DIRECT NUMERICAL SIMULATION OF DYNAMIC ROTATING JETS

Koichi Tsujimoto[1], Sanmuga Arumugam[1], Toshihiko Shakouchi[1] & Toshitake Ando[1]
[1]*Division of Mechanical Engineering Graduate School of Engineering, Mie University, Tsu, Japan*

Abstract Jets are the most basic flow used in industrial field and are widely used for heating, cooling, mixing. Recently, the improvement of mixing efficiency is required in order to downsize many industrial equipments and upgrade their performance. In the case of jets, their characteristic, such as the diffusion, depends on the inlet condition. Therefore, by controlling jet to give appropriate inlet conditions, the mixing efficiency can be improved. Thus far previous studies have mainly investigated excitation control associated with the instability of jets. However, in our previous study, as a new method we proposed dynamic control to enhance mixing or diffusion of free jets and have found its characteristics[1]. In this study, we focus on the vector control in which an inflow is rotating around the streamwise direction. In order to investigate the performance of the proposed method, the DNS of axisymmetric jet under the vector control are conducted and its structures are visualized; the mixing efficiency based on a mixing measure are quantified.

NUMERICAL PROCEDURE

The flow is assumed to be incompressible. Thus, the governing equations are the continuity, momentum and energy equations. The Cartesian coordinate system is employed. Computational conditions such as the size of the computational domain, grid number, and Reynolds number are $(H_x, H_y, H_z) = (20D, 30D, 20D)$, where D is the nozzle diameter, $(L_x, L_y, L_z) = (128, 150, 128)$, Reynolds number $Re = 1500$ and Prandtl number $Pr = 0.707$, respectively. The spatial discretization[2] involves a sine or cosine series expansion in the x and z directions and sixth-order compact scheme [3] in the streamwise direction. A top-hat profile of both velocity and temperature is imposed as an inflow boundary condition. Figure 1 is schematic drawing of the flow field. The inlet velocity distribution is assumed to be top-hat type. In the present calculation, as shown in Fig.2, the inflow of single or multiple jet rotates around y axis.

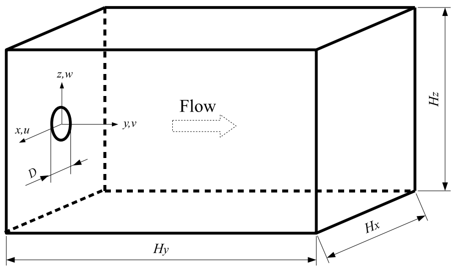


Figure 1. Coordinate system and computational domain

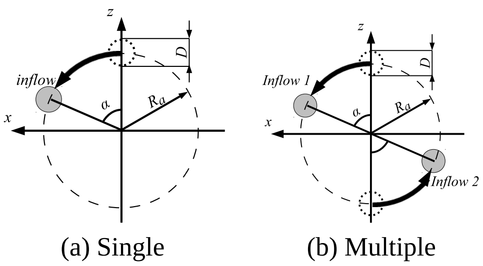


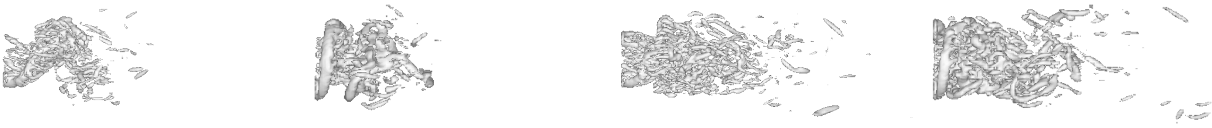
Figure 2. Schematic of rotating control

RESULTS

In order to examine the instantaneous vortical structures, isosurfaces of the second invariance of velocity gradient tensor Q (=0.05) are visualized in Fig.3. For the single and multiple jet, when the rotating frequency varies, the flow pattern largely changes. From Fig. 3(a), the upstream vortical structures of the single jet helically distribute around the rotating axis and then break down downstream, further downstream the vortical structure is invisible. As increasing the control frequency, from Fig. 3(b) the streamwise pitch of helical structure is shorter than the low frequency case. and the the structure is entangled. For the multiple jet (Fig. 3 (c) and 3(d)), double helical structures are formed (although not confirmed from figure) and then break down downstream as well as the single jet,
The streamwsie distribution of the entrainment rate normalized with the volumetric flow rate of inflow, Q_0 is shown in Fig. 4.

$$E = \frac{dQ}{dy} = \frac{d}{dy}\int\int V dxdz \tag{1}$$

For the uncontrolled case, the entrainment rate of downstream jet is nearly the same with the experimental results. On the other hand , for the controlled cases the higher entrainment rate than the uncontrolled case is attained upstream region, while the entrainment rate of downstream jet gradually decrease. In particular, it should be noted that the mixing performance of single jet is superior to that of multiple jet.



(a) St = 0.02 (Single)
(b) St = 0.06 (Single)
(c) St = 0.02 (Multiple)
(d) St = 0.06 (Multiple)

Figure 3. Instantaneous vortex structures ($Q = 0.05$)

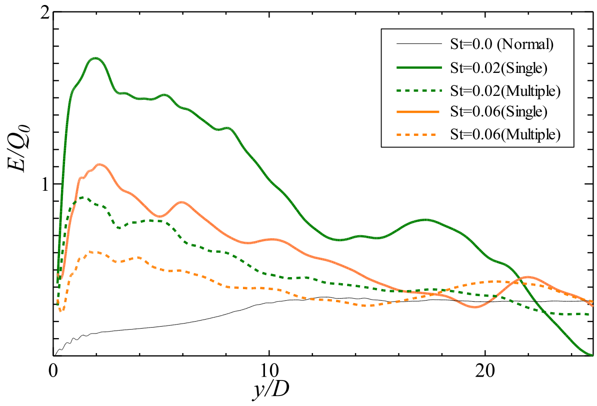


Figure 4. Streamwise distribution of entrained rate

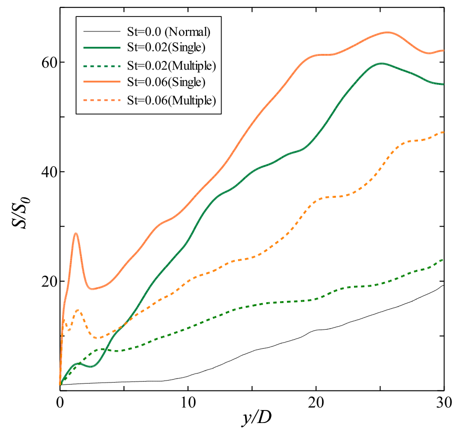


Figure 5. Streamwise mean entropy distribution

As an another mixing measure, Everson *et al.*[4] investigated the statistical entropy based on the passive scalar concentration, and they demonstrated the characteristics of this measure by examining the experimental data. As well as we validate this mixing measure based on the DNS data of active controlled jet[5].
The statistical entropy,S is defined as follows:

$$S = k\Delta V \left[\Phi \ln \Phi - \sum_{i=1}^{M} \phi_i \ln \phi_i \right]$$

In order to investigate the streamwise variation of the statistical entropy,S is summed over the plane perpendicular to the streamwise direction, and S normalized with the inflow quantity,S_0 is shown in Fig. 5. In all cases, the rotating control enhances the mixing compared with the uncontrolled free jet. Also as well as the entrainment characteristics, the mixed state of single jet is larger than that of multiple jets.

CONCLUSION

In order to improve the mixing performance of free jet, as the useful method, the dynamic rotating control is proposed. As the control parameter, the rotating frequency varies, and the flow and scalar field are investigated. From the instantaneous view of flow field, according to the increasing of rotating frequency, flow structures are largely changed. Namely it suggests that the changing rotating frequency is capable of controlling easier the flow state. From the mixing measures using the statistical entropy, it is found that the mixing performance is fairly improved compared to the uncontrolled jet.

References

[1] K.Tsujimoto, K., Ao, T.Shakouchi and T.Ando, Numerical Investigation on Flow Structures and Mixing Performances of Vector-Controlled Free Jet using DNS, *Journal of Fluid Science and Technology*, **6**-4: .401-411, 2011.
[2] K. Tsujimoto, N. Shibata, T. Shakouchi and T. Ando, Structural analysis of dynamic-controlled jet using DNS, *Journal of Fluid Science and Technology*, **.9**-3: 1-12, 2014.
[3] S. K. Lele, Compact finite difference schemes with spectral-like resolution, *Journal of Computational Physics.* **103**: 16-42, 1992.
[4] R. Everson, D. Manin, and L. Sirovich, Quantification of Mixing and Mixing Rate from Experimental Observations, *AIAA J.* **36** : 121-127, 1998.
[5] K. Tsujimoto, S. Kariya, T. Shakouchi and T. Ando, Evaluation of jet mixing rate based on DNS data of excitation jets, *Int. Journal of Flow Control*, **1**-3: 213-225, 2009.