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A MECHANISM FOR LAMINAR THREE-DIMENSIONAL SEPARATION IN DUCT CONTRACTIONS

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ABSTRACT

Strong flow disturbances have been observed in the central region of the flow at the exit plane of a contraction with laminar boundary layers. Flow visualisation shows that these disturbances are caused by a three-dimensional separation from the contraction surface. In a proposed conceptual model of this phenomenon, the separation process begins with small nonuniformities in the boundary-layer flow emerging from screens upstream of the contraction. On entering the contraction, the nonuniformities are amplified by a combination of Görtler instability, lateral pressure gradient and adverse streamwise pressure gradient to form a strong counter-rotating streamwise vortex pair which detaches from the surface. The separation can be suppressed by placing a series of screens in the contraction.

INTRODUCTION

Wind-tunnel contractions are generally required to deliver a uniform and steady flow into a region where tests or measurements are carried out. At all but very low speeds, Reynolds numbers are high enough to produce turbulent wall boundary layers throughout the wind tunnel, and there are well established design procedures for satisfying the exit flow criteria (Morel, 1975; Mikhail, 1979). If the boundary layers in the contraction are turbulent, it is relatively easy to prevent quasi-two-dimensional separation. If the boundary layers are laminar, not only is it more difficult to avoid near-wall velocity fluctuations due to quasi-two-dimensional separation and Görtler instability, but the contraction may also produce large nonuniformities and fluctuations in the central part of the duct cross-section.

WIND TUNNEL

The principal components of the wind-tunnel upstream of the test section are shown schematically in Figure 1. The maximum flow speed at the contraction exit is about 9 m/s. A centrifugal fan delivers air from the laboratory through a wide-angle diffuser and, in reducing the initial temperature nonuniformity in the flow by 97%, suppresses buoyant cross-flows. The air flow is conditioned by two honeycombs, six screens and a settling chamber before entering a high-area-ratio (20.7:1) contraction in which the duct cross-section changes from octagonal to square. Quasi-two-dimensional separation is avoided by minimising the concavity of surfaces in the adverse pressure-gradient region near the start of the contraction.

EXPERIMENTAL OBSERVATIONS

Initial Evidence of Disturbed Flow

The initial evidence of strong nonuniformity in the flow emerging from the wind-tunnel contraction was provided by observing lateral deflections in an array of streamers. The 400 mm long streamers were glued to a 3 mm diameter cylinder spanning the full height (230 mm) of the duct and located about 200 mm downstream from the contraction exit. In Figure 2 the behaviour of the streamers is observed from the downstream direction, with flow coming towards the video camera. The images are selected to show approximately maximum streamer deflection. The pattern formed by the streamers is unsteady and indicates the presence of a quasi-cyclic fluctuating flow structure with a characteristic frequency in the order of 0.3 Hz to 3 Hz. The finer details of the patterns vary with with each repetition of the observation.

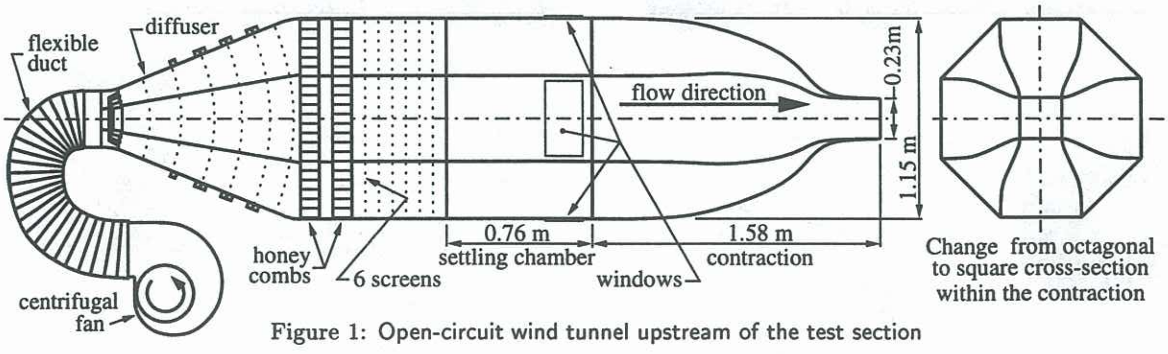

Figure 1: Open-circuit wind tunnel upstream of the test section

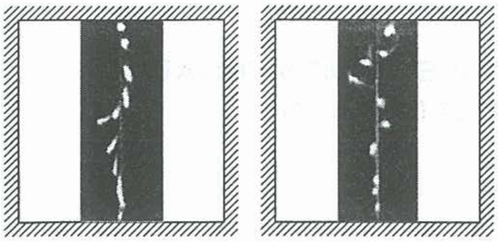

Figure 2: Flow nonuniformity revealed by streamer deflection. Air speed, $\langle U \rangle = 4.1$ m/s at the contraction exit.

Identification of the Trailing Vortex Structure

Attempts at using smoke-streakline methods for flow visualisation in the settling chamber and contraction are unsuccessful because, at air speeds lower than 0.25 m/s, the negatively buoyant smoke produces spurious secondary flows. However, feeding smoke into the the inlet of the mixing fan eventually fills the wind tunnel with a uniformly diffuse cloud containing no spurious secondary flows. Alternately removing and restoring the smoke supply generates a series of clear-air/smoke-cloud interface surfaces which, in the settling chamber, are flat and perpendicular to the mean flow direction. This indicates that the flow through the settling chamber is free of disturbances like those observed downstream of the contraction in Figure 2.

Observations of the smoke/air interface downstream of the contraction very clearly show the presence of structure in the flow. The structure is visible for several seconds after the main smoke/clear-air interface passes, either as deep holes in the smoke cloud or as long tails of smoke. Figures 3(a–d) show that the streamer deflections are closely correlated with the smoke patterns and that both are clearly produced by the same flow structure. The double circular shapes formed by distortion of the smoke cloud indicate the presence of two streamwise vortices which are associated with one of the duct surfaces by a connecting "stem" (Figure 3(e)). The details of streamer deflection confirm that the vortices in each pair counter-rotate in a direction which induces migration of the vortex cores away from the associated surface and, in the region between the vortices, lifts flow from that surface. As suggested by the variety of images in Figures 3(a–d), the location and orientation of vortices within the duct cross-section are at least partly random. At exit-flow speeds lower than about 4 m/s, the vortex pair can migrate slowly from one part of the duct cross-section to another or develop an oscillatory motion with a frequency of 0.3 to 3 Hz.

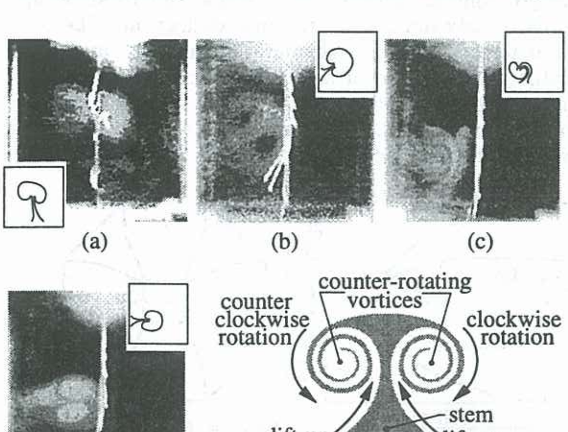

Figure 3: Streamer deflections and smoke patterns at the trailing surface of a smoke cloud. $\langle U \rangle \approx 2.4$ m/s

Direct Observation of Separation

To observe the process of separation in the contraction more directly, smoke was introduced over the full width of the wind-tunnel floor at the exit of the diffuser, and the behaviour of the smoke was observed through the windows in the settling chamber. The clearest feature of the near-wall flow is a lateral nonuniformity which is visible (Figure 4(a)) as four or five broad streaks emerging from the final settling-chamber screen. At exit-flow speeds lower than about 4 m/s, the smoke streaks tend to coalesce as they pass through the contraction. Lifting of smoke from the surface is frequently observed downstream of the coalescence. Coalescing smoke streaks are always accompanied by large streamer deflections which indicate the presence of a streamwise vortex pair. Sometimes, as in Figure 4(b), sufficient smoke is removed from the floor to make the detached vortex pair visible at the contraction exit.

The results from this experiment clearly show that the detached vortex pair observed at the contraction exit is part of a strong three-dimensional separation structure. The strength of the separation is indicated by the convergence angle of the coalescing smoke streaks which, from images similar to Figure 4(a), is approximately 10° to 15°. Strong separation is also indicated by vortex swirl angle. It is estimated from streamer deflections that vortex swirl angles near the initial lift-up are about 20° to 35°.

CONCEPTUAL MODEL OF SEPARATION

Effect of Initial Nonuniformity

The wire-mesh screens upstream of the settling chamber perform the important function of increasing the

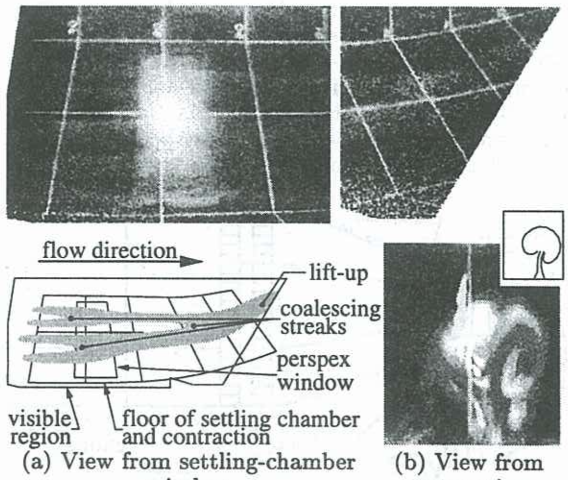

Figure 4: Coalescence of low speed streaks in the settling chamber and contraction, $\langle U \rangle = 1.6$ m/s.

uniformity of the flow. However, Böttcher and Wedemeyer (1989) show that small spatial variations in mesh density are the source of low-amplitude nonuniformities in the time-averaged flow downstream of a screen. These nonuniformities are responsible for the initial lateral variations in the thickness of the smoke layer on the floor of the settling chamber (Figure 4).

The next stage leading to strong separation in the contraction is observed as the transformation of the surface smoke layer into a series of distinct streaks as it travels through the contraction. Görtler number on the concave contraction surfaces is in the range where growth of primary Görtler instability has been observed experimentally (Floryan and Saric, 1982). Görtler instability therefore provides a mechanism for streak intensification, and the streaks are interpreted as accumulations of low-speed near-wall fluid in the updraught region beneath pairs of weak counter-rotating streamwise (i.e. Görtler) vortices.

Streamwise Pressure Gradients

The boundary-layer flow entering the contraction first encounters an adverse pressure gradient (Figure 5) and then, in the rapidly converging part of the duct, a very favourable pressure gradient. Sonada and Aihara (1981) examined the effects of streamwise pressure gradients on the development of secondary Görtler instability. Their measurements in the updraught region between adjacent Görtler vortices show that vertical distributions of mean velocity are heavily inflected and have two regions of high shear, one near the wall and the other near the top of the vortex-pair "mushroom" (Figure 5). Sonada and Aihara found that favourable pressure gradients tend to suppress the growth of velocity fluctuations and so retard the development of secondary instability. The main effect of an adverse pressure gradient is to move the outer shear layer away from the wall, with little effect on the near-wall shear layer. This increase in distance between shear-layers is interpreted as a migration of the vortex pair away from the wall.

In the wind-tunnel contraction, the adverse pressure gradient is expected to contribute to the lifting of vortices away from the surface (Figure 5) in a manner very similar to that observed by Sonada and Aihara (1981). The observed stability of the vortex

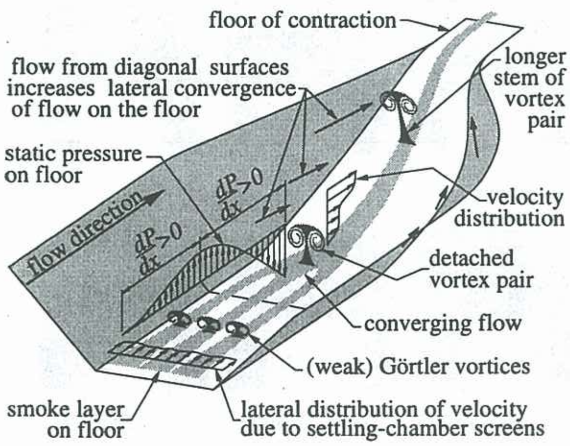

Figure 5: Conceptual model for three-dimensional boundary-layer separation.

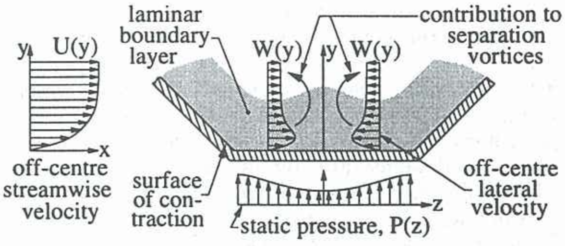

Figure 6: Schematic diagram of lateral flow and skewing of the boundary layer due to lateral pressure gradient.

pair suggests the pressure rise is insufficient to permit growth of secondary Görtler instability. It also indicates that the favourable pressure gradient and accompanying acceleration of the flow stabilise the inflectional velocity distributions produced by the upwash between the streamwise vortices, and suppress secondary Görtler instability.

Lateral Pressure Gradients

Bansod and Bradshaw (1972) show that converging lateral flows generated by *lateral* pressure gradients can also produce pairs of streamwise separation vortices. This is explained by observing that, if the deflection angle of the flow is small and viscous diffusion terms are ignored, the equation for the lateral component of momentum can be simplified to

$$U\frac{\partial W}{\partial x} \approx -\frac{1}{\rho}\frac{\partial P}{\partial z}. \qquad (1)$$

The rate of flow deflection ($\partial W/\partial x$) in the relatively low-momentum fluid of the boundary layer is therefore significantly larger than in the free stream flow. The result is a skewed boundary layer where the lateral velocity component has a maximum within the boundary layer (Figure 6). The convergence of lateral flows near the middle of the floor provides a second mechanism for amplifying the initially very weak streamwise vortices produced by Görtler instability. The relative importance of adverse streamwise pressure gradient and the skew-inducing lateral pressure gradient in the production of three-dimensional separation is indicated in Figure 7, where one vortex pair is reinforced by skew-induced vorticity and the other less centrally located vortex pair is not.

SUPPRESSION OF 3-D SEPARATION

Mechanism

The lateral convergence of near-wall flow underneath the separation vortices produces an accumulation of retarded fluid which is observed experimentally as a low-speed streak on the surface of the contraction (Figure 4) . In order to remove free-stream disturbances such as those shown in Figure 2, it is there-

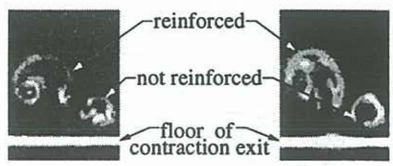

Figure 7: Selective reinforcement of streamwise vortices by skew-induced vorticity; cross-section images at the contraction exit. $\langle U \rangle = 2.4$ m/s

fore necessary to prevent low-speed streaks from developing to the stage where the associated streamwise vortices become detached from the contraction surface. Typical near-wall low-speed streaks, which are narrow features protruding into a region of high-speed flow, are removed very effectively by a screen because, as demonstrated by Mehta (1985), the screen redirects flow from regions of high velocity towards regions of relatively low velocity. However, the flow conditions immediately downstream of a screen tend to produce new low-speed streaks which once again develop into three-dimensional vortex-pair separations. This makes it necessary to use a series of screens, with the final screen located well within the favourable pressure-gradient region of the contraction.

Installation

The screens in the contraction were made of 16 MPI, 28 SWG wire mesh. Each screen was permanently dished to make it approximately perpendicular to the flow at the wall, and consequently to discourage excessive concavity of near-wall streamlines immediately downstream of the screen. In the final installation (Figure 8), one screen was placed at the start of the contraction and five more were located at downstream intervals of 170 mm. The number and spacing of screens were determined empirically.

Flow Visualisation Tests

The effectiveness of the screens in suppressing three-dimensional separation was tested by the "intermittent flooding" flow-visualisation method which was used for identifying the streamwise separation vortices. The results (Figure 9) demonstrate that large-scale separation vortices of the type shown in Figure 3 have been replaced by a small vortex pair in each corner of the duct. These vortex pairs are probably a result of near-wall lateral flows created by the tapering and disappearance of the diagonal surfaces at the downstream end of the contraction. Between the highest exit flow speed of 2.4 m/s and 0.95 m/s, the width and height of each vortex pair remain constant at about 15–20 mm. As flow speed is reduced further, the corner vortices become larger, and only at speeds lower than 0.5 m/s do separation vortices like those in Figure 3 began to reappear in the mid-span regions of the contraction surfaces.

CONCLUSIONS

Three-dimensional separation in a contraction with laminar boundary layers can generate a strong flow disturbance consisting of a single pair of counter-rotating streamwise vortices in the central part of the duct cross-section. The separation process begins with small nonuniformities in the near-wall flow emerging from the wire-mesh screens upstream of the contraction. These flow nonuniformities are convected into the concave boundary layer near the start of the contraction, where they are amplified by Görtler instability and develop into a spanwise array of counter-rotating streamwise vortex pairs and near-wall low-speed streaks. Lateral flow convergence, which is produced by lateral pressure gradients, and adverse streamwise pressure gradients accelerate the growth of one selected vortex pair and its associated low-speed streak. Eventually the vortex pair moves away from the wall of the contraction and into the free-stream flow. A series of wire-mesh screens located within the concave-surface region of a contraction can prevent the low speed streaks between streamwise vortices from developing to the stage where separation vortices detach from the surface.

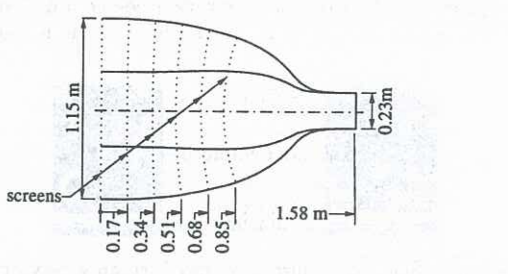

Figure 8: Location of screens in the contraction.

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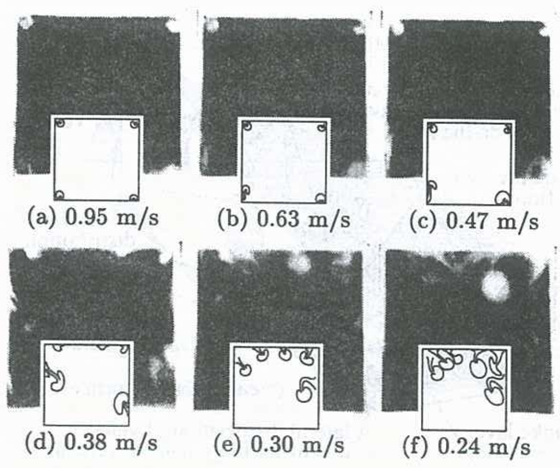

Figure 9: Suppression of three-dimensional separation with five screens in the contraction; visualisation of the flow cross-section at the contraction exit.