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Momentum- and buoyancy-driven laminar methane diffusion flame shapes and radiation characteristics at sub-atmospheric pressures

Jun Fang [a,b,*], Jing-wu Wang [a], Jin-fu Guan [a], Yong-ming Zhang [a], Jin-jun Wang [a]

[a] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, PR China
[b] Department of Mechanical and Aerospace Engineering, University of California at San Diego, CA 92093, USA

HIGHLIGHTS

- Buoyancy and momentum controlled laminar methane diffusion flame in low pressure.
- Dimensionless flame height y/C generally decreases when CRi increases.
- Radiant fraction increases at $p^{0.2}$.
- Strouhal and Froude numbers posses as $St \propto Fr^{-0.48}$.
- B-driven flames flicker slower than M-driven ones.

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ABSTRACT

Buoyancy and momentum are two major driving forces that affect the behavior of diffusion flames, which have not been fully interpreted in sub-atmospheric environments. In this work, a theoretical model based on the cylindrical flame shape is proposed incorporating with the flame width and height in order to predict the steady flame height with Richardson number. The theoretical equation of dimensionless non-flickering flame height y/C was deduced, and the value of y/C was shown to slightly increase for relatively small CRi and decrease significantly with increasing CRi. To verify this model, buoyancy (B)- and momentum (M)-driven methane laminar diffusion flames with the mass fuel flow rate in the range of 2.99–23.9 × 10^{-6} kg/s were investigated at 0.45–1.00 atm. The flow regimes are dominated by the secondary buoyancy acceleration and initial fuel axial velocity, respectively. Experimental results show that first, for steady flames y/C decreases with increasing CRi, which is consistent with the prediction of the model. The value of y/C decreases with increasing air pressure linearly at −0.046, −0.068, and −0.077 slopes for three different CRi levels. Second, radiant fraction of B-driven flames is generally bigger than that of M-driven ones due to longer soot residence time. The radiant fraction increases with increasing air pressure for both B- and M-driven flames at nearly $p^{0.2}$. Third, for flame oscillation, Strouhal and fuel Froude numbers have the following relationship: $St \propto Fr^{-0.48}$, $f \propto u_{f,0}^{0.04}/d^{0.52}$, i.e., B-driven flames flicker slower than M-driven ones. Considering the effect of air pressure, $f \propto p^{1/3-\beta}$ ($\beta \approx 0.30$ for B-driven flames and $\beta \approx 0.19$ for M-driven ones), thereby indicating that flickering frequency increases with increasing air pressure, and the increasing rate of flickering frequency of M-driven flames is higher than that of B-driven ones.

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1. Introduction

Laminar gas-jet flame lengths have been widely studied numerically and experimentally since the basic study conducted by Burke and Schuman in 1928 [1]. Studies that involve sub-atmospheric pressures have been performed because of their direct application to unwanted fires in high-altitude environments and spacecraft [2,3]. Laminar diffusion flame shape, radiation, and oscillation at sub-atmospheric pressures are important parameters for understanding turbulent combustion mechanism and for promoting fire prevention technology.

In 1993, Yuan et al. [4] studied the effect of low ambient pressure on global shape and hydrodynamic behavior of jet diffusion flame with low Reynolds number (Re). For the same fuel mass flow

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* Corresponding author at: State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, PR China. Tel.: +86 551 63607119; fax: +86 551 63601669.

E-mail addresses: fangjun@ustc.edu.cn, juf003@eng.ucsd.edu (J. Fang).

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Nomenclature

A	area (m^2)
d, r_0	inner diameter, radius of the fuel nozzle (m)
D	diffusion coefficient (m^2/s)
f	flame flickering frequency (Hz)
f_v	volume fraction
Fr	Froude number, $Fr = u_{f,0}^2/gd$
g, g'	acceleration due to gravity or buoyancy ($\mathrm{m/s}^2$)
k	absorption–emission coefficients (m^{-1})
l_F	flame length (m)
l_m	mean geometric beam length (m)
$\dot{m}$	mass flow rate (standard liters per minute (slpm), kg/s or mg/s)
p	air pressure (atm)
$\dot{q}''_{rad}$	flame radiation flux at receiver ($\mathrm{W/m}^2$)
r_F	radius of flame shape (m)
Re	Reynolds number, $Re = u_{f,0}d/\nu_f$
Ri	Richardson number, $Ri = 2(\rho_\infty - \rho_F)gr_0/(\rho_F u_{f,0}^2)$
S	air-to-fuel volume stoichiometric ratio
St	Strouhal number, $St = fd/u_{f,0}$
T_F	mean flame temperature (K)
T_∞	ambient temperature (K)

u	velocity of fluid (m/s)
Y_{ox}	mass fraction of oxidizer in ambient air
z	location in the flame axis (m)
δ	penetration depth of oxidizer (m)
ΔH_c	heat of combustion (J/kg)
ε	emissivity
ρ, ν	density or kinematic viscosity of fluid ($\mathrm{kg/m}^3$, m^2/s)
ρ_F	mean flame density ($\mathrm{kg/m}^3$)
σ	Stefan–Boltzmann constant (56.7×10^{-12} $\mathrm{kW/m^2/K^4}$)
τ_c	diffusion time (s)
τ_r	the centerline fight time or soot residence time (s)
Φ_{ox}	total flow rate of oxidizer (kg/s)
χ_R	flame radiant fraction

Subscript

f	fuel
F	flame
0	initial condition of fuel
∞	ambient

rate from 0.844×10^{-6} to 1.457×10^{-6} kg/s at 0.20–1.00 atm, the steady flame surface area increases significantly with decreasing ambient pressure. In 1996, Most et al. [5] compared the gravity and low air pressure effects and found that as the pressure increased from 0.3 to 1.0 atm at the same fuel volumetric flow rate (ethane flow rate of 1.1 L/min, Froude number (Fr) of 6×10^{-5}), the flame height increased and decreased for pressures below and above 0.8 atm, respectively. In 1997, Durox et al. [6] suggested that the buoyant jet flame flickering frequency f depended on air pressure p and gravitational acceleration g as the relationship of $f \propto p^{1/3}g^{2/3}$, which was validated by experiments using 4 and 2.2 mm diameter burners. In 1999, Sunderland et al. [7] also found flame lengths to increase slightly with reductions of burner size and ambient pressure. In 2012, Yang et al. [8] conducted a series of largely buoyancy-driven acetylene jet fire experiments at Lhasa and Hefei in China at altitudes of 3658 and 50 m, respectively. A range of parameters, including flame height, flame and plume centerline temperatures, transmittance through smoke, and irradiance, were measured and compared. In 2013, Hu et al. [9] studied the flame length of turbulent buoyant jet diffusion flames at pressure levels of 0.64 and 1.0 atm in Lhasa and Hefei, respectively. They found larger dimensionless mean flame length under low air pressure conditions.

Unlike previous studies, this paper investigates both buoyancy (B)- and momentum (M)-driven methane laminar diffusion flame shapes with the fuel mass flow rate in the range of 2.99–23.9×10^{-6} kg/s using two different burner diameters (12 and 3 mm) and under the ambient pressure range of 0.45–1.00 atm, which covers the steady and flickering flames. Furthermore, radiation, and the oscillation frequency of the observed flame flickering motions are determined and analyzed to reveal the effects of pressure on the two dominating mechanisms of flames.

2. Theoretical methods

In 1977, Roper [10] proceeded by using the Burke-Schumann approach, but allowed the characteristic velocity to vary with axial distance as modified by buoyancy and in accordance with continuity. The flame height, l_F, for the circular port burner was developed as follows:

$$l_F = \frac{1}{2\pi}\frac{\dot{m}_f}{\rho_f D}\frac{1}{2\ln(1+1/S)}\left(\frac{T_\infty}{T_F}\right)^{2/3} \tag{1}$$

where $\dot{m}_f$ is the fuel mass flow rate (kg/s), ρ_f is the density of fuel at ambient temperature ($\mathrm{kg/m}^3$), D is the diffusion coefficient (m^2/s), S is the air-to-fuel volume stoichiometric ratio, and T is the temperature (K). The subscripts ∞ and F indicate the ambient and flame, respectively.

In sub-atmospheric environments, for the stoichiometric reaction and infinite flame sheet assumption, $\rho_f \propto p$, $D \propto p^{-1}$, and air pressure has little effect on flame temperature. Thus from Eq. (1), the $l_F/\dot{m}_f$ is not dependent on ambient air pressure for the same kind of fuel combustion.

In the work of Yuan et al. [4], a cylinder model for an isothermal and isobaric diffusion flame was considered, in which burnt gases ascended freely in a cold, still environment, as shown in Fig. 1. The following assumptions were made: The flame is isothermal, isobaric, and homogeneous. The temperature and diffusivity are constant throughout the flame. The influence of the buoyancy on the flame zone is similar to that on the burnt gas zone. The gas velocity component parallel to the flame axis has a characteristic value $u_{f,z}$ that varies with height, but is uniform at a given height across the flame. The flame is a cylinder of radius r_F and length l_F. The reaction zone of the flame is stretched in space by the convective motion and radial diffusion of species. The axial diffusion is neglected. The general stoichiometric relationship prevails. Binary diffusion coefficients for oxygen and fuel gas are the same.

Using the linearized Fick's law, the total mass transport rate or diffusion rate of oxidizer Φ_{ox} across the cylindrical flame surface of height l_F can be expressed as follows:

$$\Phi_{\mathrm{ox}} = 2\pi r_F \int_0^{l_F} \frac{(D\rho_\infty)Y_{\mathrm{ox}}}{\delta(z)}dz \tag{2}$$

where Y_{ox} is the mass fraction of oxidizer in ambient air, ρ_∞ is the density of the ambient air ($\mathrm{kg/m}^3$), and $\delta(z)$ is the penetration depth of oxidizer (m). For stoichiometric reaction of methane, $\Phi_{\mathrm{ox}}/\dot{m}_f = 4$.

When chemical kinetic effects are ignored, $\delta(z)$ [11] can be written as follows:

$$\delta(z) = (2D\tau_c)^{1/2}, \quad \tau_c = z/u_{f,z} \tag{3}$$

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