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비예혼합 대향류 화염의 축대칭 모사
- 변형률이 화염구조에 미치는 영향 -

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Axisymmetric Simulation of Nonpremixed Counterflow Flames
- Effects of Global Strain Rate on Flame Structure -

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요 약

변형률이 대향류 화염의 구조에 미치는 영향을 조사하기 위해, 무중력상태에서의 축대칭 메탄-공기 대향류화염의 시뮬레이션을 수행하였다. 질소와 메탄의 혼합물인 연료 중 메탄의 몰분율 x_m= 20, 50, 80%와 각 몰분율당 변형률 a_g= 20, 60, 90 s^{-1}에 대한 화염형태와 온도 및 축방향 속도의 분포를 비교하였다. 온도와 축방향 속도 분포가 1차원 화염코드인 OPPDIF의 결과와 잘 일치하였다. 또 축대칭 시뮬레이션을 통해, 변형률이 증가하면 화염이 반경방향으로 늘어나 화염의 반경은 증가하고 두께가 감소함을 확인하였다.

Abstract - The axisymmetric methane-air counterflow flame in microgravity was simulated to investigate effects of the global strain rate on the flame structure. The flame shapes and profiles of temperature and the axial velocity for the mole fraction of methane in the methane-nitrogen fuel stream, x_m= 20, 50, 80%, and the global strain rate, a_g= 20, 60, 90 s^{-1} each mole fraction were compared. The profiles of the temperature and axial velocity of the axisymmetric simulations were in good agreement with those of OPPDIF, an one-dimensional flamelet code. It was confirmed that the flame is stretched more and the flame radius increases and the flame thickness decreases as the global strain rate increases.

Key words : methane-air counterflow flame, microgravity, fuel concentration, global strain rate, flame thickness, flame radius.

I. INTRODUCTION

In the previous study[1], the structure of the counterflow flames in microgravity was investigated for different fuel concentration in the fuel stream by using the NIST Fire Dynamics Simulator(FDS)[2]. In a wide range of the fuel concentration, the profiles of temperature and axial velocity were well predicted. An increase in the fuel concentration increased the flame thickness and peak temperature and decreased the flame radius.

In the present study, the results were

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analyzed for the global strain rate to see its effects on the flame structure. The flames in microgravity were chosen for comparisons of the results with those of the one-dimensional simulations with OPPDIF[3].

II. METHODOLOGY

The counterflow burner shown in Fig. 1 has two opposing ducts, separated by 15 mm. The fuel gas, a mixture of methane and nitrogen, flows in the lower fuel duct, and the air flows in the upper oxidizer duct. The diameter of the two ducts is 15 mm, and the wall thickness is 0.5 mm. The flame, axisymmetric about the y-axis, is located between the two ducts and shielded from the ambient air with nitrogen.

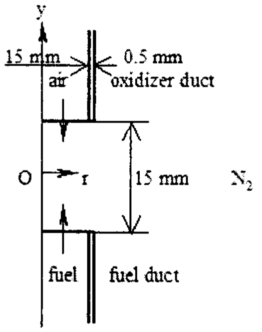


Fig. 1. The counterflow burner.

The global strain rate a_g is defined as,

$$a_g = -2V_A(1 - V_F\rho_F^{0.5}/V_A\rho_A^{0.5})/L \qquad (1)$$

where, ρ_A is the density of air, ρ_F is that of the fuel at 1 atm and 25°C, respectively, and L is the separation distance between the two ducts, 15 m. The velocity of air in the duct V_A and the velocity of fuel V_F have the same magnitude but opposite signs, i.e., $V_A = -V_F$. For given values of the global strain rate a_g, and fuel concentration x_m, the velocities V_A and V_F are calculated from Eq.(1). The values of the fuel concentration x_m, velocity V_A and V_F, and duct dimensions are defined in the input data file for the axisymmetric simulations with the Fire Dynamics Simulator(FDS)[2], while OPPDIF[3] does not require the duct dimensions except for L. A grid spacing of 0.5 mm x 0.5 mm was used. All the numerical procedures are the same as used in Part 1[1].

III. RESULTS AND DISCUSSION

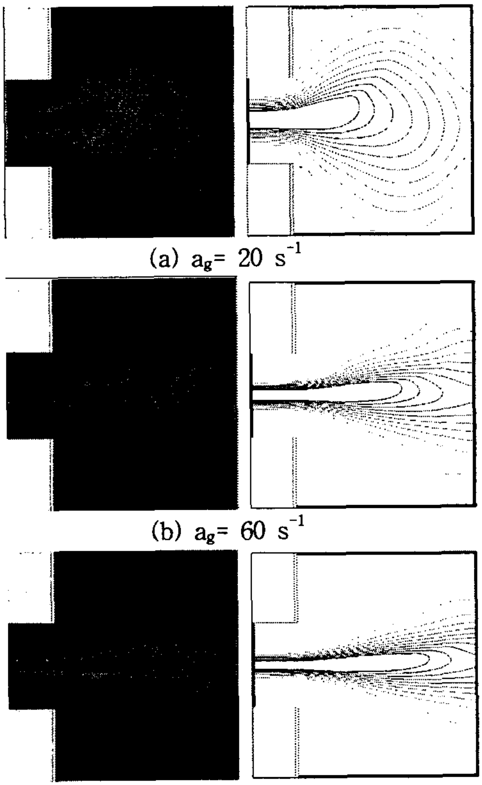
3.1. x_m= 20%

The definition of the global strain rate given in Eq. (1) shows that the velocity in the fuel and air streams is proportional to the global strain rate at a given fuel concentration. As the velocity increases, the flame is stretched more. The increase in the global strain rate therefore results in stretching the flame in the r-direction.

The flames of the fuel lean concentration, x_m= 20%, which is 20% methane (CH_4) and 80% nitrogen by volume, were compared in Fig. 2 for the three different values of the global strain rate, a_g= 20, 60, and 90 s^{-1}. The flames were obtained from the axisymmetric simulations and represented by temperature distribution and isotherms. Stretching flame with increasing global strain rate can be seen by a comparison of the flame shapes. As a_g increases from 20 s^{-1} to 60 and 90 s^{-1}, the flame radius increases and the flame thickness decreases. The isotherms show this more clearly. Each line has a 100°C increment and the inner-most one stands for 1000°C, Since the one-dimensional simulations with OPPDIF[3] do not provide the flame shape, comparisons of the flame shapes between the one-dimensional and axisymmetric simulations are not available.

The profiles of temperature and axial

velocity along the duct centerline of the axisymmetric simulations with FDS were compared with those of the one-dimensional simulations in Fig. 3. Both the temperature and velocity profiles are in excellent agreement between the one-dimensional and axisymmetric simulations. The temperature profiles also show that the flame thickness decreases when the global strain rate increases.



(a) a_g= 20 s^{-1}

(b) a_g= 60 s^{-1}

(c) a_g= 90 s^{-1}

Fig. 2. Flames of x_m= 20% (FDS)

3.2. x_m= 50%

Fig. 4 depicts the flames of the medium fuel concentration, 50% methane and 50% nitrogen by volume in the fuel stream. Decreasing flame thickness and increasing flame radius with increasing global strain rate, due to the flame stretching with increasing velocity in the ducts, is clearly shown. Since the flame thickness of x_m=50% is thicker and the flame radius is smaller compared with the flames of x_m= 20% at the same global strain rate, the effects of the global strain rate on the flame structure are more clearly discernible.

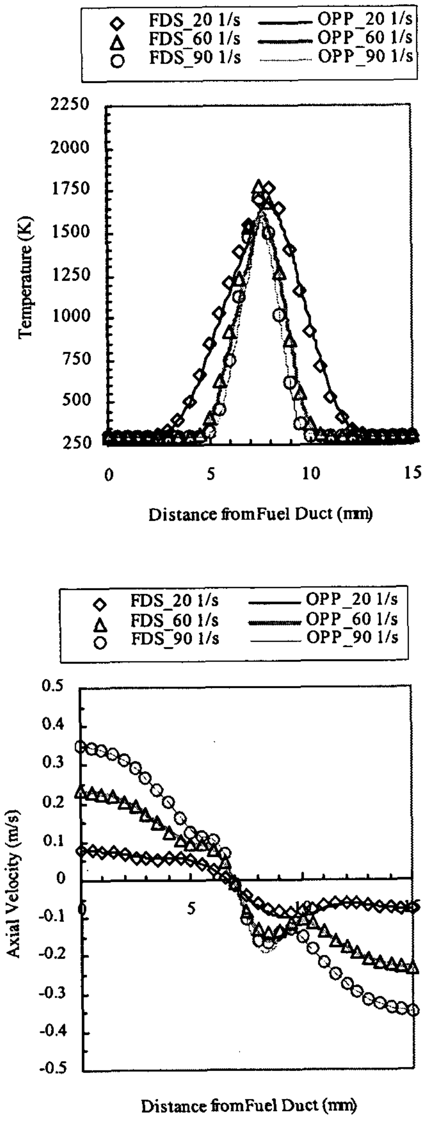
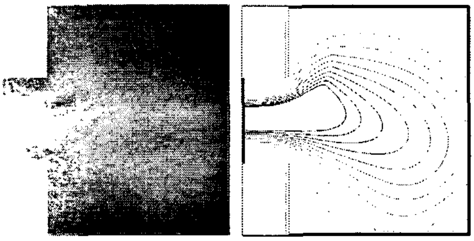
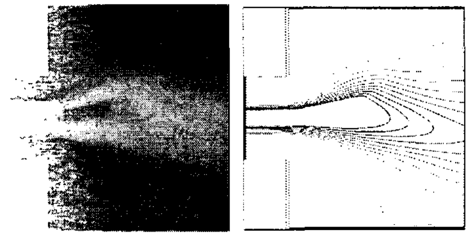


Fig. 3. Comparison of temperature and axial velocity profiles for x_m= 20%.

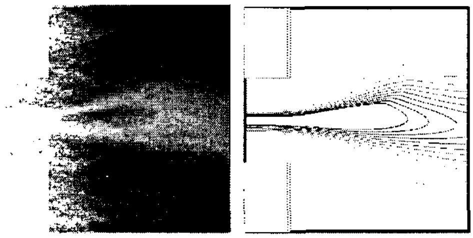
ig. 5, the profiles of the temperature xial velocity of the one-dimensional and axisymmetric (FDS) simulations gree well each other except for the peak perature at a_g= 60 s^{-1}, which is edicted, and the under-predicted velocity in the high temperature t the distance from the fuel duct bout 8.5 mm. The flame thickness s thinner as the global strain rate



(a) a_g= 20 s^{-1}



(b) a_g= 60 s^{-1}



(c) a_g= 90 s^{-1}

ig. 4. **Flames of x_m= 50% (FDS)**

xm= 80%

6 compares the flames of the fuel ase, x_m= 80%. As seen in Figs. 2 and n the mole fraction of methane is e flame is thicker and its radius is r at the same global strain, compared e two lower fuel concentrations, x_m= 20 and 50% (e.g., compare the flames of a_g= 20 s^{-1} in Fig. 2, 4, and 6). This makes much more clear the effects of the global strain rate on the counterflow flame that stretching the flame increases its radius and decreases the flame thickness.

The profiles of the temperature and axial velocity plotted in Fig. 7 are in good

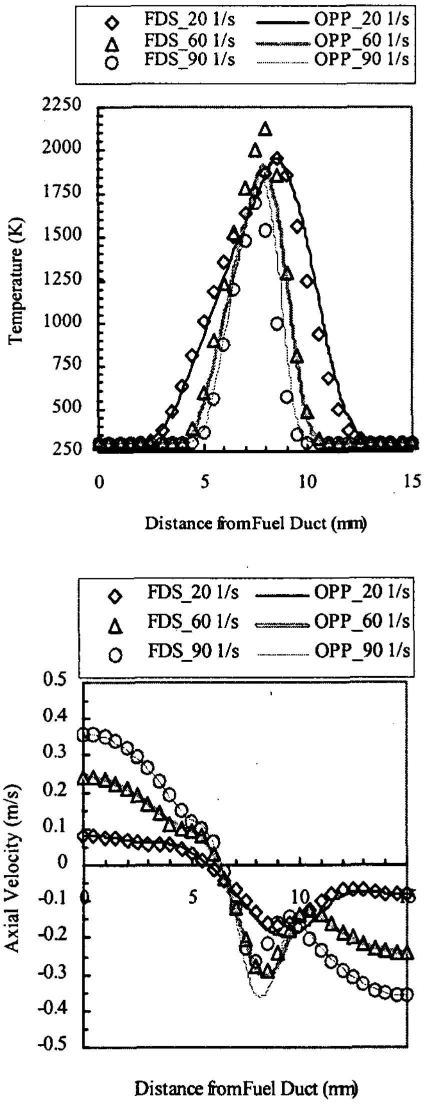
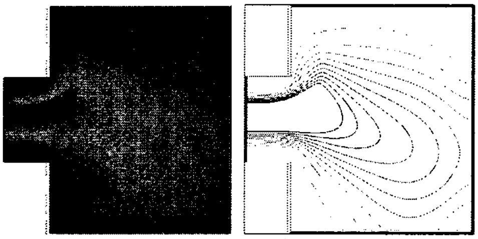
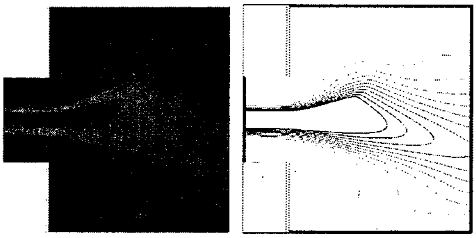


Fig. 5. Comparison of temperature and axial velocity profiles for x_m= 50%.

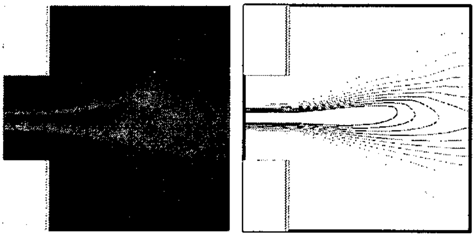
agreement between the axisymmetric (FDS) and one-dimensional (OPPDIF) simulations. There are some discrepancies in the peak temperature of a_g= 20 and 60 s^{-1}, and the axial velocity in the high temperature region of a_g= 90 s^{-1}. These errors are similar to those of the fuel concentration x_m= 50% in Fig. 6.



(a) a_g= 20 s^{-1}



(b) a_g= 60 s^{-1}



(c) a_g= 90 s^{-1}

Fig. 6. Flames of x_m= 80% (FDS)

IV. CONCLUSIONS

The axisymmetric counterflow flames of the nonpremixed nitrogen diluted methane-air were simulated by using Fire Dynamics Simulator and OPPDIF to investigate the effects of the global strain rate on the flame structure. The numerical parameters include a_g= 20, 60, and 90 s^{-1} for each mole fraction of methane in the fuel stream, x_m= 20, 50, 80%. The flame thickness decreased and its radius increased as the global strain rate increased in all the three fuel concentrations, by stretching the flames in the r-direction. The temperature and axial velocity profiles along the duct centerline were in good agreement between the one-dimensional and axisymmetric simulations.

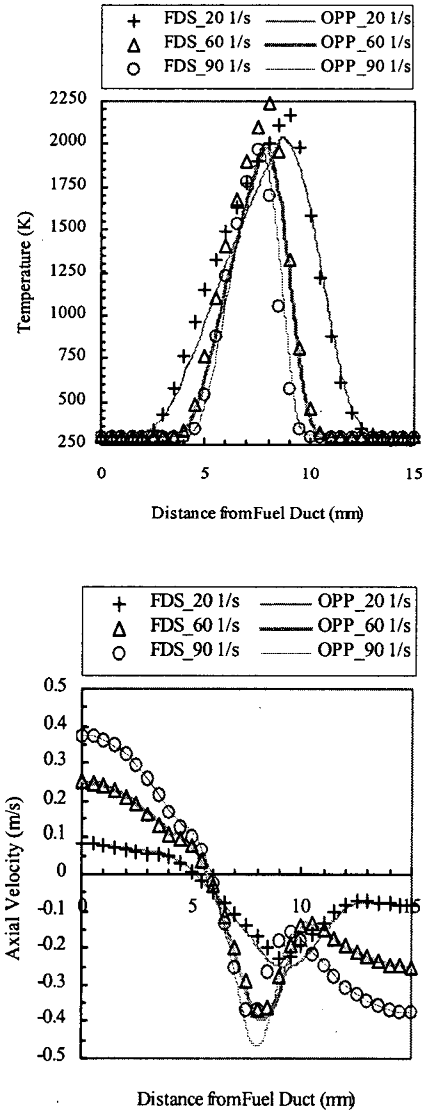


Fig. 7. Comparison of temperature and axial velocity profiles for x_m= 80%.

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