Direct Numerical Simulation of Jet Mixing Control Using Combined Jets

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In order to develop an efficient jet mixing method, direct numerical simulations of combined jets are carried out. The Reynolds number defined with a nozzle diameter is \( Re = 1500 \). Spatial discretization is performed by adopting a hybrid scheme of a sixth order compact scheme in the streamwise direction and Fourier series in the cross section. The distance between two jets is fixed at six times the jet diameter, and the inclination angle of the jets is changed from 45 to 70 deg. The results reveal that the turbulence intensity increases with a decrease in the inclination angle and that the jet width increases via jet excitation. These findings suggest that the diverse requirements of jet mixing control can be satisfied by a flexible combination of jets.

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1. Introduction

Many industrial applications require an improved mixing efficiency. Since new industrial applications, such as micro-gas turbines respond to load change according to the operating conditions, jet mixing should be flexibly controlled in a combustion system. However, the conventional method does not easily respond to the load change. In this paper, we propose a combined jet, which is an assembly of many jets, as an attractive method for meeting the demands for various control strategies. On the other hand, DNS (direct numerical simulation) is capable of providing detailed information to improve the performance of jet mixing. In particular, with regard to the control of a vortical structure, it is advantageous to develop the method using DNS(1)–(3) and LES (large eddy simulation)(1). Therefore, we also perform DNS to develop an efficient method of jet mixing. The impingement of two inclined jets is mainly examined as a combined jet, and the inclination angle and excitation of jets are selected as the control parameters.

2. Numerical Methods

2.1 Code and flow parameters

The flow is assumed to be incompressible and isothermal. Thus, the governing equations are the continuity and momentum equations:

\[
\nabla \cdot \mathbf{u} = 0
\]

\[
\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \times \mathbf{u} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{u}
\]

where \( \mathbf{u} \), \( \mathbf{\omega} \), \( \rho \), and \( \nu \) denote velocity, vorticity vector, density, and kinematic viscosity of fluid, respectively. The nonlinear terms are written in the rotational form \( \mathbf{\omega} \times \mathbf{u} \) to conserve the total energy; thus, \( p \) represents the total pressure. The configuration of the flow field is illustrated in Fig. 1. The Cartesian coordinate system is em-
ployed. Computational conditions such as the size of the computational domain, grid number, and Reynolds number are $(H_x, H_y, H_z) = (14D, 12D, 14D)$, where $D$ is the nozzle diameter, $(L_x, L_y, L_z) = (256, 200, 256)$, and $Re = 1500$, respectively. Since the grid spacing is equal in each direction, the resolutions are $\Delta H_x = \Delta H_z = 0.05D$ and $\Delta H_y = 0.06D$. In previous DNS(4), in which the Reynolds number is 2400. The Kolmogorov length scale, $\eta$ in a fully developed region ($y = 20D$) is estimated based on the experimental data as $\eta = 0.08D$. Therefore the grid spacing of the present simulations are nearly equal to the Kolmogorov length scale; thus our present simulation will be sufficiently resolved. The spatial discretization involves a Fourier series expansion in the $x$ and $z$ directions and sixth-order compact scheme(5) in the streamwise direction. A top-hat velocity profile with coflow $V_2$ is imposed as an inflow boundary condition. In order to investigate the effect of the inclination angle ($\alpha$) and excitation ($S_t$; Strouhal number), two or three cases for each parameter are examined. These conditions are listed in Table 1. After the quasi-steady state is attained, statistical properties such as the mean velocity and turbulent intensity are ensemble-averaged at each grid point during 140 time scales $D/V_1$.

### Table 1 Calculation condition

<table>
<thead>
<tr>
<th>Case</th>
<th>$\alpha$(deg)</th>
<th>Strouhal number</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>90</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
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</tr>
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<tr>
<td>3</td>
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<td>0</td>
</tr>
<tr>
<td>4</td>
<td>45</td>
<td>0.4</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>0.4</td>
</tr>
</tbody>
</table>

#### 2.2 Numerical accuracy

In order to verify the present simulation code, the DNS of a natural round jet is performed. Random perturbation, whose strength is 1% of the mean flow velocity, is superposed on the inlet velocity as the inflow condition. The grid number and computational volume differ from those of a combined jet; however, the resolution is the same for all the cases. Although the experimental data of a jet with a low Reynolds number has not been verified sufficiently, we compare our result with experimental data(6) ($Re = 2566$) to the best extent possible. Figure 2 (a) and (b) shows the radial distribution of the streamwise velocity and turbulence intensity near the downstream end of the computational volume, respectively. In contrast to the turbulence intensity, the mean streamwise velocity is in good agreement with the experimental data. In the literature(6),(7), it is revealed that the profile of the turbulence intensity differs slightly between laboratory experiments, which is not shown here. We also confirm that the present data are within the range of the scatter of the experimental data. One of the primary advantages of DNS is the capability to visualize the vortical structures. This will enable us to validate the simulation from a different view point. In Fig. 3, the isosurfaces of a Q value defined with the second invariance of the velocity gradient tensor are shown. A positive Q value is shown to identify the core of coherent vortical structures(8). Large-scale vortical structures such as vortex rings are strengthened from the inlet to the center of the computational volume (potential core length: approximately $x/D = 6$). Further a helical-like structure emerges, and the breakdown of these structures produces a large number of fine-scale vortices. These features are qualitatively consistent with those of a previous DNS(1),(2), suggesting that the resolution of our present simulation is also qualitatively sufficient.

#### 3. Results and Discussion

##### 3.1 Parallel combined jets

As the simplest case of a combined jet, the characteristic of parallel jets are examined by changing the distance between the jet axes denoted by, ‘$S$’. The distances are set as $S/D = 1.1$ and 2.0 in order that two jets interact with each other as much as possible. The visualized
coherent structures are shown in Fig. 4. In Fig. 4 (b), each jet behaves like a single jet within a certain distance from the inlet, and after the breakdown of the large-scale vortical structure, the fine-scale vortices merge near the end of the computational volume. On the other hand, even in the case of a short distance (Fig. 4 (a)), the interaction between the two jets is weak. It is observed that a part of the large-scale vortical structure is deformed by a high-speed flow between the two jets, while the other part apparently retains the features of a single jet. Although the two jets couples with each other further downstream, a drastic structural change in our computational volume is not expected. Therefore we discontinue our investigation of the parallel jet.

3.2 Flow pattern of the impinging case

Three cases are examined to investigate the effects of the impingement on jet mixing. The distance $S$ is fixed as $S/D = 6$ for all the simulations of the impinging case shown in Fig. 1. The inclination angle is decided based on the physical characteristics of the round jet as follows: i) When the inclination angle is less than $\alpha = 45$ deg, the effect of crossflow is predominant in the mainstream. Thus, the $\alpha = 45$ deg is set as the lower limit of the inclination angle to eliminate inefficient momentum transfer. ii) For $\alpha = 60$ deg, the distance between the inlet and the impinge-
ment. In addition, (not shown here) an animation of the vortical structures reveals that the impingement position is relatively stable and confirms that the fundamental flow patterns of the three cases are qualitatively similar.

3.3 Effects of inclination angle

We are particularly interested in developing a jet mixing control that can respond flexibly to load change. For this purpose, we assume that the mixing control can be achieved easily by changing the inclination angle. In Fig. 5, the left column shows that the jet width on the $x-z$ plane depends on the inclination angle. This can be explained by the model described in Fig. 6. In Fig. 6 (a), the vortex lines of each jet curve in the clockwise direction and incline towards the $y$-axis; consequently a $\omega_y$ component generated. Therefore, the intensity of the $\omega_y$ component governed by the direction of the vortex line becomes symmetric with respect to the $y$-axis, as shown in Fig. 6 (b). According to the distribution of $\omega_y$, outflows along the $x$-axis are formed and consequently, the jet spreads in the $x-y$ plane. Since the $\omega_y$ component increase with a decrease in the inclination angle, the jet width in the $x-y$ plane is controlled easily by changing the inclination angle. On the other hand, the effect of the inclination angle on the $y-z$ plane is complex; in particular, the jet width increases considerably in case 1. This result will be discussed later.

Figure 7 shows the instantaneous vortical structures that are extracted using the Q value. The image of the entire vortex structure is generally in good agreement with the contour of the mean streamwise velocity shown in Fig. 5. Since an angle larger than 60 deg allows the flow structures to develop before the impingement, large-scale vortical structures such as vortex rings that break down to produce a large number of fine-scale vortices are formed. On the contrary, despite the absence of a large-scale vortical structure before the impingements, the increase in the number of fine-scale vortices in case 1 is more significant than that in the other cases. Thus, these findings suggest that the impingement causes an abrupt generation of fine-scale vortices with or without a large-scale vortical structure in the upstream region.

We focus on the improvement, in the efficiency of jet mixing under the present control; however, we do not have a complete estimate of the mixing efficiency. In particular, if the transport equation of the passive scaler is solved, we can directly evaluate the mixing efficiency. However,
for this purpose, we did not make previous arrangements. Here, assuming that the turbulent kinetic energy represents the mixing efficiency, the integrated turbulent kinetic energy defined by Eq. (3), is used to evaluate the global modification under the present control scheme.

\[
S_z \equiv \int_{L_z/2}^{+L_z/2} \int_{-L_x/2}^{+L_x/2} \frac{1}{2} (u'^2 + v'^2 + w'^2) \, dx \, dz
\]  

(3)

As shown in Fig. 8, the intensity in each case is greater than twice that of a single jet, and it increases with a decrease in the inclination angle. In particular, case 1 (\( \alpha = 45 \) deg) exhibits a significantly enhanced turbulent kinetic energy. In order to investigate the reason for the enhancement based on the vortical structures, strong coherent vortices are visualized in Fig. 9. In this figure, unlike the above mentioned results, a large threshold value of Q is used and the view is switched to the \( x-y \) plane. In Fig. 9 (c), the fine-scale vortices are observed only downstream, while the large-scale structures are invisible in the entire flow field. However, the large-scale vortex rings are formed with a decrease in the inclination angle, as shown in Fig. 9 (a) and (b). The occurrence of the large-scale structures apparently contributes to the mixing enhancement depending on the inclination angle. Since their axis of rotation is parallel to the \( x-y \) plane, the extremely jet expansion observed in Fig. 5 (a) is attributed to the flow normal to the \( y-z \) plane due to the strong large-scale structures.

![Fig. 8 Streamwise distribution of integrated turbulent kinetic energy](image)

![Fig. 9 Visualized \( x-y \) plane view of instantaneous strong vortical structures (\( Q = 2.0 \))](image)

(a) Case 1 (\( \alpha = 45 \) deg)  
(b) Case 2 (\( \alpha = 60 \) deg)  
(c) Case 3 (\( \alpha = 70 \) deg)
3.4 Effects of excitation

Thus far, various types of control schemes for the improvement of jet mixing have been examined in laboratory experiments. As a major example, acoustic excitation via a loudspeaker is the most commonly used method for the controlling the jet mixing\(^9\). It leads to the enhancement of the axisymmetric mode, this mode is considered to be the most unstable mode before the end of the potential core of a round jet and whose enhancement produces stronger vortical structures. In particular, we are interested in determining whether such an excitation will work satisfactorily in the combined jet. A numerical experiment\(^{(1),(2)}\), revealed that such an acoustic excitation can be simulated through periodic disturbances of a single frequency corresponding to the most unstable mode. In the present simulation, periodic disturbances are superimposed on the inlet velocity. Their amplitude is set to 5% of the inlet velocity, and a forcing frequency corresponding to the Strouhal number, \(St = 0.4\) estimated from an instability mode of the round jet is selected\(^9\). In order to demonstrate the modulation of the mean flow features under the excitation, the contours of the streamwise velocity are shown in Fig. 10. As shown in Fig. 11, although strong vortical structures are formed upstream through the numerical excitation, the global flow pattern is similar to that of the case without the excitation. In case 4, it should be noted that the jet width in the \(y\)–\(z\) plane reduces further as compared to that in the case 1 (\(\alpha = 45\) deg). Figure 12 shows the distribution of the integrated turbulence intensity. Since the flow of the excited cases evolves earlier than that of the nonexcited cases, the turbulence is enhanced upstream before the impingement. However, their peak values are suppressed because the breakdown is promoted by the excitation. The strong coherent vortices are visualized in Fig. 13. In contrast to Fig. 9, Fig. 13 shows that the existence of the large-scale mode is obscure, and the strong large-scale vortical structure observed in Fig. 9 (a) and (b) is not clearly observed.
From this fact, the above mentioned result of the reduction in the jet width in the $y-z$ plane can probably be attributed to the suppression of large-scale motion through the excitation. Furthermore, although the excitation enhances the instability in the upstream region, the downstream instability mode is not always excited, suggesting that the selected frequency should correspond to the preferred downstream mode. However, we do not examine whether upstream excitation affects the downstream instability. We intend to investigate the effect due to another excitation frequency.

4. Conclusion

In the present paper, we have performed the DNS of combined jets to control jet mixing. The major conclusions are summarized as follows:

1. In the case of parallel jets, it is found that the interaction between the two jets is too weak to change the flow structure drastically, even when they are separated by a short distance.

2. The combined jet, which is an assembly of two inclined jets, is capable of controlling the mixing by chang-
ing the inclination angle; it can also change the jet width by the excitation of each jet.

3. From the visualization of 3D vortical structures, it is found that the mixing enhancement is attributed to the large-scale structure being formed after the impingement of the two jets. Moreover, significantly enhanced mixing occurs in the case with a smaller angle when the large-scale instability mode is enhanced downstream of the impingement.

References


