

REACTION KERNEL STRUCTURE OF A SLOT JET DIFFUSION FLAME IN MICROGRAVITY

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INTRODUCTION

Diffusion flame stabilization in normal earth gravity (1 *g*) has long been a fundamental research subject in combustion [1]. Local flame-flow phenomena, including heat and species transport and chemical reactions, around the flame base in the vicinity of condensed surfaces control flame stabilization and fire spreading processes. Therefore, gravity plays an important role in the subject topic because buoyancy induces flow in the flame zone, thus increasing the convective (and diffusive) oxygen transport into the flame zone and, in turn, reaction rates.

Recent computations [2-5] show that a peak reactivity (heat-release or oxygen-consumption rate) spot, or *reaction kernel*, is formed in the flame base by back-diffusion and reactions of radical species in the incoming oxygen-abundant flow at relatively low temperatures (~1550 K). Quasi-linear correlations were found between the peak heat-release or oxygen-consumption rate and the velocity at the reaction kernel for cases including both jet and flat-plate diffusion flames in airflow. The reaction kernel provides a stationary ignition source to incoming reactants, sustains combustion, and thus stabilizes the trailing diffusion flame. In a quiescent microgravity environment, no buoyancy-induced flow exists and thus purely diffusive transport controls the reaction rates. Flame stabilization mechanisms in such purely diffusion-controlled regime remain largely unstudied. Therefore, it will be a rigorous test for the reaction kernel correlation if it can be extended toward zero velocity conditions in the purely diffusion-controlled regime.

The objectives of this study are to reveal the structure of the flame-stabilizing region of a two-dimensional (2D) laminar jet diffusion flame in microgravity and develop a unified diffusion flame stabilization mechanism. This paper reports the recent progress in the computation and experiment performed in microgravity.

EXPERIMENTAL TECHNIQUES

Microgravity experiments were conducted using the 2.2-s drop tower in the NASA Glenn Research Center. Figure 1 shows a conceptual sketch of a slot burner (1.02 × 25.4 mm inner cross-section, 152 mm length, 0.25 mm lip thickness; 360 brass) placed in a combustion chamber (255 mm i.d. × 533 mm length). Methane jet was ignited using an electrically heated kanthal wire (29 AWG, ~30 mm length) ~2 cm above the jet exit in microgravity. Standard color video recording via a fiber-optic link was made for the mean fuel jet velocity of $U_j = 0.236$ m/s in still air and $U_j = 0.142$ m/s and 0.071 m/s in a still 30 mol.% O₂/70 mol.% N₂ mixture. Diagnostic techniques to be used in the near future include Mach-Zehnder interferometry and particle image velocimetry.

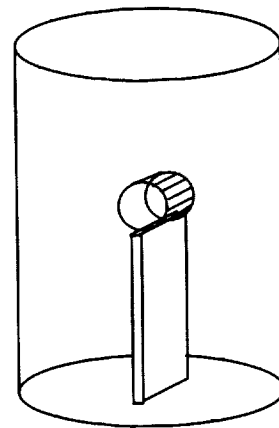


Fig. 1 Slot jet diffusion flame concept.

NUMERICAL METHODS

In this study, the structure of a 2D methane jet diffusion flame was simulated in zero-gravity (0 g) using a transient two-dimensional code (known as UNICORN [6, 7]). Time-dependent governing equations, expressed in Cartesian coordinates, consist of mass continuity, axial and transverse momentum conservation, energy conservation, and species conservation equations with the ideal-gas equation of state. The transport coefficients are estimated using molecular dynamics and mixture rules. The enthalpy of each species is calculated from polynomial curve-fits. The detailed chemistry model [8] for 24 species and 81 elementary steps is used. The finite-difference forms of the momentum equations are integrated using an implicit QUICKEST scheme, and those of the species and energy equations are obtained using a hybrid scheme of upwind and central differencing. Computations were performed using a 601×201 non-uniform grid system covering a physical domain of 60×40 mm. The grid system is clustered near the flame zone to resolve the large gradients in flow variables. The slot burner width of 3 mm, a lip thickness of 0.5 mm, and constant wall temperature of 500 K are used in computations. In this paper, the results obtained for the mean jet velocity of $U_j = 0.236$ m/s and the near-still external air velocity of $U_a = 0.001$ m/s are reported.

RESULTS AND DISCUSSION

Figure 2 shows video images (end view) of methane jet diffusion flames on a slot burner in microgravity. The flame in air (Fig. 2a) showed a round shape with a distortion due to initial ignition non-uniformity. Debris of the igniter wire is seen in the image. Because of the end effect allowing diffusion of the fuel and oxygen in the direction parallel to the long side of the slot, the flame was elongated hemispherical rather than cylindrical. There were relatively large quenched regions near the base on both sides of the burner. The flames in an oxygen-enriched atmosphere (Figs. 2b and 2c) appeared more cylindrical and blue. For $U_j = 0.142$ m/s (Fig. 2b), a luminous zone presumably due to soot formation at ignition remained inside the blue flame envelop, while for $U_j = 0.71$ m/s (Fig. 2c), it disappeared.

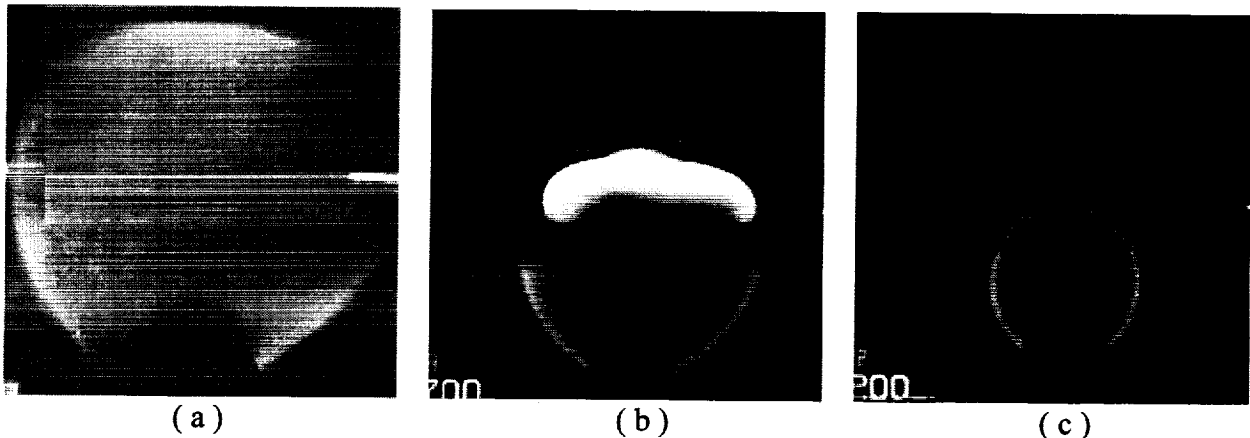


Fig. 2 Video images of methane jet diffusion flames on a slot burner in various still oxidizing atmospheres in microgravity. (a) $U_j = 0.236$ m/s, air; (b) $U_j = 0.142$ m/s, 30% O_2 /70% N_2 ; (c) $U_j = 0.071$ m/s, 30% O_2 /70% N_2 .

Figure 3 shows the calculated velocity vectors, isotherms, and heat-release rate. The

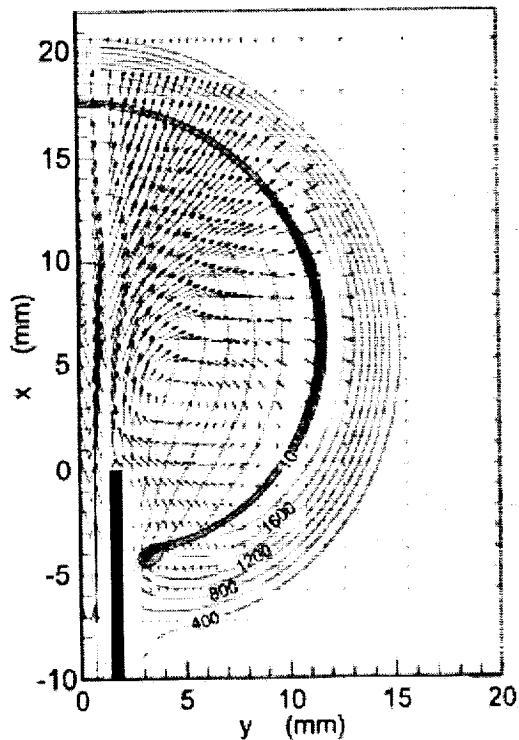


Fig.3 Calculated velocity vectors, isotherms (K), heat-release rate ($\text{J}/\text{cm}^3\text{s}$).

computed flame was nearly circular (cylindrical) with a quenched region near the burner wall. The velocity vectors show the expanded fuel jet downstream and the air entrainment in the flame base region. The maximum flame temperature was approximately 1900 K in the upper portion of the flame. There existed a peak heat-release rate spot, i.e., reaction kernel, at the flame base as was observed in the jet and flat-plate diffusion flames in moderate airflow calculated previously [2-5]. However, the magnitude of the heat-release rate peak ($\sim 29 \text{ J}/\text{cm}^3\text{s}$) in the present flame was an order of magnitude smaller, and the reaction kernel temperature ($\sim 1370 \text{ K}$) and velocity ($\sim 0.013 \text{ m/s}$) were much lower as well.

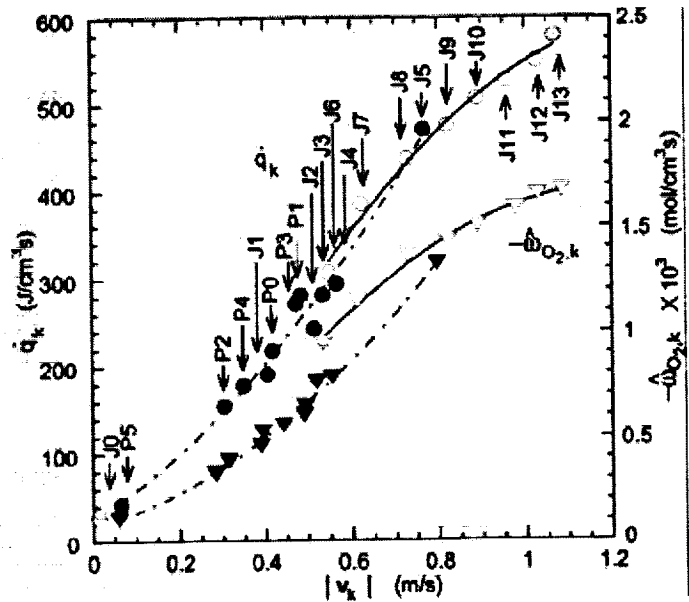


Fig. 4 Reaction kernel correlations. \circ, \bullet , \dot{q}_k ; ∇ , $-\dot{\omega}_{O_2,k}$. Open, C_2 -chemistry; filled, C_1 -chemistry.

Table 1 Test conditions

Case No.	Air Velocity (m/s)	Fuel Velocity (m/s)	Chem. model
<i>2D Jet Diffusion Flame (0 g)</i>			
J0	0.001	0.236	C_2
<i>Axisymmetric Jet Diffusion Flames (1 g, upward)</i>			
J1	0.19	1.7	C_1
J2	0.19	11.5	C_1
J3	0.36	1.7	C_1
J4	0.36	6.9	C_1
J5	0.72	1.7	C_1
J6	0.36	1.7	C_2
J7	0.50	1.7	C_2
J8	0.66	1.7	C_2
J9	0.72	1.7	C_2
J10	0.75	1.7	C_2
J11	0.78	1.7	C_2
J12	0.80	1.7	C_2
J13	0.80	1.7	C_2
<i>Flat-Plate Burner Flames</i>			
P0	0.65 (0 g)	0.02 (0 g)	C_1
P1	0.65 (upward)	0.02 (horizontal)	C_1
P2	0.65 (downward)	0.02 (horizontal)	C_1
P3	0.65 (horizontal)	0.02 (upward)	C_1
P4	0.65 (horizontal)	0.02 (downward)	C_1
P5	1.2 (horizontal)	0.008 (downward)	C_1

Figure 5 shows the reaction kernel correlations of the peak heat-release rate or oxygen consumption rate with the total velocity. The test conditions for the data points are listed in

Table 1. The data set includes the results for the 2D (case J0, this study) or axisymmetric jet- (J1-J13) and flat-plate diffusion flames (P0-P5) [2-5]. Either C₁- or C₂-chemistry model [8] was used. All cases are for 1 g except for cases P0 and J0 for 0 g. There exist strong positive correlations between the reactivity and the incoming velocity at the reaction kernel. A previous paper [4] extended the correlations at higher ends (cases J6-J13) and successfully predicted the lifting limit of jet diffusion flames. The data points for the present results (case J0) further extended the correlation at lower ends toward a non-convective, pure diffusion-controlled regime. Extrapolations of the curves for $|v_k| = 0$ would give the heat-release rate or oxygen consumption rate in the pure diffusion-controlled regime.

CONCLUSIONS

The slot jet diffusion flames were observed experimentally in microgravity and simulated numerically. In the experiment, the end effect of the slot burner resulted in the formation of an elongated hemispherical flame. The computation showed that the peak reactivity spot, reaction kernel, was formed at the flame base of a 2D jet diffusion flame even under a low-convective zero-gravity condition. The computational results extended the reaction kernel correlations toward the pure diffusion-controlled regime. Thus, the flame stabilization mechanism based on the reaction kernel hypothesis derived previously is applicable to extremely low convective conditions as well.

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