Two-Dimensional Turbulent Separated Flow

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Abstract

MANY different flow cases with nominally two-dimensional turbulent separated flow regions are discussed in Refs. 1 and 2. Because intermittent flow reversal and backflow occur in the near-wall region, directionally sensitive measurement techniques must be used to examine the flow structure.

The experimentally-observed structure of detached flows on streamlined surfaces and around sharp-edged corners is discussed in detail for steady and unsteady incompressible and compressible cases. In all cases, large-scale structures dominate the flow behavior, producing large shearing stresses in the middle of the detached shear flow and strongly influencing the local intermittent backflow. The turbulence structure strongly lags the mean flow behavior in the detachment and reattachment processes. For unsteady periodic separation, there is considerable hysteresis of the flow during a cycle.

A number of differential and integral calculation methods are discussed. Traditional attached flow turbulence models and correlations do not describe detached flows well. Methods that include experimentally-observed features and/or correlations of detached flow parameters seem to perform best, although further improvements are still needed.

Contents

The purpose of this Synoptic is to summarize a recently written AGARDograph on "Two-Dimensional Turbulent Separated Flows,"[1] which reviews our understanding of the physical behavior of such flows and reviews calculation methods. Unless we properly model the physical phenomena, we cannot develop robust calculation methods that require only a few adjustable empirical numerical parameters. A more recent review of calculation methods[2] is also summarized. Nearly 500 references are contained in Refs. 1 and 2.

The physical behavior of turbulence is flow dependent, so detailed experimental information is needed for understanding such flows and modeling the physics for calculation methods. The fact that there is flow reversal in mean two-dimensional separated flows requires that directionally-sensitive measurement techniques be used to obtain valid data. The degree of flow reversal is an indicator of the detached flow state. Laser anemometry should be exploited further to provide needed information on the structure of turbulent separated flows. While traditional hot-wire anemometry has a less useful future, the thermal tuft and pulsed-wire anemometry appear to be quite useful, especially so for variable-density and dirty flows. Holography has been shown to be quite useful for research in compressible separated flows. Pitot tubes should be totally abandoned for velocity measurements in flow regions with intermittent backflow since reliable data interpretation is not possible.

Experimental Results

As a turbulent boundary layer undergoes an adverse pressure gradient, the flow near the wall decelerates until some backflow first occurs (Fig. 1) at incipient detachment (ID), defined as the near-wall location where the fraction of time that the flow moves downstream γ_{pu} is 0.99. Large eddies, which bring outer region momentum toward the wall, supply some downstream flow. These large eddies grow rapidly in all directions and agglomerate with one another to decrease the average frequency of passage as detachment ($\bar{\tau}_w = 0$; $\gamma_{pu} = 0.5$) is approached. Substantial pressure gradient relief begins near intermittent transitory detachment (ITD) defined as $\gamma_{pu} = 0.8$ near the wall.

Several common experimentally-observed features for all types of separating and reattaching flows are discussed. In the vicinity of detachment, the turbulence intensities become the largest in the middle of the shear layer. Lower $-\overline{uv}/u'v'$ correlation coefficients occur than for attached flows. Large-scale structures pair to form larger structures which pass downstream at lower frequencies. Mean velocity profiles look similar to those for mixing layers, except near the wall where backflow occurs. The mean backflow profile scales on the maximum mean backflow velocity and its distance from the wall. The backflow is strongly controlled by the maximum shear stress within the flow. The traditional semi-logarithmic law-of-the-wall velocity profile does not describe the backflow.

For thick regions of mean backflow, such as occur for the detached flow just downstream of a bluff body, there are relatively few instants of forward flow. For thinner regions of mean backflow, the backflow is more intermittent. The large-scale structures that dominate detached flows, supply the turbulence energy to the near-wall backflow, either by inrushes of outer region fluid toward the wall or by turbulence energy diffusion by pressure fluctuations. Velocity fluctuations in the backflow are greater than or at least comparable to the mean backflow velocities. For highly intermittent backflow zones, the mean backflow does not appear to come from far downstream.

In the vicinities of detachment and reattachment, the normal stress terms in the momentum and turbulence energy equations become important. Large streamwise variations in the mean velocity and turbulence profiles occur. The reattachment length, which is measured from detachment to reattachment, is the most important streamwise length on which to scale the streamwise variations of skin friction, upstream-downstream flow direction intermittency, static pressure recovery, and mean-square surface pressure fluctuations.

Reattaching flows have significantly higher Reynolds stresses than detaching flows for the same mean velocity profile shape factor. Some distance downstream of reattachment, these stresses decay to levels for attached boundary layers. This lag and hysteresis of the turbulence structure carries over to unsteady detaching flows. When the unsteady

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flow is increasingly detached, $(\partial \gamma_{pu_{\min}}/\partial t<0)$, the ensemble- or phase-averaged velocity profile looks like a steady free-stream profile for the same $\gamma_{pu_{\min}}$. The phase-averaged profile looks more like a reattaching steady flow when $\partial \gamma_{pu_{\min}}/\partial t>0$. Organized unsteadiness strongly affects detached flows, but low-amplitude flow oscillations have a negligible effect on mean velocities of attached turbulent flows.

Under some conditions very low-frequency, self-induced unsteadiness is present in flows that are unconstrained and can flap. Little turbulence shearing stress is associated with these large-scale motions. Imbalances between fluid entrained by the detached flow and that returned in the recirculation or stalled fluid zone or interactions of large-scale structures with the surface can produce these low-frequency motions. Interactions between the inviscid and turbulent flow regions can also be responsible for such oscillations.

Shock-induced detachment produces a flow structure similar to that for detached incompressible flows. Mean velocity profiles and the turbulence structure downstream of reattachment look qualitatively like that for incompressible reattaching flows.

Calculation Methods

Several inviscid models have been used to calculate the approximate time-mean behavior of some detached flows. Massive detached flow zones around an airfoil can be described using pressure gradient relaxation and a dead flow zone to obtain reasonably good lift and drag values. Simulations of the instantaneous behavior of high Reynolds number, two-dimensional separated flows from sharp edges have been performed using discrete vortex models with good qualitative results. When three-dimensional effects are included there is significant improvement, especially near reattachment.

All of the known boundary-layer models make use of the established ideas for attached turbulent boundary layers. Eddy viscosity, mixing length, turbulence kinetic energy, and entrainment models are used as well as empirical correlations. Integral methods are possible, even though there are large regions of backflow because the displacement of streamlines from the surface, the backflow, and the pressure distribution can be computed simultaneously or iteratively with a given velocity profile model. On physical grounds, the local large eddy structure strongly influences the local backflow so a downstream-marching calculation method for the velocity field is possible. Unfortunately, many of the calculation methods have drawn too heavily from attached flow concepts without making use of available experimental knowledge about these flows. For example, most methods do not incorporate the correct physics for the backflow region: namely, that turbulence diffusion and dissipation control the backflow behavior and that the backflow mean velocity profile is determined by the large-scale fluctuations which scale on the maximum shear stress.

Most integral methods use Coles' law-of-the-wall and law-of-the-wake velocity profile to determine the relationships among integral thicknesses, the skin-friction relation, or at least the forms of the relationships. This profile does not fit closely the mean velocity profiles of detached turbulent boundary layers, even when the sign of U_τ is changed to account for mean backflows. Thus, earlier researchers who used this profile with attached flow constants did not obtain

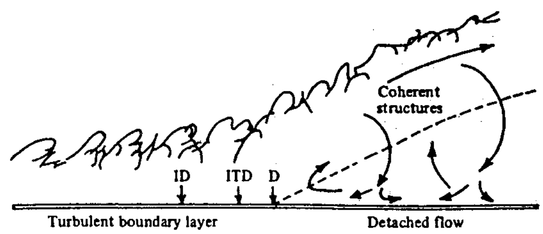

Fig. 1 Flow model with the coherent structures supplying the small mean backflow.

very good results. As more experimental data have become available, better fits of data to the forms of the relationships among parameters have been obtained. One idea that needs to be pursued in an integral method is the use of $\tau_{\max}$ as the descriptive shearing stress. This is the scaling shear stress for the shear layer upstream and downstream of detachment. The wall shear stress is very small in detaching flows and influences only the near-wall region.

As in the case of integral methods, inverse computational schemes must be used for differential methods to eliminate the weak singularity at $\tau_w=0$. One of the most impressive methods is the Johnson-King hybrid Reynolds stress/eddy viscosity model for separating flows, which accounts for experimentally-observed lower eddy viscosities than given by the Cebeci-Smith model. An ordinary differential equation for the maximum turbulent shearing stress $-\overline{uv}_{\max}$ along the path of maximum turbulence kinetic energy was derived form the turbulence energy equation. This model approximately accounts for the large-eddy diffusion effect on the "nonequilibrium" flow condition. While not making the numerics substantially more complicated, this model is capable of calculating subsonic flows and transonic airfoil and diffuser flows with shock waves.

The k-ϵ model has been widely tested by a number of researchers for two-dimensional bluff-body flows, e.g., cavity, rib, and sudden expansion flows, where detachment occurs at a well-defined location. The model performs well for confined axisymmetric flows with separation, and the same applies to confined plane flows in which the influence of an opposing wall is felt strongly, i.e., for large blockage ratios. When the opposing wall is moved away, the model tends to underpredict the size of the recirculation zone; the same is true also for unconfined separated flows, except for those situations where vortex shedding occurs and the steady-model approach is not suitable. Various modifications to the k-ϵ model have been suggested to improve its performance for separated flows, but none of them proved entirely satisfactory. The k-ϵ, algebraic stress, and Reynolds stress models do not contain a large eddy diffusion term. This partially explains why the k-ϵ model does not do well for large unconfined separated flows, but does reasonably well for high blockage confined flows where smaller scale motions have much more influence.

References

[1]Simpson, R. L., *Two-Dimensional Separated Flow*, AGARD-AG-287, Vol. 1, NATO, June 1985.

[2]Simpson, R. L., "A Review of Two-Dimensional Turbulent Separated Flow Calculation Methods," *IUTAM Symposium on Boundary Layer Separation*, edited by F. Smith and S. Brown, Springer-Verlag, 1987.