LES OF TURBULENT FLOW AND MIXING IN A MICRO CAN COMBUSTOR

Hang Seok Choi
Combustion and Environment Group, Eco-Machinery Engineering Department,
Korea Institute of Machinery and Materials,
171 Jang-dong, Yuseong-gu, Daejeon, 305-343, South Korea
hschoi@kimm.re.kr

Tae Seon Park
School of Mechanical Engineering,
Kyungpook National University,
1370 Sangyeok-Dong, Buk-gu, Daegu, 702-701, South Korea
tsparkjp@knu.ac.kr

Kenjiro Suzuki
Department of Machinery and Control Systems,
Shibaura Institute of Technology,
307 Fukasaku, Saitama, 337-8570, Japan
ksuzuki@sic.shibaura.ac.jp

ABSTRACT

Turbulence and mixing in a micro can type combustor are investigated by means of Large Eddy Simulation (LES). Attention is paid for a combustor with a baffle plate having oxidant injection and fuel injection holes and study is made for three cases of different baffle plate configurations. From the result, it is confirmed that mixing is promoted by interaction between the jets and large vortical flow regions generated between the jets and wall downstream of the fuel jet. This is effective to accelerate the slow mixing between fuel and oxidant suffering from low Reynolds number in a micro combustor. In particular, the vortical flow region ahead of fuel jet front plays an important role for rapid mixing. Discussion is made for the time and space averaged mixedness parameter which shows peculiar characteristics corresponding to different vortical flow structures for each baffle plate shapes.

INTRODUCTION

Currently, a micro gas turbine (MGT) has been widely drawing attention as a distributed energy generation system for an individual household or a small community. In parallel to the progress of MGT technology, a fuel cell has been highlighted for its high efficiency and environmental advantages. Electricity generation efficiency of solid oxide fuel cell (SOFC) recently becomes 50 % or higher, and its working temperature is in the range from 700 $°C$ to 1,000 $°C$. Therefore a system hybridizing MGT with SOFC is promising. In this study, focus is given to an innovative micro can combustor with multiple fuel and oxidant jets injected through holes drilled in a baffle plate as illustrated in Fig. 1, which is proposed as a combustor for the MGT/SOFC hybrid system. This micro combustor is expected to secure zero emission of toxic gases like CO and a stable flame for burning the effluent of SOFC in an extraordinary fuel lean condition.

Combustion in a very small chamber may not simply resemble a scaled-down version of its large-scale counterpart. This is mainly due to the difference of Reynolds number. Mixing between fuel and oxidants becomes much slower in a small combustor resulting in relatively longer and sooty luminous flames. Thus, the mixing enhancement is a key factor on developing such a small combustor satisfying another requirement to secure the flame stability. To solve these problems in the present study, the baffle plate with multiple-jets for oxidant and fuel injection is introduced to intensify the mixing between fuel and oxidants and maintain flame stability, simultaneously. From the previous works by Choi et al. (2001) and Woodfield et al. (2003), it is seen that the proposed micro can combustor with multiple-jets is very effective to meet the both requirements of mixing enhancement and flame stability. In the present study, Large Eddy Simulation (LES) is applied to a turbulent flow in the micro can combustor to elucidate the characteristics of turbulent mixing between fuel and oxidant jets in it.

NUMERICAL METHODS

Mathematical Formulation

For LES, filtered forms of continuity and momentum equations for incompressible fluid are expressed as follows:

$$\frac{\partial \hat{u}_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial \hat{u}_i}{\partial t} + \hat{u}_j \frac{\partial \hat{u}_i}{\partial x_j} = \nu \frac{\partial^2 \hat{u}_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} - \frac{1}{\rho}\frac{\partial \hat{p}}{\partial x_i}. \tag{2}$$

where $\hat{u}$, $\hat{p}$ and τ_{ij} are the filtered velocity, filtered pressure and the subgrid-scale stress tensor respectively. In Eq. (2), τ_{ij} must be modelled. So, dynamic subgrid-scale model (Lilly, 1992) is adopted in the present study for τ_{ij} as follows:

Table 1: Calculation condition

Case	D_o/D_f	V_o/V_f	Re_{tube}
A	1	2	1529
B	2	0.5	1529
C	0.5	8	1529

$$\tau_{ij} - 1/3\delta_{ij}\tau_{kk} = -2\nu_t \widehat{S}_{ij}, \qquad (3)$$

here $\widehat{S}_{ij} = (\partial\widehat{u}_i/\partial x_j + \partial\widehat{u}_j/\partial x_i)/2$ and ν_t is the eddy viscosity to be obtained.

In this article, cold mixing between fuel and oxidant is studied. So, the following additional filtered governing equation of a mixture fraction, Z, is used to represent the evolution of mixing. Here the mixture fraction, Z, is defined to be 1 for pure fuel and 0 for pure oxidant.

$$\frac{\partial\hat{Z}}{\partial t} + \frac{(\partial\hat{u}_i\hat{Z})}{\partial x_i} = \frac{\partial}{\partial x_i}[D(\frac{\partial\hat{Z}}{\partial x_i}) - s_j], \qquad (4)$$

where $\hat{Z}$ is a filtered mixture fraction and D is the diffusion coefficient of mixture fraction. This assumed as constant, i.e. $D = \nu/Sc = 0.7$ and Sc is the Schmidt number. s_j is a subgrid-scale scalar flux approximated as $s_j = -(\nu_t/Sc_t)(\partial\hat{Z}/\partial x_i)$. In the present study, the turbulent Schmidt number is set constant, i.e. $Sc_t = 0.7$.

Computational Procedure

To numerically solve the finite-difference equivalents of Eqs. (1) through (4), a fractional step method is used. So, the time integration of the discretized governing equations is carried out based on an Adams-Bashforth method. As for the spatial discretization of the equations, the fourth-order COMPACT scheme (Lele, 1992) for the convective terms, and the fourth-order central differencing for the diffusion terms and other remaining terms are applied.

Computational Condition

Table 1 describes the three different calculation conditions and Fig. 2 shows the computational domain of baffle plate A and its grid system. An inlet hole for fuel is located in the center of the baffle plate and is surrounded by six oxidant inlet holes. Here, D_o is oxidant hole diameter and D_f for fuel hole diameter. In Fig. 2, x, y and z axes correspond to streamwise, transverse and spanwise directions, respectively. L is the streamwise length of the computational domain and D_{tube} is the combustor can diameter and L/D_f is 12.5 and D_{tube}/D_f is 5.5 for the case A in Table 1. The total grid number is set as $51 \times 55 \times 109$ for all the three cases of Table 1. As illustrated in Table 1, only the diameter ratio, D_o/D_f, is changed and other geometrical parameters are kept the same. Where, V_o/V_f is the oxidant to fuel velocity ratio and Re_{tube} is the Reynolds number based on the combustor can diameter, D_{tube}. For the three cases, Re_{tube} is not changed. This means that the fuel and oxidant flow rates are kept identical.

RESULTS AND DISCUSSIONS

Figure 3 shows the iso-surface of instantaneous negative Λ_2 value in the half volume of the micro combustor with the baffle plate A. Here, negative Λ_2 is used to capture a vortical flow region as proposed by Jeong and Hussian (1995) and Jeong et al. (1997) and applied by Choi and Suzuki (2005) in the LES study of turbulent heat transfer from a wavy wall. As can be seen in the figure, in oxidant-jet regions strong vortices are generated, develop and finally interact with each other, i.e. between fuel and oxidant jets or oxidant and oxidant jets. This makes the flow field more turbulent and significantly enhances the scalar mixing at such a low Reynolds number condition as will be discussed later. This can be confirmed from the distribution of production rate of turbulent kinetic energy, i.e. P_k. Here, $P_k = -\overline{u_i u_j}(\partial\overline{U}_i/\partial x_j)$, u_i and u_j are the velocity fluctuations and $\overline{U}_i$ is the mean velocity. In Fig. 4, high P_k region is found to intensively distribute around the oxidant jets and this high P_k region is broadened, wrinkled and merged each other toward the downstream. In Fig. 5, P_k contours are presented for the three cases of different baffle plates. Note that all P_k values are non-dimensionalized by the inlet fuel jet velocity, V_f, of case A. As expected, in case A the value of P_k is high in the outer edges of air jets. On the contrary, near the fuel jet boundary P_k is higher in case B. For the case C, the higher region of P_k is very similar to the case A, but the magnitude of P_k is largely elevated as the air jet velocity increases. From the above results, it can be expected that the vortices caused by jet flows issuing from the present multi-jet type baffle plate become very efficient for the turbulent scalar mixing. However, another important large vortical motion appears in the micro combustor and this will be discussed in the next paragraph.

Figure 6 displays the contours of instantaneous streamwise velocity and fluctuation of mixture fraction for the baffle plate A. Here, the fluctuation of the mixture fraction is defined as $z' \equiv Z - \overline{Z}$ and Z is an instantaneous mixture fraction and $\overline{Z}$ time mean mixture fraction. In that figure, contours of z' are displayed by color grade, and black solid and dotted lines are for velocity contour. The dotted lines indicate negative values of instantaneous velocities. From the velocity contour, flow recirculation regions can be found and those exist between the jets and wall and in front of the fuel jet. Especially near the flow recirculation region located in front of the fuel jet, the fluctuation of mixture fraction, z', has high negative or positive magnitude. This means that at the region active scalar mixing takes place as a result of the vigorous flow recirculation. The characteristics of the flow recirculation and its effect on mixing are investigated in the following.

Figures 7, 8, and 9 show the time mean streamwise velocity and mixture fraction contours in two x-y planes. The upper one is in the plane slicing the middle of the space between the neighboring oxidant jets and the lower one is slicing the center of one of the oxidant holes. The contour of mixture fraction is expressed by color grade and streamwise velocity contour is drawn by a solid line for positive value and a dotted line for negative one. For the three cases, flow recirculation regions appear between jet(fuel or oxidant) and combustor wall in the upstream in the both two planes. But, the recirculation region which is generated in front of the fuel jet exists only in the cases A and C. This makes the rapid mixing of fuel and oxidant so, the contour of higher region of mean mixture fraction, $\overline{Z}$, is more shortened compared with that of the case B. Furthermore, in case C the recirculation region is stretched and extended toward the upstream of the fuel jet resulting in the smallest length of the higher $\overline{Z}$ region among the three cases.

The effect of these vortical flow regions on the scalar mixing will now be scrutinized by evaluating mixedness parameter.

Figures 10, 11, and 12 represent the radial distributions of time mean mixedness parameter (Cetegen and Mohamad, 1993; Verzicco and Orlandi, 1995). As they suggested, mixedness, f, is defined as follows:

$$f = \frac{4}{A}\int_A Z(1-Z)dA. \quad (5)$$

Here, A is the area or volume in the computational domain over which integration is carried out and Z is the instantaneous mixture fraction. f varies between 0 and 1 again, i.e. $Z = 0$ for pure oxidant flow region and $Z = 1$ for completely unmixed fuel region. In the following, discussion is given to the time and space mean values of the mixedness, f, averaged circumferentially in space and over appropriate time span. In Fig. 10 is found, at the positions $x/D_f = 1$ and $x/D_f = 2.5$ near the injection holes of jets in case A, that the distribution of mixedness has two peak values. The first peak is located very close to the outer boundary of the fuel jet. The value of f increases toward the combustor wall and its second peak arises close to the wall. The jet entrainment and consequent mixing are responsible for the first peak and the second one is affected by the flow recirculation region between jet and wall as can be seen in Fig. 7. However, moving to the downstream around $x/D_f = 5.5$ remarkable change of mixedness distribution occurs. The peak position is first shifted to the center of the baffle plate and higher value of the mixedness is maintained as good as to the half of the baffle plate toward the combustor wall from the center. This can be explained by the action of the flow recirculation region positioned in front of the fuel jet and through this large vortical flow, a quite large portion of fuel is smeared into the wall recirculation region. These two large vortical motions, therefore, make the rapid mixing in the combustor. For further downstream at $x/D_f = 7.5$, the distribution of mixedness becomes almost flat.

In Fig. 11 near the jet injection holes at $x/D_f = 1$ and $x/D_f = 2.5$ the distributions of mixedness look similar to the case A. But, the flow recirculation near the wall hardly works for the scalar mixing unlike the case A and for the downstream at $x/D_f = 5.5$ and $x/D_f = 7.5$ the peak region is still confined near the fuel jet. It is evident that in case A the flow recirculation region formed in front of fuel jet feeds the fuel into the wall recirculation region effectively so that quick scalar mixing is realized. However, in case B there is no such a large vortical flow motion. Therefore significant mixing only happens at the region between fuel and oxidant jets. In Fig. 12, the shape of the distribution of mixedness parameter resembles that of the case A but, the shift of the peak position to the center of the baffle arises early at $x/D_f = 2.5$ because of the expansion of the flow recirculation region upstream toward the fuel jet holes.

CONCLUDING REMARKS

In the present study, turbulent flow and mixing are scrutinized by using LES for a micro combustor with a baffle plate having oxidizer holes and fuel hole and study was made in three cases of different baffle plate configuration. Baffle plate is mounted from expectation to enhance the slow scalar mixing in the low Reynolds number condition of the micro combustor. In this study, the mixing is found to be greatly affected by the flow recirculation regions formed between jet and wall and in front of the fuel jet flow. Especially, the existence of the large vortical flow located in front of the fuel jet plays an important role to enhance the mixing between fuel and oxidant fluids. In cases A and C, the mixing ability of the baffle plate is more pronounced than in case B. Furthermore, in case C the flow recirculation region is stretched toward upstream allowing shorter tube length for complete mixing resulting in shorter flame in the combustor.

REFERENCES

Cetegen, Baki M., and Mohamad, Nazri, 1993, "Experiments on Liquid Mixing and Reaction in a Vortex", *J. Fluid Mech.*, Vol. 249, pp 391-414.

Choi, H. S., Nakabe, K., Suzuki, K., and Katsumoto, Y., 2001, "An Experimental Investigation of Mixing and Combustion Characteristics on the Can-Type Micro Combustor with a Multi-Jet Baffle Plate", *Proceedings, IUTAM Symposium on Turbulent Mixing and Combustion*, U. Grigul et al., ed., Hemisphere Publishing Corp., Washington, D.C., Vol. 2, pp. 136-137.

Choi, H. S. and Suzuki, K., 2005, "Large Eddy Simulation of Turbulent Flow and Heat Transfer in a Channel with One Wavy Wall", *Int. J. Heat and Fluid Flow*, to appear.

Jeong, J., and Hussain, F., 1995, "On the Identification of a Vortex", *J. Fluid Mech.*, Vol. 285, pp. 69-94.

Jeong, J., Hussain, F., Schoppa, W. and Kim, J., 1997, "Coherent Structures near the Wall in a Turbulent Channel Flow", *J. Fluid Mech.*, Vol. 332, pp. 184-214.

Lele, S. K., 1992. "Compact Finite Difference Schemes with Spectral-Like Resolution", *J. Comput. Phys.*, Vol. 103, pp. 16-42.

Lilly, D. K., 1992, " A Proposed Modification of the Germano Subgrid-Scale Closure Model", *Phys. Fluids*, Vol. 4, pp. 633-635.

Verzicco, R., and Orlandi, P., 1995, "Mixedness in the Formation of a Vortex Ring", *Phys. Fluids*, Vol. 7, pp 1513-1515.

Woodfield, Peter L., Nakabe, K., and Suzuki, K., 2003, "Numerical Study for Enhancement of Laminar Flow Mixing Using Multiple Confined Jets in a Micro-Can Combustor", *Int. J. Heat Mass Transfer*, Vol. 46, pp. 2655-2663.

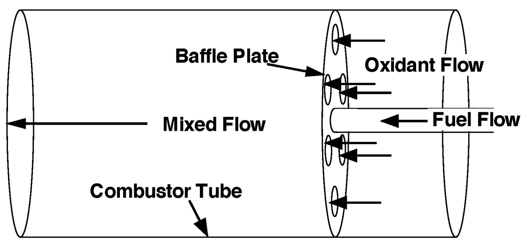

Figure 1: Configuration of a micro can combustor

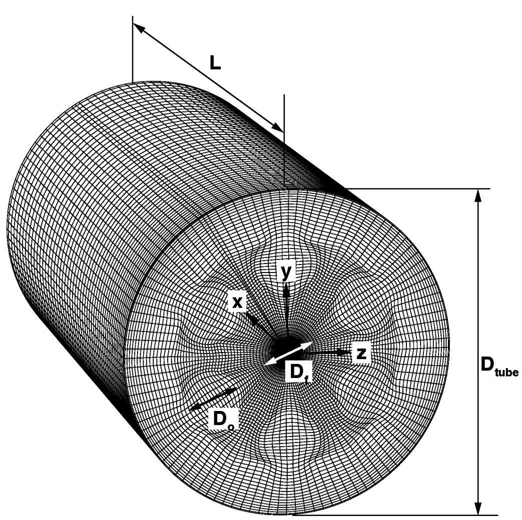

Figure 2: Computational domain of baffle plate A

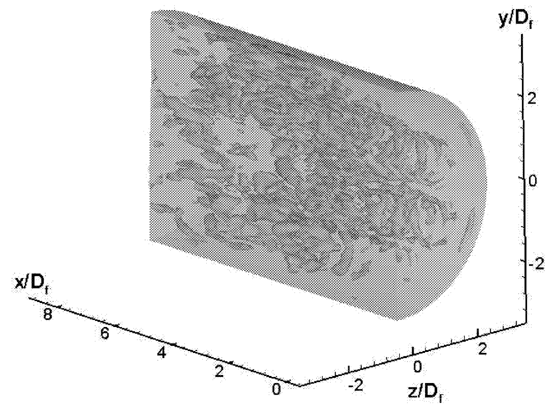

Figure 3: Iso-surface of instantaneous negative Λ_2 in baffle plate A

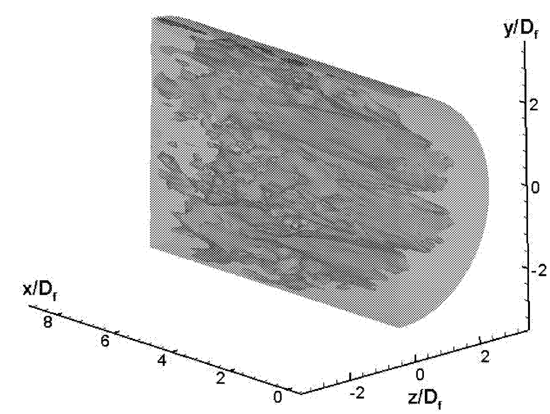

Figure 4: Iso-surface of production rate of turbulent kinetic energy in baffle plate A

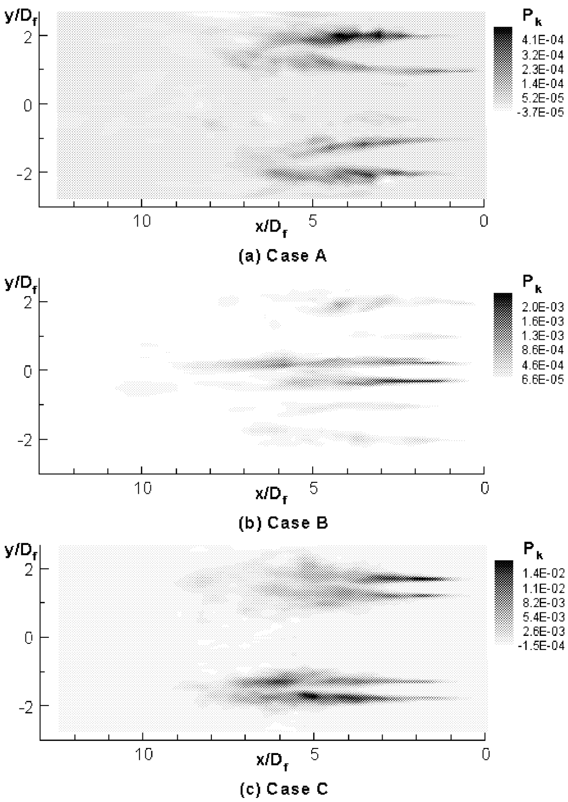

Figure 5: Contours of production rate of turbulent kinetic energy

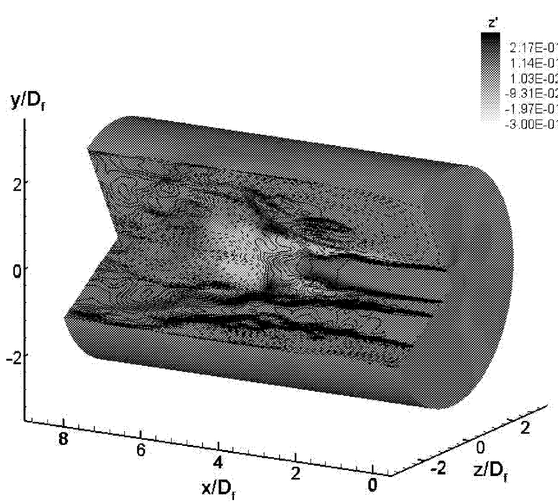

Figure 6: Contours of instantaneous streamwise velocity and fluctuation of mixture fraction for baffle plate A

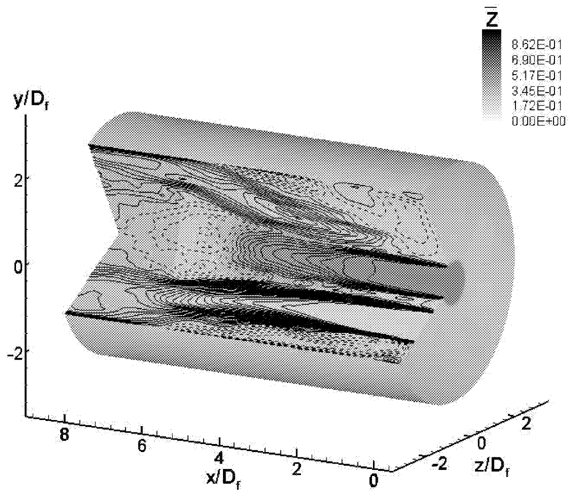

Figure 7: Contours of steamwise velocity and mixture fraction in case A

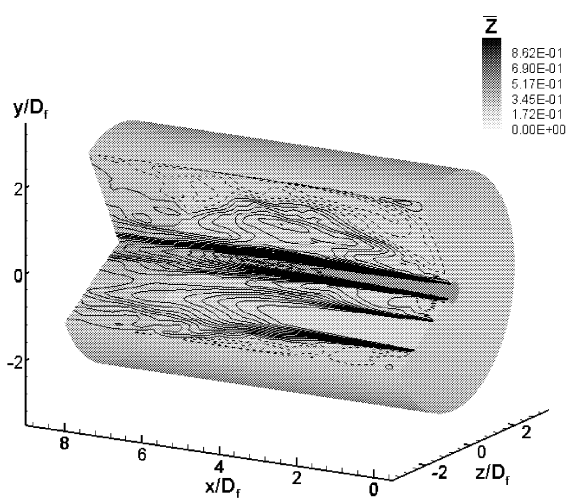

Figure 8: Contours of steamwise velocity and mixture fraction in case B

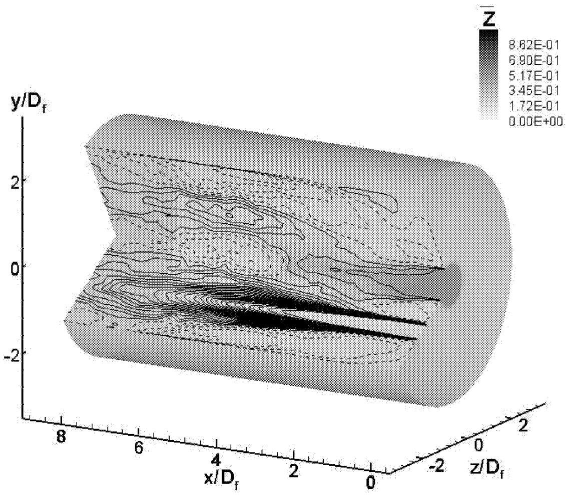

Figure 9: Contours of steamwise velocity and mixture fraction in case C

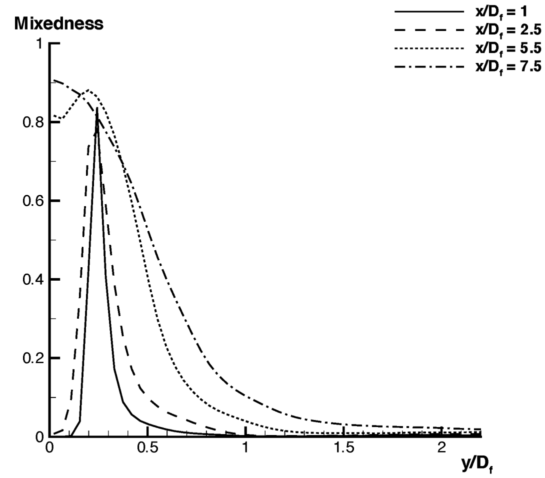

Figure 11: Radial distributions of mixedness parameter at four streamwise positions in case B

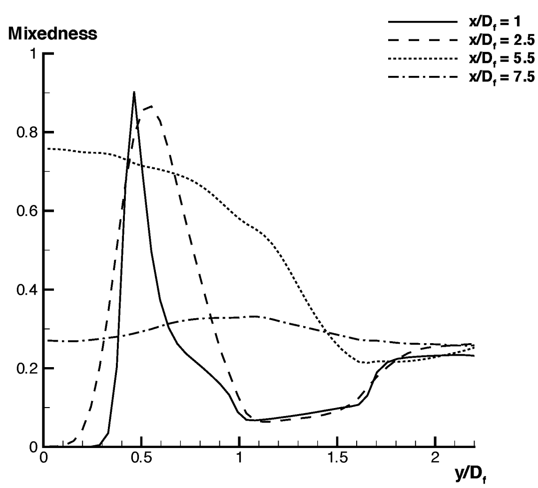

Figure 10: Radial distributions of mixedness parameter at four streamwise positions in case A

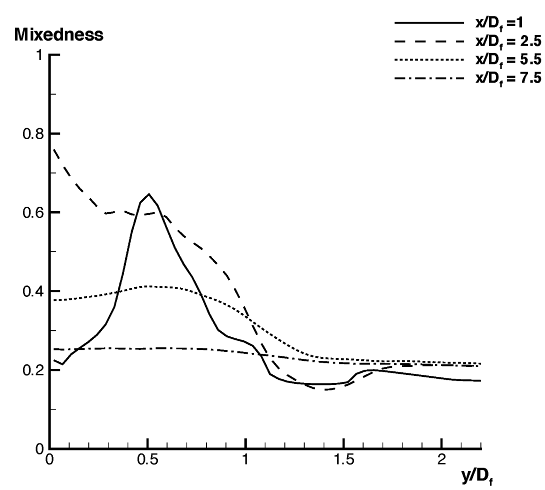

Figure 12: Radial distributions of mixedness parameter at four streamwise positions in case C