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비예혼합 대향류화염의 구조와 소화

Structure and Suppression of Nonpremixed Counterflow Flames

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요 약

화염변형률과 소화약제의 첨가 및 부력이 비예혼합 대향류 화염의 구조와 소화에 미치는 영향을 조사하기 위해 필라멘트와 열전대를 이용한 실험과 Oppdif 및 FDS를 사용한 수치해석을 수행하였다. 소화농도에 가까운 메탄-공기의 확산화염에 대하여 2.2초의 무중력 낙하실험과 정상중력에서의 측정결과를 수치모사의 결과와 비교하였다. 변형률 7 s^{-1}에서 100 s^{-1}까지 무중력상태에서 측정한 임계소화농도로부터 질소의 임계소화농도에 최대치가 있음을 확인하였다. 또한, 부력의 효과, 즉, 화염의 곡률과 두께 변화를 FDS의 계산결과로 확인하였다. 무중력상태에서 화염의 최고온도와 그 위치에 대한 실험치와 계산값이 일치함을 알 수 있었다.

ABSTRACT

Measurements with filaments and thermocouples and computations with Oppdif and FDS were carried out to investigate the impact of flame strain, agent addition, and buoyancy on the structure and extinction of nonpremixed counterflow flames. Measurements through 2.2 s drop tests in microgravity conditions and experiments in normal gravity conditions were compared with the results of computations. For the global strain rates 7 s^{-1} through 100 s^{-1}, the turning point behavior in the critical nitrogen concentration at 0-g was confirmed. The effects of buoyancy, that is, changes in the flame curvature and thickness were also confirmed by the computations with FDS. There was agreement in the peak flame temperature and its position between the computations and the measurements in the near extinction methane/air diffusion flames in microgravity.

Keywords : Methane-air counterflow flame, Flame structure and suppression, Microgravity, Experiments, Computations, Extinction concentration

1. Introduction

The agent concentration required to achieve suppression of low strain rate nonpremixed flames is an important fire safety consideration. In a microgravity environment such as a space platform, unwanted fires will likely occur in near quiescent conditions where strain rates are very low. Diffusion flames typically become more robust as the strain rate is decreased. When designing a fire suppression system for worst-case conditions, low strain rates should be considered.

The first comprehensive extinction measurements of very low strain non-premixed flames in microgravity were reported by Maruta *et al.*[1] The extinction of methane-air flames with N_2 added to the fuel stream was investigated using the JAMIC 10 s drop tower. The minimum methane concentration required to sustain combustion was measured to decrease as the strain rate decreased until a critical value was

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observed. As the global strain rate was further reduced, the required methane concentration increased. This behavior was denoted as a "turning point" and was attributed to the enhanced importance of radiative losses at low strain rates. In terms of fire safety, a critical agent concentration assuring suppression under all flow conditions represents a fundamental limit for nonpremixed flames.

The objective of this study is to investigate the impact of radiative emission, flame strain, agent addition, and buoyancy on the structure and extinction of low strain rate nonpremixed flames through measurements and comparison with flame simulations by using the Fortran Program Computing Opposed Flow Diffusion Flames (Oppdif)[2] and the Fire Dynamics Simulator (FDS).[3] The suppression effectiveness of a suppressant (N_2) added to the fuel stream of low strain rate methane-air diffusion flames was measured. Flame temperature measurements were attained in the high temperature region of the flame (T > 1200 K) by measurement of thin filament emission intensity. The time varying temperature was measured and simulated as the flame made the transition from normal to microgravity conditions and as the flame extinguished.

2. Methodology

The counterflow burner considered in this study is composed of two opposed ducts of 15 mm diameter and 0.5 mm thickness and 15 mm separation as shown in Fig. 1. The methane diluted by nitrogen flows in the fuel duct, and air flows in the oxidizer duct.

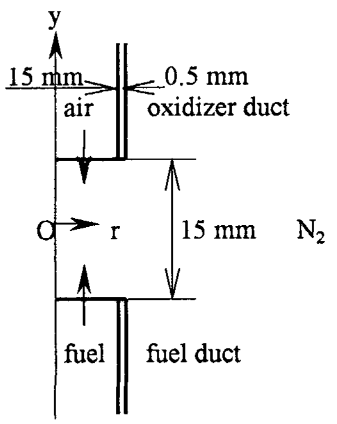

Fig. 1. Schematic of the counterflow burner.

Assuming that the fluids are ideal gases, the governing equations are as follows:

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \quad (1)$$

Conservation of linear momentum:

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = \frac{\partial p}{\partial x_i} + \rho g_i + \frac{\partial \tau_{ij}}{\partial x_j} \quad (2)$$

Conservation of energy:

$$\frac{\partial \rho h}{\partial t} + \frac{\partial \rho h u_i}{\partial x_i} - \frac{Dp}{Dt} = Q + \frac{\partial}{\partial x_i}\left(\lambda \frac{\partial T}{\partial x_i} - q_r\right) + \frac{\partial (u_i \tau_{ij})}{\partial x_i} \quad (3)$$

Conservation of species:

$$\frac{\partial \rho Y_i}{\partial t} + \frac{\partial \rho Y_i u_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\rho D_i \frac{\partial Y_i}{\partial x_j}\right) + w_i \quad (4)$$

where, t represents time, ρ the density, and u the velocity. D/Dt is the substantial derivative in Eq. (3), Q is the heat release rate per unit volume, λ is the thermal conductivity, T is the temperature, q_r is the radiative heat transfer rate per unit area, Y is the mass fraction, D in Eq. (4) is the diffusion coefficient, and w is the chemical production rate per unit volume. The shear stress τ is

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \delta_{ij}\frac{2\partial u_k}{3\partial x_k}\right) \quad (5)$$

where μ is the viscosity, and δ_{ij} is the Kronecker delta. The pressure p is

$$p = \rho RT \quad (6)$$

and the enthalpy h is

$$h = c_p T \quad (7)$$

where R is the gas constant, and c_p is the constant pressure heat capacity.

The boundary conditions on the velocity and temperature of the reactant stream are $V = V_F$ at the fuel duct exit, $V = V_A$ at the oxidizer duct exit, no slip condition at the duct wall, and T=300 K in fuel and air streams in the ducts.

Two flame codes were utilized. The structure and extinction of methane-air flames with N_2 addition were investigated using the Fortran Program Computing Opposed Flow Diffusion Flames (Oppdif),[2] an one-dimensional numerical simulation employing detailed models of molecular transport and chemistry,[4] but ignores buoyancy. A term for the radiative heat loss rate was added to the energy equation in the one-dimensional flame code. Radiative losses were modeled with a narrowband spectral model.[5] A transient two-dimensional (axisymmetric) solutions to the Navier-Stokes equations including buoyancy using the mixture fraction approach based NIST Fire Dynamics Simulator (FDS)[3] where the direct numerical simulation (DNS). The effects of global strain rate and buoyancy were investigated and results were compared with the measurements at 0-g.

Flame suppression and the temperature field in low-strain diluted methane/air nonpremixed flames were measured in microgravity using a counterflow flame configuration. Experiments were performed at the NASA Glenn research facility using the 2.2 s drop. A 15 mm diameter stainless steel counterflow burner was enclosed in a 25 *l* cylindrical chamber. The duct separation distance was 15 mm. The burner ducts were designed to have minimal dead volume as glass beads and a series of fine mesh steel screens were used to impose a near plug flow velocity profile at the burner exit.

To control each of the reactant gas flows, a fast response time (~10 ms) pressure controller was used in series with a critical flow orifice. The total system response time was equal to the flow control response time plus the residence flow time from the mixing tee to the flame zone, estimated as 0.0665 s to 0.6397 s for strain rates of 50 s^{-1} and 7 s^{-1}, respectively. The flow of dry air and methane were calibrated using a dry cell primary flow meter. A 0.25 mm diameter, 7 cm long coiled resistance igniter wire (Pt + 30% Rh) positioned between the fuel and oxidizer ducts was used to ignite the flame. A rotary brushless torque actuator was used to control the position of the ignition wire.

Extinction measurements were performed by incrementally increasing the agent flow, while maintaining a constant global strain rate, a_g, accomplished by simultaneously reducing the air or fuel flow. The value of a_g in the axisymmetric counterflow configuration is defined as:

$$a_g = \frac{2V_A}{L}\left[1 - \frac{V_F}{V_A}\left(\frac{\rho_F}{\rho_A}\right)^{0.5}\right] \quad (8)$$

where V and ρ denote the velocity and density of the reactant streams at the boundaries, L is the duct separation distance, and the subscripts A and F represent the oxidizer and fuel streams, respectively. The standard uncertainty in agent extinction concentration was 2% based on repeat measurements.

Measurement of the visible emission intensity from a 13 μm SiC filament placed along the burner centerline allowed the determination of flame temperatures for T>1200 K. Radiation emitted by the filament was recorded using a digital CCD camera with a close-up lens. Spatial resolution of the image was 0.07 mm/pixel. The camera exposure was adjusted to prevent image saturation (over-exposure) at the maximum flame temperature. The intensity measurements were calibrated using Oppdff.[2] The uncertainty is 50 K based on repeat measurements.

3. Results and Discussion

In Fig. 2, 12 s^{-1} near-extinction methane/air diffusion flames in normal and microgravity (fuel of 20% CH_4 + 80% N_2) computed with FDS are compared. The effects of buoyancy are clearly shown. Flame is flat at 0-g where no buoyancy exists while is curved at the exit of the oxidizer duct. The flame thickness at 0-g is much thicker than that of the at 1-g. It is noted that the flame at 0-g slightly curved towards the oxidizer side is due to reaction of the fuel (80% methane and 20% nitrogen by volume) and oxygen.

Fig. 3 shows extinction measurements performed for stain rates of 7 s^{-1} through 100 s^{-1}, confirming the "turning point" behavior observed previously by Maruta *et al.*[1] and confirming the viability of these 2 s duration extinction measurements. The maximum nitrogen volume fraction in the fuel stream needed for extinction was found to be 0.855±0.016 at a strain rate of 15 s^{-1}, consistent with the results of Maruta *et al.*[1]. These values are different from analogous measurements performed by Bundy *et al.*[6]

(a) 0-g

(b) 1-g

Fig. 2. Simulation of a 12 s^{-1} diluted methane/air diffusion flame in normal and microgravity (Fuel of 20% CH_4 and 80% N_2).

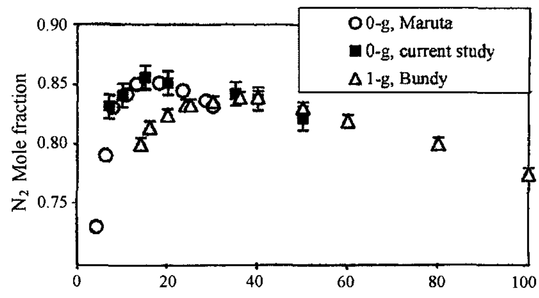

Fig. 3. Critical mole fraction of N_2 in the fuel stream required to extinguish a methane/air diffusion flame in normal and microgravity. Flammable region is below the data points.

in normal gravity, implying that the local oxidizer-side strain rate differs in normal and microgravity for small a_g. On-going particle imaging velocimetry (PIV) measurements are quantifying these differences.

Drop measurements and FDS simulations of the position of the maximum flame temperature are compared in Fig. 4 as a function of time after microgravity occurs for constant flow conditions, $a_g=20\ s^{-1}$ and the fuel of 18% CH_4 and 82% N_2. There is general agreement between the model and the measurements within measurement uncertainty.

For $a_g=20\ s^{-1}$ and the fuel composed of ~20% CH_4 + 80% N_2, Fig. 5 shows agreement between the simulated (Oppdif and FDS) and measured (SiC filament and thermocouple) temperature profiles in

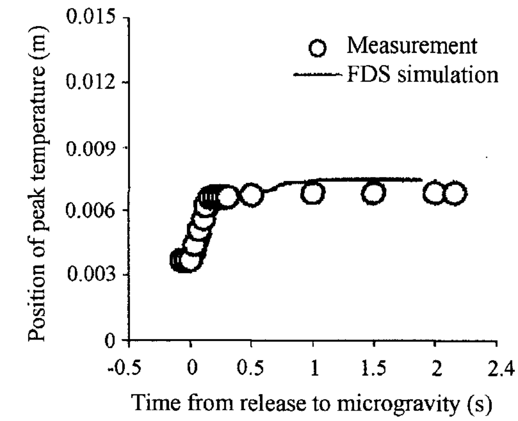

Fig. 4. The measured and calculated (FDS) position of the peak flame temperature as a function of time after microgravity occurs.

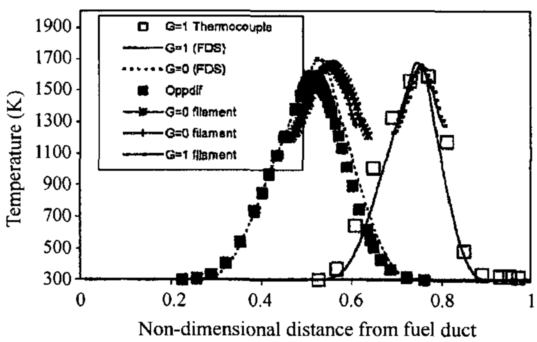

Fig. 5. Comparison of the calculated (FDS and Oppdif) and measured flame temperatures.

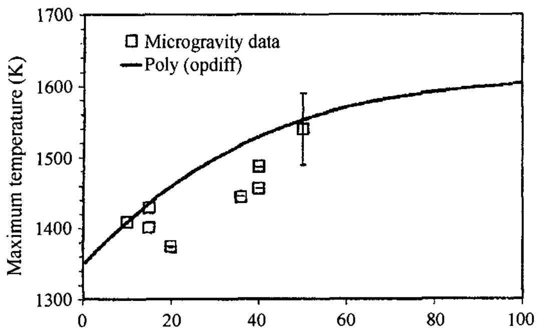

Fig. 6. Comparison of the calculated (Oppdif) and measured peak flame temperature in near extinction methane/air diffusion flames in microgravity.

normal and microgravity.

The calculated (Oppdif) and measured peak flame temperature in near extinction methane/air diffusion flames at 0-g is compared in Fig. 6. Conditions were extremely near extinction, such that the agent concentration was greater than 99.4% of that required for extinction, corresponding to the conditions shown in Fig. 3. It shows consistent trends between the calculated (Oppdif) and measured peak flame temperatures in near-extinction methane/air diffusion flames in microgravity. As the strain rate decreases, the peak flame temperature decreases until low peak temperatures are observed, rather unusual for a flamelet.

4. Conclusions

To investigate the impact of flame strain, agent addition, and buoyancy on the structure and extinction of low and moderate strain rate nonpremixed flames, measurements with filaments and thermocouples and computations with Oppdif and FDS were carried out. Extinction measurements performed for stain rates of 7 s^{-1} through 100 s^{-1} showed the turning point behavior at 0-g. The maximum nitrogen volume fraction in the fuel stream needed for extinction was found to be 0.855±0.016 at a strain rate of 15 s^{-1}, consistent with the results of Maruta et al. Changes in the flame curvature and thickness due to the presence of buoyancy were confirmed by the computations with FDS. There was general agreement in the position of the peak flame temperature and the temperature profiles between the computations and the measurements in both normal and microgravity. It showed consistent trends between the calculated and measured peak temperatures in near extinction methane/air diffusion flames in microgravity.

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Nomenclature

a_g : global strain rate
c_p : constant pressure heat capacity
g : gravitational acceleration, 9.81 m/s^2
h : enthalpy
L : separation distance between ducts
p : pressure
Q : heat release rate per unit volume
q_r : radiative heat transfer rate per unit area
R : gas constant
T : temperature
t : time

u : velocity
V : velocity at duct exit
w : chemical production rate per unit volume
δ_{ij} : Kronecker delta
λ : thermal conductivity
μ : viscosity
ρ : density
τ : shear stress

Subscripts

A : air
F : fuel