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COLLOQUIUM ON FLOW SEPARATION (JANUARY, 1979).(U)

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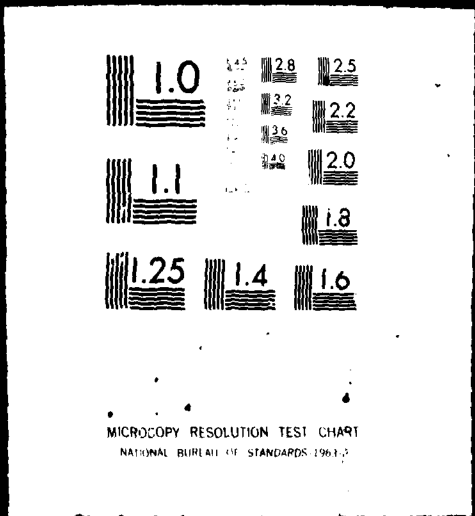

universal correlation for separating flows. The wave speed of the eddies

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LEVEL II

PROJECT SQUID

TECHNICAL REPORT SMU-3-PU

SUMMARY REPORT ON COLLOQUIUM ON FLOW SEPARATION (January 1979)

AUGUST 1979

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School of Mechanical Engineering
Chaffee Hall
Purdue University
West Lafayette, Indiana 47907

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Technical Report SMU-3-PU

P R O J E C T S Q U I D

A COOPERATIVE PROGRAM OF FUNDAMENTAL RESEARCH
AS RELATED TO JET PROPULSION
OFFICE OF NAVAL RESEARCH, DEPARTMENT OF THE NAVY

CONTRACT N00014-75-C-1143 NR-098-038

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SUMMARY REPORT

ON

COLLOQUIUM ON FLOW SEPARATION
(January, 1979)

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PREFACE

A Colloquium on Flow Separation was held under the auspices of Project SQUID (Office of Naval Research) at the Southern Methodist University, Dallas, Texas, on January 18-19, 1979. The invited participants were the following.

M. A. Chaszeyka, ONR Chicago Office
A. Elsenaar, NLR, Netherlands
A. D. Gosman, Imperial College, London
J. P. Johnston, Stanford University
S. J. Kline, Stanford University
J. G. Marvin, NASA-Ames Research Center
H. L. Moses, VPI and State University
S. N. B. Murthy, Purdue University
R. Narasimha, Indian Institute of Science, Bangalore
B. G. Newman, McGill University
D. J. Peake, NASA-Ames Research Center
V. A. Sandborn, Colorado State University
W. R. Sears, University of Arizona
J. D. A. Walker, Lehigh University
A. D. Welliver, Boeing Aerospace Company
A. D. Wood, ONR Boston Office
W. H. Young, NASA-Langley Research Center

Mr. A. Elsenaar, Dr. A. D. Gosman and Professor W. R. Sears could not attend the Colloquium.

The Summary Report presents the general conclusions of the Colloquium.

Prior to the Colloquium, position papers were invited on the subject of turbulent flow separation from the participants. These position papers have generally been incorporated into the Summary Report. However, position papers from the following persons are presented verbatim in Appendix 1 to this report since they include certain points of view not fully covered during the Colloquium.

A. Elsenaar
A. D. Gosman
R. Narasimha
W. R. Sears
J. D. A. Walker

August 12, 1979
Southern Methodist University
Dallas, TX 75272

Roger L. Simpson
Colloquium Chairman

1. INTRODUCTION

Turbulent flow separation continues to be a nuisance to fluid dynamicists because it may be present in many practical machines or devices, thus reducing their performance, and because there is no adequate method to calculate such flows. In general, the maximum performance of such machines occurs at conditions close to the onset of separation. In order of increasing difficulty, designers need to know

(a) whether or not a boundary layer separates for a prescribed pressure distribution,
(b) how the pressure distribution is affected by boundary layer development with small regions of separated flow, and
(c) how the overall performance is affected when large regions of separation are present.

Some of the situations of interest occur in diffusers, engine inlets, fans and compressors, and on aircraft. The mean separated flow is nominally two-dimensional in many cases, but is three-dimensional in many more configurations, e.g., on a lifting body connected to a fuselage, on propulsive components, on an intake, on local protuberances, on swept edges emanating from an apex, etc. Separation from bluff bodies is just as important as for streamlined shapes, e.g., boat-tailed bodies, flame stablizers in gas turbines, large buildings subjected to wind loadings, etc. From a structural viewpoint, the aeroelastic response of the surface to strong pressure fluctuations produced by separation is an important consideration.

This Colloquium on Turbulent Flow Separation was held by Project SQUID at SMU to discuss fruitful areas for future research. A number of active researchers were invited to participate in discussions on five topics: terminology, measurements, flow modeling, unsteady effects, and control of separated flow. These topics are fundamental to future advances since a common nomenclature should be used to describe phenomena that are measured and modeled.

2. TERMINOLOGY

The term "separation" must mean the entire process of "departure" or "breakaway" [1,2,3] or the breakdown of boundary-layer flow. An abrupt thickening of the rotational flow region next to a wall and significant values of the normal-to-wall velocity component must accompany breakaway, else this region will not have any significant interaction with the free-stream flow. This unwanted interaction causes a reduction in the performance of the flow device of interest, e.g., loss of lift on an airfoil or loss of pressure rise in a diffuser.

It is too narrow a view to use vanishing surface shearing stress or flow reversal as the criterion for separation. Only in steady two-dimensional flow do these conditions usually accompany separation. In unsteady two-dimensional flow the surface shear stress can change sign with flow reversal, but without "breakaway". Conversely the breakdown of the boundary layer concept can occur before any flow reversal is encountered [1,2]. In three-dimensional flow the rotational layer can depart without the surface shear stress necessarily falling to zero; the wall shear is zero only at the singular points [4,5,6].

These singular points are readily observed by a thin oil flow-visualization indicator that marks surface skin-friction lines [6,7]. These skin friction lines are defined everywhere on the surface, even in the vicinity of lines of flow departure (separation lines according to Peake and Tobak [5]) from the surface, which are themselves ordinary skin-friction lines. There is no basis for inferring the behavior of limiting streamlines from skin friction lines in the vicinity of lines of flow departure. Since skin-friction lines are unique everywhere on the surface, they form a continuous vector field. Lighthill [6] showed that the number and types of singularities on the surface obey a topological rule: the number of nodal and/or foci singular points exceed the number of saddle point singular points by 2. Hunt et al. [8] have shown recently that this rule can be extended to the flow above the surface on planes of symmetry, on projections of conical flows, and on cross-flow planes [5].

Until recently little new information about mean two-dimensional steady freestream turbulent separation has been available. With measurements having been made and being made with different types of instrumentation in different apparati, it is important to adopt a terminology that will allow quantitative comparisons and make the most of data that are difficult to obtain. S. J. Kline and J. P. Johnston and other participants proposed the following general terms for two-dimensional steady freestream separation:

A. Detachment -- the location where the boundary layer flow leaves the wall; the locus of points where the limiting streamline of the flow leaves the surface.

B. Reattachment -- locus of points where the limiting streamline of the time-averaged flow rejoins the surface.

C. Separation -- the total process consisting of detachment, recirculation, flow free-shear layer, and in cases not involving a free wake, reattachment.

D. Stall -- zone of recirculating fluid created by pressure forces.

E. Stalled Fluid -- fluid with reverse or low velocity within a recirculating zone.*

---

*In contrast, Newman pointed out that in normal usage in the past that "detachment" is the same as "separation"; that the definition C would usually be called the "separation region and wake"; that "stall" is defined as the condition of maximum lift; and that definition D would be called "backflow".

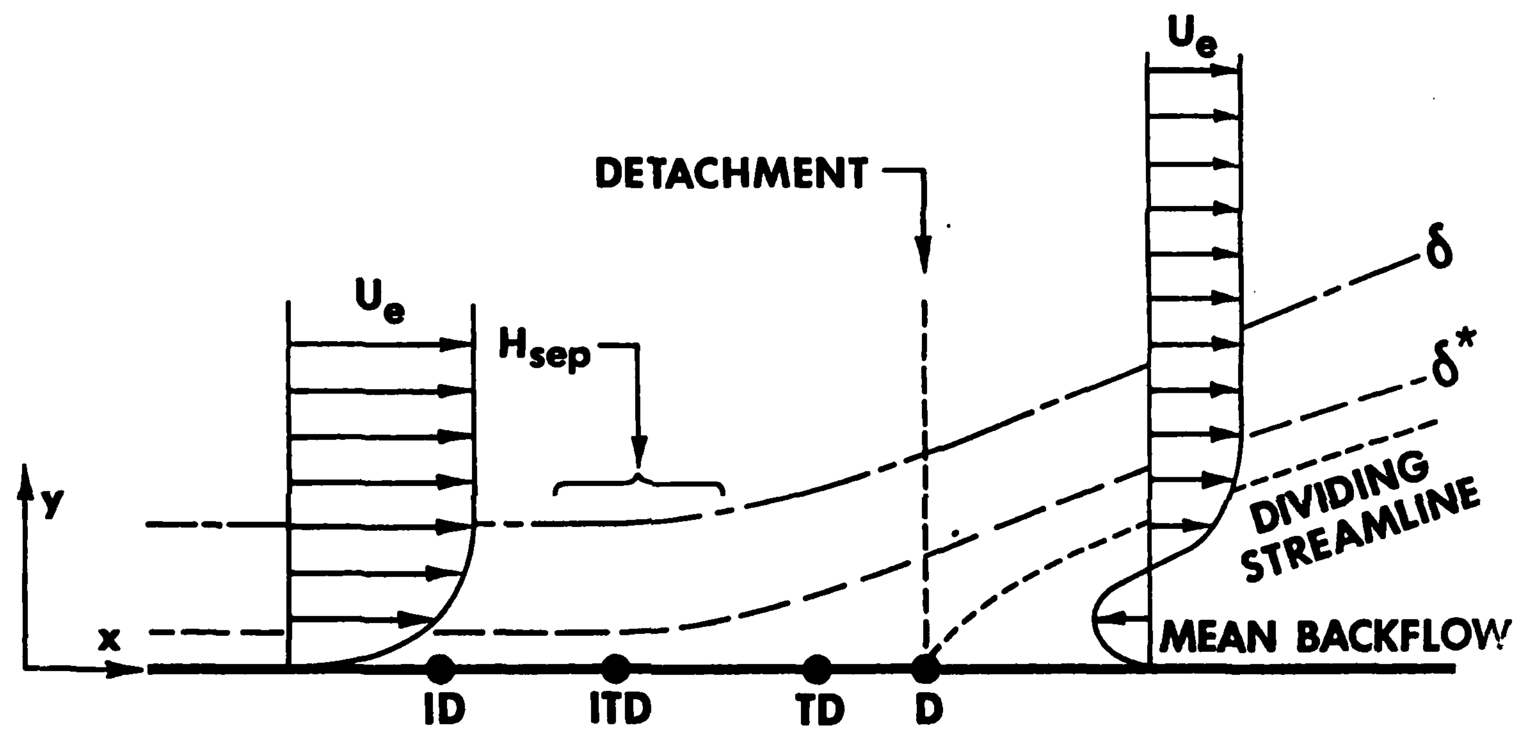

Figure 1. Definitions of two-dimensional turbulent detachment states. Distances not to scale. "% Instantaneous Backflow" means along a spanwise line at a given time, or percent of time at a point.

OLD TERM	SYMBOL	NEW TERM	CONDITION
none	ID	Incipient Detachment	1% Instantaneous Backflow
Intermittent Separation [11]	ITD	Intermittent Transitory Detachment	20% Instantaneous Backflow
none	TD	Transitory Detachment	50% Instantaneous Backflow
Steady or Fully-Developed Separtion [11]	D	Detachment	$\overline{\tau}_w = 0$

Figure 1 shows other proposed definitions of flow characteristics nearest the surface on which the separation process occurs. Except in singular cases such as a backward facing step, turbulent detachment is a zone. Sandborn and Liu [9] and Simpson et al. [10] have noted that the fraction of time that the flow moves downstream, γ_p, varies gradually from unity toward zero along this detachment zone. "Incipient detachment" has been observed in old experiments when flow markers such as a dye filament injected into liquids at the wall or a tuft mounted on the surface would move upstream occasionally. In the past this location has been loosely called incipient separation. (Here we will not use this latter term since it appears to have been used loosely to mean a flow near conditions required for the separation process to occur. In some cases such as in supersonic flow, the separation process occurred but was not documented; it was often called incipient separation.)

"Intermittent transitory detachment" was observed in old experiments when tufts or dye filaments moved upstream a noticeably greater fraction of time than "occasionally". Sandborn and Kline indicate that this location corresponds to where they previously called the location of "turbulent separation" or "intermittent separation" [11]. Currently Sandborn [12] labels the velocity profile at this position as "unrelaxed". "Transitory detachment" and "detachment" may correspond to the same location, if the streamwise velocity probability distribution at that location is nearly gaussian. "Detachment" was called the location of "steady" separation by Sandborn and Kline while Sandborn [12] notes that the velocity profile at this location is "relaxed". Until recently most predictors were concerned only with predicting D, ignoring the fact that the turbulent separation process starts upstream of this location in all but singular cases where ID and D are at the same location.

The length of the region between the ID, ITD, TD and D points will depend on the geometry and the flow, but the definitions of these points are the same. γ_p is not a sufficient variable to describe the flow behavior since it only represents the fraction of a streamwise velocity probability distribution that is positive. However, it is important that such an important feature be documented in all future work. As mentioned in section 5 below, accurate quantitative techniques are available for measuring these features.

3. FLOW PHYSICS

A. Observations of the Inviscid Flow Behavior in Steady Two-Dimensional External Flow

Figure 2 shows the chordwise distribution of the suction side velocity just outside the boundary layer U_e for an airfoil at an angle of attack. Experimental observations indicate that when detachment occurs well upstream of the trailing edge, that complete pressure gradient relief occurs until the trailing edge of the airfoil as shown between B and C. In general, one will observe this same behavior for a variety of bodies, including a circular cylinder and many different airfoil designs, several examples of which are presented by Cebeci et al. [13]. For these cases, one must conclude that in the separated flow zone downstream of detachment the velocity and pressure just outside the shear layer approach the free-streamline condition of constant pressure and velocity.

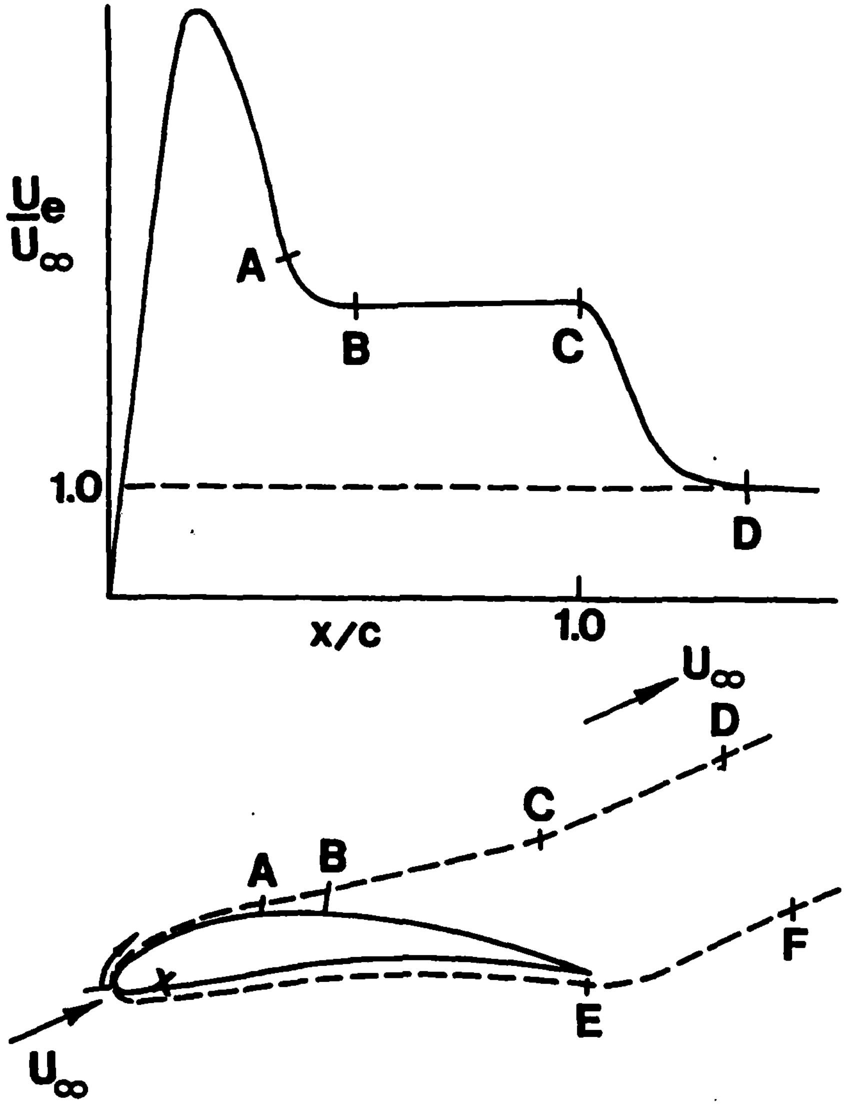

Figure 2.

Conceptual schematic of free-streamline separation: top figure - characteristic velocity distribution just outside the shear layer on the suction side: pressure gradient relief region between A and B, free-streamline region between B and C, wake relaxation region between C and D; lower figure - body (solid line) and the effective body (dashed line) that consists of the real body plus the displacement thickness, with comparable A, B, C, and D suction side locations and pressure side wake relaxation region between E and F. Suction side wake velocity and length scales much larger than those for the pressure side wake.

Downstream of the trailing edge, U_e must eventually return to U_∞ in both magnitude and direction, since this irrotational flow outside the shear layer obeys Bernoulli's equation. In cases where separation occurs close to the trailing edge, no constant pressure region is observed and the free-stream velocity continues to decrease, sometimes to below U_∞ value. In these cases the velocity downstream of the trailing edge must increase to U_∞. In this case of trailing edge separation, there is apparent strong interaction between the wakes of the suction and pressure sides, since the thickness and velocity scales are not extremely different. Thus, the free-stream velocity distribution in the region between detachment and the near wake is controlled by both shear layers. It appears that free-streamline separation occurs when the velocity and length scales of the suction side shear layer are much larger than those found on the pressure side.

The near wake region (CD on Figure 2) is a critical part of separation since it is characterized by strong interaction of both separated shear layers with the inviscid flow and controls the downstream distance to where the pressure is uniform. It is clear from the work of Jacob [14] that an accurate description of this region is very important to the overall drag prediction. With the exception of the recent measurements of Coles and Wadcock [15], there is no reliable detailed flow structure data for the near wake shear flow of a lifting airfoil with turbulent separation.

B. Observations of the Flow Behavior in Two-dimensional Diffusers

The flow behavior is primarily dependent on the diffuser geometry in two-dimensional diffusers [16,17]. A typical curve of static pressure recovery, C_p, for the four flow regimes is shown as a function of the divergence angle 2Θ in Figure 3. Line a - a represents the approximate dividing line between the unstalled and transitory stall regimes. The separation process does not occur in the unstalled regime. Line b - b divides the transitory stall regime from the fully-stalled regime. Complete pressure gradient relief occurs in the latter regime, similar to free-streamline separation for external flow.

Transitory stalls are large, pulsating separations which occur primarily in relatively narrow passages of very symmetric shape. A positive pressure gradient exists all along the surfaces in all known data. The peak pressure recovery is achieved in this regime. The flow first detaches near the end of the diffuser, forming a stall. The stalled region grows toward the diffuser throat with fluid from the diffuser exit. After sufficient growth the stall becomes unstable, is entrained by the mainstream flow and is washed out of the diffuser. The sequence repeats itself. Kline and Johnston suggest that the positive dP/dx is essential in sustaining the transitory stall fluctuating flow pattern, since Smith and Kline [18] have shown that the maximum unsteadiness occurs just before some fixed stall zone is observed. Large transitory stalls appear to occur only in internal flow. Of the four flow regimes it is the most complex and the least predictable.

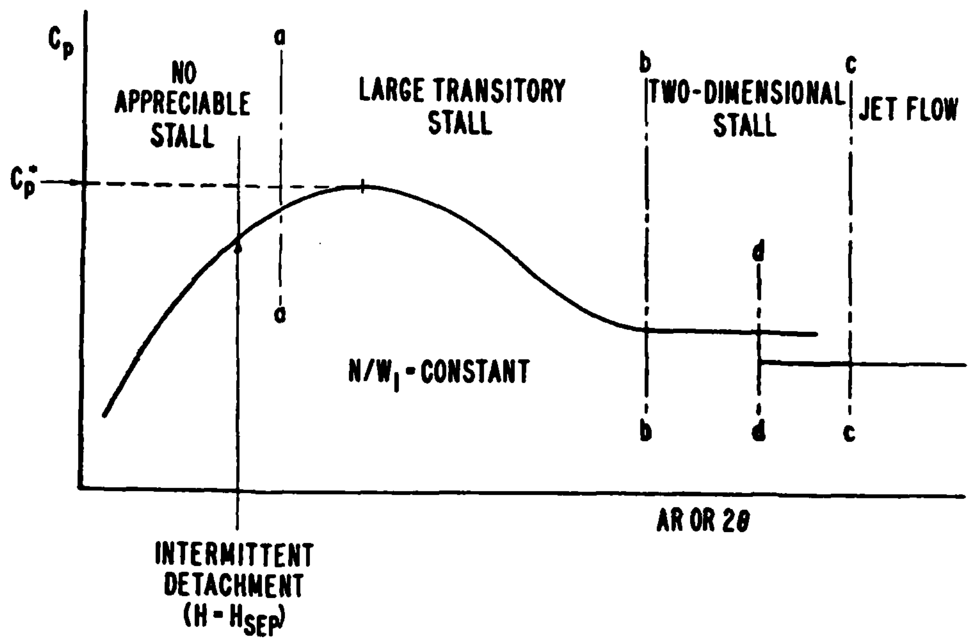

Figure 3.

Behavior of C_p with increasing area ratio or 2θ [16, 17]. Good predictions possible in shaded regions.

C. Some Features of the Turbulent Boundary Layer

The laser anemometer measurements of Simpson et al. [10] and current measurements underway at SMU have revealed much about the structure of a steady freestream two-dimensional turbulent boundary layer. Although there was no transitory stall in these experiments, there was not complete pressure gradient relief downstream of detachment, but rather a minimal pressure gradient. Figure 4 shows the airfoil type inviscid freestream velocity distribution for the earlier flow that was produced in a two-dimensional converging-diverging wind tunnel. Boundary layer measurements were made on the flat straight floor. A similar, but different, streamwise velocity distribution was obtained for the current experiments.

Upstream of Separation. Upstream of the vicinity of separation, a mean two-dimensional adverse pressure gradient turbulent boundary layer has well accepted characteristics. The "law of the wall" and "law of the wake" describe the mean velocity profile while the qualitiative turbulence structure is not markedly different from the zero-pressure-gradient case; the turbulence energy, dissipation, production, and spectral distributions behave in a known fashion. The maximum turbulent shearing stress $-\overline{uv}_{max}$ is less than 1.5 $(\tau/\rho)_w$. The wall "bursting" frequency n behavior and the spanwise structure spacing λ_z in the viscous sublayer behave similarly to that for the zero-pressure-gradient case, i.e., $U_e/n\delta$ = constant and $\lambda_z(-uv)^{1/2}_{max}/\nu \simeq 100$. The bursting frequency correlation constant is 10, not 5 as in the zero pressure gradient case, because of lag produced by the pressure gradient.

Perry and Schofield [19] proposed a correlation for the mean velocity profiles in unseparated flow in the presence of strong adverse pressure gradients, based upon 145 mean velocity profiles taken from Coles and Hirst [20] and including equilibrium and non-equilibrium profiles. This correlation applies only when the maximum shearing stress $-\overline{uv}_{max}$ exceeds 1.5 $(\tau/\rho)_w$. Nearest the wall, the traditional law-of-the-wall velocity profile holds. Further away a half-power profile exists while in the outer region a velocity-defect correlation exists. The data of Simpson et al. [10] and Samuel and Joubert [21] support this correlation.

The normal stresses terms $\partial(\overline{u^2} - \overline{v^2})/\partial x$ and $(\overline{u^2} - \overline{v^2})\partial U/\partial x$ in the momentum and turbulence energy equations, respectively, are not insignificant near separation in the region where the Perry and Schofield correlation holds. Up to one-third of the turbulence energy production in the outer region is due to this effect [10,22] as separation is approached. The relations between dissipation rate, turbulence energy, and turbulent shearing stress are slightly modified since some turbulence production is not related to the shearing stress. The convective terms of the momentum equation make the shearing stress gradient less than the streamwise pressure gradient so that the traditional law of the wall is valid.

The turbulence structure is slightly different also. While $U_e/n\delta$ = constant continues to describe the bursting frequency, n decreases as separation is approached since the boundary layer thickness δ grows and U_e decreases. $\lambda_z(-uv)^{1/2}_{max}/\nu = 100$, indicating that since $(-\overline{uv})_{max} > (\tau_w/\rho)$ that this is a more

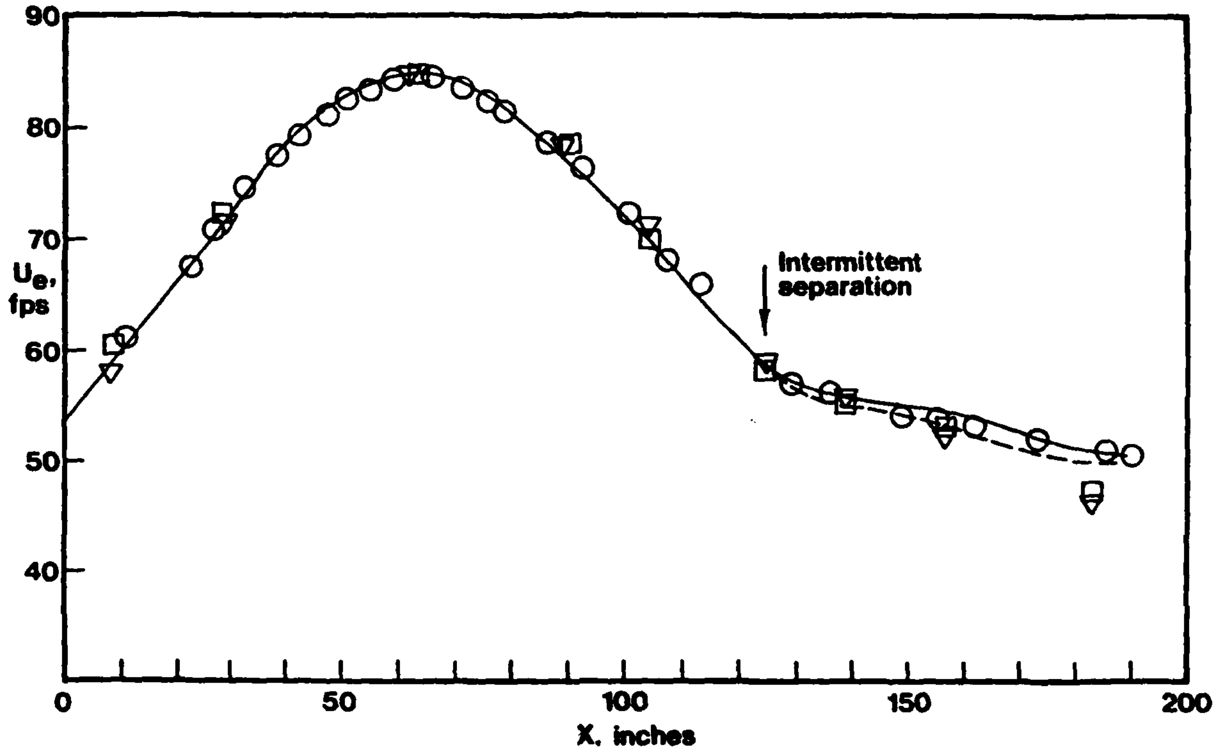

Figure 4.

Free-stream velocity distribution at boundary layer outer edge: O from bottom wall static taps; ◻ from the bottom boundary layer pitot probe. Solid and dashed lines denote results from minimum pressure gradient model of Collins and Simpson [35].

universal correlation for separating flows. The wave speed of the eddies near the wall was about 14 U_τ all along the flow, as for zero pressure gradient flows. Beginning upstream of separation and continuing downstream, the spanwise integral length scale of the turbulence near the wall increases like δ^2. Since δ also grows rapidly along the flow, this means that the near wall separating flow is increasingly dominated by the large-scale outer flow.

Downstream of Separation. As the turbulent boundary layer approaches separation, there is flow reversal near the wall intermittently or only a fraction of time (incipient detachment). The time-averaged mean pressure gradient drops rapidly downstream of the beginning of intermittent backflow. Since the velocity probability distribution at a given x and y location is almost gaussian when the shearing stress is small, then intermittent backflow is present where $u/U > 1/3$. The pressure gradient appears to have reached a minimal level at the detachment location. A consensus view is that any length between ID and D in Figure 1 is possible and is probably related to the ratio of scales of motion in the outer and reversed flow regions. In terms of the flow geometry, the length of the detachment zone should decrease for increasing divergence of the surface from the mainstream flow direction. Continual backflow near the wall will occur when the divergence of the surface exceeds the rate at which streamwise momentum and energy can be transported toward the wall.

The two-parameter correlation of Sandborn [11,12] (Figure 5) for intermittent transitory detachment (intermittent separation) and detachment (fully-developed separation) seems to check the known data accurately. Scatter in this correlation appear to be due to the different experimental techniques used. No known one-parameter correlation seems to work as well.

Downstream of detachment, λ_z is an order of magnitude greater than upstream of intermittent transitory detachment. $U_e/n\delta$ = constant still appears to be valid, indicating that large eddies govern the wall flow. The spanwise integral scale grows from about 1/6 the boundary layer thickness upstream to about 1/3 the shear layer thickness downstream.

The region with intermittent backflow, which grows in the streamwise direction, never extends outward past the location of the maximum shearing stress. The region of the turbulent-non-turbulent interface next to the free-stream also grows in the streamwise direction but does not extend closer to the wall than the location of the maximum shearing stress. Thus, these two regions do not overlap. The separated flow field shows some profile similiarity for U, u, γ_p, and other fluctuation quantities, with the maximum fluctuation u_{max} or $(-\overline{uv}_{max})^{1/2}$ serving as a velocity scale and the distance from the wall to the maximum being the length scale. It behaves progressively more like a free shear mixing layer in the streamwise direction.

Figure 6 shows our most recent LDV measurements in the vicinity of separation [23]. $\gamma_p < 1$ downstream of the 127 inches location. A one-half power and a logarithmic velocity profile regions are distinct further on down-

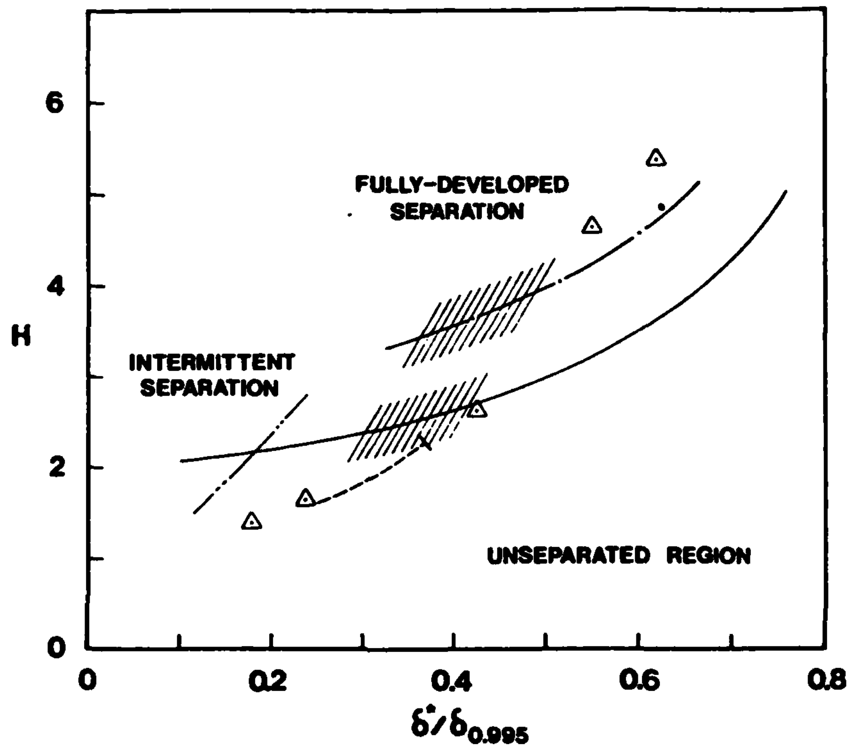

Figure 5.

Sandborn's correlation, H vs. $\delta^*/\delta_{0.995}$ Δ Simpson et al. [10]. Shaded area - data for intermittent and fully-developed separation [11]. Dashed line - path predicted by Perry and Schofield correlation [19]; solid line - intermittent separation; single dot line - fully-developed separation; double-dot line - data [9] for a diverging curved surface.

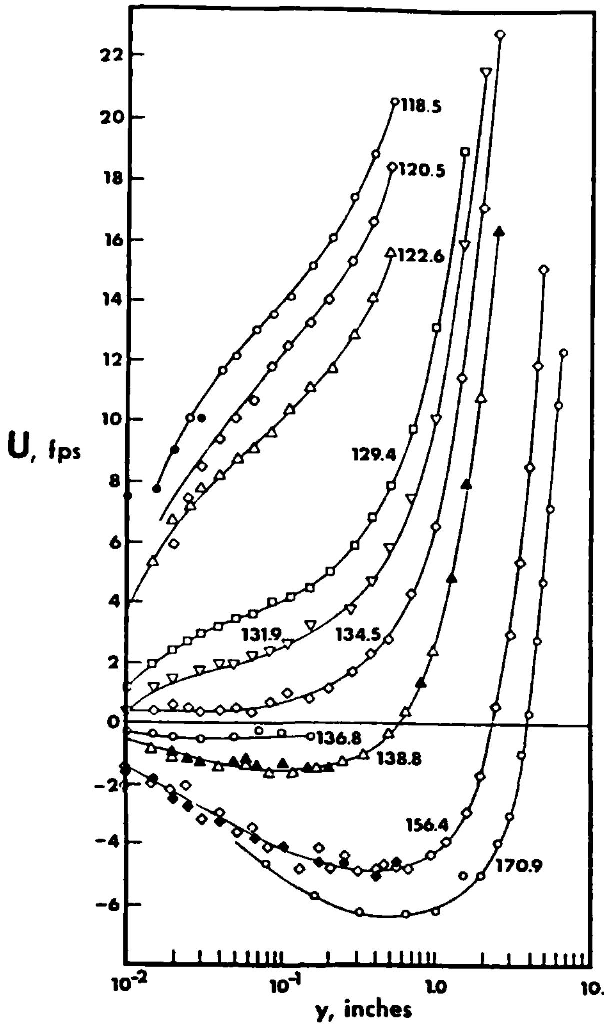

Figure 6. Mean velocity profiles at several streamwise locations for steady freestream separating flow [22,23]. Solid lines for visual aid only.

stream until the detachment (fully-developed separation) location at 135.5 inches. Further downstream, the mean backflow velocity profiles have similar shapes and appear to scale on boundary layer thickness δ. The backflow region is strongly dominated by turbulent fluctuations that are greater than or at least comparable to the mean velocities, as shown in Figure 7. Since the freestream flow is observed to be rather steady, this means that the near wall fluctuations are not mainly due to a flapping of the entire shear layer, but due to turbulence within the separated shear layer. The mean backflow in this flow and the earlier flow [10] appears to be just large enough to satisfy continuity requirements after the shear flow separates to minimize streamwise pressure gradients. γ_p never reaches zero in either flow, indicating that backflow is never present all of the time.

It appears clear to this writer that since the mean backflow is governed by the turbulence and by continuity requirements, that it is unrealistic to try to force the mean shearing stress $-\overline{uv}$ to be a function of the local mean velocity gradient. Eddy viscosity and mixing length models infer that the fluctuations in velocity are small compared to the mean flow and that mean velocity gradients are not much different from instantaneous velocity gradients. Unfortunately separated turbulent flows like the type studied at SMU do not satisfy these assumptions.

It does not appear that the "law-of-the-wall" type of velocity profile ($U^+ = f(y^+)$) based on a wall shearing stress can be valid for the backflow, unless significant turbulence energy production occurs near the wall. Turbulence energy balances deduced from the current SMU series of experiments indicate that an almost negligible amount of turbulence energy production occurs in the mean backflow region as compared to normal and shear stresses production in the outer region. Large-scaled turbulence diffusion appears to be the main mechanism of bringing turbulence energy into the wall region. Since the mean advection of turbulence energy appears to be small in the backflow region, dissipation must balance this influx by diffusion. Classical turbulence energy arguments [24] indicate that production must equal dissipation in a logarithmic region governed by the law of the wall, which is not satisfied by the mean backflow region.

Figure 8 shows a good correlation of the mean velocity profiles in the backflow region of the current SMU flow when normalized on the maximum negative mean velocity U_N and its distance from the wall N. A slightly poorer correlation results when δ is used instead of N. The law of the wall is not consistent with this correlation since both U_N and N increase with streamwise distance while the law-of-the-wall length scale ν/U_τ varies inversely with its velocity scale U_τ. Thus, it appears that representation of the backflow with the law of the wall does not have much basis.

D. Separation From Sharp-edged Bluff Bodies

The main obstacle to understanding this class of flows comes from the fact that the major separation occurs near the sharp edges of the body, with accompanying large variations in velocity and pressure around the detachment location. Here intermittent detachment is located very near detachment. Some type of Kutta

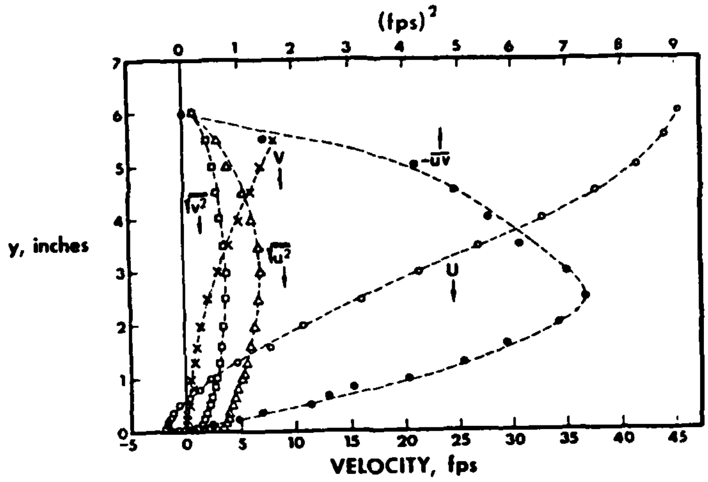

Figure 7. Mean and fluctuation velocity profiles for the 138.8 inches locaion [22,23].

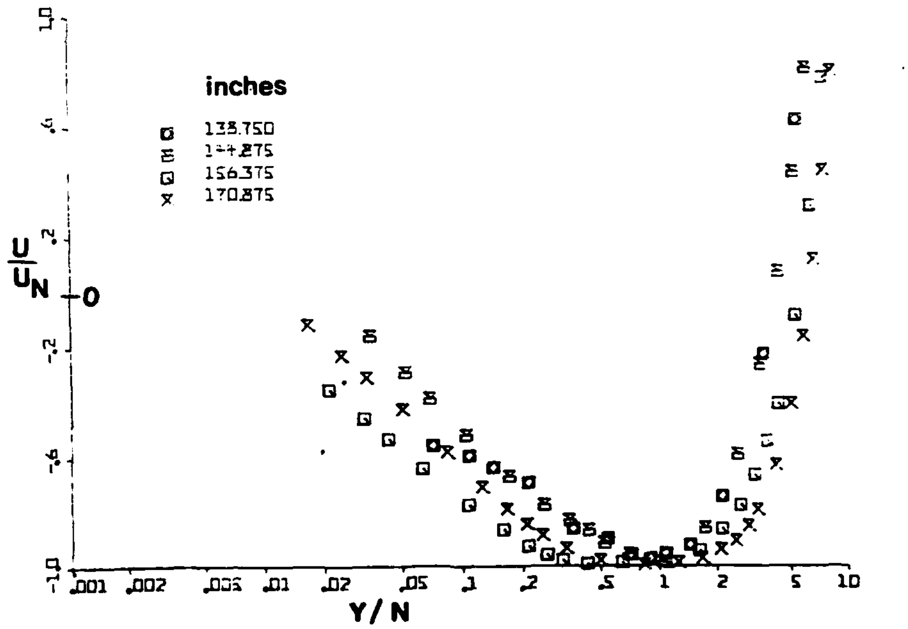

Figure 8. Backflow mean velocity profiles [22].

condition must be used to describe the flow in the vicinity of detachment, which is very difficult to define with the current lack of experimental data in this vicinity. Downstream of detachment the length scale of the energetic outer region flow is comparable in size to that of the backflow region. The zone of recirculating fluid is a substantial portion of the entire detached shear layer.

Gosman has pointed out that insufficient reliable data exist to define the structure of the backflow region. Future experiments should be on large-scale models using laser anemometry or other quantitative directionally-sensitive techniques. Moss et al. [25] have recently presented turbulence structure measurements for a backward facing step obtained with pulsed-wire anemometry. Unfortunately, no near wall measurements were obtained because of the large size of the probe.

Figure 9 shows some recent laser anemometer results for flow over an airfoil at a large angle of attack [26]. While detachment from this surface does not occur at a sharp edge, this flow contains many of the features of such a flow, such as comparable length scales in the outer shear flow and backflow regions. Mean velocity profiles obey a similarity distribution downstream of the quarter-chord point. The shape of the profile in the outer part of the backflow region is similar to that obtained in the current SMU experiments.

At a higher Reynolds number of 1.4×10^6 discrete vortices are shed from near the crest of the airfoil at regular time intervals. They initially move up and then move in the streamwise direction by the 15 percent chord location. The vortex speed accelerated from about one-half of the free-stream value near the crest to nearly the free-stream speed at the trailing edge. The vortex paths are less regular near the trailing edge, but the repeatability of the period of the vortex passage remains high from leading edge to trailing edge. While this vortex-shedding behavior is not yet completely explained, it emphasizes again the important influence that the flow behavior near detachment has on the downstream flow and the entire flowfield.

E. Three-dimensional Separation

Three-dimensional turbulent boundary layers near separation have an extra degree of freedom to move in a lateral direction that is not present in nominally two-dimensional cases. Only slightly three-dimensional pressure gradients are required to induce three-dimensional boundary layer flow. All known flows appear to be either of the swept or the shed vortex or focus types; no turbulent three-dimensional separation bubbles are observed.

The wall shear stress is zero only at singular points, as discussed in section 2 above. From this viewpoint three-dimensional cases are less complex than two-dimensional ones. Mean flow measurements are easier to make since pitot-static and hot-wire anemometer techniques can be used satisfactorily, but without great angular sensitivity. Hot-wire turbulence measurements are more difficult to obtain because the sensor must be properly aligned with the flow. Only relatively recent are measurements being made using the laser anemometer [27].

4. FLOW MODELING

The weaknesses and limitations of modeling turbulent separation largely reflect the same weaknesses and limitations of any other turbulent flow case. All methods that are used are "postdictive", to use Saffman's word, rather than predictive because so much experimental information has been used to develop them. Few, if any, of these methods apply to wide class of flows [28]. Non-dimensional correlations, zonal models, and numerical solutions for the Reynolds-averaged equations appear to be the useful engineering approaches for the next 10 years [28]. Large eddy simulation with subgrid closure and complete solution of the Navier-Stokes equations will remain research methods until significant advances in computation speed and cost reduction occur.

The objective of zonal modeling is to divide the flowfield into several regions, each dominated by a particular type of flow, and to analyze each region by the computationally optimum numerical technique for that region. No single turbulence closure model is the best for all regions, so one needs to use the best available for that region. In order to make the best use of available computer capability for large flowfields of interest, it is important that the following approaches be followed:

1. locally asymptotic solutions should be used in regions where the flow detail is known, e.g., the law of the wall should be used when applicable;

2. locally-fine computing meshes should be used in regions where large changes of terms in the governing equations occur;

3. curvilinear flow-oriented co-ordinates should be used so that relatively large grids can be used without sacrificing flow detail;

4. the simplest form of the governing equations that contain all important terms should be used; the simplest turbulence models that will work should be used.

Two general types of models for separated flows have been used: rotational and/or irrotational inviscid "simulations" for the entire flow field or inviscid/turbulent shear flow interaction models for the freestream and the turbulent shear flow. Most of this work has been done for steady two-dimensional cases, as described next, but some attention has been devoted to three-dimensional cases.

A. Inviscid Separated Flowfield Simulation

Several models of this type have been developed, each with some kind of ad hoc assumption about the separated flow pressure distribution or vorticity. The separated flowfield (BCDFE in Figure 2) was represented as a dead flow region in most applications to airfoils. Bhateley and Bradley [29] used an equivalent airfoil system consisting of a linearly varying vorticity distribution over the surface of each airfoil element to simulate the separated wake. The computed boundary-layer displacement thickness was superimposed on the airfoil contour to form an equivalent airfoil surface for each element. This procedure was iterated until convergence occurred. The flow downstream of a separation point was allowed to develop as a free-streamline flow on only that part of the equivalent airfoil having attached flow. The pressure distribution downstream of the separation was assumed constant and equal to that value of pressure obtained by linear extrapolation of the equivalent body boundary point pressures to the separation point. They used the experimentally obtained separation point.

Very good predictions of lift and pressure coefficient were made with this method as long as the free-streamline model satisfied the data. For low angles of attack, trailing edge separation was present for their test cases and pressure coefficient predictions in this regime were not good. When there was a long relaxation zone (AB on Figure 2) their estimate of the free-streamline pressure was also in error. They pointed out the deficiency of not having a wake model. In summary, their method did not include any pressure gradient relief model (for AB on Figure 2), no wake model, and used experimental data to locate separation. It still did a good job in many cases of predicting the pressure coefficient, which basically supported the free-streamline idea. Maskew and Dvorak [30] developed a similar model that was used to predict the gross features of the flow shown in Figure 9.

Jacob presented a similar type method for single airfoils [31] and for multiple-element airfoils with the capability of inclusion of ground effects [32]. Vortex and source distributions on the contour were used and a boundary layer calculation was made for the attached flow. (The location of transition was found to be as important as the location of detachment in these predictions.) The detachment point was predicted to be where H = 4, which as observed from Figure 5 is in good agreement with Sandborn's criterion for detachment (fully-developed separation) for low curvature bodies such as in the flow of Simpson et al. [10]. The displacement thickness effect was described as an outflow from the airfoil. The "dead air" or detached zone was simulated with a separation streamline that was required to be tangent to the surface beneath B on Figure 2, rather than tangential to the superimposed displacement thickness distribution at B, as it should be. The pressure was required to be equal at three special points of the separating streamlines, at the separation locations on the suction and pressure sides and at point C above the trailing edge. In addition, the pressure was allowed to vary "very little" between points B and C. Thus, the separation streamline was not exactly a free-streamline, but in practice was close to being one. A source distribution along the body in the dead air region provided the outflow in this region. The circulation-contributing part of the potential flow and the outflow were adjusted to obtain the equal pressures at the three points. Geller's [33] method for cascade flow is basically very similar to Jacob's [31] earliest procedure. The boundary layer displacement effect was assumed small and the simulated wake was assumed to have an infinite length.

This model of Jacob gives good predictions for the lift coefficient for free-streamline separation. Like Bhateley and Bradley, this method did not include any pressure gradient relief model at separation and any wake model. These authors pointed out that the pressure drag calculation is very sensitive to the dead air pressure value, much more so than the lift. They concluded that their dead air pressure prediction needed improvement to improve pressure drag calculations.

Jacob [14] modified his method to simulate the effect of the wake on the drag and lift. The position of a sink, whose magnitude equaled the source strength in the dead air region, was located in the wake with a simple algebraic model equation that produced good drag results for a wide variety of cases. A very important conclusion from this work is that the wake flow behavior strongly influences the drag.

Perry and Fairlie [34] simulated a separating and reattaching two-dimensional turbulent bubble as an inviscid region with constant vorticity. This model is partially justified since the vorticity in the outer region of the Perry and Schofield velocity profile correlation is nearly independent of distance from the wall for the upstream attached flow. The elliptic nature of the flow is reflected by the streamfunction equation. The inner part of the boundary layer and the effects of viscosity are neglected. Generally good agreement was achieved between experimental and predicted streamline patterns. They felt that the weaknesses of this simulation were due to the neglect of entrainment and the diffusion of vorticity.

B. Inviscid/turbulent Shear Flow Interaction Models

The approach in all of the models of this type is to simultaneously or iteratively calculate the inviscid potential flow and the separated turbulent shear flow. Various numerical methods have been used for the inviscid flow and various turbulence models in integral or finite-difference formulations have been used for the shear flow. Rather than review all procedures that are known at this writing, a representative sample of the physical models that are used will be discussed.

Two methods use an ad hoc assumption about the inviscid flow pressure. Woolley and Kline [35] calculated fully-stalled diffuser flows with the <u>valid</u> assumption that the pressure is constant downstream of detachment. An acceptable attached boundary layer calculation method is used upstream of detachment. The Sandborn criterion is used to predict detachment. The displacement thickness in the detached flow zone is treated as a free boundary with the same static pressure as that at the latest calculated detachment location. A Plemelj integral technique is used to evaluate the potential flow. Good results were obtained for fully-stalled flows.

Collins and Simpson [36] used the somewhat more generalized assumption that a <u>minimum freestream pressure gradient</u> is achieved downstream of detachment. This degenerates to the constant pressure assumption in the case of fully-stalled diffuser flows but also handles cases such as the SMU flows where a small residual positive pressure gradient remains after detachment. In this method an attached turbulent boundary layer procedure is used until intermittent transitory detachment (intermittent separation). The displacement thickness and displacement thickness gradient calculated at this location are used as initial conditions for the detached flow displacement thickness. A far downstream condition on δ^* is used that is physically realistic, e.g., that the direction of the displacement thickness approaches the direction of the far downstream potential flow. With these conditions, the potential flow is solved iteratively with possible displacement thickness distributions until one is found that satisfies the minimum pressure gradient condition.

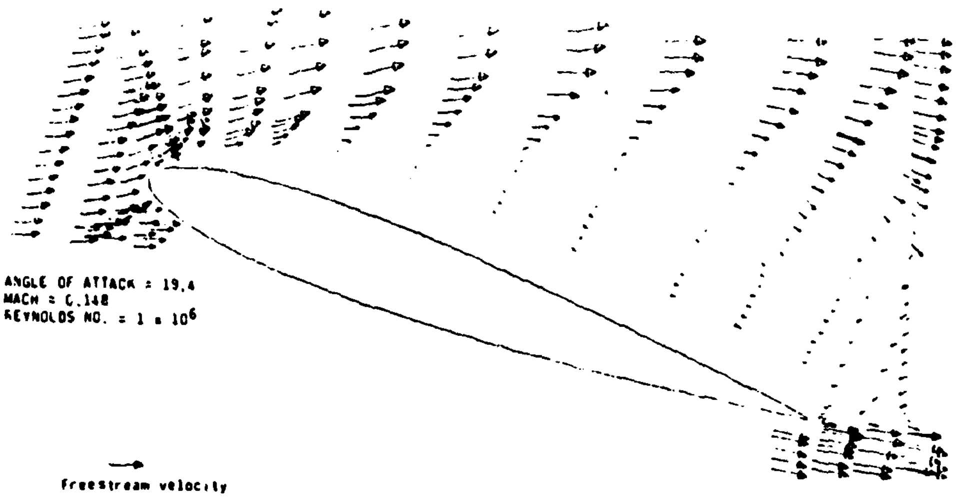

Figure 9. Low-Mach-number resultant mean velocity vectors for an airfoil with large separation [26].

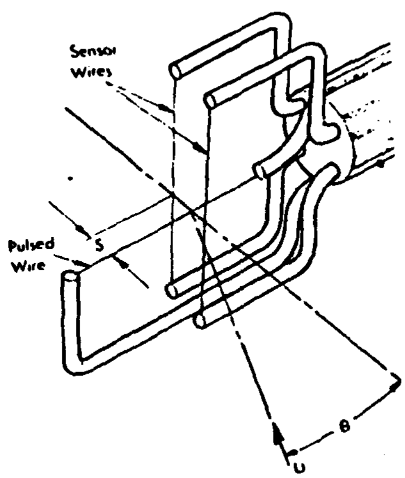

Figure 10. Schematic of the pulsed-wire anemometer [52].

Notice that neither of these methods require any turbulence model to predict the potential flow. Collins and Simpson used the resulting U and V velocity distributions at the boundary layer edge and calculated inward toward the wall. Only a continuity requirement was used in the backflow, but good estimates of the mean backflow resulted.

All of the other methods use a turbulence model for the entire detached shear layer that is tied to the local mean velocity gradient. This approach appears reasonable for the outer region but not the mean backflow, considering the discussion in section 3.C. above. Ghose and Kline [17] used the Plemelj integral approach for the inviscid freestream flow and an integral method with the law-of-the-wall and law-of-the-wake velocity profiles for the shear layer. An entrainment model and a shear lag equation with different constants upstream and downstream of detachment were used. Sandborn's detachment criterion was also used. Predictions of pressure rise in transitory diffuser stall were reasonably good but the backflow velocity profiles were not very good. Moses, et al. [37] used integral momentum and kinetic energy equations and the law of the wall and the law of the wake for the shear layer. These equations were solved simultaneously with those for the inviscid freestream in finite difference form by successive line relaxation. Predictions of pressure rise were good but backflow velocity profiles also need improvement.

Others [38,39,40] use a mixing length and/or eddy viscosity model in the backflow. Even with adjustment of turbulence model "constants" to fit one feature or another, these models do not predict simultaneously the backflow velocity profile, the streamwise pressure distribution, and the fact that length scales increase along the flow.

The NASA-Ames group solves the time-dependent, Reynolds-averaged Navier-Stokes equations in an explicit finite-difference method that uses an eddy-viscosity model [41,42]. The elliptic nature of the separated flow fields and the coupling between the viscous and inviscid regions are handled automatically. In contrast to iterative schemes, the solution is marched in time to a steady state if one exists. As discussed in section 7 below, this approach can predict some unsteady flow cases. Results for a circular arc airfoil in steady transonic flow are in good agreement with experimental pressure and skin-fricition data when small regions of mean backflow are present. However, for flows with larger regions of separated flow, it was stated [41] that improvements in turbulence modeling are required before good agreement with experiment can be expected.

The situation for prediction of separation from sharp-edged bluff bodies is in no better condition. The inviscid and shear flows need to be calculated simultaneously since the direction of the separating streamline at detachment cannot be specified a priori. Gosman also notes that the most obvious turbulence model weakness in current methods is the use of the law-of-the-wall velocity profile, especially near detachment and reattachment locations. He further notes that research on more general methods of modelling the wall layer will be beneficial.

It appears reasonable, in view of the experimental observations in section 3.C. above, to search for a backflow model not grounded on mixing length theory and a wall shear velocity U_τ scale, but on turbulence energy diffusion and dissipation processes and $(-\overline{uv})^{1/2}_{max}$ as a velocity scale.

Clearly, more experimental data are needed to define the structure of the backflow, if any fundamental improvement in prediction methods is to be made. The next generation of turbulence models should also try to predict γ_p to test further their validity, since data for this parameter are available and provide further flow information. In essence, we are in an impasse situation until further data are obtained that will reveal proper backflow model(s).

C. Three-dimensional Predictions

Three-dimensional turbulent boundary layers near separation are more complicated than two-dimensional flows in almost every way, except for the general lack of backflow beneath a given part of the outer region flow. The additional spatial variable makes the possible flow pattern more difficult to determine than in the two-dimensional case. The kinematic topological rules must be used to aid the selection of allowable flow patterns. Since "separation" means "breakaway" of the shear flow as discussed in section 2 above, significant interaction occurs between the three-dimensional turbulent and inviscid flows.

Unfortunately most known boundary layer prediction methods appear to have been validated only well upstream of separation, where only a small interaction occurs. At the now famous "Tronheim trials" [43], quasi-three-dimensional flows were calculated, in which only two spatial co-ordinates were required locally for fully three-dimensional cases. Rotta [44] has extended a two-dimensional $k - \varepsilon$ model to the three-dimensional case. In developing new methods, several groups are using advanced numerical techniques to deal with complicated body shapes and the large number of unknowns.

Varying degrees of success have been reported with different turbulence models near separation. The mixing length model appears to be inadequate for flow near separation on a swept wing. The eddy viscosity model does not appear to work well for flows with vortex separation. When only the shear flow inertia and vorticity are important, then fairly good predictions can be made with a poor turbulence model.

The time-dependent computational approach by the NASA-Ames group that was mentioned in Section IIB above has been applied to some three-dimensional steady-flow cases with encouraging results. For example, the three-dimensional interaction of a swept shock wave with a turbulent boundary layer was computed with better agreement with measurements than two-dimensional separated flow-field computations with a similar turbulence model [45]. This is probably because there appears to be no flow phenomenon present that resembles the reversed flow that is present for two-dimensional separated flows.

For large three-dimensional separated flow regions the situation is even more complicated. When the separated flow has a well-defined structure, as in the case of leading edge vortices, theories predominantly based on an inviscid approach can be developed with some success [46]. However, when the location and formation of the three-dimensional separated region is critically dependent on the interaction of the turbulent and inviscid flow-fields, no method seems to be applicable today.

Even more so than in the two-dimensional case, there is insufficient data available to describe the structure of swept and shed vortex types of flow with large regions of separation. Peake has suggested that the external or internal flow over an axisymmetric duct at an angle of attack would make a good case from which to learn much about the turbulence structure. Turbulence measurements are also needed for separation from a cone at an angle of attack since none are currently available.

5. MEASUREMENTS AND TECHNIQUES

The general philosophy toward measurements should be that only techniques that are sensitive to the magnitude and direction of the flow and have sufficient spatial resolution should be used. No comparisons of predictions should be made with experimental data obtained by techniques that lack these requirements for a given flow zone of interest. Flow visualization should always accompany quantitative measurements. Redundant measurements using different techniques should be made when possible. Measurements of as much flow detail as possible should be made in experiments used for developing turbulence models. Other measurements, in perhaps more practical flow conditions, should be made in enough detail to permit validation of these models.

Table 1 represents a brief comparison of some measurement techniques for separated flow [47]. Several additional comments are needed. Rubesin et al. [50] used a fine hot-wire on the surface of a polystyrene substrate for a surface heat transfer gage. Since the thermal conductivity of the polystyrene is about a seventh the value of that for commonly used quartz, a significantly lower heat loss to the substrate results and the effective size of the sensor is greatly reduced. This important development permits the calibration of this type gage in laminar flow for direct use in turbulent flow. Higuchi and Peake [51] have developed and used similar surface gages to determine the magnitude and direction of the surface shearing stress in three-dimensional flows.

The pulsed-wire anemometer probe, shown schematically in Figure 10, has three fine wires. The central wire is pulsed with a short duration voltage pulse that in turn heats the fluid that is passing over that wire at that time. This heated fluid is convected away with the local instantaneous velocity of the flow. The other two wires on the probe are operated as resistance thermometers. They are used to measure the time for the heated fluid tracer to travel from the pulsed wire to one of the other wires. The component of velocity that is perpendicular to all three wires is measured, being the distance S between each wire divided by the pulse travel time. The flow direction is determined by which wire detects the thermal pulse.

Table 1

Brief comparison of some measurement techniques for separated flow.

	Quantity	Method and References	Comments
1.	Surface shear stress	Preston tube [48]	a,b,d,f
		Floating element [49]	c,f
		Surface heat transfer [50,51]	b,g
2.	Velocity	Pitot-static	a,b,e,f,d,m
		Hot-wire array or hot-films on substrate(s)	a,b,d,m,n,s,t
		Laser anemometer [23]	h,l,n,o,r
		Pulsed-wire anemometer [52,53]	d,l,m,n,q
		Flying hot-wire [15,54]	d,h,j,k,n,o,s,t
		Reverse flow sensing hot-wire [55]	i,j,p,q,s,t
3.	Static pressure	Surface fluctuations [56]	
		Fluctuations in flowfield [57]	a,d,i,j,k,l,m,n

List of Comments

a. Not directionally sensitive in presence of flow reversal; can be used in most types of three-dimensional flow with proper alignment.

b. Difficult to interpret in zones of high local turbulence intensity.

c. Measurements need correction for pressure gradients.

d. Can cause interference with flow and/or itself, especially near a wall.

e. Cannot measure turbulence.

f. More reliable at high velocities.

g. Requires careful calibration.

h. Very expensive to implement.

i. Confidence in method low because of limited reported experience.

j. Not on the market, must be custom-built.

k. Mechanically very complex in some applications, perhaps impossible in internal flows.

l. In air flow turbulence, data obtained by sampling individual particle speeds rather than as continuous time series.

m. Large probe volume.

n. Problems with measurement very close to solid surfaces.

o. Measuring system and flow field must be closely integrated and require expensive, custom design of traversing equipment.

p. Appears to preclude measurement of cross-correlation, $\overline{uv}$.

q. Basic limit on maximum velocity measurable with presently known configurations.

r. Requires seeding with particles.

s. Requires clean fluid for stable, long-time calibration.

t. Requires careful management of fluid temperature.

The "flying hot-wire anemometer" [15,54] is swung through the flow at a known velocity and position as a function of time. Basically this introduces a sufficiently high bias velocity to the hot-wire so that the flow with respect to the wire is in an approximately known direction. Subtracting the bias velocity from the signal velocity determines the unknown fluid velocity contribution. Many passes through the flow are required to obtain enough samples and sophisticated computer reduction is required.

Laser anemometry [23] holds the best future for providing accurate, continuous, and simultaneous measurement of all three velocity components in a small focal volume of interest. At the time of the 1976 assessment of the use of LDA for separated flows [47], discontinuous and intermittent LDA signals of variable quality were obtained from particle seeded flows. In 1978 it is now possible, but very expensive, to instantaneously measure all three components of the velocity with a low-powered laser and obtain a nearly continuous signal. Photon correlation signal processing has reached maturity [58,59]. Virtually no seeding particles are required--natural particles are sufficient for light scattering. Problems of particle lag are minimized. However, in any case, there is still the uncertainty of how the near wall turbulence phenomena affect the motion of particles and thus produce biased LDA signals.

6. Unsteady Effects

While all turbulent flows are inherently unsteady, the term "unsteady" will mean here an organized time dependent motion in contrast to the unorganized motion of turbulence. Periodic flow is by far the most common organized time-dependent motion. Two types are possible: one where a periodic flow condition is imposed on a turbulent boundary layer; and the other where the turbulent flow interacts with adjacent flow regions to set up a quasi-periodic motion.

Dynamic stall on helicopter and compressor blades is an example of the first type [60,61]. The transitory stall in a diffuser which was discussed above is an example of the second type. Recently [42,62,63], an induced quasi-periodic motion was observed under some conditions (Figure 11) in shock-induced separation from an airfoil for steady transonic flow upstream. Shock-induced and trailing edge separation alternated between the two sides of the airfoil.

Calculations using the time-dependent Reynolds-averaged Navier-Stokes equations with a quasi-steady mixing length turbulence model gave fairly good predictions of the oscillation period, which was long compared to turbulence time scales. In this case the standard deviation of the period was about 2%, while that for transitory diffuser stall is about 40% [18]. This indicates that an induced organized unsteadiness can still have varying degrees of periodicity. An important practical implication of the airfoil result is that it may be possible to predict when airfoil buffet will occur.

In cases where the period of the unsteadiness is relatively long as compared to turbulence time scales, it should be acceptable to use the quasi-steady approximation that the turbulence structure is unaffected by the unsteadiness. When the frequency of the organized unsteadiness is comparable to energy-containing turbulence frequencies, this approximation cannot be used. For example, Acharya and Reynolds [64] have shown that available turbulence models fail for the latter conditions in an unseparated channel flow.

As mentioned above, the bursting frequency of the energy-containing motions in a turbulent boundary layer decreases as separation is approached. Thus, while a quasi-steady turbulence model may be adequate far upstream of separation, more interaction between the organized and turbulent unsteady motions occurs downstream [65,66]. Until recently little experimental data were available for unsteady turbulent boundary layers. Data [66,67] now indicate that the quasi-steady assumption is adequate away from the wall when the energy-containing turbulence frequencies are well away from the periodic frequency. In the near wall region significant non-quasi-steady flow behavior occurs [66].

While the quasi-steady turbulence models can be used with caution in near term prediction efforts, a deeper understanding of organized unsteady effects is needed from experiments. As mentioned below some imposed periodic motions appear to have some benefit for separation control.

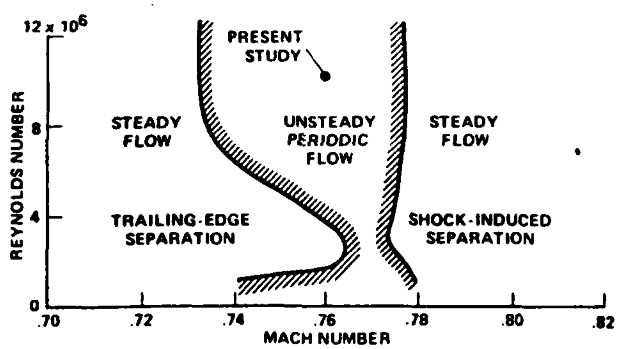

Fig. 11 Experimental flow domains [62].

7. Control of Separated Flow

The minimum requirement for a separation control device is that it improve the performance of the flow device of interest enough to warrant its installation. Design constraints decide which control can be used. In essence, boundary layer control devices either inject tangential momentum laden flow, remove momentum deficient fluid, or cause greater entrainment of energetic free-stream fluid into the boundary layer for the desired result [68].

Tangential injection is effective in preventing separation [70], but is avoided by manufacturers because of flow ducting and energy requirements. Vortex generators and slightly loaded sharp-edged vanes that control separation by mixing are preferred by these manufacturers because they are relatively simple to add and to change and require no additional energy source. Injection of air normal to the flow surface at discrete locations has the same effect as a sharp-edged vane [71].

Nevertheless, there are still some cases where tangential injection can be useful. For example, vanes, flaps, and vortex generators probably cannot effectively control dynamic stall on a helicopter blade for two reasons. Considerably increased drag would be realized during the part of the cycle that stall does not occur, unless a mechanism to retract these protuberances into the blade is used during that time. More importantly, due to the thick unsteady separated flow that accompanies stall, these protuberances would be mixing low momentum fluid and not energizing the stalled flow.

The merits of several injection arrangements have not been fully investigated. Recent work [72] indicates that about 30% lower tangential injection momentum and mass flowrate are required for a given boundary layer control benefit when an asymmetric velocity profile jet is used. In essence, the portion of the jet flow near the wall has a significantly lower velocity than the outer part, so less momentum is wasted on unnecessarily large surface shearing stresses. Turbulent flow prediction methods for uniform and asymmetric velocity profile jets are fairly well developed [72,73].

Little information is published on pulsating tangential wall jets. Only two previous studies are known. In these cases the flow abruptly increases to a constant maximum value and then abruptly decreases to zero flow a short time later. A discrete vortex is formed and moves downstream along the surface [74]. A 50% reduction in the mass flowrate required for a given control benefit was achieved by Oyler and Palmer [75] as compared to steady blowing. The effectiveness was attributed to its improved ability to entrain and mix with the surrounding fluid, which was primarily due to the greater jet velocity produced for a given average mass flowrate. The boundary layer quickly attached the surface when the pulsating jet turned on, but detached slowly when the jet was turned off [76]. As long as the discrete vortex that was formed by the pulsation remained above the surface, there was attached flow on the surface.

The above flows are two-dimensional in the mean. There exists the possibility that spatially-intermittent blowing, from say a series of round jets or from a continuous slot blocked at regular intervals with spacers, would be more effective than blowing with the same momentum from a continuous two-dimensional slot. The basis for suggesting this comes from observations of the delay of separation behind vortex generators. With counterrotating generators the kinetic energy of the mean flow near the surface is enhanced downstream of each diverging pair of vanes and reduced in the passages on either side. These effects are due to the counter-rotating vortices near the surface. The net effect of such mixing is however beneficial in delaying global separation. It is therefore likely that local separation has to be prevented only at periodic spanwise positions to avoid complete breakdown of the flow.

A "whistler nozzle" [77] for the wall jet lip may also improve the performance of these cases. This device consists of a convergent nozzle section, a constant area section, and a step change to an exit section with a larger constant area. The exit section excites a standing acoustic wave which greatly increases mixing near the jet. Work is needed to verify this possible improvement.

CONCLUDING REMARKS

The preceding sections have given an indication of the types of approaches that have been and are being pursued to understand and predict separated turbulent flow. A key question, that was a central theme for the Project SQUID Colloqium, was "Is there anyway or anything that can be used to make a significant breakthrough in the prediction of turbulent separated flow?' Unfortunately, no quick and inexpensive approach appears to be likely. However, much better experimental measurement techniques and computational capability are available than in the past. The key to future developments lies in detailed benchmark experiments that will unlock the structure of separated flows in two and three dimensions. Without these data to validate models, predictors will be unable to make any real progress.

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APPENDIX I

Colloquium on Turbulent Separation
Southern Methodist University,
Dallas, Texas, USA

"POSITION PAPER"

by

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BACKGROUND

Comments are based on interest in the field of transport-wing design and development with applications both in the low speed and transonic speed regime. The relation with turbulent flow separation can be expressed in the following problem areas, listed in order of increasing difficulty :

item 1 does the boundary layer (on the wing surface) separates for a prescribed pressure distribution ?

item 2 how will the pressure distribution be affected by the development of the boundary layer, including small regions of separated flow (beneath the shock, at the trailing edge, at sharp corners in slats or at flap locations).

item 3 what are the aerodynamic characteristics when large regions of separated flow are present, like maximum lift prediction, lift-divergence boundaries and buffet-loads.

Each of these problem areas will be discussed shortly with respect to achievements and outstanding questions. Some typical references are given without any intention to be complete.

Item 1 - Separation Prediction

Separation prediction using the boundary layer equations is nowadays a solved problem for two-dimensional flows. For three-dimensional flows significant improvements have been made over the last 5 years, but the problem is much more complex. Specific points are

- the need for advanced numerical methods to deal with complicated body shapes and the large number of unknowns;
- the complicated topology for three-dimensional separations (ranging from quasi two-dimensional separation lines to fully three-dimensional lines of convergence and singular points);
- the need for improved turbulence modelling.

Numerical techniques to cope with the first point are available. As an example NLR is developing a calculation method for three-dimensional turbulent boundary layers using appropriate physical scaling and an implicit, higher order numerical scheme.

Some examples of the complicated topology of three-dimensional separation are given in figure 1 taken from a theoretical study of separation near a wing root. This kind of flow represents a severe test to the mathematical representation and numerical procedure of the calculation method.
There is some need for improved turbulence modelling (see ref. 1) but deviations from rather simple two-dimensional models (like eddy-viscosity or the turbulent energy concept) are expected to be small in many practical applications.

Item 2 - Small and Strong Interactions

The coupling of boundary layer methods and potential flow methods for attached flows is a standard procedure for two-dimensional flows and is beginning to be explored in three-dimensions. The problem is solved insofar boundary layer theory holds: small interactions can be treated in an iterative way. Locally, however, the interactions may be much stronger. A typical example is the trailing edge problem. In most calculation methods the trailing edge (Kutta condition)is treated in an heuristic way (see for example ref. 2). A sound approach to this problem for two-dimensional flows is obtained with the method of matched asymptotic expansions (see Melnik, ref. 3). This approach helps much to understand the physics of the interaction process. As an example Melnik shows for (almost) symmetrical trailing edge flows that the turbulent structure is not a critical quantity, provided the condition of the turbulent boundary layer at the start of the interaction is well known. Also the potential flow and viscous flow are critically dependent on each other and must be solved simultaneously, a situation that might be called strong interaction. Other examples of strong interaction are shock-wave boundary layer interaction and small regions of separated flow on the profile surface.

Although the method of matched asymptotic expansions is quite powerfull, its use up till now has been restricted to relatively simple two-dimensional situations each of them requiring an elaborate mathematical analysis.

A much more general approach is obtained by solving the complete Navier Stokes equations in the entire flow field and this has become almost practical in two-dimensions (ref. 4), although still requiring large amounts of computer time. An assumption must be made for the turbulence model and evidence up till now has revealed that this assumption might be quite critical. During the last 10 years some generalised turbulence models have been proposed (ref. 5) but none of these seems to be really general. The construction of a turbulence model has always been the result of a combination of physical intuition and a lot of empiricism based on careful experimentation (A good example of this is the development of Bradshaw's turbulent kinetic energy method). In some flows large "eddy's" are dominant (like wake flows), in others the small scale structure is important (the wall region of a turbulent boundary layer). Extra rates of strain (curvature, strong acceleration or deceleration) might play a dominant rôle in certain classes of flows. A generalised turbulence model must be able to describe all these phenomena in great detail and it is highly unlikely, even if we know roughly by careful experimentation which processes are important, that we are able to combine them in one single model.
There is one other draw back to the solution of the complete Navier Stokes equations. All the interactions are treated on an implicit way. Details of the interaction process are not revealed. The physical experiment is replaced by a numerical experiment. However, if one wants to control the physics (e.g. lower the drag, increase the lift, control the shock-wave movement etc.) explicit information about the different interaction processes is needed.
In order to solve the Navier-Stokes equations on two-dimensional flows already large amounts of computing time are necessary. The extension to complicated three-dimensional flows will require an order of magnitude more computing time. The viscous flow itself, however, will be confined to a relatively small part of the flow field, however strongly interconnected with the development of the non-viscous flow field.

The above arguments lead to the conclusion that "piece-wise" solutions must be found for certain regions of the flow. Each of these regions might require its own equations combined with a specific turbulence model, developed after careful experimentation. These "piece-wise" solutions must be "patched" together. to arrive at the complete solution. In this "patching" process the basic interactions must be described physically in an explicit way. The large draw-back to this approach is the low degree of universality resulting in a large effort for program organisation. There may be some prospects however in the use of a universal formulation for the local viscous flow regions (apart from the turbulence model) like Navier-Stokes or "parabolised" Navier Stokes equations (refs. 6, 7) combined with a general frame-work to represent the interactions with the non-viscous flow.

Item 3 - Large Regions of Separated Flow

The prediction of off-design boundaries like maximum lift is of great practical interest. In a number of applications for two-dimensional flows (e.g. refs. 8,9) rather crude assumptions seem to be sufficient to describe qualitatively separated flow regions in a correct way (like the free streamline approach with certain restrictions on the pressure in the separated region or the shape of the region of re-circulating flow). It is not quite clear if the details of the turbulent flow in the separated region are of critical importance. It is clear however that other factors will play a dominant rôle like transition, prediction of bubble-formation and bubble-burst and local compressibility and curvature effects. Much more experiments are needed to assess the validity of the different calculation methods. Much more detailed experiments are needed to increase the understanding of details of the flow like transition or bubble burst (a good example of what is needed is ref. 10).

For three-dimensional flows the situation is even more complicated. When the separated flow has a well-defined structure, as in the case of leading edge vortices, different theories, predominantly based on an inviscid approach, are being developed with an increasing success(see e.g. ref. 11). However, when the location and formation of the three-dimensional separated region is critically dependent on the viscous non-viscous interaction, as in the case of a transport-type wing past maximum lift or lift-divergence, no method seems to be applicable today and one must rely on windtunnel tests.

To conclude these short comments it is interesting to refer again to figure 1. Although one is able to predict theoretically that the boundary layer will separate (left part of figure 1), the calculation of the complicated flow field that results from the viscous interaction (right part of figure 1) is still a long way to go.

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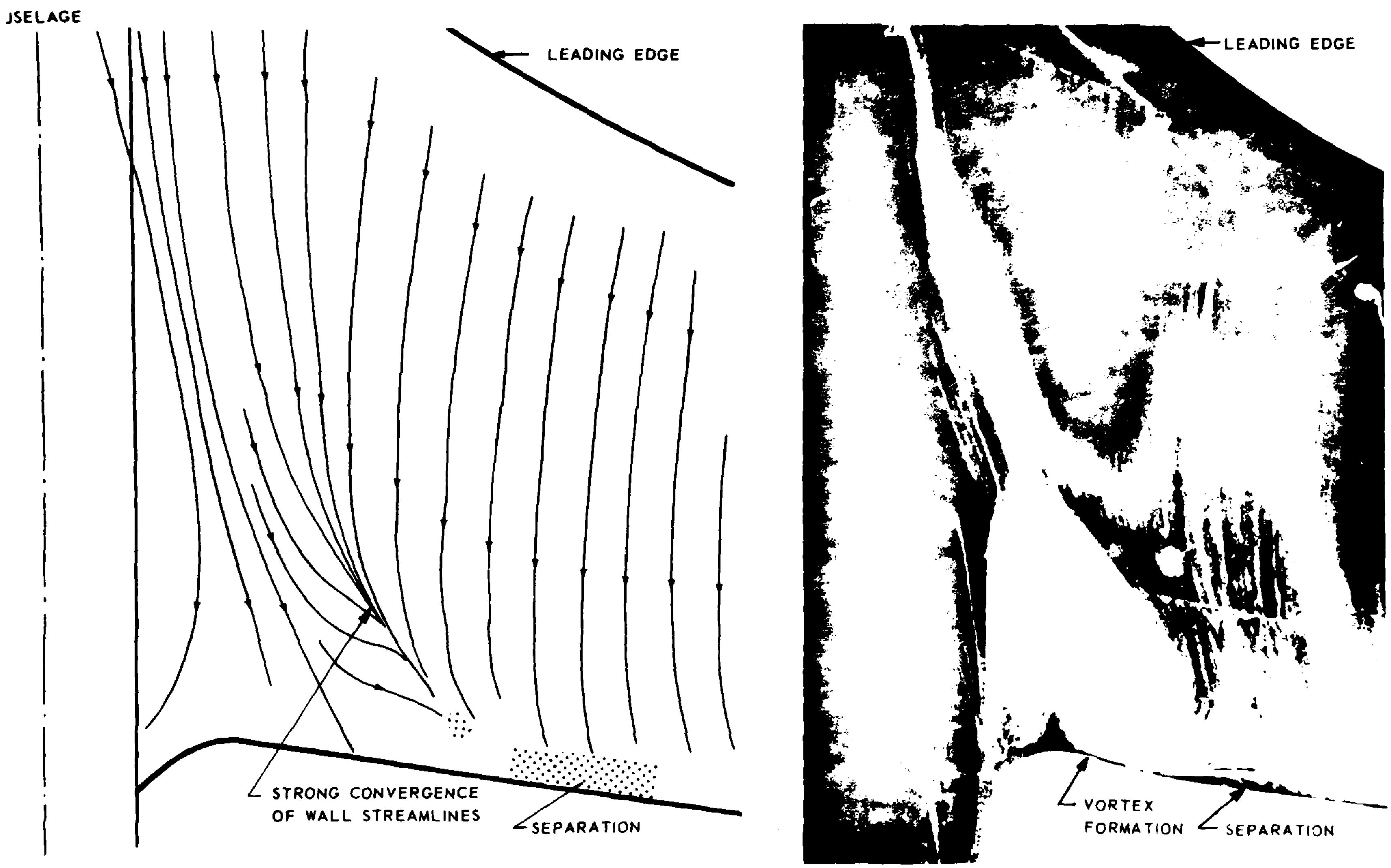

Figure 1   Surface flow patterns near a wing root calculated and observed in the windtunnel

Turbulent Flow Separation from Sharp-Edged Bluff Bodies: 'Position Paper' for Project SQUID Colloquium on Turbulent Flow Separation

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1. Introduction

This brief 'position paper' focuses on the problem of predicting turbulent flow separation from bluff bodies such as occurs, for example, downstream of an abrupt enlargement in a duct (Fig. 1a) or in the vicinity of surface-mounted prismatic obstacles (Fig. 1b). Although separated flows of any kind are difficult to predict, this particular class has been singled out here because in addition to being of considerable practical importance (e.g. in connection with the performance of bluff-body flame stabilisers in gas turbines or, at the other end of the size scale, with wind loadings on large buildings) it also appears to be the least tractible of all separated flow phenomena to available prediction methods.

The main obstacles to the analysis of this class of flows stem from the fact that the major separation occurs at, or very near, the sharp edges of the body, with attendant steep variations in velocity and pressure around the separation location. Indeed, as is well known, potential flow theory predicts that for a sharp corner an infinite pressure gradient is required to turn the flow which undergoes infinite acceleration in so doing, while creeping flow theory shows that even in the absence of abrupt turning viscous effects also give rise to steep pressure gradients, with the separation stream-lines trajectory being determined by phenomena occuring within a 'Stokes radius' $r_s \equiv \nu/U_\infty$ of the corner, ν being the kinematic viscosity of the fluid and U_∞ a representative velocity of the external flow.

The task of prediction is alleviated somewhat in the example of Fig. 1a by the fact that the oncoming flow is, firstly, confined and, secondly, directed along one of the intersecting walls forming the corner: this causes the separation streamline to leave the corner more or less parallel with the oncoming flow, as indicated in the diagram, which in fact shows the predicted velocity field obtained by Ideriah (1) using the type of method described in section 2.1 below. That tolerable accuracy is achievable in these circumstances is demonstrated in Fig. 2, where Ideriah's predictions of the velocities crossing the mid-plane of the cavity are compared with the experimental data.

If by contrast the approaching flow is both unconfined and not directed along one of the walls forming the corner, as in the example of Fig. 1b, then the separation streamline parts at an angle which difficult, if not impossible, to specify a priori. Not surprisingly this situation turns out to be far less amenable to prediction, as will be demonstrated shortly: for this reason attention will hereafter be focussed on this case.

2. Important development

2.1 Prediction methods

With the exception of those analytical studies based on potential and creeping flow models respectively, analyses of bluff-body separated flows have relied on finite-difference solutions of the governing differential equations of motion, supplemented, in the case of turbulent flows, by the equations of a 'turbluence model'.

Almost without exception standard finite-differencing practices such as those described by Caretto et al (2) and Hirt et al (3) have been employed in approximating the equations of motion, the main concession to the presence of the corner being sometimes to concentrate the computational grid in its vicinity. (A further elaboration was introduced in the laminar-flow study of Kiya and Arie (4) in the form of an elliptical coordinate frame fitted to an elliptical body, the idea being that an accurate simulation of a thin bluff body could be obtained by stretching the ellipse axis perpendicular to the incident flow: however this seems to be the sole example of this approach).

On the turbulence-modelling side, the few turbulent-flow predictions made thus far have all been obtained with the aid of the 'k-ε' model in the 'high Reynolds number' form described by Launder and Spalding (5), in conjunction with the Couette-flow-based matching laws for the wall layer described in the same reference.

2.2 Applications

Although the present interest is in turbulent flows, it turns out that there are some pertinent lessons to be extracted from the efforts to predict laminar separation from the leading edge of unconfined sharp-edged bluff bodies: accordingly this information will be examined first.

Fig. 3 is an extract from a paper by Castro (6) describing calculations of laminar flow past the configuration of Fig. 1b. Plotted are the predicted trajectories of the separation streamlines corresponding to two different Reynolds numbers (10 and 100) and various differencing schemes, including the relatively recent flow-oriented 'skew' scheme proposed by Raithby (7). These results were all obtained with the same, comparatively fine computational mesh comprising some 1450 points: yet there are significant differences. Some of the discrepancies are no doubt due to numerical diffusion (which will tend to cause early reattachment) but it is also clear that differences also arise near the separation point itself, which are probably attributable to inadequate resolution there. Regretably, and somewhat surprisingly, it would appear that no experimental data exist to define the correct trajectory, although it will most probably lie closest to the prediction corresponding to the largest reattachment length.

In the light of the above observations it is perhaps to be expected that the predictions for turbulent flow in like circumstances obtained by Vasilic-Melling (8) with the kind of turbulence model described above and some 900 grid points seriously underestimate the reattachment length of the downstream separation zone, as is shown in the comparison of Fig. 4 between measured and predicted streamline patterns, (the data being those of Good and Joubert (9); similar results are obtained with data from other sources. The more detailed plots of Figs. 5 and 6 show that the upstream velocity and pressure distributions are predicted reasonably well, but the downstream distributions of these quantities show very poor agreement. Although it was originally thought that the discrepancies were not numerical in origin, subsequent experience has shown that the inferences drawn from the numerical accuracy tests performed at the time were incorrect. This latter conclusion is reinforced by the fact that plausible variations in the turbulence model constants of the kind indicated in Fig. 6a made during the study could not produce changes of the magnitude required to procure reasonable agreement.

Similar comparisons made by Vasilic-Melling between measurements and predictions of <u>three-dimensional</u> flow around a surface-mounted cube-shaped bluff body produced similar results, as is shown by the plot of the velocity field in the plane of symmetry of Fig. 7, the upstream and downstream velocity profiles of Figs. 8 and 9 respectively and the surface pressure distributions of Fig. 10. Although it was heartening to see in this case certain characteristic features of these flows reproduced such as the overall separation pattern around the body (Fig. 7) and the formation of streamwise vortices in the wake (Fig. 11), it is nonetheless clear that quantitative agreement is inadequate for all but the upstream region.

It is evident from both of the turbulent flow examples presented above that, as in the laminar flow case, poor prediction of the initial separation angle (cf Figs. 4 and 7) is an important contributor to the large errors which occur downstream. In the light of the laminar flow experience and the unlikelihood that turbulence modelling errors could be influential near the leading edge, (since the oncoming flow is essential inviscid) it must be concluded that once again the fault lies with the finite-difference solutions. It is also reasonable to suppose that other numerical solutions based on similar differencing practices are similarly affected.

3. Suggestions for further research

3(a) Numerical analysis

Success in predicting this class of flows evidently hinges on obtaining adequate resolution of the corner separation, which is no eary task. However the following three ideas seem promising, applied either individually or in combination:

(a) <u>Use of 'locally asymptotic' solutions to the equations of motion</u>: the idea here is to obtain analytical solutions to the equations valid in the immediate vicinity of the corner such as those reported by Weinbaum (10); and to then build their implications into the finite-difference equations for this region. The analytical solutions will of necessity be approximate but it is believed that they will nonetheless form a more suitable starting point than the simple profile assumptions inherent in standard finite-differencing schemes. It should also be said that this proposal seems to be the only feasible route to simulating the experimentally-observed (11) sensitivity of these flows to rounding of the corners.

(b) Introduction of locally-fine computing meshes: here the proposal is to locally refine the computing mesh in the corner region, as illustrated in Fig. 12, and thereby achieve better resolution. Although conceptually simple, such refinement introduces complexities into the solution of the finite-difference equations and more importantly, into their formulation where the fine mesh adjoins the coarser one.

(c) Adoption of flow-oriented coordinates: this proposal has already been tried to some extent by Kiya and Arie (4), without great success, (they were unable to obtain grid-independent solutions), although their mesh arrangement was not optimal. The arrangement of Fig. 13 might however improve matters by reducing numerical diffusion in the critical fast-moving flow as it rounds the corner. In this arrangement, the forward part of the mesh roughly corresponds with the potential flow streamlines, while the downstream part is roughly aligned with the shear layer. The generation of such a mesh could be done in a self-adaptive way, although for initial explorations a trial-and-error approach would probably suffice.

The above comments should not be taken to imply that the numerical accuracy attainable elsewhere in the flow is regarded as satisfactory: it is just that in this particular instance the corner errors probably outshadow those occurring elsewhere.

3.2 Experiments

Further experiments are required to fill existing gaps about the behaviour of these flows particularly concerning situations like that of Fig. 1b. There is an obvious need for detailed laminar-flow measurements for this configuration in order to provide a well-defined testing-ground for numerical procedures free from the additional complexities of turbulence.

The main gaps on the turbulent-flow side relate to the corner itself, where the available data are deficient in two respects; firstly the resolution around the corner is poor due to the relatively small size of the body in relation to the resolution of the measuring instruments.

Secondly, most studies have employed hot-wire anemometry (see e.g. (9), (12)), whose deficiencies in separated flows due to uncertainties in flow direction and high turbulence levels are well-known. The application of techniques such as laser-Doppler anemometry can in principle overcome these deficiencies as has already been demonstrated by Durao and Whitelaw (13): however they too were limited in resolution by the scale of their experiment. What is needed are similar experiments on large-scale models, coupled with measurements of the surface pressure distribution near the corner.

3.3 Turbulence modelling

Although definitive assessment of the performance of turbulence models in these circumstances must await the developments outlined above, it is already possible to identify features of the model employed by Vasilic-Melling and others which are unlikely to be satisfactory. Perhaps the most obvious of these is the use of the one-dimensional Coutte-flow-based matching laws for the wall layer, which are unlikely to be correct in regions of strong acceleration and streamline curvature such as occur around separation and reattachment locations. This deficiency is also important in connection with the prediction of 'simpler' kinds of separated flow, especially where surface heat transfer is of interest. Clearly therefore research on more general methods of modelling the wall layer is bound to be beneficial.

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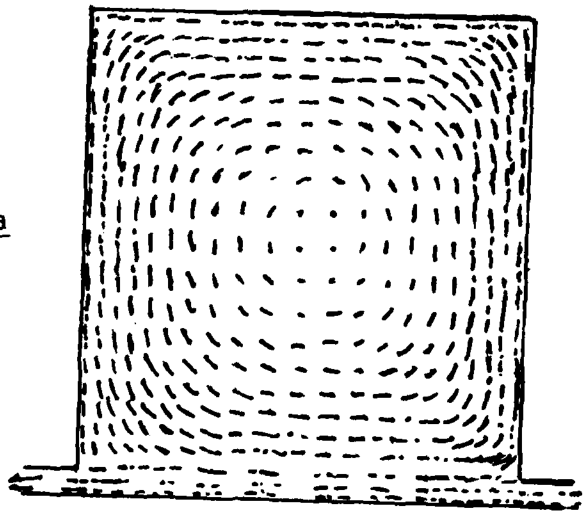
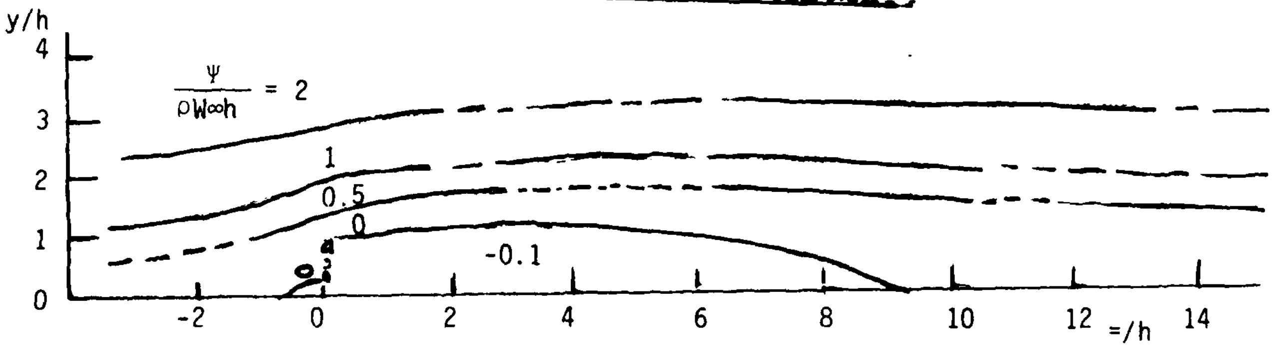
Fig. 1a





Figs. 1a & 1b Illustrations of two classes of problems involving separation from sharp-edged bodies.

a. Cavity flow, showing velocity field prediction of Ideriah (1).

b. Flow over surface-mounted fence, showing streamline prediction or Vasilic-Melling (8).

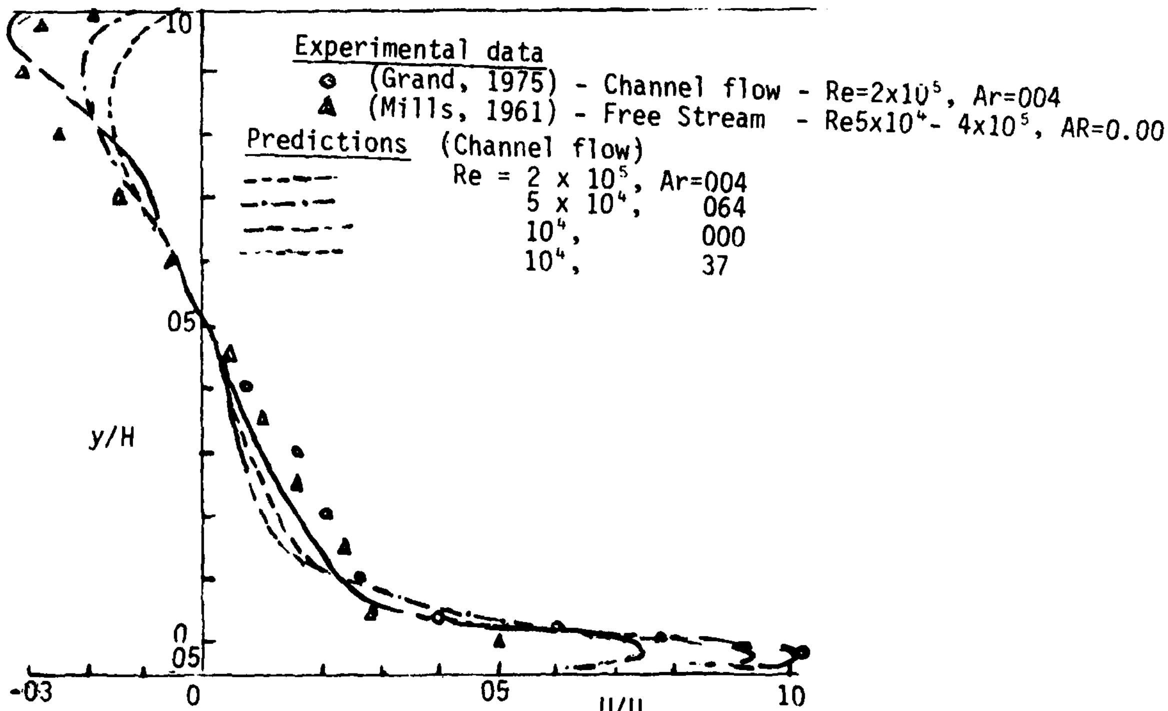


Fig. 2 Comparisons between measured and predicted velocity profiles in a cavity flow, from Ideriah (1).

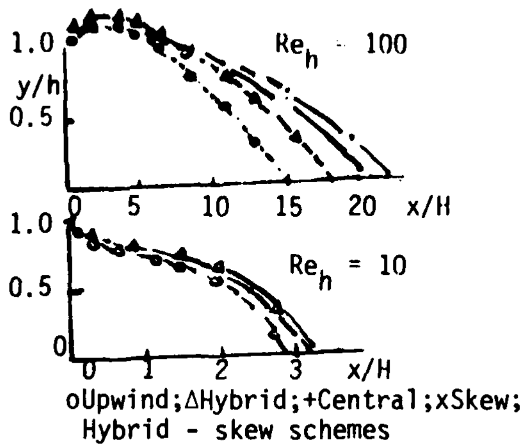


Fig. 3 Predictions of laminar separation from a surface mounted fence, from Castro (6)

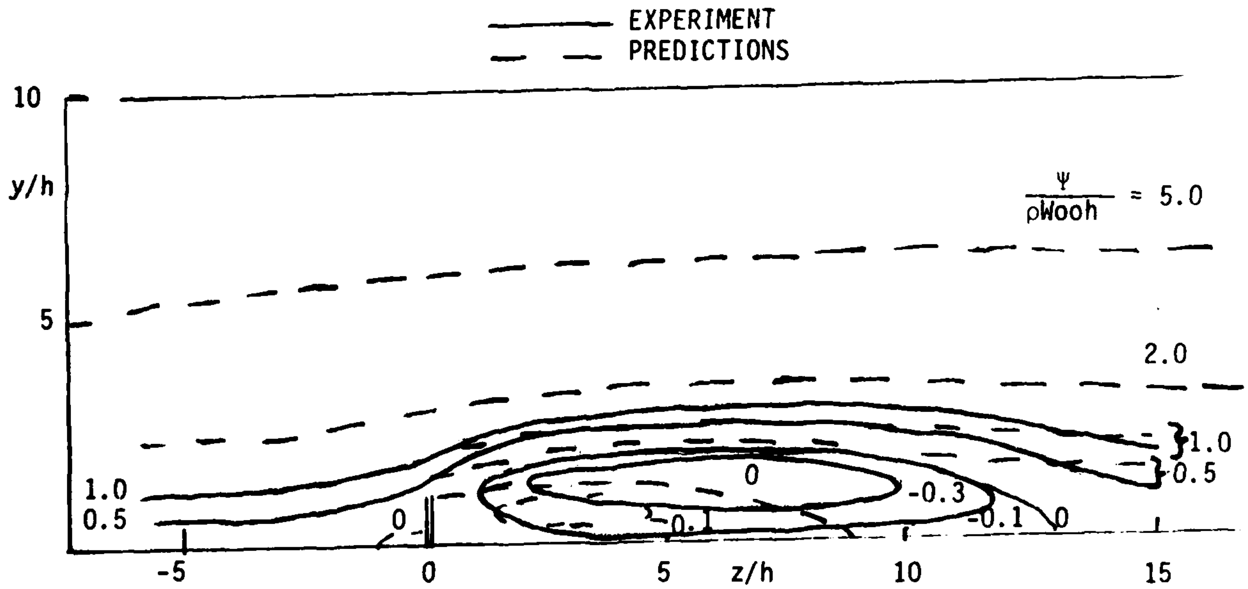


Fig. 4 Measured and predicted streamlines corresponding to the turbulent fence-separation experiment of Good and Joubert (9), from Vasilic-Melling (8)

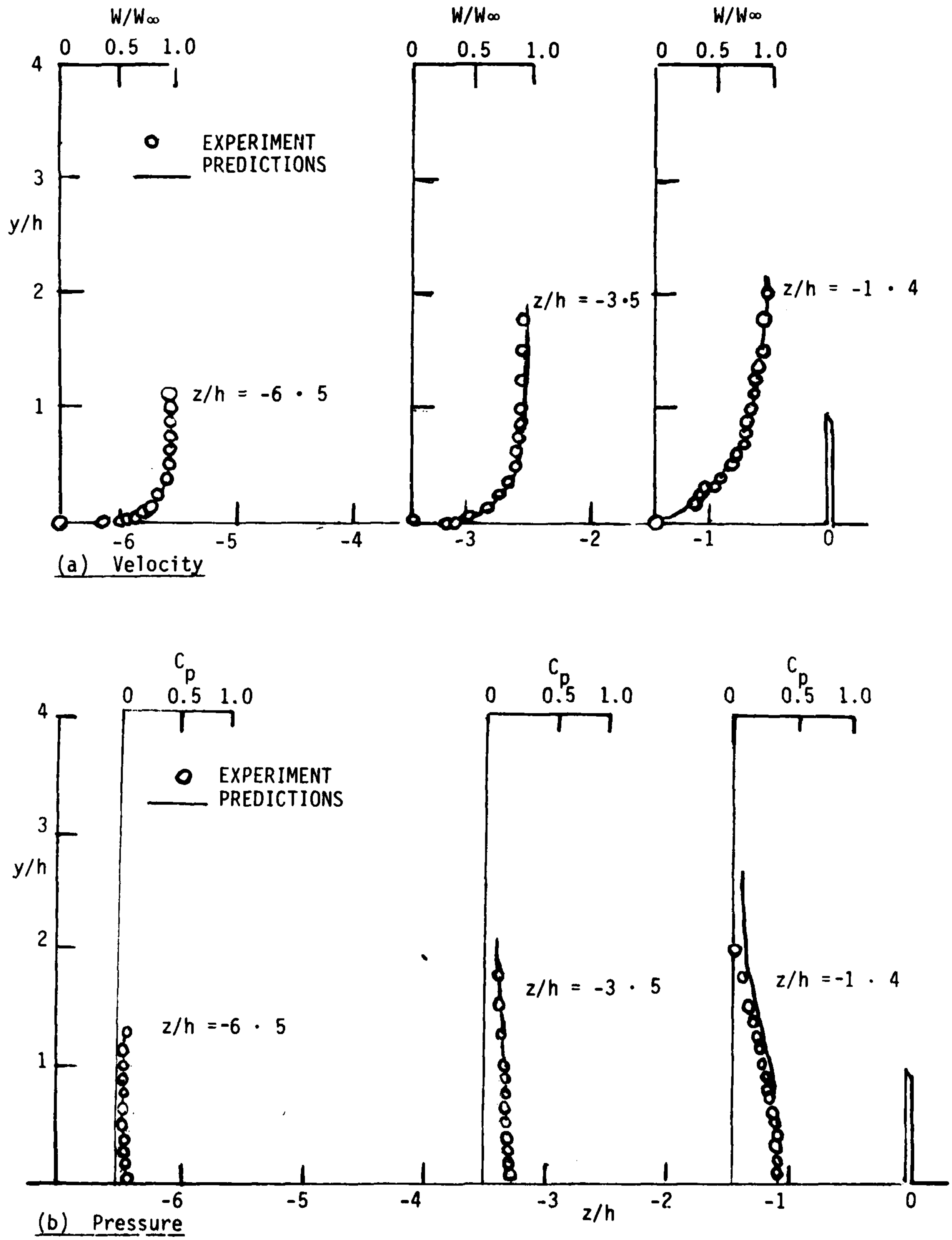


Fig. 5 Comparisons measured and predicted profiles upstream velocity and pressure correspond to Fig. 4.

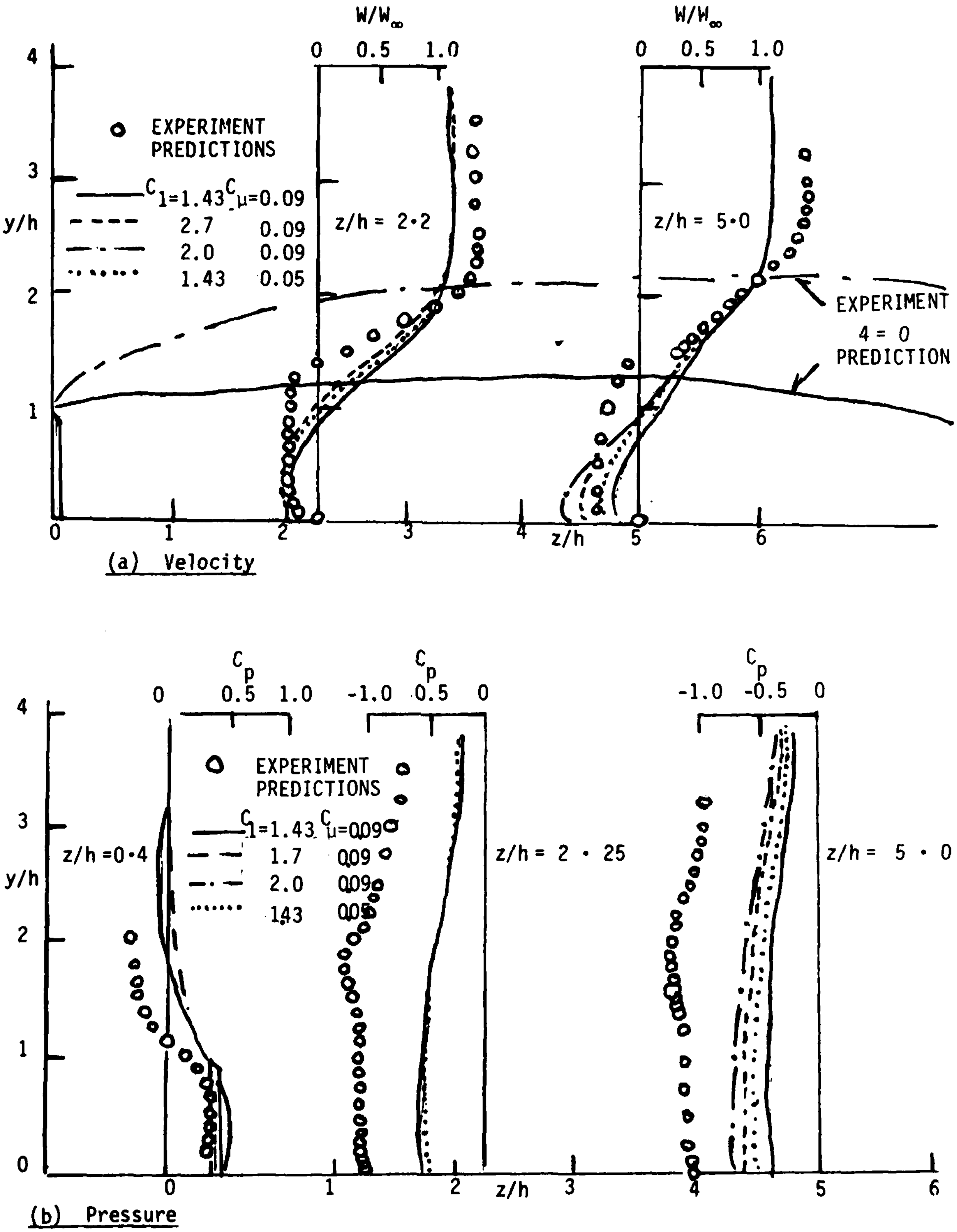


Fig. 6 Comparisons measured and predicted profiles downstream velocity and pressure correspond to Fig. 4

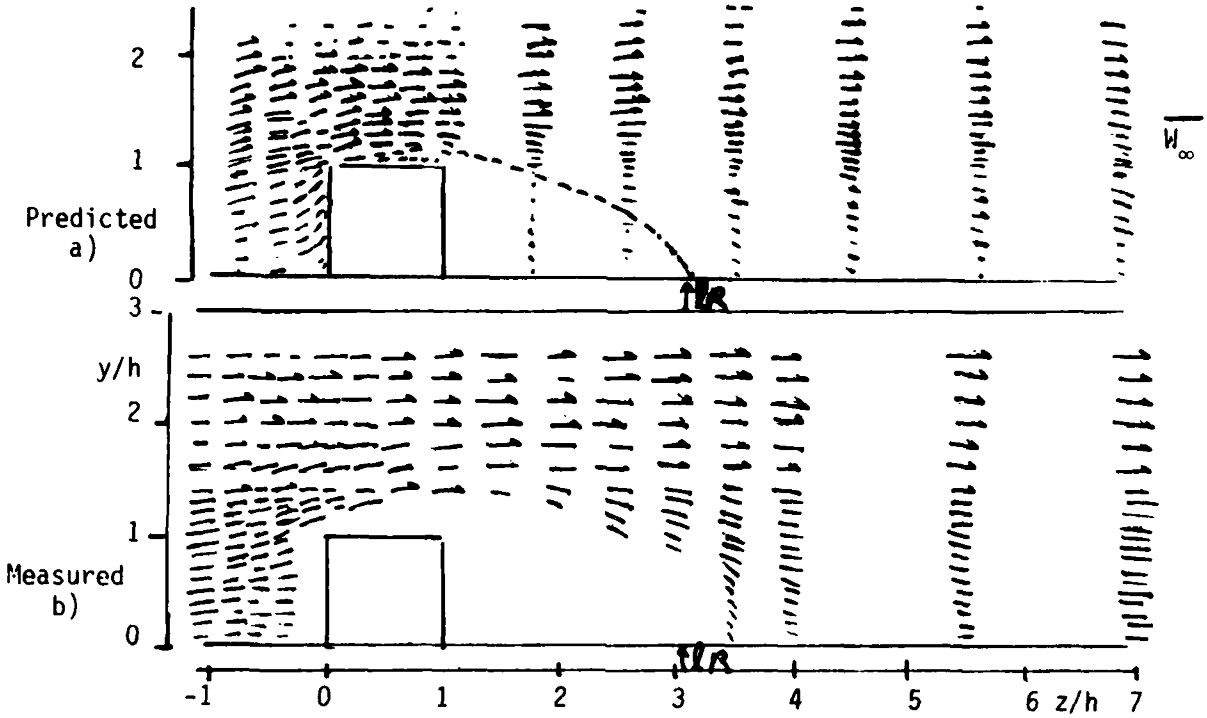


Fig. 7 Prediction of the velocity field in the longitudinal symmetry plane of a flow past a surface-mounted cube, from Vasilic-Melling (8)

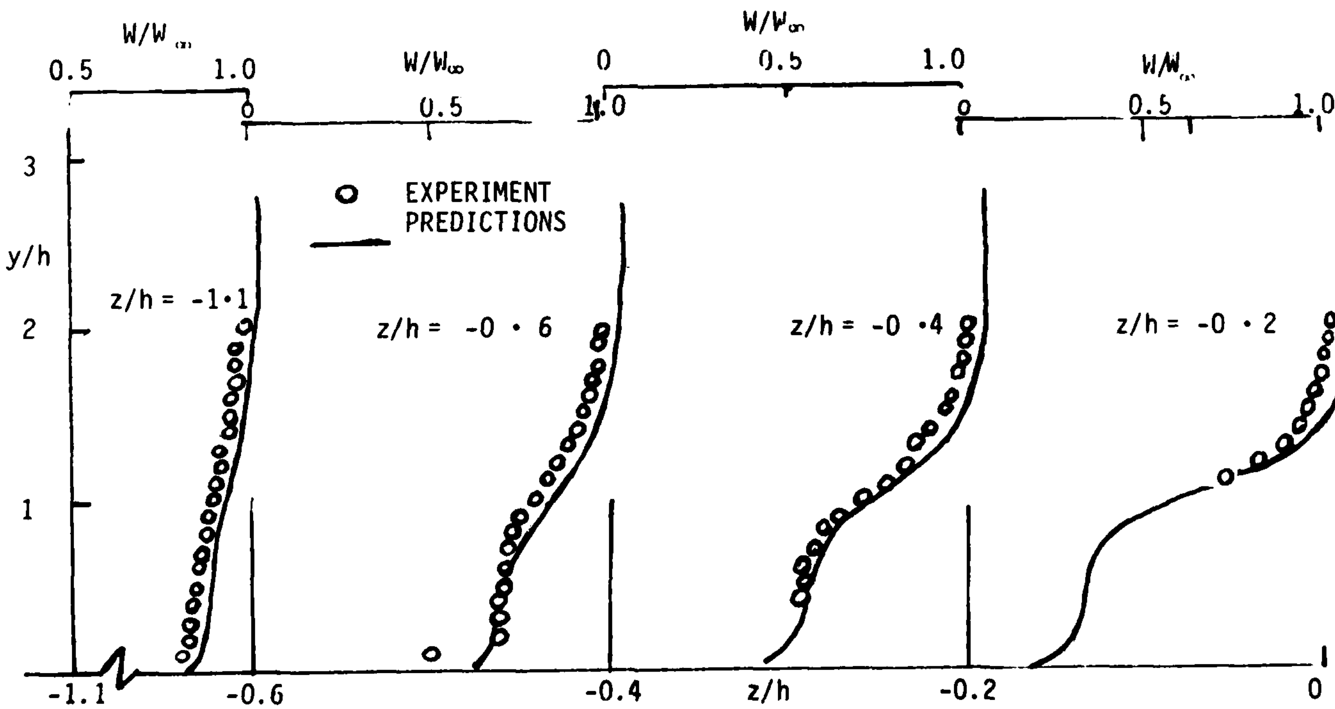


Fig. 8 Comparisons of measured and predicted upstream velocity profiles corresponding to Fig. 7

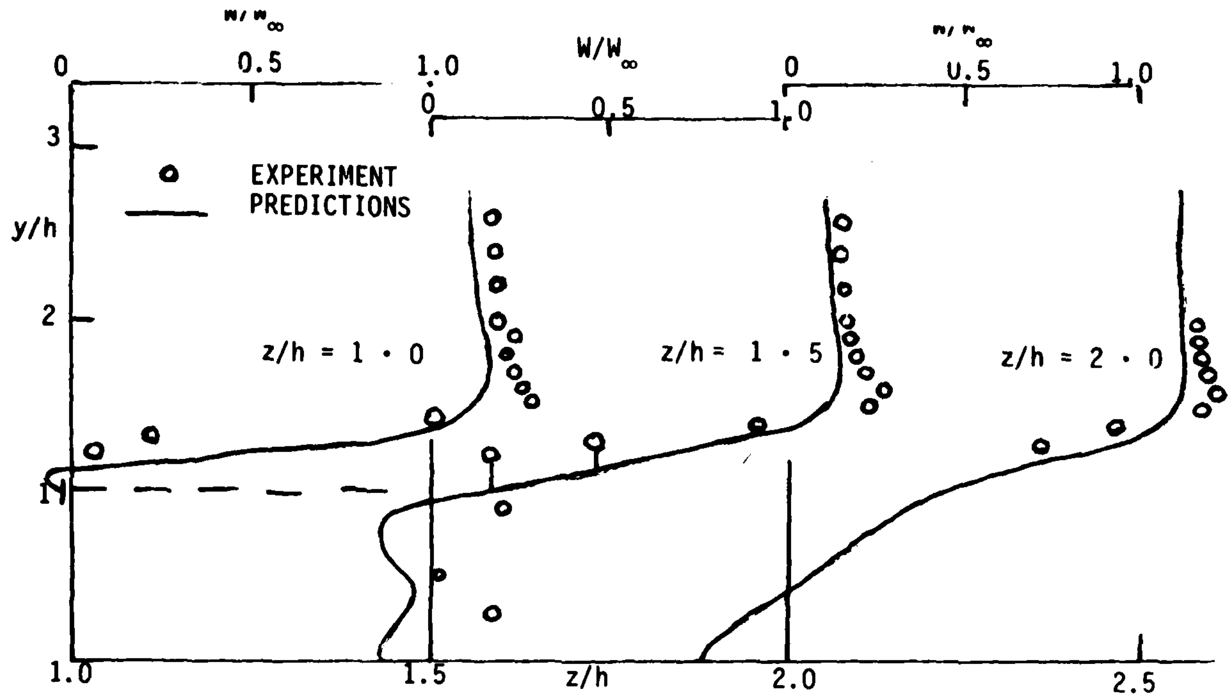


Fig. 9 Comparisons of measured and predicted downstream velocity profiles corresponding to Fig. 7

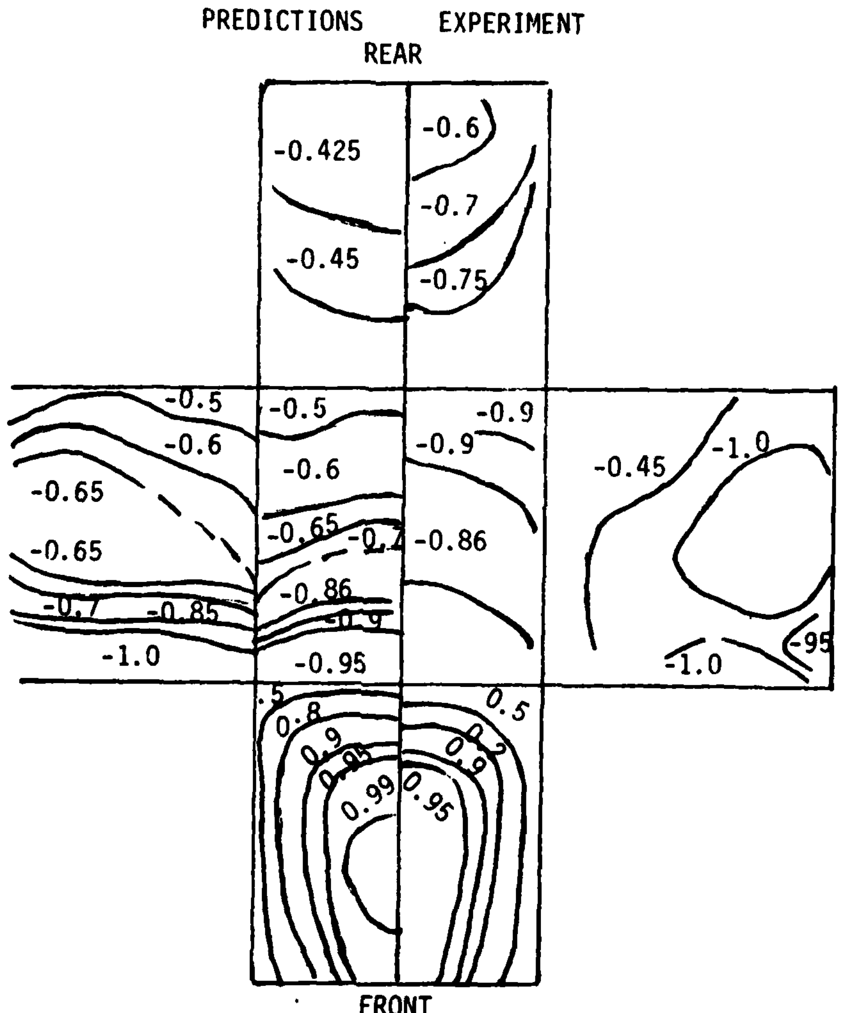


Fig. 10 Comparison of measured and predicted surface pressures corresponding to Fig. 7

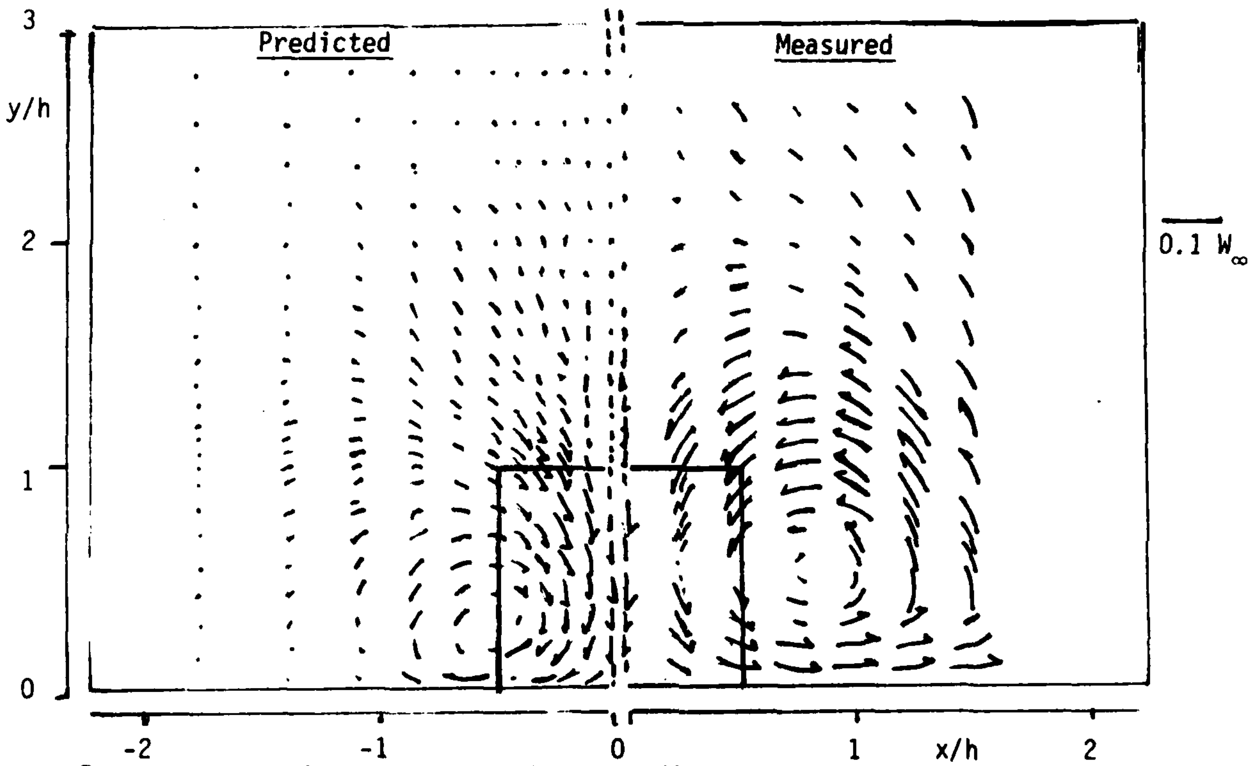


Fig. 11 Comparison of measured and predicted wake structure corresponding to Fig. 7.

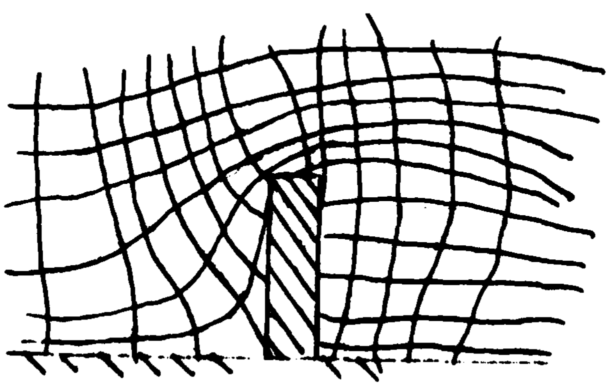


Fig. 13 Illustration of a flow-oriented grid arrangement.

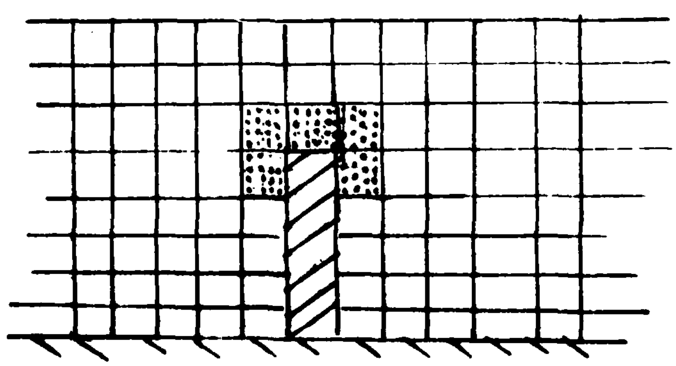


Fig. 12 Illustration of a locally-fine grid arrangement.

POSITION PAPER FOR COLLOQUIUM ON TURBULENT FLOW SEPARATION

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0. PREAMBLE

What follows is a personal view of two areas of research inspired by applications in supersonic flows; (i) the use of blowing to control shock-induced separation, and (ii) the design of optimum aft-bodies. I shall try to highlight certain basic issues that, although of direct significance in application; do not appear to me to have been satisfactorily resolved. In keeping with what I understand to be the spirit of the Colloquium, I have not hesitated to make provocative or speculative statements when it has seemed that they might bring the basic issues into better focus.

Relevant references are listed at the end of sections 1 and 2.

1. CONTROL OF SHOCK-INDUCED SEPARATION BY BLOWING

1.1 The status

The idea of using air injection or blowing for boundary layer control is not new, and has been studied in some detail at low speeds (see e.g. Lachmann 1961). At supersonic speeds, where applications cover aircraft intakes and control surfaces, several exploratory studies have been reported. (Peake 1966, Grin 1967, Lakshmikantha et al. 1969, Grin and Zakharov 1974, Wong 1977, Viswanath et al. 1978; see references for a more complete list) on the use of blowing to control shock-induced boundary layer separation; these studies have all shown that blowing is generally effective. Some workers (Grin 1967, Lakshmikantha et al. 1969) have even attempted to give simple correlations for the effectiveness of injection, but these are based on limited data and their general validity is not established yet. Reviews of the present position in the subject have been offered by Peake (1976) and Viswanath at al. (1977).

From the point of view of applications, the two basic questions are, of course, how much to inject and where for getting the 'best' results. For reasons that will shortly become clear, I do not believe there are convincing answers to these questions yet.

At the outset it is convenient to distinguish between two types of injection depending on the location of the injection slot:

(i) U-type, in which injection is upstream of where the separation point would have been in the absence of injection;

(ii) D-type, in which injection is downstream of the same point, but within the reverse flow region.

Peake (1966) had made another important distinction between wall flow and wake (or outer) flow reversal. (See figure 1). Based on his experiments with what we call U-type supersonic injection, he suggested that there was an optimum slot location at which both wall and wake flow reversals were avoided. For his experimental conditions (Mach 1.8, small tunnel, wedge-generated shock impinging on flat plate), Peake concluded that this optimum was at $l_i \simeq 6\delta$, where l_i is the distance of the slot from the shock and δ is the local boundary layer thickness. At $l_i \gtrsim 6\delta$, wall separation would occur, and at $l_i \lesssim 6\delta$ wake reversal would occur.

Grin (1967) made similar experiments in controlling boundary layer separation at a compression corner at a free stream Mach number 2.5. He concluded that injection of small quantities of air (about 6% of the mass flow in the boundary layer) can be effective in increasing the pressure rise to incipient separation. He also obtained a correlation for the pressure rise to incipient separation and the injection distance l_i. This correlation uses a jet penetration length, defined as the distance from the slot at which the boundary layer has a power law profile. His correlation showed that the efficiency of the jet falls off exponentially with distance.

Experiments in a 1 in. x 3 in. (25 x 75 mm) tunnel at IISc, with U-type tangential sonic injection into the free stream at Mach numbers of 2.2 and 2.6, suggested that the minimum wall jet stagnation pressure $(\hat{P}_i)$ required to suppress wall separation should be [+]

$$\hat{P}_i = 1.25\ \Delta p(l_i/\delta)^{0.7}$$

where Δp is the observed pressure jump across the shock (Lakshmikantha et al. 1969). Figure 2 shows the IISc data as well as those of Peake. Although subsequent examination casts doubt on some features of this correlation, it is interesting to note that it does not contain the slot width b in any form!

(The parameter b/δ varies between 0.1 and 0.4 in these experiments.) Thus, the total injectant mass flow appears to be irrelevant, at least for suppressing wall flow reversal. This is in stark contrast to the general assumption that injection effectiveness depends on a parameter like the momentum coefficient, which is a measure of the total injected momentum (or its excess over the free-stream velocity) in terms of the momentum deficit in the boundary layer. (Thus, Wong (1977) uses

$$C_\mu = \frac{m_j (U_j - U_\infty)}{\rho_\infty U_\infty^2 \theta}$$

where m_j = injectant mass flow, U_j = jet velocity, U_∞ = free stream velocity, ρ_∞ = free stream density, θ = boundary layer momentum thickness.)

The other data shown in figure 2 will be discussed subsequently.

+This correlation was inspired by the idea that the wall jet effectiveness could be determined in terms of the maximum excess velocity in the jet/boundary layer combination over the velocity in the original boundary layer.

The IISc experiments, like those of Peake (1966), suffered from the limitations of the small tunnel used. Similar experiments have therefore been conducted during the last few years (Viswanath et al. 1977, 1978) in the relatively cleaner separated flow induced by a compression corner (Mach 2.5, tunnel size 7in x 5 in (180 mm x 130 mm). The results of these experiments appeared to give further support to the correlation of Figure 2; but they also revealed some interesting and unexpected features.

The first is what may be called 'separation reversal'; with increase in P_i, the extent of the separation bubble or zone, as inferred from wall static pressure distributions, first decreases, and then increases as P_i exceeds a certain critical value which depends on l_i and the ramp angle (see figure 3). This puts a serious limitation on the range of P_i that can be usefully employed. The values of $\Delta p/P_i$ at which separation reversal occured are also shown in figure 2. These are clearly not values at which separation is suppressed, and therefore ought to have plotted well above the correlation curve of figure 1; that they do not is one of the reasons that the correlation may be questioned.

The second phenomenon is that the upstream influence in the absence of injection was much larger than what would be expected from earlier observations (Grin 1967, Spaid and Frishett 1972) at similar flow conditions and ramp angle. It was found that this was largely due to the pressure of the injection slot itself, which in the absence of injection acts as a backward facing step, and strongly distorts the turbulent boundary layer before it encounters the adverse pressure gradient. (We suspect that this effect was present in Peake's experiments also, as the slot geometry was similar to ours.) The reason that the effect had remained undetected in earlier work might well have been the compensating effect, in the shock-generator/flat plate configuration often used, of the shoulder expansion fan from the shock generator eating away a significant part of the total pressure rise across the shock and hence also the upstream influence.

The IISc experiments have also shown that D-type injection can be very effective in suppressing separation, and might reduce (if not eliminate) both adverse effects mentioned earlier as associated with conventional U-type injection. Figure 4 shows a part of the evidence that led us to this conclusion.

At this juncture, it is appropriate to mention the studies of Chinneck et al. (1955) on the use of tangential blowing to improve control effectiveness in the presence of normal shock-induced turbulent boundary layer separation at transonic speeds. Experiments with both U- and D-type injection (as we call them here) were made and it was found that D-type was more effective. In their study, however, there was simultaneous variation of several parameters including strength and location of the shock; further, no quantitative estimates of the relative merits of U- and D-type injection at given flow parameters were offered. Possibly for these reasons, further work on D-type injection does not seem to have been undertaken.

Interestingly, D-type injection has been studied only in conditions where it was obtained naturally rather than by design; e.g. when large scale separation is present, as in interactions involving normal shock waves. This appears to be true of a recent study by Wong (1977) who used discrete slot injection to control shock-induced boundary layer separation in supersonic inlets.

The mechanism of suppression of separation with D-type injection presumably lies in removing the reattachment point by energizing the reverse flow region rather than the boundary layer upstream of separation, but more detailed studies are necessary to throw light on the observation.

The present work thus suggests that, it flow past a ramp, for example, it may be best to inject at the ramp corner itself, in the manner shown in figure 5. The upstream influence for this configuration in the absence of injection should be negligible. Some flow visualization experiments using schlieren techniques have been very encouraging and a detailed study is now under way at IISc.

1.2 Open Quenstions

From this survey of the present status of work on boundary layer control by blowing in shock-induced separation, it appears that the following basic issues have not yet been satisfactorily resolved.

i) There is some evidence that the actual mass flow used as injectant is not crucial for effective boundary layer control. Rather, the parameter involved seems to be the velocity excess imparted to the flow near the wall by injection. If this is true, it clearly has far-reaching implications for practical blowing devices.

ii) It is understandable that wake flow reversal might have deleterious effects if the objective of boundary layer control were, say, to ensure uniform flow at the compressor face of an air intake on an aircraft. It is not clear however that in general wake flow reversal is always so deleterious. Furthermore, the available evidence seems to indicate that once the momentum at the wall is enhanced sufficiently by injection, the wake flow would also be eventually controlled.

iii) If D-type injection is indeed superior to U-type, one would have to change one's ideas regarding the basic mechanism of boundary layer control. In particular, text-book explanations of how blowing energises slow moving fluid near the wall and therefore, enables it to overcome adverse pressure gradients would need to be drastically revised. The destruction of the reattachment of flow downstream of separation might well be as effective a mechanism for boundary layer control; presumably in this case one is interfering with the feedback loop from reattachment to separation.

iv) Some preliminary work at IISc already supports the idea that, for flow past a ramp, the best location for the injection slot would be at the ramp corner itself. This seems to have many other incidental advantages as well and therefore merits further study.

v) There appears to be some connection between the phenomenon of separation reversal described earlier and the analysis of 'critical' points in separated flows that have been investigated by various workers (see e.g. the review of laminar separated flows by Brown and Stewartson 1969). It is possible that, at the higher blowing pressures, the feed-back from the larger displacement thickness of the wall-jet/boundary-layer combination increases the adverse pressure gradient to such an extent that the favourable effects of injection are completely lost.

vi) One totally unexplored area in boundary layer control is that of using intermittent operation. For example, as I have argued elsewhere, it might well turn out that blowing in puffs (at an appropriate period) would be as effective as continuous injection, but be less demanding in injectant mass flow. This is an area of research that should be very rewarding.

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2. DESIGN OF AFT BODIES

2.1 The status

The problems of estimating and (when necessary) reducing the base drag of an aft body configuration have been of concern for many years. From the classical work of Chapman (1955) and his colleagues we know that supersonic wings with blunt trailing edge have certain aerodynamic as well as structural advantages; and that the optimum trailing edge thickness depends on the base pressure. There are of course many situations where a blunt base has to be accepted even though it offers no particular aerodynamic average; it is then necessary to consider how the base drag may be reduced.

Such reduction may be achieved by the use of base bleed, the introduction of serrations in the base, or by what is perhaps the 'softest' of these methods, namely the design of appropriate boat-tailing. It is this last device that we wish to consider here. It was noted by Nash (1963) in an extensive review on base flows that boat-tailing had not received the attention that it deserved; while tests have been made in wind tunnels on fairly specific configurations, systematic studies have been lacking.

For this reason we have during the last few years undertaken a programme to generate data that should enable prediction of base pressure as well as more rational design of aft bodies.

The pioneering investigation of Chapman and his colleagues showed how the base pressure was affected by variations in Reynolds and Mach number; in particular the effect of the <u>state</u> of the boundary layer - whether laminar or turbulent - was high-lighted. Since then some boundary layer measurements have occasionally been made in base flow studies. (e.g. Fuller and Reid, 1958), but by and large the subject has not received sufficient attention. The well-known paper of Korst (1956) included an analysis of boat-tailed bases and a favourable comparison of the theory with a few experiments made by Eggink (1949); however, the analysis ignores the boundary layer at separation. It has now become clear that base pressures lower than the supposedly limiting Chapman-Korst values are possible, and that the agreement noted in earlier work should perhaps be attributed to a fortuitous combination of deficiencies in the theory and the ignored effect of the boundary layer. Excellent reviews of the subject, published by Roshko (1966) and Nash (1967) more than ten years ago, made it clear that while the Chapman-Korst analysis cannot be accepted literally it contains some of the basic physical ideas necessary for understanding base flows. Incidentally these reviews are still very useful, as many of the basic problems they considered still remain; the only remarkable development in the last ten years is surely the appearance of a rash of 'prediction methods' whose value still remains to be properly established.

It may be noted here that boat-tailed bases may well provide a more severe test for these 'prediction' methods; data on normal bases are now so well established that agreement between theory and experiment for this geometry can no longer be considered a strong recommendation for a prediction method.

On boat-tailed bases the boundary layer is likely to be an even more significant parameter than on normal bases, especially if the boat-tailing involves a sharp corner ahead of the base. There is now considerable experimental evidence (Sternberg 1954, Vivekanandan 1963, Viswanath and Narasimha 1972) that expansion round such a corner may even cause partial or total reversion of the originally turbulent flow to a laminar state. It is interesting that such reversion was already suspected as a possible factor in the base pressure problem by Gadd and others in 1956.

One approach that seemed attractive to us was to split the problem into two different parts. The first concerns the effect on base pressure of the angle between flow at separation and the reattachment surface. This problem can be conveniently investigated in a wind tunnel by experiments on flow past inclined backward facing steps (figure 6), with realistic values of the ratio of the step height to the boundary layer thickness. (It is unlikely that with fully turbulent flows viscosity or Reynolds number exerts a primary influence.) The second part of the problem concerns the effect of boat-tailing on the boundary layer at the separation point. The acceleration experienced by the boundary layer will certainly distort it and possibly even relaminarize it (if it were originally turbulent).

This might well have undesirable effects on the total base drag.

Indeed, using the results of our experiments on inclined steps, we believe it is now possible to identify those earlier experiments in which reversion (unsuspected by their authors) could have affected the base pressure substantially (figure 7). A detailed analysis (Viswanath and Narasimha 1974) shows that the lack of agreement between the base pressure measured in these experiments and the correlation developed by us for fully turbulent flows occurred in precisely the conditions where reversion might be expected. The identification of these conditions becomes possible because of a successful criterion for reversion in supersonic flows subjected to server acceleration (Narasimha and Viswanath 1975).

Using this correlation it is now possible to formulate a rational procedure for designing two-dimensional aft bodies at supersonic Mach numbers. For example, the optimum boat-tailing angle can be computed for given Mach number, Reynolds number and aft body length. The results of one such calculation are shown in figure 8. Note that the boat-tailing can achieve substantial reduction in drag, but that the range of parameters available for optimisation is limited by the possibility of reversion of the approaching boundary layer. As the diagram shows, if the boat-tailing length is sufficiently large the boundary layer that is relaminarized at the expansion corner might go back once again to a turbulent state. Although the conditions under which this retransition can take place cannot be specified with confidence, it is believed that the kind of results shown in the diagram are at least qualitatively correct.

2.2 Open Questions

i) The splitting of the problem of boat-tailed bases into two distinct parts as described above is obviously useful but would be worth a direct check.

ii) Most correlations of base pressure data are given in terms of free-stream conditions. It would seem that local conditions just prior to separation ought to be more suitable parameters, but even this assumption needs examination.

iii) The state of the boundary layer at separation clearly influences the base drag experienced by the body. However, it is not certain that this effect can be sufficiently well determined by gross parameters of the boundary layer, such as its momentum thickness. It is conceivable that some of the discrepancies that one observes in base pressure data are attributable to distortion suffered by such boundary layers before they arrive at the separation point.

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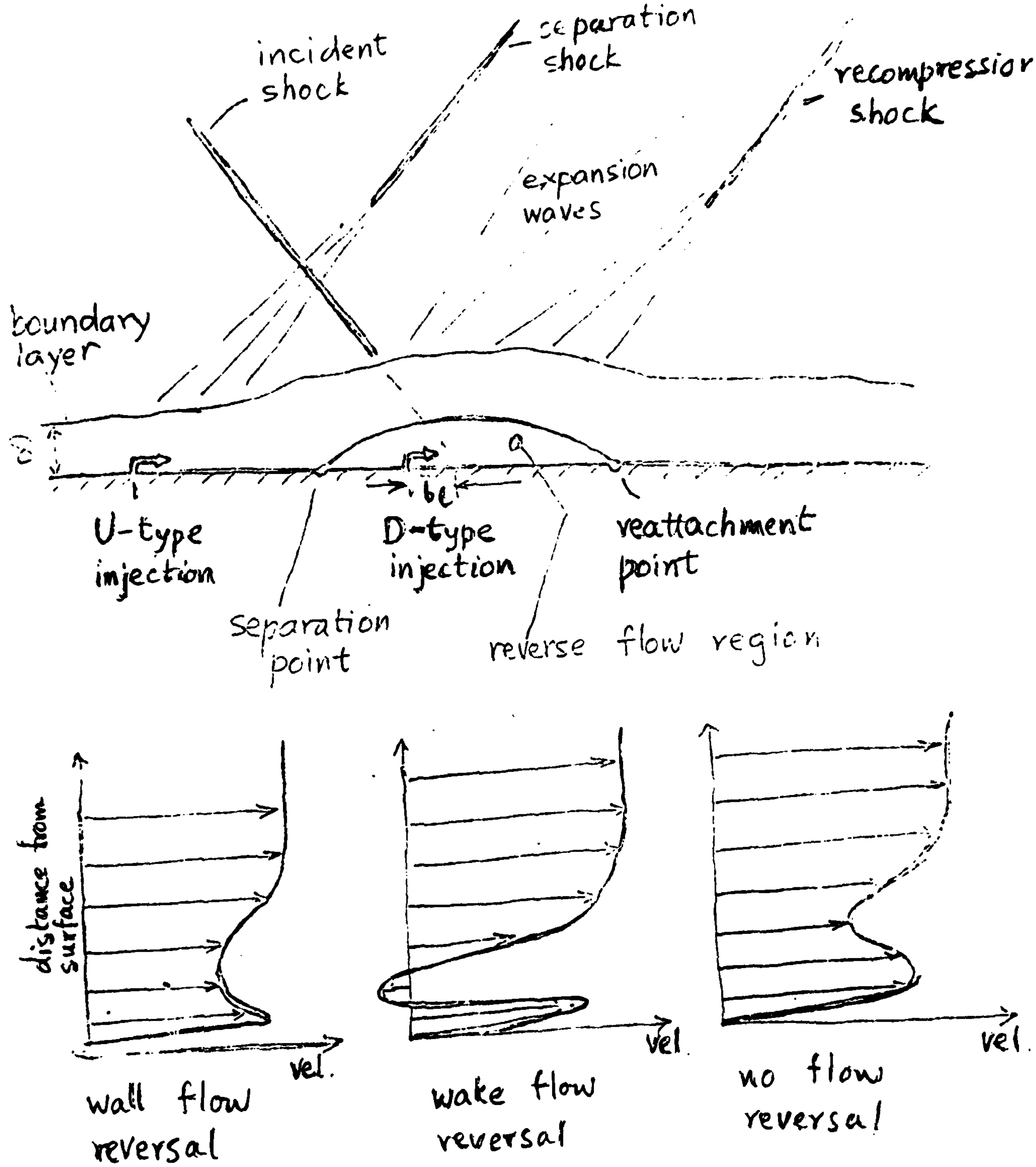


FIGURE 1 DEFINITIONS

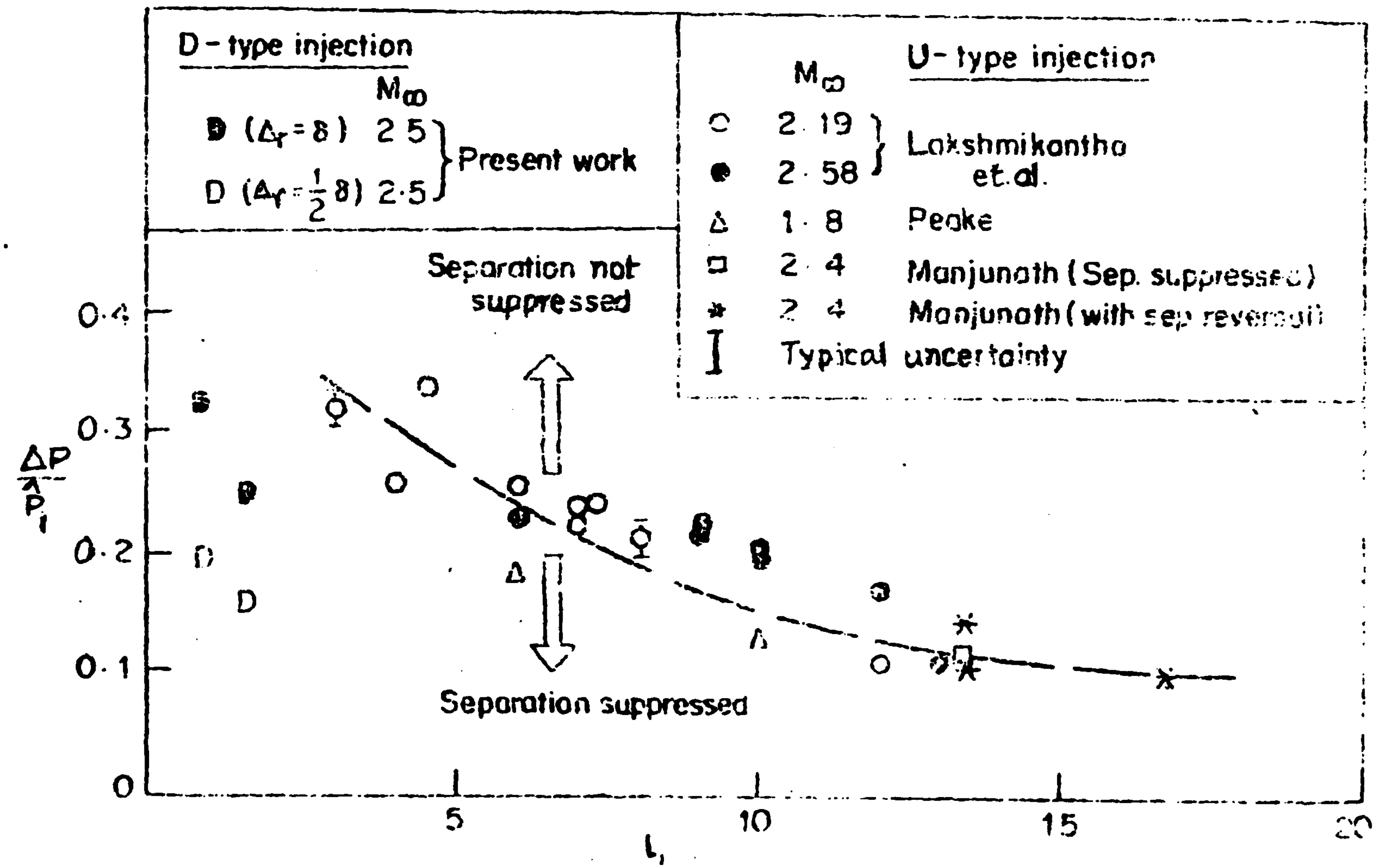


Fig. 2. CORRELATION OF MINIMUM PRESSURE TO SUPPRESS WALL SEPARATION

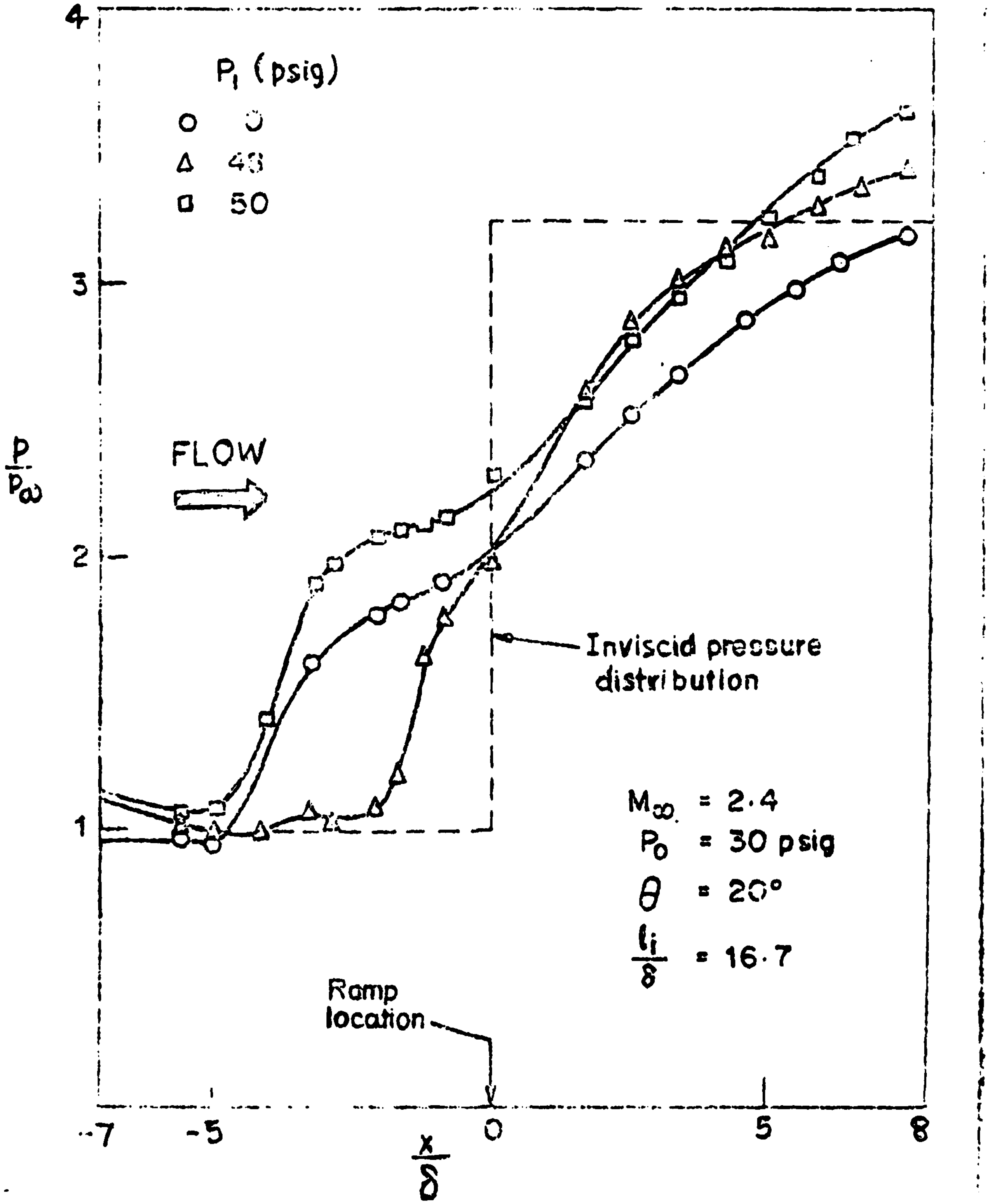


FIG. 3. PRESSURE DISTRIBUTIONS SHOWING SEPARATION REVERSAL.

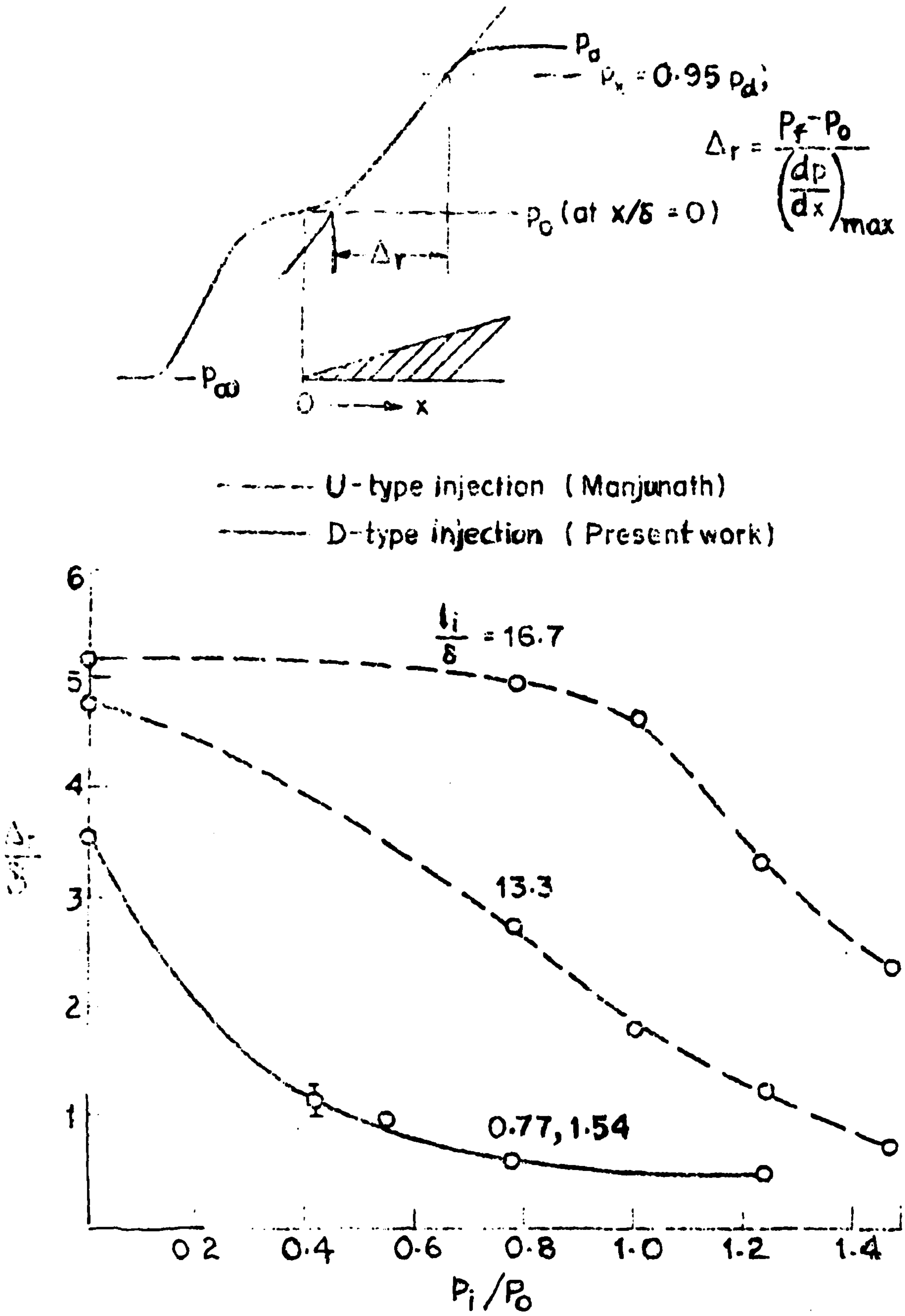


FIG. 4. VARIATION OF REATTACHMENT LENGTH WITH INJECTION

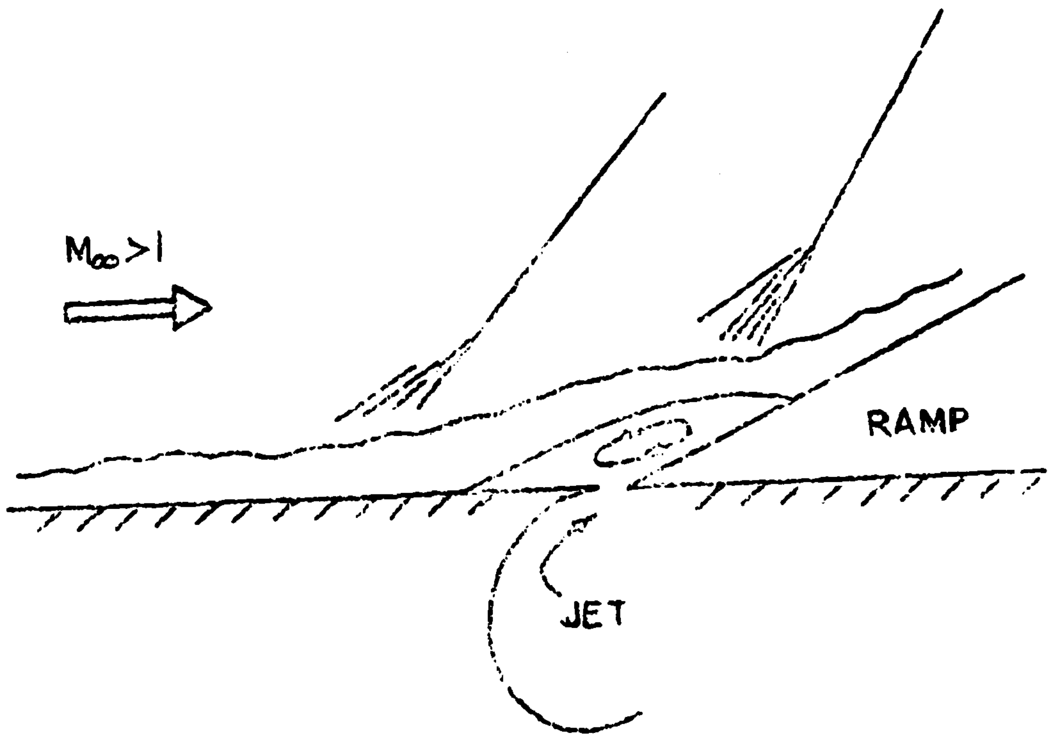
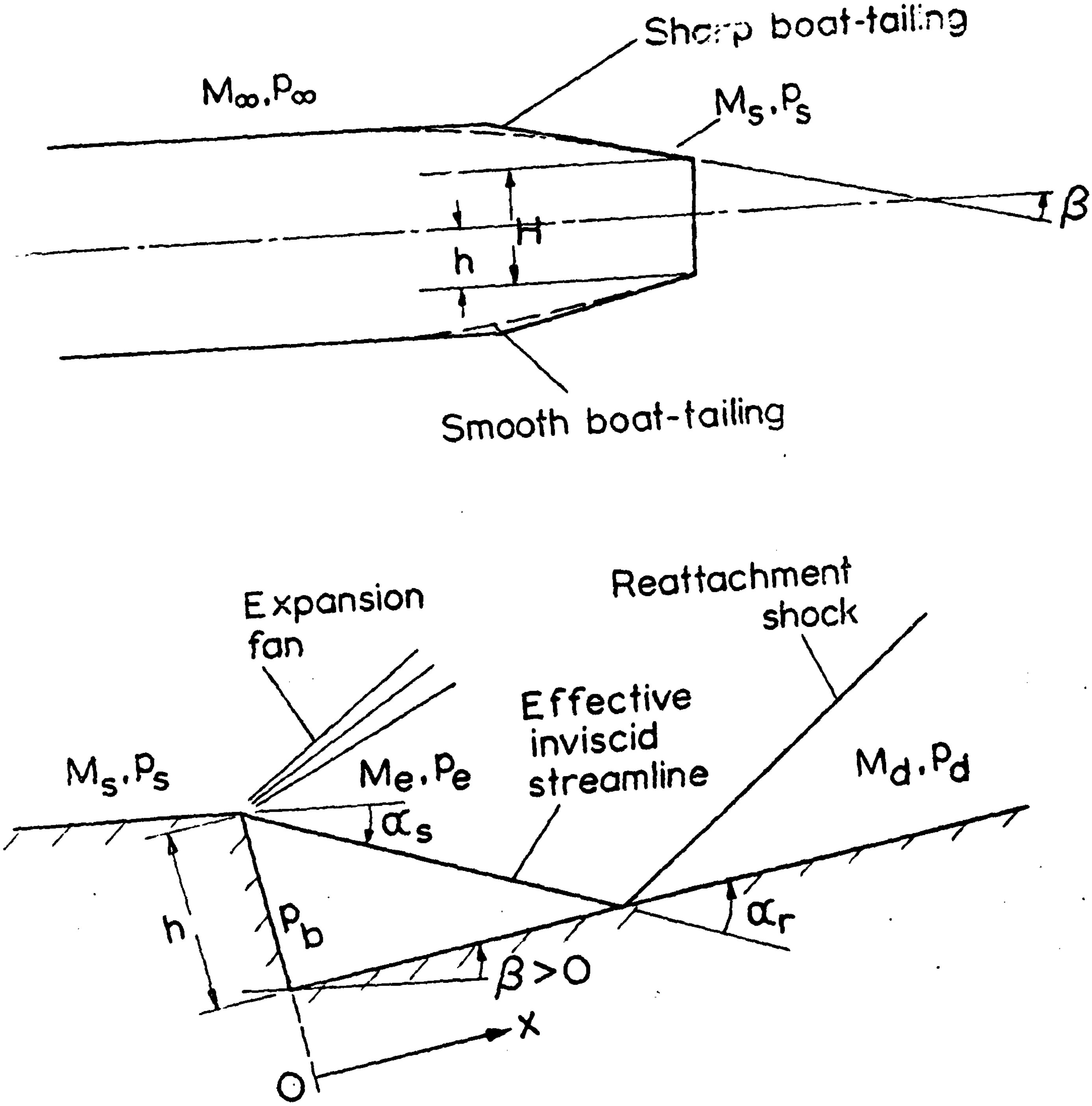


FIG. 5. PROPOSED INJECTION CONFIGURATION



Sharp boat-tailing
M_∞, p_∞
M_s, p_s
H
h
β
Smooth boat-tailing
Expansion fan
Reattachment shock
Effective inviscid streamline
M_s, p_s
M_e, p_e
M_d, p_d
α_s
α_r
h
p_b
$\beta > 0$
x
O

FIG. 6

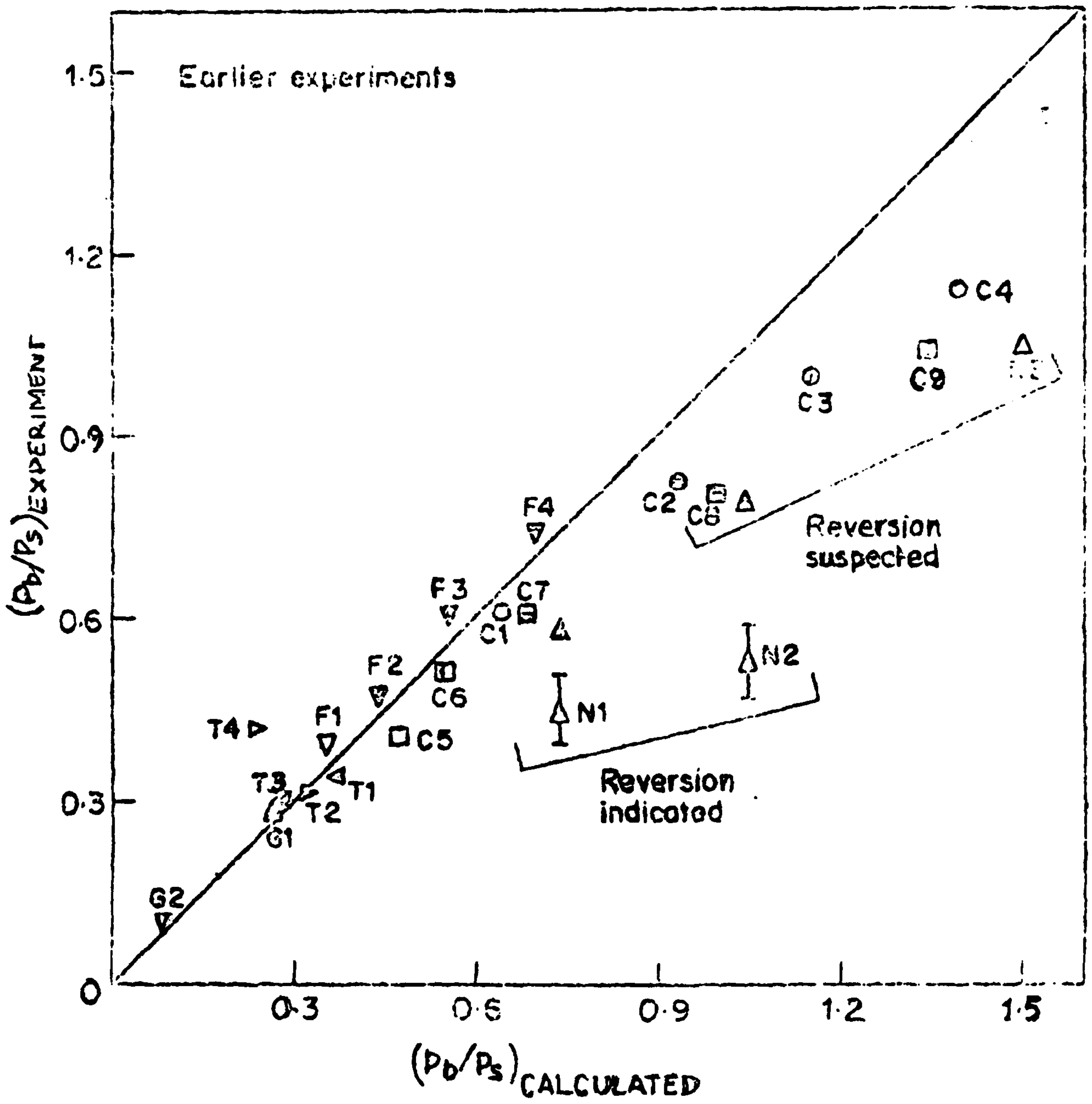
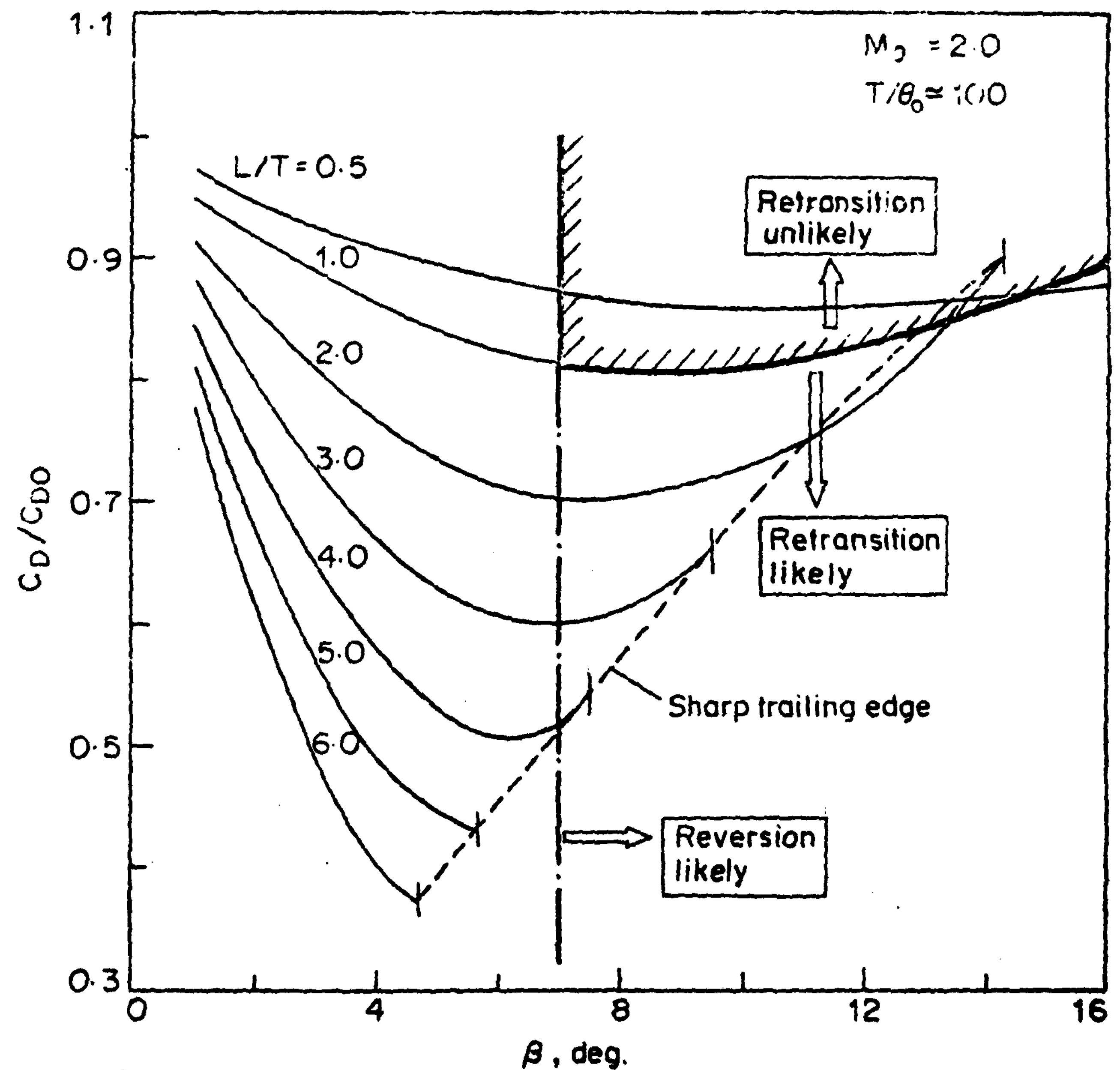


FIG. 7. COMPARISON BETWEEN MEASURED BASE PRESSURE AND ESTIMATE FROM THE CORRELATION



$M_0 = 2.0$
$T/\theta_0 \approx 100$
L/T = 0.5
1.0
2.0
3.0
4.0
5.0
6.0
Retransition unlikely
Retransition likely
Sharp trailing edge
Reversion likely
C_D/C_{DO}
β, deg.

FIG. 8

UNSTEADY TURBULENT-BOUNDARY LAYER SEPARATION

W. R. Sears - University of Arizona

I suppose it is my duty to remind the participants of the mysteries of unsteady boundary-layer separation, which Professor D. Telionis and I studied and preached about for years, and which Professors Jim Williams and, more recently, S. F. Shen have written so convincingly about.

If there are some who haven't heard our sermons, here is the gist: To be meaningful and useful in fluid-flow problems, "separation" must mean "breakaway" - the breakdown of boundary-layer flow (cf. Prandtl). But this phenomenon is related one-to-one with reversal of wall-shear only in the special case of steady flow past a stationary wall. In other cases - steady flow past moving walls and unsteady flow past moving or stationary walls - the phenomena are different and are generally not related to any such convenient criterion as vanishing of wall-shear. Nevertheless, at least in laminar flow there is a precise point where the breakdown occurs. It is characterized by abrupt thickening of the layer and abrupt increases in quanities, such as v (the normal-to-wall velocity component), that are small in boundary-layer flow. Shen has shown that this singular behavior is a breakdown of the matching betweeen the inner (boundary-layer) and outer (inviacid) regions of flow.

What is important to note here is that flow reversal in the boundary layer can occur well upstream of this breakdown, or conversely the breakdown can occur before any flow reversal is encountered. Thus the engineer concerned with lift of an airfoil, performance of a diffuser, or other important technical consequences of flow breakaway must not expect them to be related to vanishing wall-shear unless, of course, there is justification for an appropriate quasi-steady approximation.

Unfortunately, turbulent-boundary layer separation is already complicated and imprecise in steady flow. Qualitatively the same events occur as in laminar flow, but they are often less dramatic. It is a great temptation to latch onto flow-reversal and the vanishing of wall-shear in this case the average wall-shear as a criterion for separation, since it is relatively easy to detect. But where would that leave us in cases of unsteady turbulent separation and separation at moving walls? There have been studies of these cases, based on reasonable but crude models of turbulent shear, and it is not surprising that they lead to qualitatively the same conclusions as for the laminar case.

It is my conviction that all the concepts that have been found useful in the laminar case have to be carried over - that we will find mean-flow reversal well upstream of separation in some cases and separation without mean-flow reversal in others. Unfortunately, accurate prediction of these phenomena seems a formidable task. Surely the archtypal case of (statistically) steady flow past moving walls must be attacked, experimentally as well as theoretically, in the turbulent case as it was in the laminar case. I do not think this has been done.

In closing this "position paper", I want to make two points, one optimistic and one quite pessimistic:

First: There will surely be important technical cases where the quasi-steady approximation is acceptable; i.e., where instantaneous vanishing of mean wall-shear can be said to indicate, approximately, the transient point of separation - where the differences between steady and unsteady separation can be ignored. But, clearly, we must have better understanding in order to know the limits of validity of this simplification. The quasi-steady approximation says more here than in the laminar case: it has to include the assumption that the turbulence itself is the same as in the related steady flow!

Second: (the pessimism): All of "unsteady turbulent flows" has hanging over it the requirement that the unsteadiness must be slow compared to the phenomena we call turbulence. Since we now know that turbulent boundary layers have important large-scale features, it is possible that this requirement is pushed pretty hard in truly unsteady boundary-layer flows. If so, our attempts to describe and predict unsteady separation may have a limited future.

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Position Paper
for
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Southern Methodist University
-by-

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1. Introduction

Separated flows occur in a wide variety of engineering applications involving external flows. Despite the practical importance of such flows, progress in the theoretical description of separated high Reynolds number flows has been rather slow. In view of the complex nature of separation, it is not surprising that there are a number of formidable mathematical problems associated with describing a separated flow theoretically; some of these difficulties will be discussed in this paper.

With the development of larger and faster computers it might be imagined that flows past bodies at high Reynolds numbers may eventually be calculated by a full numerical solution of the Navier-Stokes equations; one reason that this approach is not viable for turbulent flows at present is that a "universal" turbulence model is still as elusive as ever. However this is not the only reason that mitigates against such an approach and even in the case of laminar flows, the viewpoint that fully numerical solutions of the Navier-Stokes equations will ever serve as a general design tool seems extremely optimistic. It is well known that as the Reynolds number becomes large, severe difficulties are encountered in maintaining the numerical mesh sizes small enough to adequately resolve the physical non-uniformities in a separated viscous flow. Furthermore for a given Reynolds number considerable problems are encountered in obtaining convergence of the numerical scheme in a steady flow calculation as the numerical mesh sizes are reduced. It is relatively well known that convergence of numerical schemes for non-linear elliptic equations is easier to obtain when numerical mesh sizes are relatively coarse, principally because the number of finite difference equations in such a calculation is relatively small. However it is important to recognize that the primary objective is not to produce numbers but to produce numbers which represent the solution of the Navier-Stokes equations to some reasonable level of accuracy. In this vein, calculation of streamline patterns which look "reasonable" does not constitute a serious test of accuracy and there exists a considerable body of seriously inaccurate Navier-Stokes solutions in the literature which at first glance appear plausible. It seems prudent to be pessimistic about the long term viability of this approach for high Reynolds number flows when one considers the current progress that has been made on two of the most fundamental laminar problems where separation occurs; for the circular cylinder and sphere in a uniform flow, reliable numerical solutions of the steady Navier-Stokes equations have only been obtained up to Reynolds numbers of 100 (Dennis & Chang, 1969) and 40 (Dennis & Walker, 1971) respectively. The outlook for such an approach in nominally steady turbulent flows is even less inviting. I believe the real and lasting progress in the area of turbulent separation will only be made (a) once the basic physical mechanisms in the turbulence are more clearly understood and (b) through the use of somewhat more subtle mathematical techniques such as the method of matched expansions. In the method of matched expansions the entire flow field is divided into separate regions and it is possible in theory to isolate which terms in the Navier-Stokes equations are important to leading order and which are not; when such a procedure can be carried out the solutions in each region of the flow are matched asymptotically to obtain an accurate composite picture of the flow at high Reynolds numbers. Although a considerable amount of progress has been made over the past twenty years in the application of such methods to laminar flow problems, the theoretical description of laminar separation is far from complete. Since a number of the theoretical problems encountered in the analysis of laminar separation are also relevant to turbulent separation, it is worthwhile to identify what I believe to be the important unsolved problems in laminar separation are and this is done in the next section.

2. Steady Laminar Separation

In the classical description of high Reynolds number laminar flow past bluff bodies the flow field is regarded as double structured consisting of an inviscid region comprising the majority of the flow field and a thin viscous boundary layer adjacent to the body surface. The computation of the flow field is initiated by calculation the ideal flow field corresponding to the particular body shape ; normally the inviscid flow solution is irrotational because it is usually assumed that the flow far upstream of the body is uniform. The second step is the computation of the boundary layer solution; the origin of the streamwise coordinate in the boundary layer is fixed at the frontal stagnation point of the inviscid flow and the boundary layer develops downstream in both directions away from the stagnation point. Because the boundary layer equations are parabolic, the boundary layer solution may be constructed in a step-by-step manner downstream away from the stagnation point on both the upper and lower surface of the body. When the classical picture is appropriate, as is the case for example in slender bodies at zero angle of attack or where separation is inhibited by some means (see for example, Crisalli & Walker, 1976), the calculate may be carried out to the point where the body terminates. It is the parabolic nature of the boundary layer equations which allows this type of calculation; as long as the streamwise velocity u is everywhere positive, disturbances propogate only in the downstream direction. If on the other hand, u becomes negative at some station in the boundary layer, disturbances will propogate upstream as well as downstream and in this environment step-by-step numerical marching procedures will fail. It is important to appreciate that the only assumption inherent in the boundary layer equations is that the boundary layer is thin and that the fact that u is negative in the boundary layer does not in general imply a breakdown of the boundary-layer equations. As an example, consider the small regions of reversed flow that are known to occur on the upper surfaces of airfoils near the front stagnation point. This type of separation is illustrated schematically in figure 1.

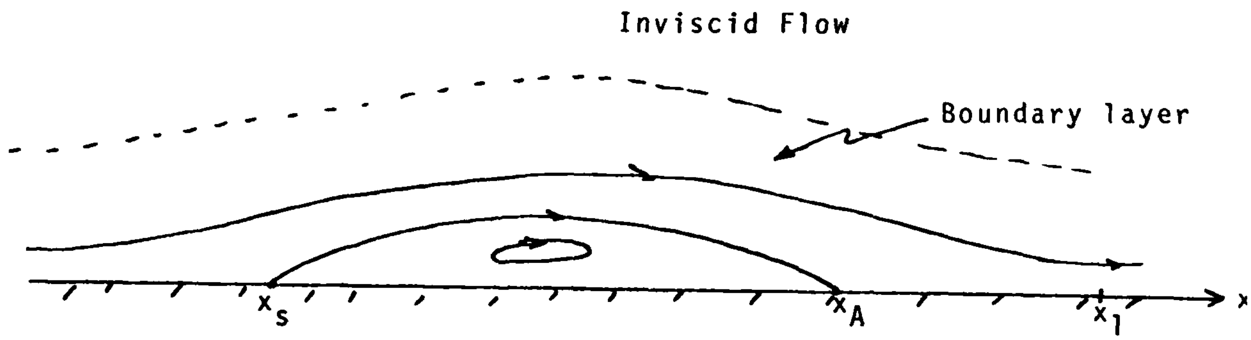

Figure 1. Schematic sketch of a small separation bubble.

The situation sketched in figure 1 will occur when an adverse pressure gradient leads to reverse flow in the boundary layer but re-attachment of the separation bubble is brought about because of a rapidly imposed change in the mainstream velocity to a favorable pressure gradient. In such a situation the boundary layer remains thin and the effect of the separation bubble on the mainstream pressure distribution is small. It is of interest to comment on how such a boundary layer flow might be computed.

Given an initial velocity profile upstream of the point of separation x_s, the boundary layer solution may be calculated in a step-by-step manner (using numerical marching techniques normally associated with parabolic equations) arbitrarily close to the point x_s; this is because the term $u\partial u/\partial x$ in the boundary layer equations has $u>0$ everywhere in the boundary layer for $x<x_s$ and consequently disturbances spread only in the positive x-direction. Once reversed flow occurs u vanishes and changes sign within the boundary layer and now disturbanced propogate in both the upstream and downstream directions. The boundary-layer equations in the region $x_s \leq x \leq x_A$ are of course still parabolic but are of a fundamentally different mathematical character (than in the region $x<x_s$) which is known as singular parabolic. Singular parabolic equations occur in a number of different applications (see for example, Walker & Dennis, 1972) and such problems are most easily solved using boundary value numerical procedures which are normally associated with elliptic equations. In the example illustrated in figure 1 it is necessary to impose a downstream condition, say at $x=x_1$ and the solution in the range $x_s \leq x < x_1$ can then be computed as a boundary value problem using relaxation procedures normally associated with elleptic equations. Alternate iterative methods to compute the flow in the separated zone may possibly be constructed but it is important to understand that it is not possible to march through a separation bubble in one pass and that any procedure which is contorted into doing so is not well conceived and is contrary to the physics of the flow. It should be remarked that although the theoretical problems associated with the type of separation problem illustrated in figure 1 are not easy, progress has been made in recent times on such problems.

Physically the type of separation sketched in figure 1 gives rise to a lower order or weak interaction with the inviscid outer flow. Another type of separation, which gives rise to a strong interaction with the outer flow, is probably a more important problem insofar as engineering applications are concerned but unfortunately is also a much more difficult problem. This is the catastrophic separation behind bluff bodies which is illustrated schematically in figure 2.

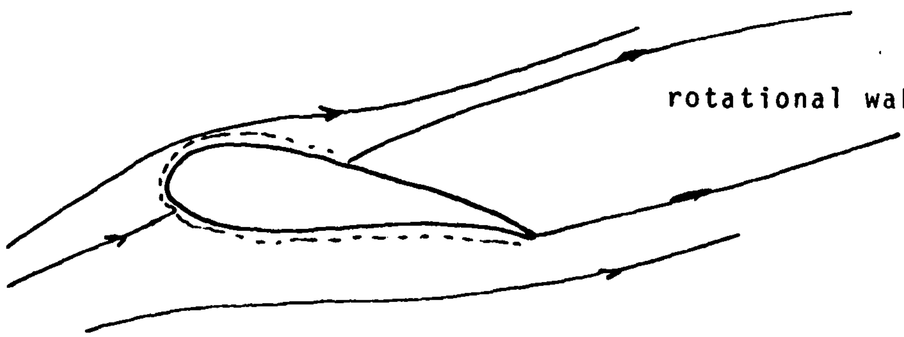

Figure 2. Schematic sketch of catastrophic separation.

For the type of separation illustrated in figure 2, boundary layer separation at some time in the past has given rise to a large region of reversed flow behind the body which has caused a major modification of the pressure distribution around the entire body. In the situation illustrated in figure 2 the classical picture of a thin viscous boundary layer embedded in an otherwise inviscid and irrotational flow fails. It is of interest to reflect why and how this failure occurs from a theoretical point of view. A classical problem which has been studied extensively in the literature is the flow past a circular cylinder at high Reynolds numbers and this will serve as an illustrative example here.

When the solution of the cylinder problem is attempted using classical methods, the irrotational inviscid solution is readily obtained and a numerical solution for the boundary layer solution constructed using a numerical marching procedure which is initiated at the front stagnation point of the cylinder. At approximately 108° in angular distance from the front stagnation point the skin friction approaches zero and the calculation procedure cannot be continued further. It is well known that the solution of the boundary layer equations becomes singular near the point of zero skin friction and this is the famous Goldstein singularity. Although the singular behavior terminates the boundary layer calculation, the singularity is of course not a real feature of the physical problem and the explanation of the phenomenon lies in the fact that the initial assumption that the steady external flow field is irrotational is not appropriate. This notion is confirmed by experiment in that neither the ideal pressure distribution or the predicted location of the separation point agree with measured data.

There are two alternate approaches which may then be adopted for the steady flow problem. First a model for the external flow which takes into account the possibility of boundary layer separation and which allows for rotational flow in the wake region could be considered. A number of such models have been suggested over the years, such as treating the separated zone as a dead air region. In recent preliminary study, Abbott (1977) models the separated zone using blowing from the body surface and in an iterative procedure is able to obtain good agreement with measured values for the lift coefficient associated with a particular airfoil shape. At present most of these models are not well founded in theory and not entirely satisfactory. A relatively recent model by Sychev (1972) is a possible exception to this statement. The advantages of such a model are evident since a rotational inviscid flow could then be coupled to a viscous solution near the body; however at present the theoretical problems associated with such an approach seem rather imposing.

3. Unsteady Laminar Separation

The second alternate approach to the steady problem is consideration of a time-dependent flow for which the desired steady solution is the terminal state. The simplest situation to consider is that where the body is impulsively started from rest and the time-dependent flow is calculated through to the steady state. In the early stages of the flow development the inviscid irrotational solution is the correct outer solution and the effects of viscosity are confined to a thin boundary layer near the body surface; the boundary layer equations describe the time-dependent flow near the body up to and beyond the time when separation occurs. The term separation is used here in the classical sense and implies the presence of a recirculating region of flow which is either closed or attached to the body. Such problems have been studied extensively (see for example Riley (1975)) and it is well known that at a certain point in time after boundary-layer separation occurs, a severe and accelerating thickening of the boundary layer occurs. It is at this stage that an inviscid-viscous interaction is imminent between the boundary layer and outer inviscid flow. Beyond this point in time, the pressure distribution around the body can be expected to progressively deviate from the ideal pressure distribution as the separated flow in the boundary layer erupts into the inviscid region. It should also be expected that once the interaction starts to occur the separation point will continue to move away from the location predicted by steady boundary layer theory. Strong interaction problems between time-dependent boundary layer flows and outer inviscid flows are thus rather important; however to date it has not been possible to successfully treat the interaction problem for any situation in which a separating boundary interacts strongly with the outer flow. This is rather unfortunate not only because the high Reynolds number calculation cannot at present be carried through an important phase of the motion but also because interactions are also a vital feature of most truly unsteady high Reynolds number flows. Hopefully the theoretical difficulties associated with strongly interacting boundary layer flows will be resolved by future research but at present such problems must be regarded as one of the major unsolved problems in fluid mechanics.

4. Turbulent Separation

It is evident that the constitutive relations which are currently used in most prediction methods will have to be altered both upstream of separation and downstream of the separation point. At present the development of such models is inhibited by the relative scarcity of reliable profile and turbulence data in a flow approaching separation and also in the separation zone. As such models are developed it will be possible to consider small zones of separated turbulent flow in a manner similar to that discussed in connection with the laminar problem. It appears that weakly interacting turbulent separated flows may actually be an easier problem than the corresponding laminar case once good turbulence models are available. The case of a strongly interacting turbulent separation zone is much more difficult because the same theoretical difficulty associated with the laminar problem (in modeling a rotational inviscid region) also applies in the turbulent case. Without such a model for the outer flow, the best one can hope to do is compute the boundary layer flow up to the point of time-mean separation; just as in the laminar case, any numerical procedure which is made to march through a zone of separated flow in one pass is not well conceived. Moreover the boundary layer flow up to the point of time-mean separation should be calculated using the measured pressure distribution because (as has been previously indicated in connection with the laminar problem) pressure distributions computed using ideal fluid theory are inappropriate in a strongly interacting separated flow.

Over the past decade much effort has been expended in seeking to model turbulence using a wide variety of higher order equations rather than attempting to model the momentum equation alone. Such methods inevitably introduce a large group of additional turbulence terms which must in turn be modeled. There now exists a wide variety of such models and an even wider variety of "universal" models. Unfortunately the performance of prediction methods based on such procedures has been rather disappointing. Although it is true that, given an experimental data set, a particular "prediction method" may be forced through the data by either juggling the "universal constants" or by postulating whole new modeling functions, it is questionable what long term scientific benefits accrue from such procedures. The basic difficulty is that a good understanding of the basic physical processes that take place in turbulent flow near a wall is still elusive. Despite a wealth of experimentation, the cause of the bursting phenomenon and the wall layer streaks as well as the nature of the vortex interactions which are observed in the outer layer of the turbulent boundary layer are not well understood (even in a constant pressure boundary layer). It seems likely that until some of these questions are resolved on a theoretical basis, progress toward good turbulence models will be very slow. In this regard, I believe that the major effort should be directed at explaining the origin of the Reynolds stress terms in the momentum equation; if the argument is made that it is too difficult to obtain good models for the momentum equation, it seems unlikely that the modeling problem is any easier in the higher order equations.

Because flow separation in a turbulent boundary occurs first in the inner region of a turbulent boundary, the turbulence model for the wall layer flow is particularly important if the boundary layer development upstream of separation is to be computed accurately. The phenomenon of time-mean separation is heralded by a phenomenon of transient reversed flow in the inner region upstream of the location of the mean separation point. Consequently turbulent time-mean separation is a much more complex than steady laminar separation principally because the turbulent separation zone is apparently in continuous motion. It has been recently suggested (Simpson, 1977) that as a flow approaches separation terms arising from the normal Reynolds stresses in the governing equations become comparable to the terms arising from turbulent shear stress. If this is the case, it poses another theoretical problem in that whenever this occurs gradients with respect to x become comparable to those with respect to y. Consequently boundary layer equations can no longer be used to describe the flow and a rescaling of the Navier-Stokes equations needs to be considered. Even if this potential difficulty immediately upstream of a point of time-mean separation could be resolved, it is important to recognize that it is not theoretically possible to push a numerical method through a zone of time-mean reverse flow. Within the zone of time-mean separation a calculation procedure and set of equations is required which reflects the fact that disturbances propogate in both the upstream and downstream directions.

Over the past twenty years a considerable amount of experimental work has been carried out in the area of the coherent structure of turbulent boundary layers. Although the nature of the time-dependent turbulent flow is not well understood, it is evident at this stage that relatively ordered and repeatable events do occur. Despite these experiments, turbulence modeling has for the most part continued to be carried out with little regard for the nature of the time-dependent flow. For the wall layer, most modern prediction methods used a model which is based on the original work of Van Driest (1956); in effect Van Driest considers oscillatory solutions of the heat oonduction equation as a model for the wall layer flow. The basic model has been altered over the years to attempt to account for the effects of pressure gradient, (see for example Huffman & Bradshaw, 1972; Cebeci & Smith, 1974); unfortunately it has been demonstrated by Scharnhorst et al (1977) that such modifications lead to a behavior of the mean profile in the overlap region which is algebraic and not logarithmic. Experiments confirm the validity of the logarithmic law in a flow approaching separation; for this reason, it is to be expected that models of the Cebeci-Smith (1974) type will progressively deviate from profile data as the inner region pressure gradient turn P^+ becomes $O(1)$ as a flow approaches separation.

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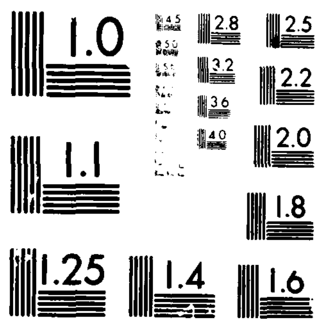

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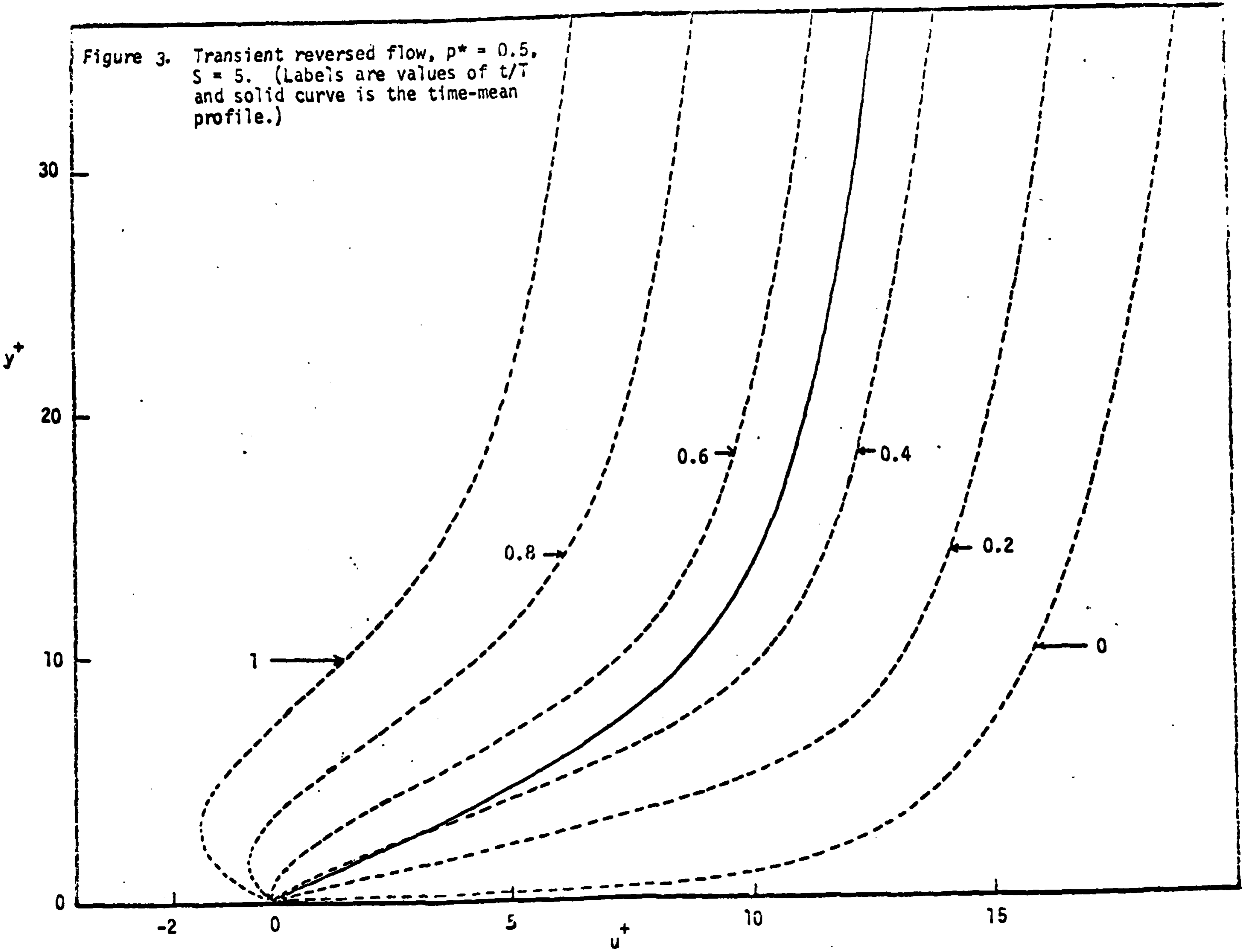
The basic difficulty with models of the Van Driest type is that it is now well established that the time-dependent flow in the wall layer is not a simple oscillatory motion about the mean; for the majority of the time the wall layer flow is relatively well ordered (the quiescent period) although the organized motion between wall layer streaks is eventually interrupted during the bursting process. Because the bursting is of relatively short duration, Walker & Abbott (1977) have argued that the major contribution to the mean velocity profile in the wall layer must be produced during the quiescent period; furthermore it was argued by these authors that the equations governing the leading order flow for all three velocity components in the wall layer during quiescent period are linear and of the heat conduction type. The important assumptions in this analysis are that during the quiescent period: (a) the integrity of the wall layer is maintained and the thickness of the wall layer is $O(\nu/u_\tau)$; (b) the wall layer streaks are present with a mean streak spacing λ; (c) the characteristic spacing in the spanwise direction is λ and (d) the dimensionless mean streak spacing $\lambda^+ = \lambda u_\tau/\nu$ is large. Walker and Scharnhorst (1977) then consider all possible similarity solutions of the leading order equations which correspond to the organized motion observed between adjacent streaks during the quiescent period. An approximation to the mean profile is then obtained by time-averaging the similarity solutions over a typical quiescent period T_q; in this procedure the contribution due to the bursting is neglected on the grounds that this event is of relatively short duration; consequently $T_q \approx T$ where T is the mean period between bursts. The resulting mean profile has been compared extensively with data by Scharnhorst et al (1977) and, unlike the Van Driest profile behaves properly even as a flow is approaching separation. In this connection, one point is worthy of mention; in figure 3 the instantaneous velocity profiles and the corresponding time mean profile is plotted for one of the Fourier coefficients of the solution between streaks; it may be observed that the model contains the transient reversed flow phenomenon observed in turbulent separation.

The problem of obtaining a constitutive model for the outer layer directly from a typical event in the time-dependent flow is much more difficult because in this case it is necessary to analyze the bursting phenomenon; unfortunately there is as yet no plausible explanation of why bursting occurs. It has been suggested recently (Walker, 1978; Doligalski & Walker, 1978) that the bursting from the wall layer may be closely connected with the influence of vorticular structures in the outer layer on the wall layer; in the cited references it has been demonstrated that when a two-dimensional vortex is in motion above a plane wall, a violent eruption of the boundary layer flow is to be expected within a relatively short period of time.

Figure 3. Transient reversed flow, $p^* = 0.5$, $S = 5$. (Labels are values of t/T and solid curve is the time-mean profile.)



While this approach appears promising in eventually resolving why bursting occurs, the actual eruption is a complex viscous-inviscid interaction between the two layers of the turbulent boundary layer. As discussed by Doligalski & Walker (1978) and in §3 of this paper the theoretical problems associated with such an interaction are at present formidable and it appears that for the present we shall have to be content with eddy viscosity models for the outer region.

In a recent prediction method, Scharnhorst (1978) uses the method of matched expansions to isolate the leading terms in an asymptotic expansion for large Reynolds numbers in each region of the boundary layer. The procedure is based on a numerical solution of the outer layer equations which is continually matched to the analytical wall layer profile (given by Walker & Scharnhorst, 1977) as the calculation proceeds downstream. For the outer layer only, Schamhorst (1978) uses an eddy viscosity model similar to the Cebeci-Smith model; the Cebeci-Smith model in its simplest form contains the von Karman constant K and a constant K = 0.0168. It soon became apparent that universal values of K and K would not produce good predictions of measured profile data, particularly in an adverse pressure gradient; Schamhorst (1978) suggests simple linear correlations for K and K as functions of the Clauser pressure gradient parameter $\beta_c = (\delta^* dP_\infty/dx)/\tau_w$ and the results of the prediction method are shown in figure 4 for the adverse pressure gradient flow of Samuel & Joubert (1974). Because of the considerable uncertanities in experimental measurements of the wall shear, particularly in an adverse pressure gradient I believe the best method of evaluating a prediction method is to ascertain how well the method represents the measured profile data. It may be observed that the comparisons are quite favorable but deteriorate at the last two stations as P^+ increases. It emerges that the deficiency is in the model itself and in order to predict flows in which β_c becomes large the basic model for the eddy viscosity must be supplemented as a flow approaches separation.

5. Summary

At present it would be useful to consider the following experimental studies:

1) an extensive flow visualization study of catastrophic turbulent separation. Recent flow visualization methods developed by Smith (1978) using hydrogen bubble wires and a television camera provide a significant amount of detail. Such a study would more clearly define the basic nature of the phenomenon, both upstream of the time-mean separation point and within the separated zone. For example it would be of interest to determine what effect if any, the coherent structures in the outer layer have on the separation zone.

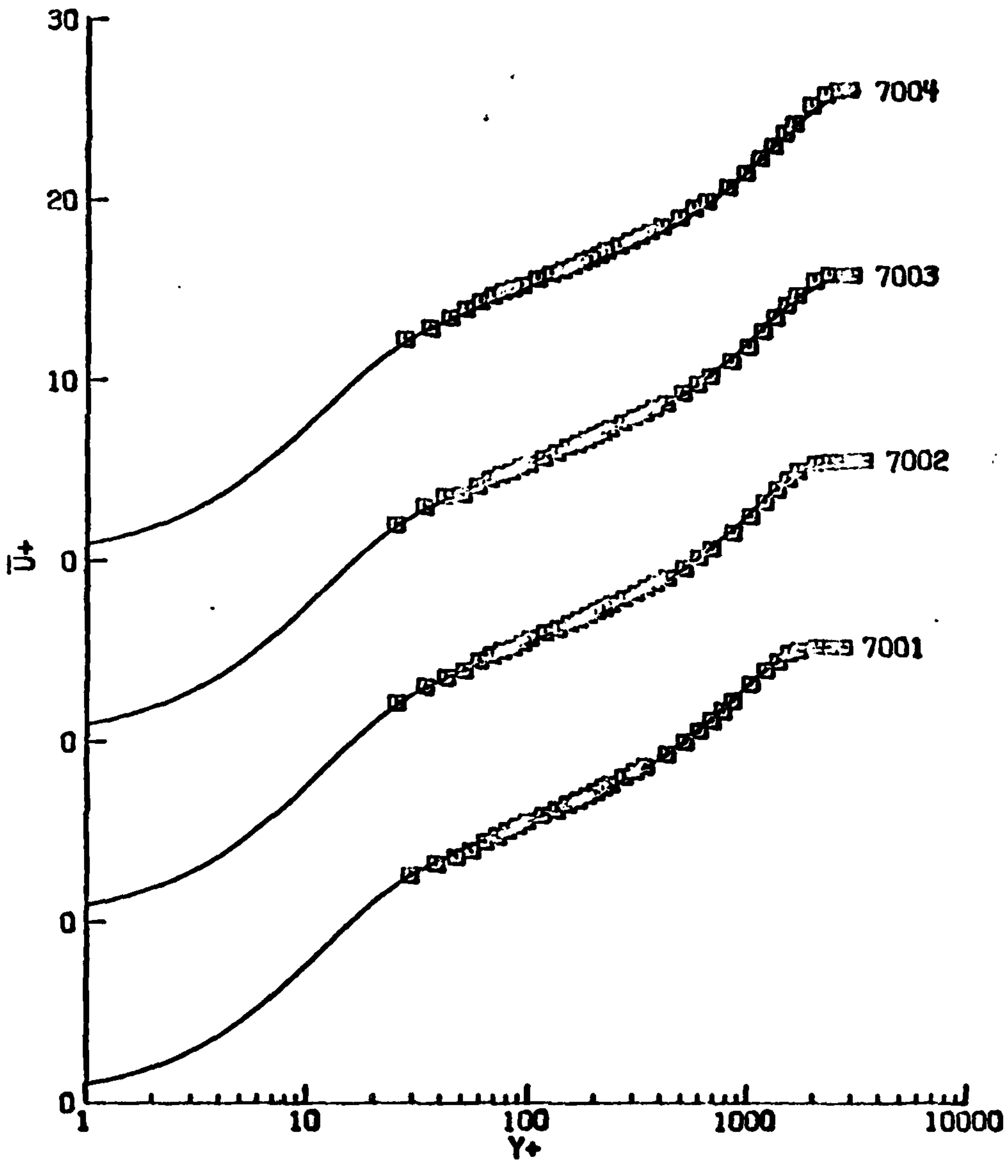


Figure 4. Predicted velocity profiles for adverse pressure gradient flow of Samuel & Joûbert (1974). Labels correspond to successive stations downstream. Note the shifted origins.

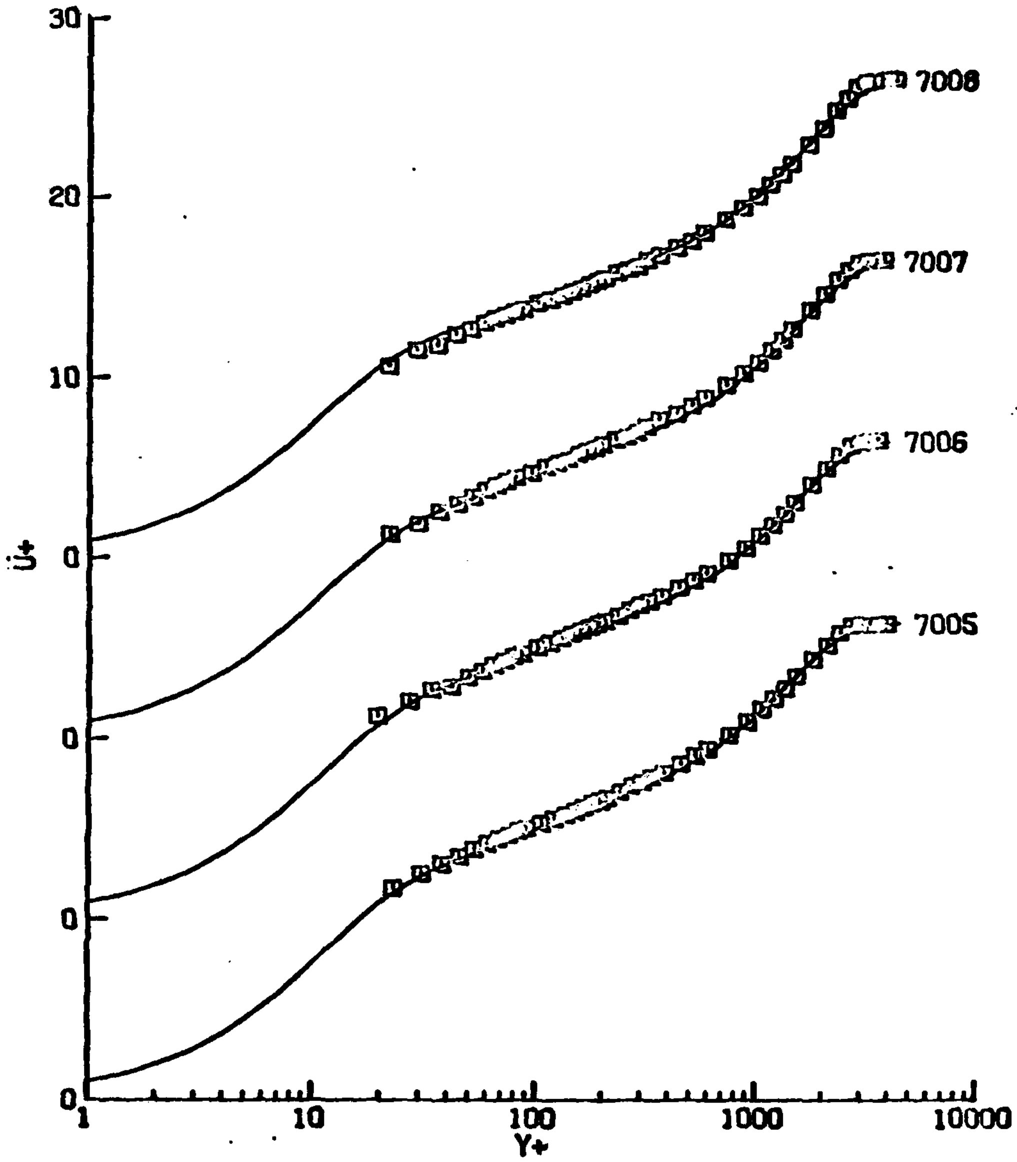


Figure 4. Continued

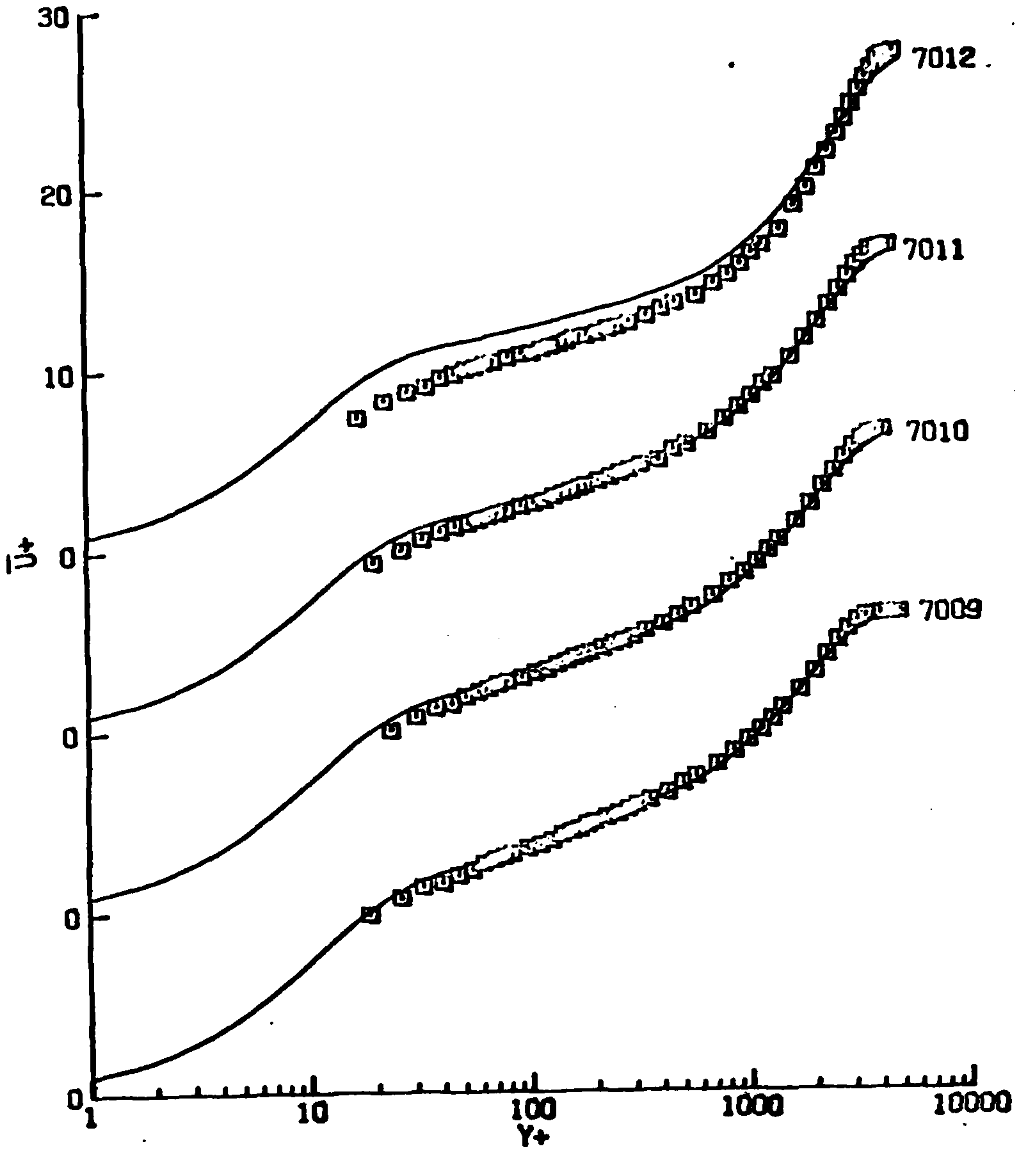


Figure 4. Continued

2) mean profile as well as turbulence measurements are extremely useful in forming improved constitutive relations. In particular it would be useful to further investigate the relative importance of the normal Reynolds stresses; if the suggestions of Simpson (1977) in regard to the normal Reynolds stresses are valid, this will have important consequences in the analytical treatment of separation (as discussed in §4).

From a theoretical point of view:

1) Wall layer models of the type suggested by Huffman & Bradshaw (1972) should be avoided.

2) Modifications of current eddy viscosity models will be needed to be considered if accurate profile predictions are to be obtained as a flow approaches separation.

3) Research into improved models for rotational inviscid wake flows is important as well as research into time-dependent interacting boundary layer flows.

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A summary report is presented on the proceedings of a Project SQUID Colloquium on turbulent flow separation, along with selected position papers prepared for the Colloquium. Both current status and prospects for future research are discussed.

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