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Axial temperature profile in vertical buoyant turbulent jet fire in a reduced pressure atmosphere

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HIGHLIGHTS

- Data achieved in a reduced pressure through unique experiments at high altitude.
- Difference from those obtained in normal pressure clarified.
- Virtual origin of jet fires correlated non-dimensionally globally for both pressures.
- Axial temperature profiles correlated non-dimensionally with virtual origins.

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ABSTRACT

Characteristics of a vertical jet fire in a reduced pressure atmosphere (at high altitude) have not been quantified in the literatures. In the reduced pressure atmosphere, the air/oxygen density is lower, which in turn affects both combustion and entrainment, and hence the axial temperature profile of a diffusive turbulent jet fire. Experiments have been conducted in this work to investigate the axial temperature profiles of propane turbulent buoyant jet fires produced by nozzles with diameters of 4–10 mm in both reduced- (0.64 atm) and normal pressure (1 atm) atmosphere. It is found that the maximum temperature in the flame zone is a bit higher, the temperature decreases faster vertically and is somewhat lower in the buoyant plume zone in the normal pressure than those in the reduced pressure. The virtual origin is then deduced and clarified to be larger in the reduced pressure, however, it can be correlated non-dimensionally with flame Froude number (Fr_f) in a 2/5 power law function for both these two pressures. Finally, the normalized axial temperature profile against non-dimensional height above the virtual origin can be still well characterized into three regions in the reduced pressure by the same power law functions as those in the normal pressure.

1. Introduction

A jet fire usually forms due to the leakage and ignition of hydrocarbon gas fuel or two-phase flow, in case of pipe or safety valve broken, or similar accidental scenarios. Jet fires can pose serious adverse impact, such that there have been extensive investigations into jet fire characteristics in the past decades on temperature profile [1–3], flame height [4–10], lift-off [11–19], radiation [20–22] and soot volume fraction [23–25] for their importance in practical significance. A series of semi-empirical theories and correlation models have been developed and proposed in the literatures. Axial temperature profile is an important parameter in characterization of a vertical turbulent diffusive jet fire.

The behavior of a turbulent diffusion jet flame is dominated by entrainment either buoyancy-controlled (where the flow is governed by buoyancy) or momentum-controlled (where the nozzle fuel flow velocity is the characteristic velocity). An indicator is that the flame height increases with increase in the fuel supply flow rate in the buoyancy-controlled regime, but in contrast it is only determined by the nozzle diameter and does not change with fuel supply rate in the momentum-controlled regime. So, the behavior of a jet fire transfers from buoyancy-controlled to momentum-controlled with the increase in nozzle flow velocity (or nozzle fuel supply rate) to be even sonic.

Gomez-Mares et al. [3] has studied the axial temperature distribution for sonic (momentum-controlled) jet fire (flame length larger than 4 m and up to 9 m) with empirical equations correlated. McCaffrey [7] has proposed till now the most classical three-region-theory in characterizing the vertical temperature profile of a buoyant turbulent diffusive fire plume, based on correlation of measured data from a 30 cm methane pool-type porous bed burner. In his theory, the vertical temperature profile is divided into

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Nomenclature

D	inner diameter of the nozzles (mm)
Fr	Froude number
Fr_f	flame Froude number, in Eq. (5)
g	gravitational acceleration (m/s^2)
HRR	heat release rate (kW)
$\dot{Q}^*$	dimensionless heat release rate, in Eq. (1)
Us	velocity of the fuel ejected from the nozzle orifice (m/s)
S	air to fuel mass stoichiometric ratio
T_0	ambient temperature (K)
T_z	plume temperature at height Z (K)
ΔT	flame temperature rise (K)
$\overline{\Delta T_f}$	mean peak flame temperature rise (K)
Z_0	virtual origin (m)
Z	vertical height above nozzle (m)

Greek symbols

ρ_0	ambient air density (kg/m^3)
ρ_s	fuel density at nozzle (kg/m^3)

Subscripts

0	ambient
f	flame
s	gas fuel

three regions: the continuous flame region, the intermittent flame region and the buoyant plume region, as described by following global non-dimensional expression:

$$2g\frac{\Delta T}{T_0} = K\left(\frac{z}{\dot{Q}^{2/5}}\right)^{2\eta-1} \qquad (1)$$

where $K = (\frac{\kappa}{C})^2$, η and κ are constants with different values for the three regions as listed in Table 1.

The above equation has been validated by extensive experiments for pool fires e.g., [26–28] and porous gas burners with low (or nearly zero) initial fuel momentum. Imamura and Sugawa [29] has shown that there are still limitations of its application to turbulent jet diffusive fires as the initial fuel momentum from the nozzle is not negligible. This effect can be accounted for by a parameter, named as virtual origin Z_0, a hypothetical point source to revise the vertical height Z by requiring that at the flame tip location $(Z - Z_0)$ the calculated temperature using the plume equation is equal to the flame temperature [e.g., 29].

Although there have been extensive works and experimental measurements on characteristics of a vertical jet fire, they are all carried out and convinced to be only applicable for normal (standard) pressure atmosphere. There is, however, need to extend these correlations for conditions at low pressure such as at high altitudes, for example, Tibet. In a reduced pressure atmosphere, the local air and oxygen density should both decrease proportionally to the ambient atmospheric pressure. The change of their density will affect both combustion and entrainment, which in turn dominate the axial temperature profile of a vertical turbulent diffusive jet fire. Some earlier works have been reported for pool fire characteristics in the reduced pressure atmosphere at high altitude in Tibet [e.g., 26–28]. Their characteristics are found to be remarkably different from those in the normal pressure atmosphere. It should be also noted that the burning of a liquid pool fire, where complex thermal feedback and fuel evaporation process is incorporated, is definitely different from burning of gaseous jet fires. As the entrainment changes, the flame height should also change accordingly. It has been observed that the flame is higher in the reduced pressure atmosphere [26–28]. The virtual origin, as an important physical parameter relating closely to the flame height, thus should also change and needs to be clarified, for correlating the axial temperature profile of a vertical buoyant turbulent diffusive jet fire in a reduced pressure atmosphere.

Table 1
Empirical constants in McCaffrey's plume equations [7].

Region	$Z/\dot{Q}^{2/5}$ (m/kW$^{2/5}$)	η	κ	C
Continuous flame	<0.08	1/2	6.9	0.9
Intermittent flame	0.08–0.2	0	1.9	0.9
Buoyant plume	>0.2	−1/3	1.1	0.9

In this work, a series of experiments are conducted for buoyancy-controlled turbulent jet diffusion flame (flame length up to 1.2 m) correspondingly in both normal pressure (Hefei City: 50 m and 1 atm) and a reduce pressure (Lhasa City: 3650 m and 0.64 atm) atmosphere at high altitude. The axial temperature profiles are measured for different size nozzle jet fires at different propane fuel supply rates, and are further compared for these two different atmospheric pressures with their differences clarified. The virtual origins of the jet fires are correlated for both these two atmospheric pressures. The axial temperature profiles are then correlated non-dimensionally with vertical location accounting for the virtual origins. The classical three-region-theory is checked for its global applicability in the reduced pressure atmosphere.

2. Experimental

2.1. Experimental facility

Fig. 1 shows the experimental apparatus and measurement setup to study the axial temperature distributions of vertical buoyant turbulent diffusive jet fires in a still air. The facility consists of a fuel supply system, thermocouples and nozzles made of stainless steel. The nozzle diameters are 4 mm, 5 mm, 6 mm, 8 mm and 10 mm with thickness of 2.5 mm and length of 30 cm. The propane gas fuel flow rate is regulated by a throttle valve and measured by a controlled volumetric flow meter. The real mass flow rate is calibrated according to ambient pressure.

The flame fluctuation character is recorded by a digital CCD camera to quantify the intermittent flame region. The CCD camera records 25 frames per second with size of 720 pixels × 576 pixels. Time series flame images are recorded in the experiments for each flow rate, and decompressed into frames and processed in sequence. All the images are converted to gray scale image and then to binary image. A luminance threshold, characterizing the variance in the fluctuation of luminance using Otsu method [30], is chosen to quantify the flame appearance intermittency as to identify the three regions of the jet fire. The intermittency is represented by the probability distribution which is obtained by averaging about 1000 consecutive images of each case [31], as shown in Fig. 2. According to Audouin's proposal [32], the three regions of the a fire can be clarified as the continuous flame where the presence probability is 0.95 from the flame base, the intermittent flame where the presence probability is 0.95 down to 0.05 and the buoyant plume upper region from the presence probability 0.05.

A thermocouple tree consisting of 14 thermocouples (K type) with diameter of 0.5 mm is installed along the axial central line