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Effect of bottom wall proximity on the unsteady flow structures of a combined turbulent wall jet and offset jet flow

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ABSTRACT

The present paper deals with a turbulent dual jet consisting of a wall jet and an offset jet. The flow field has been numerically simulated using two-dimensional unsteady RANS equations. The Reynolds number based on the separation distance between the two jets (s) is $Re = 10,000$. The width of the offset jet nozzle equals the separation distance between the two jets. To examine the influence of the bottom wall, the width of the wall jet nozzle (h) has been varied in a range $0.2 \leq h/s \leq 2$. According to the computational results, for $h/s = 0.2$, the flow field remains to be always steady with two counter-rotating stable vortices in between the two jets. On the contrary, within the range of $0.3 \leq h/s \leq 1$, the near flow field demonstrates a periodic vortex shedding phenomenon similar to what would be observed in the near wake region for flow over a two-dimensional bluff body. Within this flow regime, the Strouhal number based on the vortex shedding frequency gradually decreases with the progressive increase in h/s. However, for $h/s > 1$, although the periodic vortex shedding phenomenon is still evident in the flow field, the Strouhal number becomes insensitive to the bottom wall similar to the flow behaviour for a flow over an unconfined cylinder.

1. Introduction

When a bluff body is placed in close proximity of a solid surface, the near wake flow structures and dynamics, most notably the vortex shedding phenomenon, depend on the gap height between the wall and the solid body. Such flow problems are encountered in many practical situations, for example, pipelines near a sea or river bed, wires near walls or chinneys near tall buildings and tubes placed near heat-exchanger walls.

Several studies have been conducted on the area pertinent to the turbulent flow over a bluff body placed close to a solid surface. Most of the studies in this area fall under the category of experimental measurement. Bearman and Zdravkovich [1] have investigated the flow around a stationary circular cylinder near a solid wall and observed a periodic vortex shedding phenomenon for the ratio of gap height between the wall and cylinder to the cylinder diameter $g/d \geq 0.3$. The critical gap height below which the shedding phenomenon is suppressed is found at $(g/d)_{crit} = 0.4$ in [2]. In both the studies, the Strouhal number ($St_d = fd/u_\infty$), a measure of vortex shedding frequency, becomes insensitive to g/d ($St_d \approx 0.2$), once the shedding takes place. In contrast to this fact, for $g/d < 5$, according to the experimental results of Angrilli et al. [3], the Strouhal number is found to increase with the decrease in gap height. A possible reason for this discrepancy is the lower range of Reynolds number used in the experiment. Choi and Lee [4] have found the critical gap height for a circular cylinder at $(g/d)_{crit} = 0.3$ which is smaller than that for an elliptical cylinder ($(g/d)_{crit} = 0.4$) having the vertical height same as the diameter of the circular cylinder. Price et al. [5] have divided the interaction between the cylinder wake and the wall boundary layer into four different flow regimes based on the values of g/d. For $g/d \leq 0.125$, the vortex shedding phenomenon is completely suppressed. In the range $0.25 \leq g/d \leq 0.375$, although a coupling between the inner shear layer shed from the bottom side of the cylinder and the separated wall boundary layer is possible, the flow characteristics are same as the previous regime (i.e. $g/d \leq 0.125$). Within the range $0.5 \leq g/d \leq 0.75$, the periodic vortex shedding begins to occur. For $g/d \geq 1$, no separation takes place in the wall boundary layer either upstream or downstream of the cylinder and the flow behaviour is essentially same as that of an isolated cylinder. Instead of four flow regimes in Price et al. [5], Wang and Tan [6] have found only three distinct flow regimes as a function of g/d. In the suppressed regime ($g/d \leq 0.2$), no vortex shedding phenomenon

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Nomenclature

Roman Symbols

$C_{1\epsilon}$, $C_{2\epsilon}$	constants in the model equation for ϵ
C_μ	turbulent viscosity constant of the $k-\epsilon$ model
d	diameter of the circular cylinder (dimensional), height of the square cylinder (dimensional)
f	frequency of vortex shedding (dimensional)
G	production of turbulent kinetic energy (non-dimensional)
g	gap height between the wall and the cylinder (dimensional)
h	height of the wall jet nozzle (dimensional)
I	turbulence intensity
k	turbulent kinetic energy (dimensional)
N	number of grids
P	non-dimensional pressure
p	dimensional pressure
Re	Reynolds number based on the separation distance between two jets ($u_0 s/\nu$)
Re_d	Reynolds number based on the dimension of bluff body ($u_\infty d/\nu$)
St	Strouhal number based on the separation distance between two jets (fs/u_0)
St_d	Strouhal number based on the dimension of bluff body (fd/u_∞)
s	separation distance between the wall jet and the offset jet (dimensional),
T	time period (non-dimensional)
t	time (dimensional)
U_i	non-dimensional Cartesian mean velocity components (U, V)
$\tilde{U}_i$	non-dimensional Cartesian periodic velocity fluctuation components ($\tilde{U}$, $\tilde{V}$)
U'_i	non-dimensional Cartesian stochastic velocity fluctuation components (U', V')
u_i	dimensional Cartesian mean velocity components (u, v)
u_o	inlet velocity of the offset jet (dimensional)
u_w	inlet velocity of the wall jet (dimensional)
u_τ	friction velocity (dimensional)
w	height of the offset jet nozzle (dimensional)
X_i	non-dimensional Cartesian coordinates (X, Y)
x_i	dimensional Cartesian coordinates (x, y)

Greek Symbols

Δ	non-dimensional wall boundary layer thickness
$\Delta\tau$	time-step size (non-dimensional)
δ	dimensional wall boundary layer thickness
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
∞	freestream
0.5	half of maximum
cp	combined point
$crit$	critical
i, j	indices
m	maximum
mp	merged point
n	non-dimensional quantity
T	total
t	turbulent
x	x-direction
y	y-direction

Overbar

$\overline{(\,)}$	time-averaged quantity (averaged over 20 vortex shedding cycles)

occurs. In the near wall regime (i.e. $0.3 \leq g/d \leq 0.6$), the periodic vortex shedding occurs and the wall has a strong influence on the shedding frequency. In the far wall regime ($g/d \geq 0.8$), the Strouhal number becomes insensitive to the solid wall ($\text{St}_d = 0.19$) resembling a flow behaviour of an unconfined stand alone cylinder.

Similar to the circular cylinder, many studies have been carried out for flow over a square cylinder placed near a solid wall. Durão et al. [7] have observed an onset of vortex shedding activity when the ratio of gap height between the wall and cylinder to the height of the cylinder $g/d = 0.35$. For $g/d \geq 0.35$, the Strouhal number remains constant at $\text{St}_d = 0.133$. Bosch et al. [8] have identified a regular vortex shedding phenomenon for $g/d \geq 0.5$. The measured value of Strouhal number at $g/d = 0.75$ is found to be $\text{St}_d \approx 1.4$ which is close to the reported value of St $= 0.13$ in [9] for flow over a square cylinder in the absence of a bottom wall. In another study, Bosch and Rodi [10] have compared the predicted results using the standard $k-\epsilon$ model and the modification attributable to Kato and Launder [11] (abbreviated as Kato–Launder model) with their experimental counterparts. The Kato–Launder model is found to produce more reasonable predictions over the Standard $k-\epsilon$ model. Martinuzzi et al. [12] have detected four gap-dependent flow regimes in case of flow over a square cylinder close to the wall. As stated in [12], for $g/d < 0.3$, the periodic vortex shedding activity is completely suppressed. In the range $0.3 \leq g/d \leq 0.6$, the flow reattaches on the bottom surface of the cylinder intermittantly causing an irregular shedding of vortices. When g/d lies in the range $0.6 \leq g/d \leq 0.9$, the wall exerts a greater influence on the flow. For larger gap heights, $g/d > 0.9$, the vortex shedding activity is similar to an unbounded cylinder. As reported by Wang and Tan [13], the commencement of vortex shedding phenomenon takes place at the critical gap height $(g/d)_{crit} = 0.5$ and the Strouhal number remains to be constant at $\text{St}_d = 0.145$, once the vortex shedding occurs. A summary of above discussed experimental studies is given in Table 1.

The present study involves a wall jet [14–24] and an offset jet [25–35]. A wall jet is generated when a jet flows tangentially along the solid wall parallel to the axis of the nozzle. An offset jet refers to a jet whose axis at the nozzle exit is offset by a distance from the solid wall.

Fig. 1 shows a schematic diagram of a combined wall jet and an offset jet. Two plane turbulent jets (wall jet and offset jet) with identical jet inlet velocity (u_0) are issued into a quiescent ambient from the two nozzles separated by a nozzle plate with height s. The height of the wall jet nozzle is h and the height of the offset jet nozzle is w. The origin of the coordinate system is located at the intersection point of the jets exit plane (y-axis) and the bottom wall (x-axis). As the two jets individually discharges from a nozzle, they deflect to each other and eventually merge together at the merging point (mp). The flow region between the merging point and the jet