# 차폐가스가 대향류 화염구조에 미치는 영향의 조사

박외철
부경대학교 안전공학과
(2002. 2. 2. 접수 / 2002. 5. 30. 채택)

# Investigation of Effects of Shield Gas on Counterflow Flame Structure

**Woe-Chul Park**
Department of Safety Engineering, Pukyong National University
(Received February 2, 2002 / Accepted May 30, 2002)

**Abstract** : The effects of shield gas on the structure of methane-air nonpremixed counterflow flames were numerically investigated. The near extinction flame of a low global strain rate 20 $s^{-1}$ of 19% methane diluted by 81% nitrogen by volume and undiluted air was computed. The flame shape, centerline temperature and axial velocity profiles were compared for different velocity of the shield gas and with and without the shield gas. The effects of the velocity of the shield gas were negligible for $V_S/V_F \leq 2$ in normal gravity. Under normal gravity conditions, the flame shape and its position with the shield gas were different from those of the flame without the shield gas, whereas no discernible effects of the shield gas along the centerline were observed in zero gravity.

**요 약 :** 메탄-공기의 비예혼합 대향류 확산화염 차폐가스가 화염구조에 미치는 영향을 수치적으로 조사하였다. 20 $s^{-1}$의 저변형율, 메탄가스 19%와 질소 79%의 혼합가스 연료와 공기의 확산화염을 대상으로 하였다. 질소차폐가스의 속도와 차폐가스의 유무에 따른 화염의 형태와 중심선상의 온도 및 축방향 속도의 분포를 비교하였다. 정상중력에서 $V_S/V_F \leq 2$일 때 차폐가스의 유동이 화염구조에 미치는 영향은 무시할 수 있었다. 정상중력에서 차폐가스가 없는 경우의 화염형태와 그 위치는 차폐가스가 있는 경우와 다르지만, 무중력에서는 중심선상에서 차폐가스의 영향이 거의 없었다.

**Key Words :** numerical simulations, air-methane counterflow flame, shield gas, flame structure

## Nomenclature

$a_g$ : Global strain rate
$g_o$ : Gravitational acceleration constant, 9.81m/s2
G : Dimensionless gravitational acceleration, g/go
L : Separation distance between two ducts
p : Pressure
Q : Heat release rate per unit volume
T : Temperature
t : Time
u : Velocity
v : Axial velocity
$V_O$ : Mean velocity in oxidizer duct
$V_F$ : Mean velocity in fuel duct
$V_S$ : Velocity of shield gas
w : Chemical production rate per volume
$\lambda$ : Thermal conductivity
$\rho$ : Density of fluid
$\rho_F$ : Density of fuel
$\rho_O$ : Density of air

## 1. Introduction

In most experimental studies of counterflow diffusion flames, the nitrogen shield gas flow has been applied to prevent the reaction between fuel gas and ambient air. In some cases, however, no shield gas was used (e.g., Maruta et al.[1]). The velocity of shield

---

wcpark@pknu.ac.kr

gas, $V_S$, is approximately the same magnitude as the fuel velocity, $V_F$, and the effects of the shield gas flow on the flame structure have been neglected. In the most experiments it is necessary to find the effects of the velocity of shield gas flow on the flame structure. An investigation of the flame structure with and without the shield gas is also needed under normal and conditions.

Recently, a unsteady three-dimensional numerical method[2)] for fires based on direct numerical simulations or large eddy simulation has been evaluated on the axisymmetric counterflow diffusion flames. Park[3)] showed that the method agreed well with the one-dimensional flame code OPPDIF[4)] in zero gravity. Park and Hamines[5)] investigated the velocity boundary conditions in counterflow flames, and found that the screen inserted in the ducts has highly sensitive to the flame structure. They also found that imposing a top hat velocity at the inner surface of the screen is reasonable. In the present study, the same numerical method was utilized to find the effects of the shield gas on the structure of the laminar counterflow diffusion flame. Flame shape and the centerline temperature and velocity profiles were compared for different velocity of nitrogen shield gas under normal gravity conditions, and with and without the shield gas under normal and conditions.

## 2. Methodology

Fig. 1 shows the geometry and dimensions of the counterflow ducts. The inside diameter of each duct is 15 mm, its wall thickness is 3.5 mm and the separation distance between the two ducts is 15 mm. A concentric tube of 22 mm diameter around the oxidizer duct supplies the nitrogen gas. There is a set of screen inside each duct at 0.6 mm from the exit to get a uniform velocity at the exit. Following the investigation of the velocity boundary conditions of Park and Hamines,[5)] a top hat velocity profile was imposed at 1 mm from each duct exit. Methane diluted by nitrogen flows in the bottom fuel duct and undiluted air flows in the top oxidizer duct.

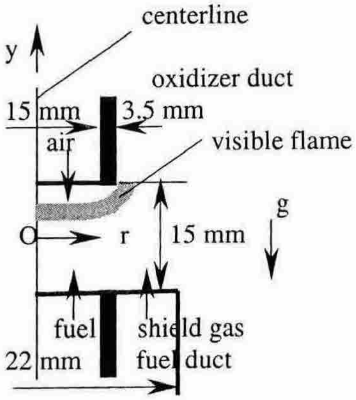


Fig. 1. Schematic diagram of counterflow ducts.

The governing equations are as follows :

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u_i}{\partial x_i}=0 \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t}+\frac{\partial \rho u_i u_j}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\rho g_i+\frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

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

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

The thermal radiation was not included in the present study because heat loss by thermal radiation is not significant[1)].

The NIST Fire Dynamics Simulator (FDS)[2)] was used with the direct numerical simulations and the mixture fraction combustion model[6)]. Following the previous study,[3)] the computational domain size, 40 mm × 40 mm, and a uniform grid size, 0.5 mm × 0.5 mm were used.

For the given fuel concentration and global strain rate, the mean velocity in each duct, $V_F$ and $V_O$ were calculated by the definition of the global strain rate[7].

$$a_g = \frac{2V_O}{L}\left[1+\frac{V_F}{V_O}\left(\frac{\rho_F}{\rho_O}\right)^{0.5}\right] \qquad (5)$$

In the present study, a near extinction flame 19% methane and 81% nitrogen by volume at a low strain rate, 20 $s^{-1}$ was considered. For $V_F=V_O$, both $V_F$ and $V_O$ are 0.0772 m/s.

To investigate the effects of velocity of the shield gas, computations were carried out according to the veslocity ratios, $V_S/V_F$ up to 4. In this case, the velocity of the shield gas was assumed to be uniform in the concentric tube of 44 mm diameter.

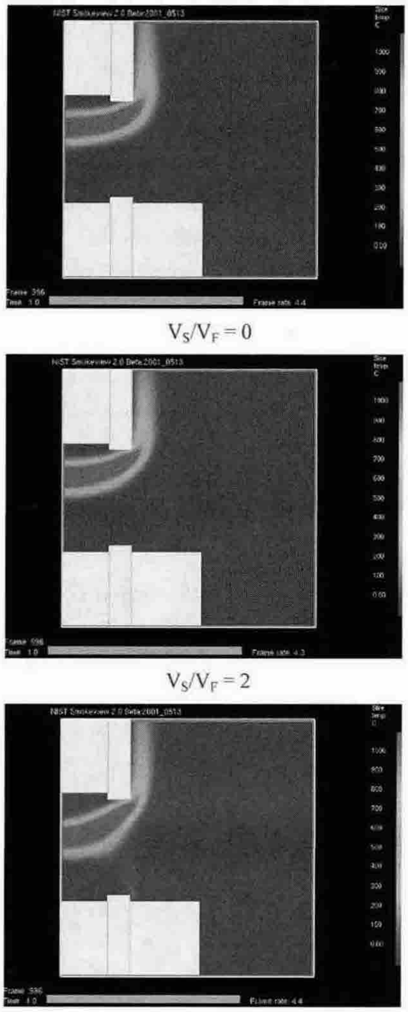
## 3. Results and discussion

Flames for $V_S/V_F=0$, 2 and 4 under normal gravity conditions are .shown in Fig. 2. No discernible difference is noted between the flames of $V_S/V_F=0$ and $V_S/V_F=2$, but the flame of $V_S/V_F=4$ shows that it was affected by the shield gas flow.

Fig. 3 is the corresponding temperature and axial velocity profiles along the centerline for the different velocity magnitudes of the shield gas. Both temperature and velocity profiles for $V_S/V_F=0$ and 1 coincide, and those of $V_S/V_F=2$ are slightly different from the zero velocity case. When $V_S/V_F=4$, the flame moved downwards, and the stagnation point also moved towards the fuel duct. This shift of the flame position was caused by the increase in the y-direction velocity near the edge of the oxidizer duct exit with the shield gas velocity. From these results, it was confirmed that the effects of the velocity of the shield gas is negligible when $V_S/V_F \leq 2$.

For comparison of the flame structure with and without the shield gas, the concentric tube where the nitrogen shield gas flows was removed. Instead, a quiescent nitrogen gas or air was assumed around the fuel and oxidizer ducts.

Fig. 4 compares the flames with and without the nitrogen shield gas. When the flame is not shielded from the ambient air, reaction takes place between the fuel and the air from the oxidizer duct, and between the fuel and the ambient air, and it forms a $\lambda$ shape flame. On the other hand, when the flame is shielded by the quiescent nitrogen gas ($V_S=0$), reaction takes place only between the fuel and the air from the oxidizer duct. This shows that the flame structure depends on the presence of the shield gas. Note that the temperature scales are not the same. This problem was found to occur with the Windows ME. The flame thickness near the centerline remained almost the same, whereas the flame position was changed with the presence the shield gas. This can be confirmed by the centerline temperature profiles.



$V_S/V_F = 0$

$V_S/V_F = 2$

$V_S/V_F = 4$

Fig. 2. Flames for different velocity of shield gas (G=1)

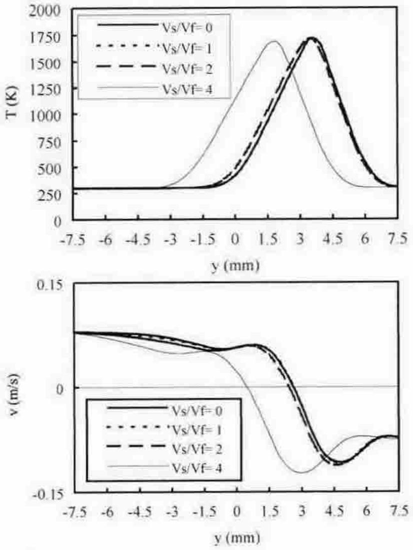
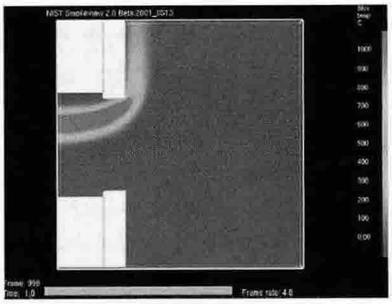
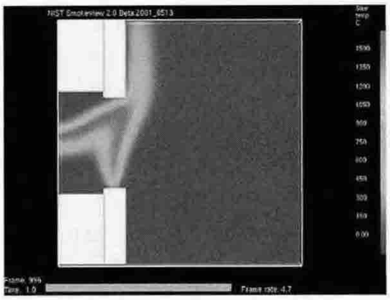


Fig. 3. Comparison of temperature and velocity profiles along the centerline for different velocity of shield gas (G=1)



flame in nitrogen gas



flame in air

Fig. 4. Flames with and without the nitrogen shield gas (G=1)

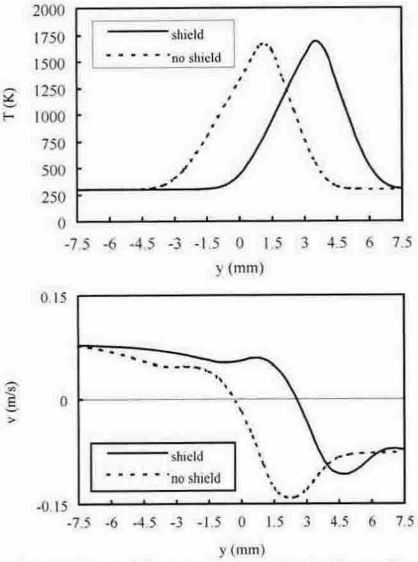
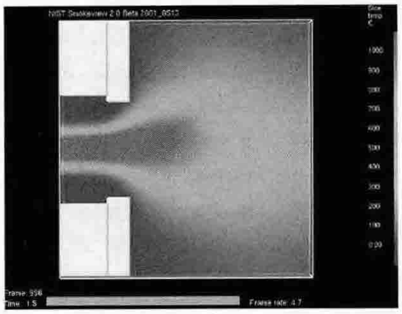
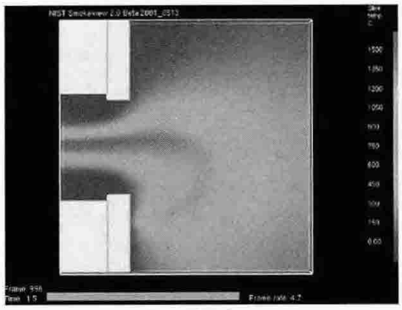


Fig. 5. Comparison of temperature and velocity profiles along the centerline (G=1)



flame in nitrogen gas



flame in air

Fig. 6. Flames with and without the nitrogen shield gas (G=0)

The temperature and velocity profiles along the centerline in normal gravity conditions are compared in Fig. 5. The flame position in the nitrogen shield gas is quite different from that in the ambient air. When the flame is in the air, the flame position is lower than in nitrogen gas. The effects of buoyancy due to reaction taken place between the fuel and the ambient air increases the y-direction velocity, and the flame position moved downwards at the center of the duct. This is similar to the flame shift by increasing velocity of the shield gas flow. If there were no effects of buoyancy, the flame position would remain unchanged. The flames will show this in zero gravity where no buoyancy exists.

Fig. 6 depicts the flames with and without the nitrogen shield gas in zero gravity. When shielded by the quiescent nitrogen gas, the flame is almost symmetrically about the r-axis. When the flame is not shielded from the ambient air, the flame shape is different from that in the shield gas, due to the additional reaction between the fuel and the ambient air. The temperature scales in the both figures are not the same as seen in Fig. 4. However, the flame position and thickness along the centerline were the same as can be seen in Fig. 7.

The temperature and axial velocity profiles along the centerline in zero gravity are compared in Fig. 7. Both temperature and velocity profiles with and without the nitrogen shield gas has no difference. The location of the peak temperature and the stagnation point with the shield gas are the same as those without the shield gas. In zero gravity, the shield gas has no effects on the flame structure along the centerline. As mentioned before, there are no effects of buoyancy in zero gravity, and this results in no effects of the shield gas on the flame structure near the centerline. Although no difference was observed between with and without the shield gas along the centerline, the flame structure outside the ducts should not be the same because of the presence of the flame between the fuel and the ambient air when the flame is not shielded by the nitrogen as shown in Fig. 6.

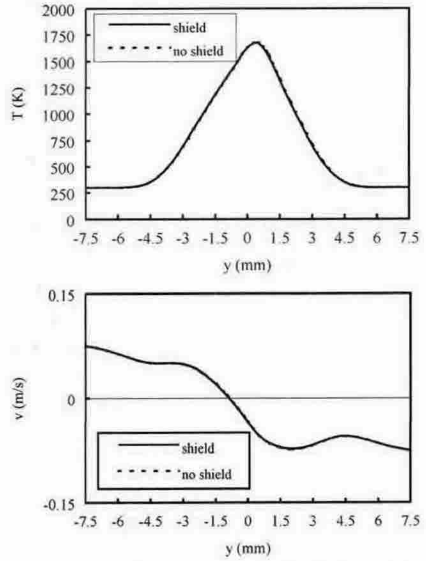


Fig. 7 Comparison of temperature and velocity profiles along the centerline (G=0)

## Conclusions

The effects of the shield gas on the methane-air nonpremixed counterflow flame structure were investigated by using the two-dimension simulation and the mixture fraction combustion model. A near extinction flame at a low global strain rate 20 $s^{-1}$, and 19% methane diluted by 81% nitrogen by volume and undiluted air was considered. It was confirmed that the effects of the velocity of the nitrogen shield gas may be significant when $V_S/V_F>2$, but are negligible for the velocity ratio smaller than 2. Under normal gravity conditions, the flame shape and its position with the shield gas were different from those of flame without the shield gas, whereas no discernible effects of the shield gas along the centerline were observed in zero gravity. The difference between the flame structure with the shield gas and that without the shield gas is caused by the presence of the effects of buoyancy and the reaction between the fuel and the ambient air.

## References

1) 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.
2) 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. http://fire.nist.gov/fds/, 2001.
3) W. C. Park, An Evaluation of a Direct Numerical

Simulation for Counterflow Diffusion Flames, Korea Institute for Industrial Safety Journal, Vol. 16, No. 4, pp. 74~81, 2001 (in Korean).

4) A. Lutz, R. J. Kee, J. Grcar and F. M. Rupley, A Fortran Program Computing Opposed Flow Diffusion Flames, SAND96-8243, Sandia National Laboratories, Livermore, CA, 1997.

5) W. C. Park and A. Hamins, Investigation of Velocity Boundary Conditions in Counterflow Flames, KSME Intl J., Vol. 16, No. 2, pp. 262~269, 2002.

6) 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.

7) K. Seshadri, and F. A. Williams, Laminar Flow Between Parallel Plates with Injection of a Reactant at High Reynolds Number, Intl J. Heat Mass Transfer, Vol. 21, pp. 251~253, 1978.