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Flame height and lift-off of turbulent buoyant jet diffusion flames in a reduced pressure atmosphere

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HIGHLIGHTS

▶ Flame heights of diffusive jet fires achieved in a reduced pressure atmosphere through unique experiments at high altitude.
▶ Flame lift off behavior is revealed for the first time in a reduced pressure atmosphere.
▶ Their difference from those in the normal pressure atmosphere is revealed and quantified.
▶ Global model is developed to account for the pressure change.

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ABSTRACT

This paper reports new experimental findings at a reduced atmospheric pressure (at high altitude in Tibet) for turbulent buoyant jet diffusion flames and global correlations for both normal and this reduced atmospheric pressure. Comparative experiments are carried out in Hefei (50 m, 100 kPa) and Lhasa (3650 m, 64 kPa) in China to measure the mean flame height and lift-off behaviors. The turbulent jet diffusion flame is produced by nozzles with diameters of 4, 5, 6, 8 and 10 mm using propane as fuel. A series of new findings are revealed and their interpretations are presented in this work. Results show that the normalized mean flame height is higher in the lower pressure atmosphere. A theory of diffusion flame height based on flame Froude number for the transition from buoyancy to momentum controlled turbulent jets can still successfully collapse the flame height data, although a 0.8 factor is needed globally to include effects of reduced entrainment and larger fluctuation in reduced pressure. The lift-off heights are revealed to be higher, while the lift-off velocities are smaller, in the reduced pressure atmosphere. The lift-off heights are correlated based on different theories. The present work provides new findings supplementary over previous classical knowledge on buoyant turbulent jet diffusion flame behaviors.

1. Introduction

Pressure effect on combustion behavior has been studied extensively in the past. The pressures considered are mainly at elevated pressure condition over 100 kPa, with its effect on flame configuration, soot emission and radiation for both premixed and diffusion flames (e.g., [1–4]). For lower pressure conditions less than 100 kPa, some experimental works have also been reported recently for pool fire and solid combustibles based on data achieved in Lhasa at high altitude (e.g., [5,6]). All these works have shown that there is remarkable pressure effect on combustion, especially in the reduced pressure atmosphere where some special combustion characteristics have been found there at the high altitude. There are also some works reported for laminar jet flame behaviors in the sub-atmospheric pressure condition (e.g., [7]). The difference of vertical temperature profiles of jet fire in normal pressure condition from that in a sub-atmospheric pressure condition due to air entrainment change has also been clarified recently [8]. Here in this work, the buoyant turbulent jet diffusion flame behaviors (flame height and lift-off) in a sub-atmospheric pressure condition (Lhasa city in Tibet: 3650 m, 64 kPa) are reported experimentally. This is to clarify the flame height behavior, especially lift-off, in a sub-atmospheric pressure, which has never been known in the past.

Turbulent jet diffusion flame height and lift-off and have been investigated extensively (e.g., [9–23]), including transition from buoyancy to momentum controlled conditions with an increase in fuel flow rate from the nozzle. Previous results on these characteristics are briefly discussed next including some comments on effect of pressure.

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Nomenclature

c_p	specific heat at constant pressure ($kJ\,kg^{-1}\,K^{-1}$)
D	source diameter (m)
Fr_f	flame Froude number
g	gravitational acceleration (m/s^2)
h	lift-off height (m)
ΔH_c	heat of combustion per unit fuel mass (kJ/kg)
$\dot{m}_p$	mass flow rate (kg/s)
M	molecular weight of the gas
p	ambient pressure (Pa)
$\dot{Q}$	heat release rate (kW)
$\dot{Q}^*$	dimensionless heat release rate
R	ideal gas constant (8.31 J/(K mol))
r	plumes radius (m)
S	air to fuel mass stoichiometric ratio
T_0	ambient temperature (K)
$\overline{\Delta T_f}$	mean peak flame temperature rise (K)
ΔT_f	temperature rise at the flame tip (K)
ΔT_z	temperature rise at height z (K)
U_s	velocity of the fuel ejected from the nozzle orifice (m/s)
u	plume velocity (m/s)
z	vertical height above the nozzle orifice (m)
z_0	virtual origin height (m)
z_f	flame height (m)

Greek symbols

α	entrainment coefficient
α_{lhasa}	entrainment coefficient in Lhasa City
α_{hefei}	entrainment coefficient in Hefei City
α_T	entrainment coefficient correction factor
ℓ_f	flame height (m)
ρ	plume density (kg/m^3)
ρ_0	ambient air density (kg/m^3)
ρ_s	fuel density at nozzle (kg/m^3)

Subscripts

0	environment
f	flame
s	gas fuel

The flame height of a turbulent diffusion flame is dominated by entrainment either buoyancy-controlled or momentum-controlled. It increases with increase in the fuel supply flow rate in the buoyancy-controlled regime where the flow is governed by buoyancy. In contrast, the flame height is only determined by the nozzle diameter and it does not change with fuel supply rate in the momentum-controlled regime where the nozzle fuel flow velocity is the characteristic velocity. For example, Palacios and Casal [12] have studied the flame shapes of large vertical jet fire (propane sonic exit velocity with flame height up to nearly 10 m). Prior to the turbulent momentum-controlled regime, there exists a considerable turbulent buoyant regime. For the purely buoyancy-controlled diffusion flame, the normalized flame height is found to be a 2/5 power function of a dimensionless heat release rate of the fire [22,23]:

$$\frac{\ell_f}{D} \sim \dot{Q}^{*2/5} \tag{1}$$

where ℓ_f is flame height, D is source diameter and $\dot{Q}^*$ is dimensionless heat release rate [22,23],

$$\dot{Q}^* = \frac{\dot{Q}}{\rho_0 c_p T_0 g^{1/2} D^{5/2}} = \frac{\rho_s u \pi D^2 \Delta H_c/4}{\rho_0 c_p T_0 g^{1/2} D^{5/2}} \tag{2}$$

Delichatsios [9] further developed a dimensionless model for flame height relationships by using flame Froude number Fr_f as the dimensionless parameter to account for the transition from buoyancy to momentum-controlled jet flames [9–11] as well as for variations of mean flame temperature and turbulence:

$$\frac{\ell_f}{(S+1)D(\rho_s/\rho_0)^{1/2}} = \frac{13.5 Fr_f^{2/5}}{(1+0.07 Fr_f^2)^{1/5}} \tag{3a}$$

where Fr_f is defined as

$$Fr_f = \frac{U_s}{(gD)^{1/2}(S+1)^{3/2}(\rho_s/\rho_0)^{1/4}(\overline{\Delta T_f}/T_0)^{1/2}} \tag{3b}$$

It was also pointed in [9] that Eq. (3a) should be modified by a factor α_T to consider cases where entrainment or turbulent fluctuations vary:

$$\frac{\ell_f \alpha_T}{(S+1)D(\rho_s/\rho_0)^{1/2}} = \frac{13.5(\alpha_T Fr_f)^{2/5}}{[1+0.07(\alpha_T Fr_f)^2]^{1/5}} \tag{3c}$$

The correlations in Eqs. (1) and (3) have been proved to be valid in a standard pressure atmosphere [9]. One can also see by inspection that because the density of the fuel and the ambient air both change proportionally with ambient pressure, there should be no dependency of the corresponding dimensionless variables (in Eqs. (1) and (3)) on pressure (assuming that the coefficient α_T is independent of pressure in Eq. (3c)). That is to say, ideally, the above non-dimensional models should be still valid in reduced pressure atmosphere. Most et al. [24] has investigated the changes of flame height with pressures for pool-type diffusion flames produced by porous gas burner with low Fr (Froude) number of 6×10^{-5} in a 0.3 m diameter and 1 m height pressure vessel, in which it is found that the flame height increases with ambient pressure (in a power law of $p^{0.16}$ empirically) in range of less than 80 kPa and decreases with ambient pressure (in a power law of $p^{-0.5}$ empirically) in range of larger than 80 kPa. However, there is still no experimental report in the literatures on how the turbulent buoyant jet diffusion flame height behaves in reduced pressure atmosphere, a task undertaken in the present work.

Lift-off is still receiving extensive attention with different interpretation theories. A number of categories of theories [13] have been used to characterize lift-off mechanisms from which a "premixed flame turbulence intensity theory" [13–19] is classical one. Based on this theory, Kalghathi [14] reveals that the turbulent jet diffusion flame lift-off height increases linearly with nozzle fuel discharge velocity independent of nozzle diameter. The "large eddy triple flame theory" is another classical one (e.g., [20,21]). The third typical one is "edge flame theory" [25,26], which has been assessed by using cinema-PIV. But there is also no report on how the turbulent buoyant jet diffusion flame lifts off in a reduced pressure atmosphere.

In this paper, comparative experiments are carried out for buoyancy-controlled turbulent jet diffusion flame at two different altitudes: 50 m (100 kPa) and 3650 m (64 kPa) as described in the next Section 2. The experimental results are then analyzed and correlated in Section 3 whereas the last section summarizes the major findings of the research.

2. Experimental

Fig. 1 depicts a schematic of the experimental facility and measurement setup consisting of a flow supply system, a 2 m long pipe