정상중력 및 무중력에서의 저변형율 대향류화염의 전산

박 외 철
부경대학교 공과대학 안전공학과

(2002. 5. 8. 접수 / 2002. 8. 26. 채택)

Computation of a Low Strain Rate Counterflow Flame in Normal and Zero Gravity

Woe-Chul Park
Department of Safety Engineering, Pukyong National University

(Received May 8, 2002 / Accepted August 26, 2002)

Abstract : A near extinction nonpremixed counterflow flame of 19% methane diluted by 81% nitrogen by volume and undiluted air at a low global strain rate, 20 s-1, was computed. Investigations were focused on effects of the duct thickness and velocity boundary conditions on the flame structure in normal and zero gravity conditions. The results showed that, under normal gravity conditions, the effects of the duct thickness and velocity boundary conditions were significant by shifting the flame position, but negligible in zero gravity. The differences in flame structure were caused by buoyancy, and hence should be considered in the measurements in normal gravity.

요 약 : 닥트의 두께와 속도 경계조건이 정상중력 및 무중력 상태에서 화염구조에 미치는 영향을 조사하기위해 81%의 질소와 19%의 메탄이 혼합된 가연성가스와 공기의 저변형율 (20 s-1) 대향류 화염을 수치법으로 모사하였다. 정상중력에서는 닥트의 두께와 속도 경계조건에 따라 화염의 위치가 이동함으로써 그 영향이 컸으나, 무중력에서는 그 영향을 무시할 수 있을 정도로 작은 것으로 나타났다. 화염구조의 차이는 부력으로 인한 것이고, 따라서 정상중력에서의 측정에서는 닥트 두께와 속도 경계조건의 영향을 고려해야 함을 알 수 있었다.

Key Words : numerical simulations, air-methane counterflow flame, duct thickness, velocity boundary conditions, flame structure, zerogravity.

Nomenclature

a_g : Global strain rate
D : Inside diameter of duct
g_o : Gravitational acceleration constant, 9.81m/s^2
G : Dimensionless gravitational acceleration, g/g_o
L : Separation distance between two ducts
s : Distance between duct exit and location where top hat velocity profile is imposed
t : Duct thickness
v : Axial velocity
V_F : Mean velocity in fuel duct
V_O : Mean velocity in oxidizer duct
ρ_F : Density of fuel
ρ_O : Density of air

1. Introduction

In experiments of counterflow diffusion flames, the effects of the wall thickness of ducts on the flame structure have not been investigated. The effects of the duct thickness might be small in zero gravity where buoyancy is zero. Unlikely the zero gravity conditions, the flame structure might be affected by the duct thickness under normal gravity conditions. It is necessary to investigate the effects of duct thickness and velocity boundary conditions in normal and zero gravity conditions.

---

wcpark@pknu.ac.kr

Recently, the NIST Fire Dynamics Simulator (FDS), an unsteady three-dimensional numerical method for fire simulation based on either direct numerical simulations or large eddy simulation, has been developed by McGrattan et al.1), and Park2) showed that the method agreed well with the one-dimensional flame code OPPDIF3) for the axisymmetric counterflow flames. Park and Hamins4) also showed by using FDS that the flame structure is highly sensitive to the velocity boundary conditions under normal gravity conditions, but they did not investigate the velocity boundary conditions in zero gravity.

The objective of this study is to investigate the effects of the duct thickness in normal and zero gravity. Sensitivity of the velocity boundary conditions on the flame structure was also investigated at both G=0 and G=1. A near extinction flame of 19% methane diluted by 81% nitrogen by volume and undiluted air at a low global strain rate, 20 s^{-1}, was chosen for simulation where the effects of buoyancy are important, and FDS is used in the present study.

2. Methodology

The counterflow flame is formed between two opposed ducts as shown in Fig. 1. The inside diameter of each duct, D, is 15 mm, and the separation distance between the two ducts, L, is 15 mm in the study. Methane gas diluted by nitrogen flows in the bottom fuel duct, and undiluted air flows in the top oxidizer duct. The ambient gas is assumed nitrogen so that combustion takes place only between the fuel and the air from the oxidizer duct. The axis y is the centerline of the ducts.

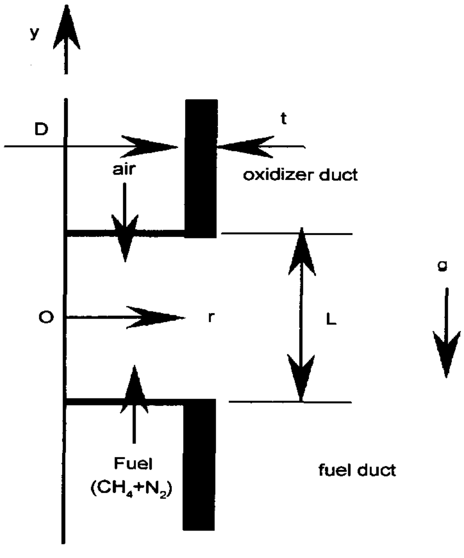


Fig. 1. Schematic diagram of duct geometry

The NIST Fire Dynamics Simulator (FDS)1) was used with the direct numerical simulations and the mixture fraction combustion model5). Based on the previous study3), the computational domain size, 40mm×40mm, and a uniform grid size, 0.5mm×0.5mm in the r- and y-directions were chosen. The thermal radiation was not included in the present study since heat loss by thermal radiation is not significant for a_g=20s^{-1} 6).

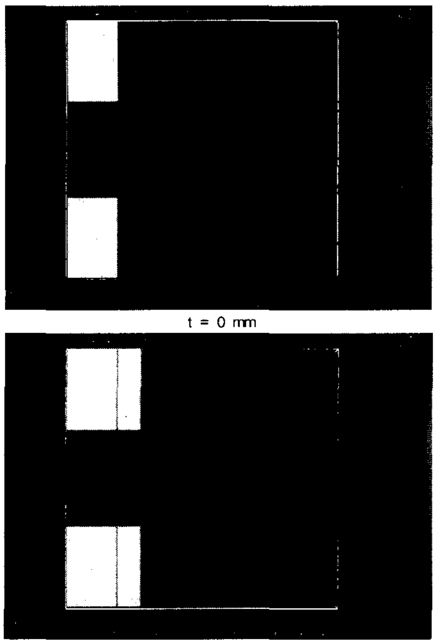
For the given fuel concentration, 19% methane and 81% nitrogen by volume, and global strain rate, a_g=20s^{-1}, the mean velocity in each duct, $V_F = V_O = 0.0772$m/s was obtained by the definition of the global strain rate7)

$$a_g = \frac{2V_O}{L}\left[1 + \frac{V_F}{V_O}\left(\frac{\rho_F}{\rho_O}\right)^{0.5}\right] \qquad (1)$$

3. Results and discussion

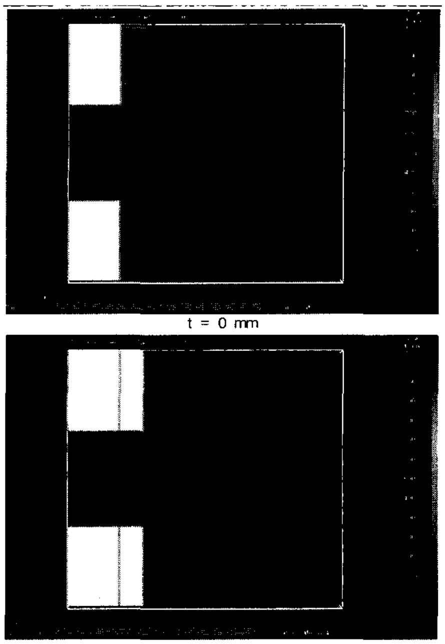
Flames are compared in Fig. 2 for duct wall thickness 0 mm and 3.5 mm in zero gravity. The top hat velocity profile was given at the duct exits. No difference is observed in flame shape. The corresponding temperature and axial velocity profile along the centerline also are the same as can be seen in Fig. 3. These results clearly show that the duct wall has no effects on the flame shape at G=0. In zero gravity, no effects of buoyancy exist, and thus the duct thickness does not change the flame structure.

Under normal gravity conditions, however, the wall thickness affects the flame structure as shown in Fig. 4. The flame of zero duct thickness has much larger curvature than that of the 3.5mm thick duct. The thicker duct blocks the flame moving upwards by the presence of buoyancy. Note that the same no slip boundary conditions on the duct walls in the numerical method for both zero and 3.5mm thick ducts. The profiles of T


t = 0 mm

t = 3.5 mm

Fig. 2. Flames for different duct thickness in zero gravity


t = 0 mm

t = 3.5 mm

Fig. 4. Flames for different duct thickness in normal gravity

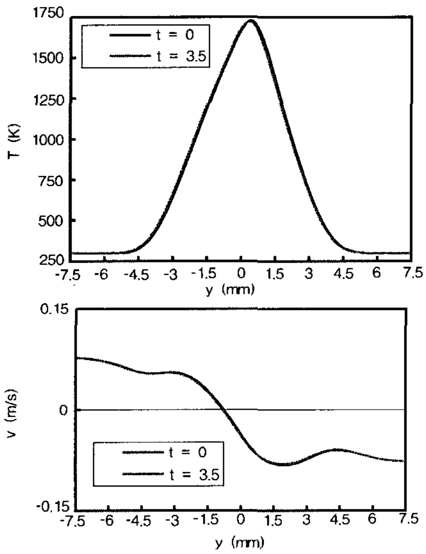


Fig. 3. T and v profiles along the centerline for different duct thickness in zero gravity

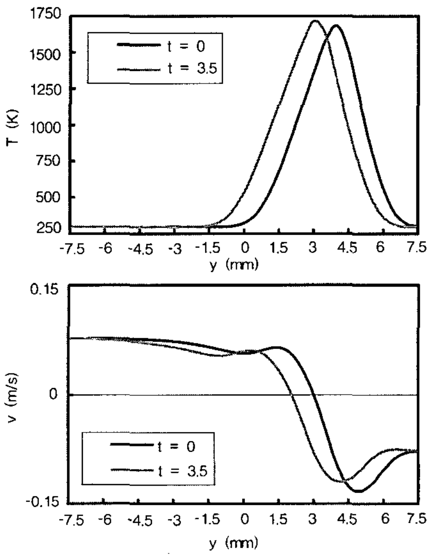


Fig. 5. T and v profiles along the centerline for different duct thickness in normal gravity

and v in Fig. 5 show shifts of the profiles by the duct wall. A thicker duct may move more the flame position and stagnation point towards the bottom fuel duct. It implies that, in an experimental study of the counter-flow flames under normal gravity conditions, a careful investigation of the effects of the duct thickness is needed. A further study is necessary toinvestigate the relation between the duct thickness and the flame position.

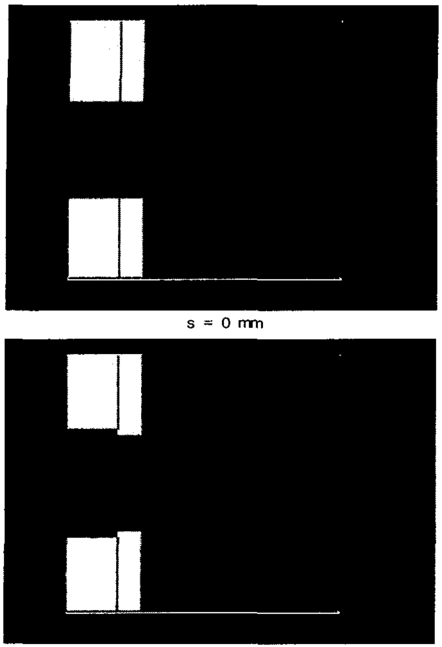


Fig. 6. Flames for different velocity boundary conditions in zero gravity (t=3.5mm)

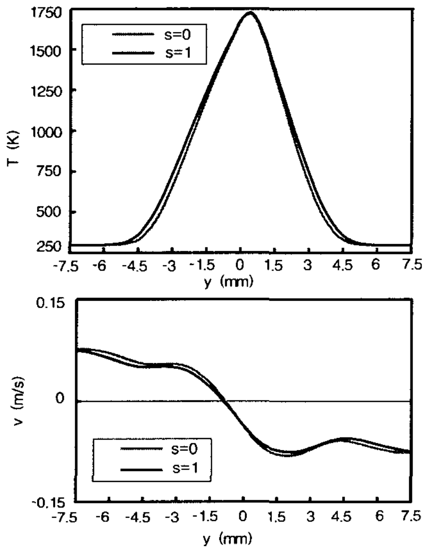


Fig. 7. T and v profiles along the centerline for different velocity boundary conditions in zero gravity (t = 3.5mm)

Park and Hamins[4] investigated the effects of the velocity boundary conditions under normal gravity conditions, and found that the flame structure is sensitive to the point where the plug flow boundary conditions are imposed in the ducts. When a set of screens is inserted in each duct for a uniform velocity at

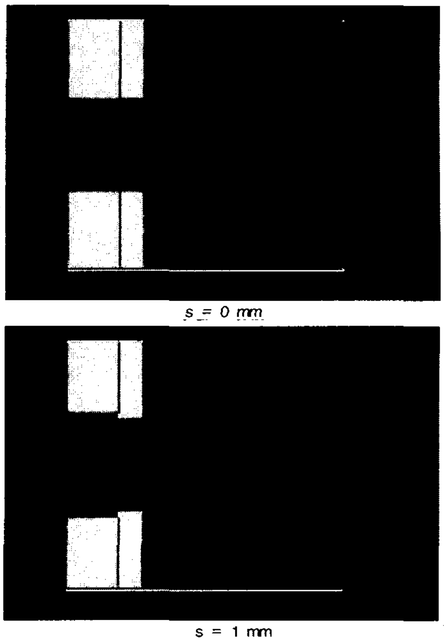


Fig. 8. Flames for different velocity boundary conditions in normal gravity (t=3.5mm)

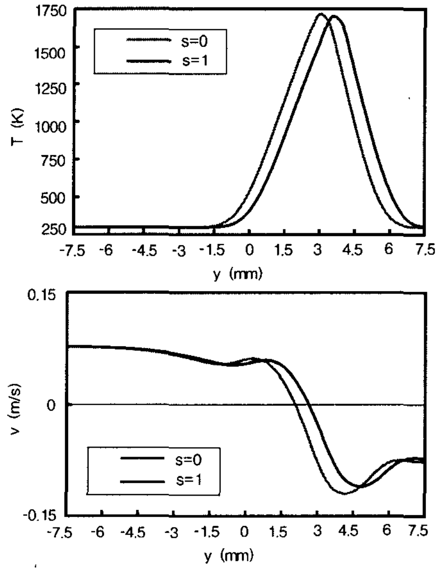


Fig. 9. T and v profiles along the centerline for different velocity boundary conditions in normal gravity (t = 3.5mm)

the exits of the ducts, it is important in numerical simul- ations to decide where the top velocity profile is imposed.

Fig. 6 compares the flames in zero gravity for different locations of the velocity boundary conditions. The flame when the top hat velocity profile is given at the duct exits(s=0mm) is similar to that when it is given at 1mm from the duct exits(s=1mm). With no buoyancy under zero gravity conditions, the effects of the velocity boundary conditions are small. The temperature and axial velocity profiles depicted in Fig. 7 confirms this negligible difference.

In normal gravity, the flame structures would not be negligible. The flames under normal gravity conditions were compared in Fig. 8. Both flames looks similar each other for different locations where the plug flow assumption was imposed. But Fig. 9 shows shifts inprofiles of the temperature and axial velocity along the centerline(y-axis). When the top hat velocity profile is given at 1 mm from the duct exit(s=1mm), theflame and stagnation point are located closer to the oxidizer duct compared with the case when the top hat velocity profile is given at the duct exits(s=0mm). The velocity boundary conditions affect the flame structure with buoyancy under normal gravity conditions. It is consistent with the results of Park and Hamins[4] that a care should be taken in the measurements of the temperature and velocity distribution when screens are inserted in the ducts at some distance from the exits.

4. Conclusions

A near extinction flame of 19% methane diluted by 81% nitrogen by volume and undiluted air at a low global strain rate, $20s^{-1}$, was investigated by using FDS with the mixture fraction combustion model. The effects of the duct thickness, the velocity boundary conditions and the shield gas were investigated in normal and zero gravity conditions. It was confirmed that the velocity boundary conditions were sensitive at G=1, but the difference was negligible at G=0. Under normal gravity conditions, the duct thickness decreased the flame curvature and moved its position by blocking the flame. No discernible effects of the duct thickness were observed in zero gravity. It was found that the differences in flame structure due to the duct thickness under normal gravity conditions were caused by buoyancy, and hence these differences should be considered in the measurements under normal gravity conditions.

References

1) K. B. McGrattan, H. R. Baum, R. G. Rehm, A. Hamins, G. P. Forney, J. E. Floyd and S. Hostikka, Fire Dynamics Simulator Technical Reference Guide V.2, National Institute of Standards and Technology, Gaithersburg, MD, U.S.A., 2001(also http://fire.nist.gov/fds/).
2) W. C. Park, “An Evaluation of a Direct Numerical Simulation for Counterflow Diffusion Flames,” J. of Korea Institute of Industrial Safety, Vol. 16, No. 4, pp. 74~81, 2001(in Korean).
3) A. Lutz, R. J. Kee, J. Grcar and F. M. Rupley, “A Fortran Program Computing Opposed Flow Diffu sion Flames,” SAND96-8243, Sandia National Laboratories, Livermore, CA, 1997.
4) W. C. Park and A. Hamins, “Investigation of Velocity Boundary Conditions in Counterflow Flames,” KSME Int'l J. Vol. 16, No. 2, pp. 262~269, 2002.
5) J. E. Floyd, K. B. McGrattan and H. R. Baum, “A Mixture Fraction Combustion Model for Fire Simulation Using CFD,” Proc. Intl Conf. on Engineered Fire Protection Design, pp. 279~290, 2001.
6) K. Maruta, M. Yoshida, H. Guo, Y. Ju and T. Niioka, “Extinction of Low-Stretched Diffusion Flame in Microgravity,” Combustion and Flames, Vol. 112, pp. 181~187, 1998.
7) K. Seshadri and F. A. Williams, “Laminar Flow Between Parallel Plates with Injection of a Reactant at High Reynolds Number,” Int'l J. Heat Mass Transfer, Vol. 21, pp. 251~253, 1978.