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Laminar jet methane/air diffusion flame shapes and radiation of low air velocity coflow in microgravity

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HIGHLIGHTS

- Laminar methane/air diffusion flames of low air velocity coflow study was conducted in microgravity and normal gravity.
- Integrated flame shapes and residence time formulas in still air and coflowing conditions were given.
- Luminous flame length and diameter decrease with increasing coflowing velocity.
- Longer residence time and larger radiation of flame were observed in microgravity.
- With coflow velocity increasing, radiation in microgravity decreases because of shorter residence time.

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ABSTRACT

Observations based on short-duration experiments under microgravity of the characteristics of laminar jet diffusion flames burning in coflowing air conditions are described. Experimental conditions were such to establish a flow with Reynolds number of 140 and low air flow velocities of 0–0.5 m/s to produce steady laminar flames. Previous studies ignored effects of air flow velocity with small air stream Froude number, indicating that flame length and diameter were independent of air flow velocity. Distinct from previous studies, we introduced integrated flame shape (maximum flame diameter and ratio of flame length to maximum flame diameter) and residence time formulas, the coflowing air effects on the flame length and maximum diameter together with the flame oscillation, flame color and radiation were investigated both in microgravity and normal gravity. The experimental results obtained showed that the characteristics of microgravity laminar jet diffusion flames were significantly affected by air-flow velocities for the absence of buoyancy. Under microgravity, with increasing coflowing air velocity, the mixing rate of fuel and air increased and the flame sheet moved closer towards the nozzle, maximum flame diameter decreased with air flow velocity increasing; in contrast, the air velocity had little effect on flame shapes in normal gravity. The microgravity flame exhibited no oscillations with the absence of buoyancy, whereas in normal gravity, flame oscillation frequency increased accompanied by a smaller amplitude with air velocity increasing. In microgravity, the residence time for soot convected by the local flow also decreased with air velocity increasing; the radiative heat loss flux of the flame then decreased, but changed little if residence time was sufficiently large. Compared with microgravity flame, the flame radiation heat loss flux of normal gravity flame was smaller with a much shorter residence time.

1. Introduction

Laminar jet diffusion flames are of interest because these provide ideal flame systems that are far more tractable for theoretical and experimental studies than practical turbulent diffusion flames. Flame characteristics in microgravity environment are fundamental properties of laminar jet diffusion flames, and these are different under microgravity from those under normal gravity. Most of the previous studies (such as those of Urban et al. [1–4]) measured the shape of such flames in still air using flight- and ground-based microgravity facilities. There are two main theoretical models available for predicting flame shapes: the Spalding and the Roper models [5,6]. To predict normal gravity flame shapes, Krishnan et al. modified the Roper model to take into account buoyancy effects and more reasonably assuming that the axial velocity varies in the axial direction while remaining constant in the radial direction. Because of the assumptions employed in the Spalding model,

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Nomenclature

A_f	flame oscillation amplitude (mm)
C_f	empirical coefficient
d	jet exit diameter (mm)
f	mixture fraction
Fr_a	air stream Froude number: $Fr_a = u_{a,0}^2/2gL_f$
Fr_f	fuel stream Froude number: $Fr_f = u_{f,0}^2/2gL_f$
g	gravity level (m/s^2)
L	characteristic optical length of flame (m)
L_f	luminous flame length (mm)
L_{sf}	flame length of soot free region (mm)
$\dot{q}''_{rad}$	flame radiant heat loss flux (w/m^2)
R_e	jet Reynolds number: $R_e = \rho_f u_{f,0} d/\mu_f$
S_c	Schmidt number
S_f	flame surface area (m^2)
T_f	flame temperature (K)
T_0	ambient temperature (K)
$u_{a,0}$	initial air flow velocity (m/s)
u_{cl}	centerline velocity of fuel flow (m/s)
$u_{f,0}$	initial fuel flow velocity (m/s)
V_f	flame volume (m^3)
W	luminous flame diameter (mm)
$W_{\max}$	maximum flame diameter (mm)
Y_{fuel}	mass fraction of fuel
Y_{oxygen}	mass fraction of oxygen
z, r	streamwise distance, radial distance
Z_{st}	stoichiometric mixture fraction
γ	ratio of L_{sf}/L_f
ρ_a	ambient air density (kg/m^3)
ρ_f	fuel density (kg/m^3)
τ_r	centerline residence time (ms)
υ_a	kinematic viscosity of air (m^2/s)
μ_f	dynamic viscosity of fuel (Pa s)

the axial velocity follows the Schlichting jet velocity profile, where buoyant jet acceleration effects are neglected; hence, the Spalding model is more suited for microgravity flames [7]. Using a simplified analysis of the structure of non-buoyant round laminar jet diffusion flames based on the Spalding model, Lin et al. [8] and Urban et al. [3] further developed a convenient way to interpret and correlate measurements of soot-luminosity boundaries (near the laminar smoke-point condition) and flame sheet locations in still air for microgravity [5].

The Spalding similarity solution have been extended by Lin and Faeth [9] to incorporate approximately the effects of coflowing oxidizer using self-similar analysis [10,11]. Using this model, the effects of coflowing air velocities on laminar diffusion flame shapes have been investigated [9,12]. These studies indicate that flame lengths are independent of coflowing air velocity, whereas flame diameters vary proportionally with the ratio $(u_{f,0}/u_{a,0})^{1/2}$. The main experiments of coflowing laminar diffusion flames about flame lengths and diameters in microgravity are summarized in Table 1 [9,12,13]. If ratio $u_{a,0}/u_{f,0} > 0.5$ and the air-stream Froude number is large, $u_{a,0}$ has little effect on flame lengths, and flame diameters vary proportionally with $(u_{f,0}/u_{a,0})^{1/2}$. For low air-flow velocity ($0.22 \leqslant u_{a,0}/u_{f,0} < 0.5$) and small Fr_a, varying $u_{a,0}$ has little effect on the flame; here, the flame is assumed burning in still air, and the flame length and diameter are independent of $u_{a,0}$. For low air-flow velocity but relatively large Fr_a, the inertial force of air cannot be neglected when compared with buoyancy especially in microgravity, which can affect the flame characteristics [14].

Soot properties and radiative heat losses of laminar jet diffusion flames have been studied by Urban et al. [15–19]. Most of these studies indicate that soot properties or laminar smoke point of flames can be affected by buoyancy and air-flow velocity, creating different soot trajectories and residence times. In microgravity conditions radiative heat losses of flames are much larger than normal gravity because of the longer residence times. However, more detailed quantitative investigations were not given about how residence times varying with coflowing air velocity affect soot production and radiation.

Distinct from previous studies, our work involved coflowing air velocities in the range $0.1 \leqslant u_{a,0}/u_{f,0} \leqslant 0.7$ with $Fr_a > 10$; in these conditions, air velocity effects cannot be neglected. By introducing integrated flame maximum diameter and residence time formulas, this work focused on how low coflowing air velocity affected the flame length and maximum diameter, flame oscillation, flame color and radiative heat loss both in microgravity and normal gravity.

2. Theoretical methods

2.1. Flame shape

There were theory models to predict flame shapes for laminar diffusion flames in still air and coflowing air. The simple self-similar analysis of Mahalingam et al. [10] and the Spalding similarity solution were extended by Lin and Faeth [9] to approximately incorporate the effects of coflowing oxidizer. The major assumptions employed are [8,9]: (1) Steady axisymmetric laminar-jet diffusion flames burning at constant pressure in still or an unbounded coflowing gas with uniform properties; (2) effects of buoyancy and associated potential energy changes are ignored; (3) the Mach number of the flow is small so that effects of viscous dissipation and changes of kinetic energy can be neglected; (4) the flame has a large aspect ratio so that diffusion of mass (species), momentum, and energy in the streamwise direction is small; (5) the governing equations can be approximated solved by far-field conditions; (6) chemical reactions all occur in a thin flame sheet with fast chemistry so that fuel and oxidant are never simultaneously present at

Table 1
Summary of previous experiments on coflowing laminar diffusion flames in microgravity.

Source	Flame system		L_f	W
Xu et al. [12,13]	Still air	$u_{a,0}/u_{f,0} < 0.2$, $Fr_f \gg 5$	Independent of $u_{a,0}$	Independent of $u_{a,0}$
Lin et al. [9]	Coflow	$0.22 \leqslant u_{a,0}/u_{f,0} < 0.5$, $Fr_a < 0.1$	Independent of $u_{a,0}$	Independent of $u_{a,0}$
Xu et al. [12,13]	Coflow	$u_{a,0}/u_{f,0} > 0.5$, $Fr_a > 1$	Independent of $u_{a,0}$	$\propto (u_{f,0}/u_{a,0})^{1/2}$
Lin et al. [9]	Coflow	$u_{a,0}/u_{f,0} > 1$, $Fr_a > 0.1$	Independent of $u_{a,0}$	$\propto (u_{f,0}/u_{a,0})^{1/2}$

Present study: flames in coflowing air condition, $0.1 \leqslant u_{a,0}/u_{f,0} \leqslant 0.7$ and $Fr_a > 10$.