controlled ethanol heat source (the dimension aspect radios range from 1 to 4, and the heat source surface area is about 36 cm^2) [21], it was found that the ratio is independent of ambient pressure and the radiative heat flux increase with increase in heat source dimension aspect ratios.

However, how a medium scale radiation-controlled rectangular heat sources with acetone used as fuel (the same thermal buoyant source surface area is about 420 cm^2, but different pool aspect radios, and heat transfer is relatively dominated by radiation) behaves in a sub-atmospheric pressure at high altitude has never been revealed, a task undertaken in this work. Some new findings will be introduced below. There are three more sections following the introduction. The second section describes the experimental procedure, devices, equipment and conditions. The third section includes the results and discussions. The last section summarizes the major findings and conclusions of this paper.

2. Experimental

The experiments are conducted correspondingly both in Hefei city in Anhui province (the altitude is 50 m and ambient pressure is about 100 kPa) and in Lhasa city in Tibet (the altitude is 3650 m and the pressure is about 64 kPa). Experiments are carried out with four rectangular heat sources with same surface area S (nearly 420 cm^2) but different source aspect ratios n ($n = L/W$, long side divided by short side; $n = 1, 2, 4, 8$) as specified in Table 1. These thermal buoyant sources are made by stainless steel plate with the size of 0.3 cm thick. And the acetone was used as fuels, the fuel mass is about 413 g.

An electronic balance with resolution of 0.01 g is placed below the insulation plate to record the mass loss history of thermal buoyancy source as shown in Fig. 1. The flame shape (e.g. mean flame height) was visualized by a digital CCD camera with the film speed of 25 frames per second. Two wide view angle water-cooled radiant flux sensors (Captect type) were used to measure the emitted thermal radiation flux by the flame. The experiments are repeated three times, showing good repeatability with averaged values used for further analysis.

3. Results and discussion

3.1. Mean flame height

The burning rates of thermal buoyancy sources in the steady burning stage (e.g. Fig. 2a) are obtained with a similar method was reported by Fang et al. [14], Wang et al. [15]. Fig. 2b showed the burning rates divided by the pressure against different aspect radios in normal and reduced pressures. It can be observed that: (a) the mass burning rate of thermal buoyancy sources with acetone used as fuels increased with the heat source aspect radio no matter in the normal pressure environment, or in the reduced environment, and more importantly (b) the burning rate of medium scale radiation-controlled rectangular thermal buoyancy sources against ambient pressures present linear relation since n ranges from 1 to 8 as experimental results can verify in Fig. 2b. It gives

$$\frac{\dot{m}''}{p} = 0.093\left(\sqrt{n} + \sqrt{1/n}\right) + 0.2045 \quad (1)$$

where p the ambient pressure, $\dot{m}''$ is mass burning rates.

The probability distribution of the flame appearance analyzed by image processing [21], is shown for one case as an insert in Fig. 3. The mean flame height, ℓ_f was obtained when intermittency is $I(z) = 0.5$.

Table 1
Summary of experimental scenarios.

Aspect ratio n	Heat sources	
	L (m)	W (m)
1	0.205	0.205
2	0.289	0.145
4	0.453	0.113
8	0.579	0.072