Effect of Velocity Ratio on Bluffbody Flow Dynamics

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Introduction

Axisymmetric bluffbodies are used to enhance mixing and stabilize combustion between two streams. They are frequently utilized in utility combustors[1] and propulsion systems[2] since they exhibit the desirable property of promoting mixing at the expense of small pressure loss. Nonreacting and reacting bluffbody flows have been a subject of extensive experimental investigation, include flows in liquids and gases, unconfined and confined flows, and large- and small-scale facilities[1-4]. Experimental observations indicate that nonreacting and reacting bluffbody flows are unsteady and, in most cases, can be characterized by large-scale, periodic oscillations.

Results and Discussion

The flowfield is governed by the continuity and Navier-Stokes equations and the solution is obtained using the vortex methods.[5-7] Simulations were performed for a thick bluffbody with diameter ratio of 10, and for six velocity ratios: $V_j = 0.3886$, 0.5, 0.667, 0.8124, 1.0, and 1.2857, all at Reynolds number of 7000. Here, we focus on the results of the first and third cases, which are typical of the steady and transitional regimes. The simulation starts with a potential flow throughout the domain and vortex sheets, introduced to cancel the slip velocity, along the solid walls. As time progresses, the vorticity diffuses normal to the walls in the form of vortex elements whose circulation is maintained constant. Eventually the flow becomes saturated with vorticity and the number of elements reaches a stationary state.

Figure 1 shows the streamline of the time-average flow for three velocity ratios: $V_j = 0.338$, 0.667, and 1.0. These results were obtained by averaging over a long sample of the unsteady velocity field. At low jet velocity, the jet is stagnated near the bluffbody by the flow recirculating from the annular stream. As the jet velocity increases, the jet penetrates further into the recirculation zone, forming a "transitional regime." At still higher jet velocities, the jet breaks through the recirculation zone and into the main stream, almost like a free jet. Results of the unsteady simulations, which are described next, show that the unsteady dynamics govern these changes.

$V_j = 0.3886$

Figure 2 shows the instantaneous location and velocity of all of the vortex-ring elements in the domain at a typical timestep. The structure of the shear layer which forms on the outer edge of the recirculation zone is illustrated by plotting the velocity vectors with respect to $V_a/2$, similar to the practice used in the visualization of free shear layers. The outer edge of the shear layer, as defined by the location of the vortices on the outer edge of the recirculation zone, is traced by a dark continuous line. The overall structure of the flow does not show appreciable change from one timestep to another. The figure shows that a steady recirculation zone forms downstream of the bluffbody. Its size, as determined from the location of the aft-stagnation point on the axis of the bluffbody, is slightly longer than $1.5D_a$. Within the recirculation zone and very close to the exit of the inner jet, a small attached toroidal eddy forms. On the outer edges of the recirculation zone, small eddies form near the bluffbody and propagate towards the aft-stagnation point. The weak oscillations associated with the passage of these eddies are depicted by the waviness of this line.

The spectrum of the radial velocity within the shear layer at $(r, z) = (0.45, 1.07)$ was obtained by Fourier-transforming the time-dependent velocity using a sample of 2000 timesteps. The dominant frequency was found to be $f = 0.077$. The Strouhal number, based on the dominant frequency f, the mean velocity $V_m = V_a/2 = 0.5$, and the momentum thickness of the boundary layer of the annular flow $\theta_0 = 0.24$, is $St = f\theta_0/V_m = 0.037$. This is close to the most unstable frequency in an axisymmetric shear layer at the same value of θ_0/R_a, $\beta\theta_0/V_m \sim 0.25$ where $\beta = 2\pi f$.[8] The close agreement indicates that the mechanism of oscillations is the growth of small perturbations along the shear layer.

The flow is weakly unsteady and the oscillations introduced by the shear-layer instability are weak. The inlet velocity distribution is steady and is a top-hat profile at all times. The perturbations amplified by the shear-layer instability are introduced via random numerical perturbations. The amplified frequency therefore is a property of the flow and is not imposed by the numerical construction. Small-scale unsteadiness has been observed in previous numerical simulations in which the inner jet velocity was set to zero or to small values. This supports our conclusion that the instability observed here is

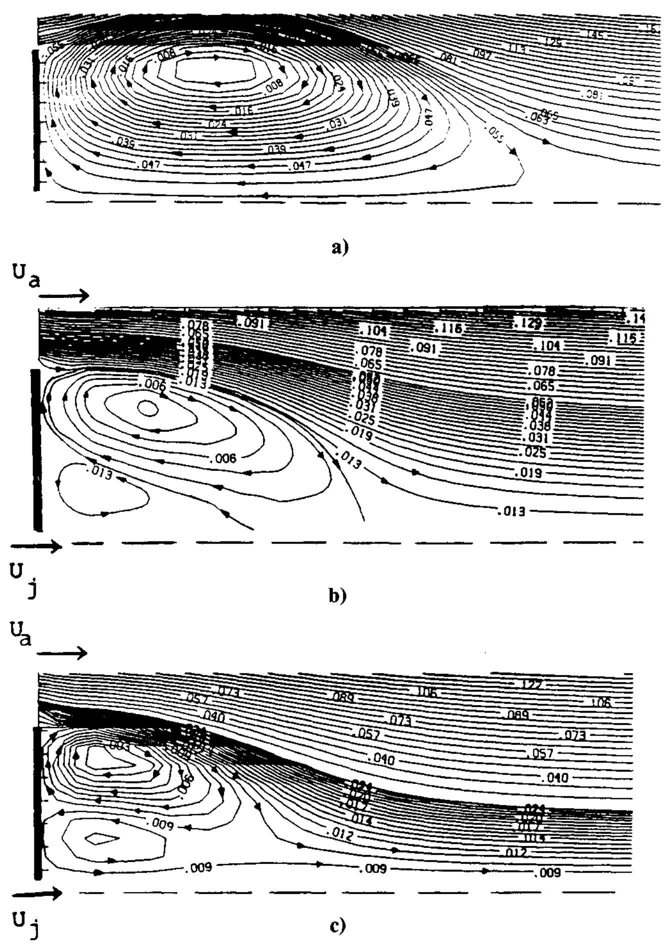

Fig. 1 Three regimes of a bluffbody flow: a) annular flow-dominated regime, $V_j = 0.338$; b) transitional flow regime, $V_j = 0.667$; and c) jet-flow dominated regime, $V_j = 1.0$.

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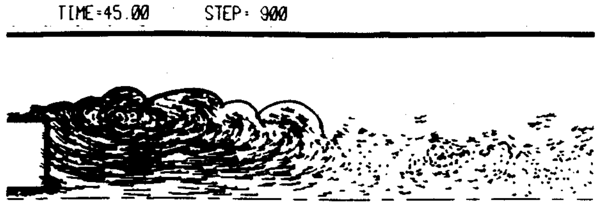

Fig. 2 Instantaneous flowfield shown in terms of the vortex-ring elements and their velocity vectors, plotted with respect to the mean velocity for $V_j = 0.3886$.

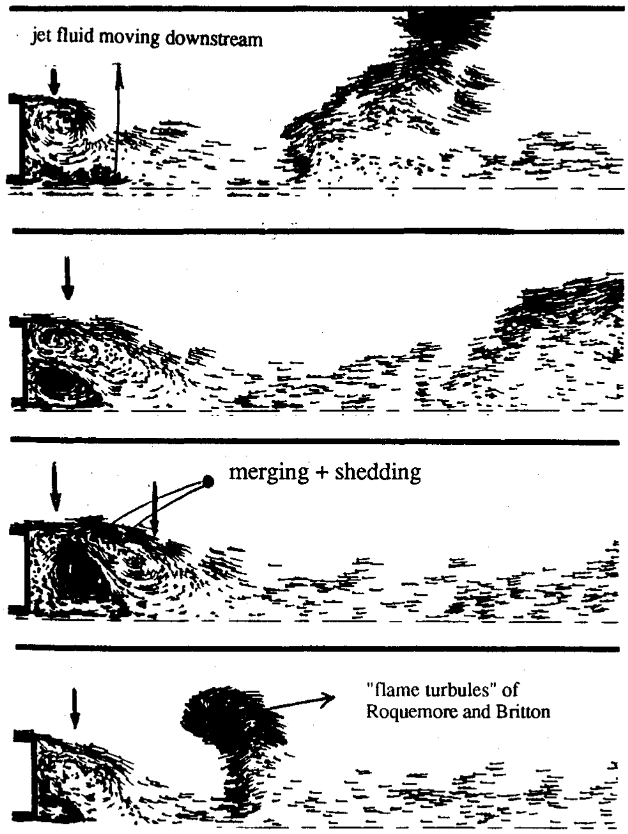

Fig. 3 Vortex-ring elements and their instantaneous velocity vectors at different timesteps during a typical cycle of formation of a composite eddy. Frames correspond to $t = 33.5$, 35.5, 37.5, and 39.5.

associated with the annular flow shear layer and that the inner jet plays a passive role in this flow.

$V_j = 0.667$

The shedding of large vortical structures in this case is shown in Fig. 3 where a typical cycle of formation of a composite structure is depicted. The cycle starts with the roll-up of the inner jet boundary layer on the inside diameter of the bluffbody, while a large composite structure which formed in previous cycles is moving downstream. Two stagnation points can be identified: a forward-stagnation point where the jet is stagnated by the recirculating outer flow, and an aft-stagnation point marking the end of the recirculation zone of the outer flow stream. As the eddy diameter grows beyond half of the size of the outside radius of the bluffbody, the annular-flow eddy is split into two: a forward eddy that moves downstream and a second, smaller eddy which stays attached to the bluffbody.

The growth of the outer eddy causes the separation of the inner jet eddy from the bluffbody. Following its separation, it merges with the inner jet eddy forming a composite eddy which is then shed from the bluffbody wake. The composite eddy then leaves the wake of the bluffbody and the cycle repeats itself. The composite eddy is responsible for the mixing between the two streams and in a reacting flow environment between a fuel jet and an airstream, it is expected that the composite eddy is where the chemical reaction occurs. The intermittent formation of this eddy leads to an intermittent combustion process. Experimental observation strongly confirms these observations, as it was found that combustion occurs only in "flame turbules"; eddy-like structures that are shed from the wake of the bluffbody.[2,4]

The unsteady characteristics of the flow are analyzed by Fourier-transforming the axial velocity at a series of points within the wake region along the centerline of the flow. Figure 4 shows the spectrum at a point $(r,z) = (0.0, 1.7)$. The peak frequencies are $St = fD_a/V_a = 0.23$ and 0.08. These are very close to the measured values[1] at the same point in the same flow. Vortex shedding from the outside diameter of the bluffbody was characterized by obtaining the velocity spectra at $(r,z) = (0.45, 1.27)$ and $(0.45, 1.87)$ where we found that the peaks occurred at $St = (0.247, 0.123, 0.062)$, and $(0.123, 0.062)$, respectively. The period of formation of a composite structure, as seen in Fig. 3, is $t = 8$, corresponding to $St = 0.125$. The origin of the frequency spectra can be explained as follows. Close to the bluffbody, the fluctuations are generated by the passage of individual eddies shed from both sides of the bluffbody at a frequency $f = 0.247$. Downstream, and as two eddies merge to form a composite eddy, the fluctuations are dominated by the subharmonic $f = 0.125$. Further downstream, a second subharmonic, corresponding to the pairing of two composite eddies, is observed.

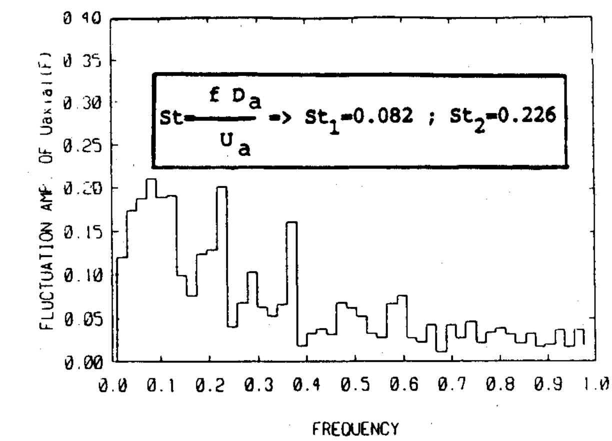

Fig. 4 Spectrum of the axial velocity along the centerline at $(r,z) = (0.0, 1.7)$ showing peaks at 0.082, 0.123, and 0.228.

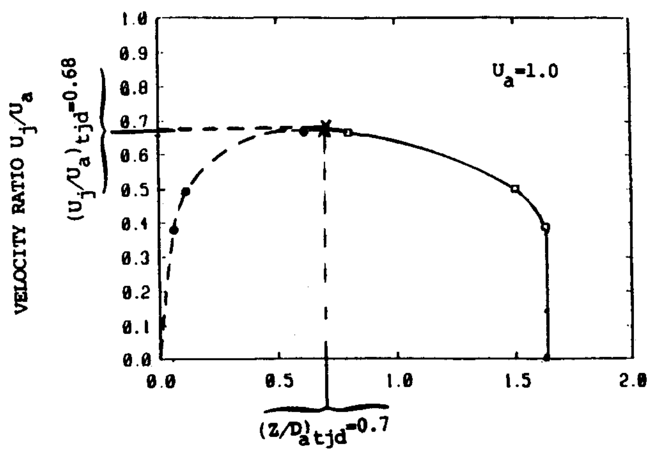

Fig. 5 Average location of the forward and aft stagnation points, shown as a broken and a solid line, respectively, as a function of the jet velocity.

The average streamline plot bears strong similarity to the measurements.[1] The measured locations of the forward and aft-stagnation points are 1.2 and $0.8D_a$. The difference between the experimental results and the numerical results is due to the small difference in the velocity ratio between the computed and experimental flows (as well as other secondary effects corresponding to the density difference between the two streams in the experiment). Quantitative comparisons between the computed and measured mean velocity profiles at different sections show good agreement, remarkably without resorting to any adjustable parameters.[6]

The effect of the velocity ratio on the flow structure is summarized in Fig. 5 where we show the locations of the forward and aft-stagnation points in terms of the velocity ratio up to $V_j = 0.667$. The two curves are extrapolated until they intersect at $V_j = 0.68$, at which the two stagnation points overlap and the structure of the recirculation zone changes. Beyond this critical velocity ratio, the stagnation point moves away from the axis and the inner jet penetrates through the recirculation zone.[5,7] This regime has been called the inner jet-dominated flow, in contrast to the annular flow-dominated regime at lower jet velocities, and the transition regime.

Figure 5 shows the difference between the two regimes discussed here, the annular flow-dominated regime and the transition regime. In the first regime, for $V_j < V_{\text{trans}}$, the forward-stagnation point moves forward and the aft-stagnation point moves backward very slowly with increasing jet velocity. The value of V_{trans} is difficult to determine precisely; the figure indicates that $V_{\text{trans}} > 0.5$. For higher jet velocity, both stagnation points move towards each other very rapidly as the jet velocity increases, the flow is highly unsteady in the wake region and is very sensitive to the jet velocity. Since this unsteadiness is not due to an unsteady boundary condition, it is generated by an instability that amplifies small perturbations randomly introduced in the flow. Contrary to the annular flow regime where the jet is stagnated close to the bluff-body, the fast penetration of the jet into the recirculation zone during transition is accomplished by the destabilization of the recirculation zone and the formation of large scale structures.

Comparison with $V_j = 1.0$

In the case of $V_j = 1.0$, the flow is strongly unsteady, and the dominant frequency of oscillation on the outside diameter of the bluffbody is $f = 0.135$. This is very close to the dominant frequency in the current case. On the other hand, the second subharmonic is at $f = 0.05$. In this case, we noticed a quiet period after two composite structure sheddings. There is an indication that the flow looses some of its organization as the jet velocity increases and that this quiet period between shedding becomes longer.[6]

Acknowledgments

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Viscous Eddies over a Grooved Surface Computed by a Gaussian-Integration Galerkin Boundary-Element Method

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Introduction

It is a well-known fact that low-Reynolds-number flows (solutions of the Stokes equations) may exhibit recirculation structures (viscous eddies) in the proximity of corners.[1] These have been observed in various geometries, for instance in Ref. 2, and were also recently found to occur in flow over a grooved surface through an analogical simulation realized by bending a suitably constrained elastic thin plate.[3]

The interest in flows over grooved surfaces has been raised in recent years by the attempts to use such surfaces for drag reduction in a turbulent stream. Several authors (see, e.g., Refs. 3, 4, and references therein) have experimentally found that a drag reduction can indeed be achieved. Bechert and his collaborators[4] proposed a qualitative mechanism of the phenomenon, in which a dominant role is played by the viscous sublayer of the turbulent stream, and calculated the effect upon the mean flow of longitudinal grooves (or riblets, depending on the way one wishes to see them) of a height comparable to the thickness of the viscous sublayer. Within the approximation given by the Stokes equations, the effect of the grooved wall is characterized by the presence of an effective plane wall that the velocity profile appears to originate from. The distance of this effective plane wall from the riblet tips takes the name of longitudinal protrusion height.

The basic action that riblets are assumed to exert is a damping of the crossflow vortices that accompany the turbulent flow. In this way they effect a reduction of the near-wall level of turbulence, and thus of the eddy viscosity and ultimately of the drag. In Ref. 5 the present authors, analytically in some geometries and numerically in others, calculated the transverse flow across the grooves within the same approximation (Stokes equations) that had been adopted in Ref. 4 for the longitudinal motion, determining the value of the transverse protrusion height and therefore of the protrusion-height dif-

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