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Periodic vortex shedding phenomenon for various separation distances between two plane turbulent parallel jets

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ABSTRACT

In the present study, two plane parallel jets with various separation distances between the two jets (d) are numerically simulated using two-dimensional unsteady RANS equations. The Reynolds number based on the jet width w is Re = 10,000. The results reveal that when the separation distance between the two jets lies in the range $0.6 \leqslant d/w \leqslant 1.4$, the flow field demonstrates a periodic vortex shedding phenomenon close to the nozzle plate similar to what would be expected in the near wake region for flow over a two-dimensional bluff body. On the contrary, for $d/w = 0.5$ and 1.5, the near flow field region remains to be steady with two counter rotating stable vortices in the recirculation zone. Within the range $0.6 \leqslant d/w \leqslant 1.4$, the time series of streamwise and transverse velocity signals display a pure sinusoidal oscillation. In this range, for a given d/w, the fast Fourier transform of both the velocity signals exhibits a single dominant frequency peak at a same value of Strouhal number (non-dimensional vortex shedding frequency) that gradually decreases with the progressive increase in the separation distance between the two jets.

1. Introduction

The flow configuration of two parallel jets is encountered in numerous engineering applications including burners, boilers, gas turbine combustors, fuel injection systems and V/STOL aircrafts. In addition to the applications mentioned above, the study of two parallel jets plays an important role in the design of exhaust stacks. An optimum distance between the two exhaust stacks is required to disperse plumes at a specified level and consequently dilute the impact of exhaust pollutant.

Fig. 1 shows a schematic diagram for the flow pattern of two plane parallel jets. According to Fig. 1, two plane turbulent jets with same inlet velocity u_0 and width w are issued into a quiescent ambient from the two nozzles separated by a distance d. The origin of the coordinate system is located at the intersection point of the nozzle exit plane (y-axis) and the plane of symmetry (x-axis) bisecting the intermediate distance between the two jets. Due to the mutual entrainment of surrounding fluids by the two jets, a low pressure zone is created close to the nozzle plate. This low pressure zone causes the two jets to deflect to each other and eventually to merge together at the merging point (mp). As a result, a flow recirculation zone is formed between the two jets. The flow region between the merging point and the nozzle exit plane is known as the converging region. Downstream of the merging point, in the merging region, the two jets begin to interact with each other and the interaction continues up to the combined point (cp). At the combined point, the two jets combine together to form an equivalent single jet. Downstream of the combined point, in the combined region, the flow resembles a single free jet. Owing to the interaction of two jets, four shear layers are formed in the flow domain: two outer and two inner shear layers.

Miller and Comings [13] have conducted the first experiment on two plane parallel jets. A comparison is made between the two plane parallel jets and a single free jet in both converging and combined regions of the flow. In the converging region, the flow structure in the core of each jet is almost similar to that of a single free jet. The flow structure of the combined jet resembles all the characteristics of a single free jet except the self-preservation of turbulence characteristics. This could be attributed to the difference in upstream condition. Tanaka [21,22] has reported the effects of separation distance between the two plane parallel jets on the mean flow and turbulence characteristics in the interference region (converging and merging regions) (Tanaka [21]) and the combined region (Tanaka [22]). Except in the initial region of two jets (near the nozzle plate and the junction of two jets), the momentum flux of each jet is conserved in the flow direction. For the combined jet, the jet's spread is found to be linear and

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Nomenclature

$C_{1\epsilon}$, $C_{2\epsilon}$	constants in the model equation for ϵ
C_μ	turbulent viscosity constant of the $k-\epsilon$ model
d	separation distance between two parallel jets (dimensional)
f	frequency (dimensional)
G	production of turbulent kinetic energy (non-dimensional)
I	inlet turbulence intensity
k	turbulent kinetic energy (dimensional)
N	number of grids
P	non-dimensional pressure
p	dimensional pressure
Re	Reynolds number $(u_0 w/\nu)$
St	Strouhal number $(f w/u_0)$
T	time period (non-dimensional)
t	time (dimensional)
U_i	non-dimensional Cartesian mean velocity components (U, V)
u_i	dimensional Cartesian mean velocity components $(u,\ v)$
u_τ	friction velocity (dimensional)
w	width of the nozzle (dimensional)
X_i	non-dimensional Cartesian coordinates $(X,\ Y)$
x_i	dimensional Cartesian coordinates $(x,\ y)$

Greek symbols

$\Delta\tau$	time-step size (non-dimensional)
ϵ	rate of dissipation of turbulent kinetic energy (dimensional)
ν	laminar kinematic viscosity (dimensional)
ρ	fluid density (dimensional)
σ_k, σ_ϵ	turbulent Prandtl number for kinetic energy and dissipation, respectively
τ	time (non-dimensional)
ω	vorticity (non-dimensional)

Subscripts

0	ambient, inlet
+0.5	jet half width in the outer shear layer
−0.5	jet half width in the inner shear layer
cp	combined point
i, *j*	indices
max	maximum quantity
mp	merged point
n	non-dimensional quantity
sym	plane of symmetry
t	turbulent
x	*x*-direction
y	*y*-direction

Overbar

$\overline{(\ )}$	time averaged quantity

increases with the increase in the separation distance between the two jets. The frequency and time domain analyses of two plane parallel jets have been performed by Ko and Lau [8]. They have pointed out that the spectral peaks in the inner shear layer are more pronounced than those in the outer shear layer. They have attributed this lack of sharpness of the peaks in the outer shear layer to be due to the flow being in the jet column mode. Elbanna et al.[6] have compared the mean flow characteristics in the combined region of two plane parallel jets with those of a single free jet. The maximum mean streamwise velocity for the parallel jets decays at the same rate with the single free jet, but its value is higher for the former case. The combined jet spreads linearly similar to the single free jet, but the spread angle is slightly lower for the combined jet. Although the self-similarity has been achieved for the mean flow, it has not been found for the turbulence quantities up to $x/w = 120$ downstream from the nozzle exit. According to the results of Lin and Sheu [11, 12] for two plane parallel jets, the mean velocity achieves self-similarity both in the merging and combined regions, while the turbulent intensity and the Reynolds shear stress approach self-similarity only in the combined region. Additionally, the distance of the merging point from the nozzle exit increases linearly with the separation distance between the two jets. In an experimental study, Nasr and Lai [17] have provided a comparison between the two plane parallel jets and a plane offset jet (where the plane of symmetry is replaced by a bottom wall). The recirculation zone for the parallel jets is found to be significantly smaller than that for the offset jet. The turbulence in the recirculation zone is considerably stronger for the parallel jets. In an another study, Lai and Nasr [9] have compared their previous experimental data with the CFD predictions using three different turbulence models (i.e. standard $k-\epsilon$, RNG $k-\epsilon$ and Reynolds stress models). The existence of recirculation zone, merging region and combined region for the two plane parallel jets has been predicted qualitatively by all the three models. However, the quantitative agreement between the predictions and the measurements has been varied as much as 18% for the merging length and 50% for the turbulence quantities. To predict the merging length, both the standard $k-\epsilon$ and Reynolds stress models perform better that the RNG model. According to their suggestion, the standard $k-\epsilon$ model is no worse than both the RNG and the Reynolds stress models to predict the complex shear flows, contrary to popular belief. A comparison of the experimental and numerical results for the two plane parallel jets has also been made by Anderson and Spall [2]. The values of the merging and combined lengths computed using the standard $k-\epsilon$ model and differential Reynolds stress model (RSM) have been found to agree well with the experimentally measured values.

In an experimental study on two plane parallel jets, Anderson et al. [1] have varied the width of both the jets simultaneously, while the separation distance between the two jets is kept constant. They have observed a distinct flow instability when the ratio of jet width to the separation distance between the two jets is greater than 0.5 i.e. $w/d > 0.5$. This instability has been characterized by a periodic vortex shedding phenomenon similar to the flow behavior in the near wake region for flow over a two-dimensional bluff body. Here, the nozzle plate separating the two jets serves as a bluff body. Within the range $0.6 \leqslant w/d \leqslant 2$, the Strouhal number corresponding to the vortex shedding frequency increases as the ratio of w/d is decreased. They have attributed this fact to the confining effect of the outer shear layers of two jets. As w/d decreases, the outer shear layers are brought more close to the vortex formation region, resulting in an increase of the vortex shedding frequency. For the larger values of w/d, the influence of the outer shear layers is diminished and the Strouhal number approaches to a constant unconfined value. Fujisawa et al. [7] have examined the interaction of two plane parallel jets with different inlet velocity ratios. They have observed that the combined jet develops on the higher velocity jet side and the width of the combined jet reduces as the velocity ratio decreases. The interaction between the two jets weakens with decreasing the velocity ratio. The results