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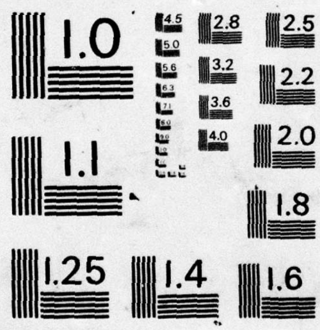

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AGARD ADVISORY REPORT No. 98

Technical Evaluation Report on the Fluid Dynamics Panel Symposium on Flow Separation

by

D.J.Peake and W.J.Rainbird

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TECHNICAL EVALUATION REPORT on the FLUID DYNAMICS PANEL SYMPOSIUM on FLOW SEPARATION

by

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FOREWORD

Upon arrival at Göttingen, we were unhappy to learn that the Chairman of the AGARD Fluid Dynamics Panel, Prof. Dr Dietrich Küchemann, was prevented by illness from attending the Symposium. His wisdom, his penetrating observations, and his wide knowledge were especially missed.

Subsequently, and with the greatest of sadness, we learnt of Dr Küchemann's death on 23 February, 1976. Dietrich was the pillar in the field of aeronautical research about which we gathered and learned. His distinguished writings and lectures were models of lucidity and pragmatism and his eminence in our field can never be replaced. We mourn the loss of a great scientist, a true and lasting friend, and will never forget his warmth, comradeship and concern for his fellow men.

CONTENTS

1. INTRODUCTION

The AGARD Fluid Dynamics Panel arranged a four-day Symposium on "Flow Separation" at the Stadthalle, Göttingen, West Germany, from 27-30 May 1975. The Programme Committee consisting of M.l' Ing. Général P. Carrière (France), Prof. J.J. Ginoux (Belgium), Dr. R.H. Korkegi (USA), Dr. U. Sacerdote (Italy) and Prof. A.D. Young (UK), was chaired by Prof. Dr. K. Gersten (W. Germany). The duties of the Session Chairmen were also undertaken by the Programme Committee. To complete the Symposium, the personal views of Prof. G. Inger, Prof. Young, Mr. J.H.B. Smith and Prof. S.M. Bogdonoff were aired on the scientific content of the meeting, in a "Round-Table" discussion that was ably co-ordinated by Prof. Gersten.

The Symposium commemorated the one hundredth anniversary of the birth of Ludwig Prandtl, the originator of the concept of the viscous boundary layer. Göttingen was a fitting place to hold such a celebration, as Prandtl spent most of his productive life in fluid mechanics at the AVA and at the University. It was noted during the course of the Symposium, that the solutions to many of the flow problems posed by Prandtl are still elusive. In particular, the modelling of the turbulence structure of viscous flows and the understanding of those flows approaching separation and re-attachment in two[12*] and three dimensions[31] requires continuing effort to elucidate the correct physics. The presentation of theoretical models in which the equations of motion are conditioned in a manner analogous with experimental techniques, such as "conditioned sampling", for instance, would also assist in exposing details of the physical phenomena (See Libby, 1975)**.

This evaluation is composed of essentially three parts: laminar separation, turbulent separation and three-dimensional separation, in accord with the programme of events at the Symposium. It was disappointing to the Selection Committee that a session on "unsteady separation" had to be cancelled through lack of papers on dynamic phenomena.

The scene was set at the beginning of each of the three sessions by a review compiled by a prominent worker in that field. Professor L. Crocco supplied a paper[2] that was read by H. Sirieix, to commence the session on laminar flow separation. Sirieix, himself, provided a survey of two-dimensional (2D) separation,[12] whilst J.H.B. Smith gave an excellent review[31] of the status of three-dimensional (3D) separations from the global and local surface condition points of view.

2. OBJECTIVE AND OVERVIEW

The aim of an AGARD FDP Specialists' meeting should be to provide good principles of design applicable to aircraft and missile configurations, from a consolidation of theory with experiment. Any programme will clearly reflect the overall bias of papers submitted to the Selection Committee, and it is unfortunate that the submissions dealt almost exclusively with academic fundamentals rather than with practical vehicles. In fact, Yoshihara's paper[42] was the only one dealing explicitly with separations on an aircraft. With the substantial interest developing in saving every last count of drag to reduce fuel costs, it was also surprising that there were only two papers[15,40] offering proposals on how to control undesirable 2D and 3D flow separations: in these instances, by blowing. After all, we study separation, firstly, to understand it, and secondly to control it[31]. We note that such control or fixing of a flow after the event is in direct contrast with the design philosophy of "controlled flow separation" advanced by Maskell and Küchemann (1956), in which the 3D separation is the beneficial and dominant feature of the overall flow field, and is inherently coupled with the vehicle shape. As we are all aware, the slender wing, that utilises this design approach, has resulted in Concorde.

We had the feeling that some experiments were contrived to suit the analytical tools available; and vice-versa. The 2D analysis drives the 2D experiments, the results from which are returned to the analysis to model the turbulence. The analysis then becomes an interpolation between experimental results. Almost equal preference appears to be given to modelling the turbulence via eddy viscosity methods[23,25], or by means of turbulent kinetic energy methods[13,34]. The continuing, but surprising, success of the eddy viscosity approach stems from the large number of practical configurations where the boundary layers are either of a type in which equilibrium conditions are maintained approximately, or of a type where pressure gradients are large in relation to the gradients of the Reynolds' stresses (Nash and Patel, 1972).

Moreover, for the sake of simplicity, the calculation of boundary layers still tends towards the exclusion of the third space dimension, leading to overt emphasis by experimenters on flows with similar 2D restrictions, in order to allow comparison with theory! At this time, only a limited number of 3D turbulent boundary-layer calculation methods for compressible flow have shown promise: notable amongst which are those of P.D. Smith (1973) and J.F. Nash (1973). More effort is clearly desirable in devising 3D boundary-layer experiments as test cases against which analysis can be checked, particularly with regard to Reynolds' stresses and fluctuating (surface) pressures. The experiment of Elsenaar et al[34] where the 3D boundary layer on a swept wing was investigated in incompressible flow provided some fine measurements of Reynolds' stresses. The utilisation of non-intrusive instrumentation[14], such as the laser velocimeter, to

*Conference paper numbers - see References.
**See Additional References.

measure 2D and 3D flowfields, demonstrates good potential[14], but more experiments are required to check the fluctuating and mean flow laser results against those from small pneumatic and hot wire instrumentation, especially close to a solid boundary.

There was an overwhelming and disproportionate time spent on the meaning and relevance of incipient separation in two dimensions, mainly as a result of the large selection of papers on 2D ramp flows: Werle et al[8] and Burggraf[10] in laminar flows: Stollery[20], Appels and Richards[21], Bogdonoff on behalf of Settles (1975), Shang and Hankey[23], and Holden[24], in turbulent flows. Holden (1975) has provided a well co-ordinated review of experimental 2D turbulent separations at high speeds in AGARDograph 203. The discussion on incipient separation, in Liepmann's view, was senseless and reminiscent of the arbitrary definition of the "edge" of the turbulent boundary layer: is it where the local velocity equals 95, 99.5 or 99.95 percent of the external stream velocity? Clearly, the arbitrary answer is in the eye of the beholder!

Why do experimenters continue to use 2D ramp models where three dimensionalities from edge, sidewall or end-plate constraints, may influence the separated flow region to a large degree - surely the axisymmetric parallel cowl or cylindrical body is the right configuration to study 2D separations about ramps, steps, or retarded flows in distributed pressure rises - see Lewis et al (1972), Peake et al (1971) and Marvin et al[25]. Fortunately, Stollery[20], Bogdonoff presenting Settles' work (1975), Holden[24] and Appels and Richards[21], showed comparisons of surface properties between flares and 2D ramps to illustrate the substantial differences between the two geometries for corresponding flow deflection angles. Notwithstanding, in axisymmetric 2D flows and even in well-organised 2D flat plate experiments, we still view subtle 3D effects[12]. Cellular limiting streamline patterns at separation, and fine periodic structure at re-attachment[18], often appear to give rise to organised vortical flows in the streamwise sense, that pass downstream within the thickness of the original boundary layer (Ginoux, 1971). If ramps are used, then the effect of aspect ratio must be checked carefully (see Holden, 1975).

The issue of incipient separation revolved around who could see the smallest separation bubble, and consequently, who could find the lowest wedge angle at which separation was observed! We feel that separation will always be present if a sharp, re-entrant corner exists, no matter how small is the ramp angle, and its determination will depend upon the resolution available from the experimental measurements near and at the surface.

Liepmann proposed that separation could be defined without contradiction for both 2D and 3D flows in terms of its effect on, say, heat transfer or skin friction; by analogy with boundary-layer displacement thickness, which we define to understand the effect of the boundary upon the inviscid flow field; or momentum deficit thickness, which we use in order to know the drag forces. In his view, "separation," to be significant, involves a strong coupling between the viscous and the inviscid flow domains, rather than the minimal changes in the inner parts of a boundary layer, caused when small separation bubbles exist.

Peake, in the discussion at the meeting, suggested that if separation causes a catastrophic change in the flow field, then the specifying of an appropriate margin prior to the occurrence of the catastrophe, is perhaps a meaningful approach. This follows the accepted practice of ensuring an adequate margin of Mach number between drag divergence and the onset of buffetting on an aerofoil section.

Stollery argued that incipient separation was the boundary between attached and well-separated flows: where there are significant departures in skin friction and heat transfer from the attached flow case. With respect to the ramp flows, however, the development of surface pressure, heat transfer and skin friction, all looked to be progressive with increasing ramp angle, rather than demonstrating sudden and large changes at the chosen ramp angle for incipient separation, α_1.

Since all separations in 2D flow provide substantial unsteadiness, the work of Sandborn and Liu (1968) and Sears and Telionis (1971) in incompressible flow, should perhaps be consulted, to give an improved picture of the time-dependent effects from the philosophical and experimental points of view. In the compressible flow régime, Horstman et al (1974) have shown that the extent of the 2D separation region, when measured in mean flow terms, depends upon the surface technique employed. Attempts at treating large scale separations as time dependent flows could well lead to an increase in our comprehension of 2D separated flows.

We observed the continuing difficulty of grasping a suitable general concept of flow separation when dealing with 3D flows, and the willingness to extrapolate 2D separation phenomena to the 3D domain[36]. Pre-conceived ideas based on 2D flow where separation lines must be perpendicular to the external flow direction are of limited value in synthesising 3D flow separations. Must we not view the case of 2D flow separation as the approach to a zero sweep condition of the 3D separation line?

Maskell (1955) laid the ground rules for the precise interpretation of the physical composition of 3D viscous flows, including the effects after the flow leaves the surface. He demonstrated that 3D flow separation is of vital significance in aerodynamic design, for the constructive role played by swept 3D lines of separation and re-attachment can be interpreted as the skeleton structure around which the elements of the entire flow field can be assembled. Once the lines of separation on a body are determined, then in principle, so is the structure of the mainstream flow containing the viscous vortices. Trailing or free (viscous) vortices spring from any lines of separation on a lifting body (and not just from a trailing-edge) to impart average downward momentum to the fluid about the body.

The aspect of incipient separation in three dimensions was also discussed, with regard to surface flow observations. For example, in the swept shock/turbulent boundary-layer interaction region, incipient separation has been defined conventionally[40] as when the envelope of the limiting streamlines forms and at the same time becomes parallel with the projection on to the surface of the shock wave in the inviscid flow: see Rogers and Hall (1960), and Stanbrook (1961). It is considered that at the occurrence of incipient separation, the substantially thickened 3D boundary layer begins to leave the region of the 3D separation line as a free viscous layer. But this is not a sudden eruption of vortical fluid. It is a progressive and smoothly increasing domain normal to the surface, as the adverse pressure gradient (or downstream distance) increases. The entry of the streamlines adjacent to the separation line into the rolled-up flow, will initially be at a very shallow angle to the surface, and difficult to determine with conventional yawmeter instrumentation[40,41]. Bertram and Henderson (1969) provided some vapour screen pictures of such viscous vortices when the pressure gradients were much stronger than the incipient case, in their experiments on corner flows, while Paper 40 indicates the same qualitative results from the gross distortion of the yaw profiles in the viscous flow. Rainbird (1963-68) has provided boundary layer and external flowfield details of the rolled-up viscous vortices from conical separations.

In contrast, Oskam and Bogdonoff[41] queried whether the envelope of limiting streamlines necessarily indicated the occurrence of 3D separation? Smith concurred with other workers[37,40] and Maskell (1955), that where an envelope of limiting streamlines exists which is followed subsequently by a divergent pattern of same (an attachment region), that a shear layer separates from the surface to roll up into a vortex. He further proposed that a conceptually useful criterion for deciding whether separation has taken place, is by considering the limit of infinite Reynolds' number. If the disturbed region remains finite in extent, then the flow is separated.

As the reader might infer from the foregoing, we feel that incipient separation in 2D and 3D flows is, perhaps, of little or no major significance. After all, the initial effects are scarcely detectable, being confined to the inner parts of the viscous layer. Sometimes, as in the cone experiments of Rainbird (1963, 1968), a parameter such as "incidence, α", which controls the severity of adverse pressure gradients, must be increased by a factor of 2 (i.e. α/θ_c from, say, 0.8 at incipient separation, to at least 1.5, θ_c being the cone semi-apex angle) before substantial changes are detected in the flow field. Then at $\alpha/\theta_c \approx 2$, for instance, the separated shear layers become distinct, the vortex cores appear at a distance above the surface of several times the thickness of the boundary layer at incipient separation, and the induced effects on, say, normal force, are readily discernible as a significant non-linearity. Hence, does the onset of separation (and its illusive prediction) matter very much?

Although as Smith[31] points out, there has been substantial progress in diagnosing and understanding 3D separated flows, no boundary-layer method can yet determine explicitly the position of a 3D separation line. Neither have we been able to calculate, by appropriate inviscid modelling, the development of coiled-up vortex sheets springing from 3D separation lines on a body of general shape. To a degree, these deficiencies result from an inadequate knowledge of the precise mechanism of 3D flow separation (and re-attachment) and hence, how to generate an adequate flow model for calculation purposes. There is clearly a need for some carefully contrived experiments to elucidate the fluctuating and mean flow details of the region near to a 3D separation line.

3. LAMINAR SEPARATION

Of significance, was the emergence of matched asymptotic (or "multiple deck") analysis[2,3,4,5,10], as a worthwhile new approach to understanding viscous-inviscid interactions and separation. This development of the groundwork laid by Stewartson (1974) and Messiter (1973), is the logical outcome of Prandtl's boundary-layer concept as a large Reynolds' number asymptotic approximation, coupled with his idea of order of magnitude analysis of the Navier-Stokes' equations for the flow adjacent to a surface.

The multiple deck analysis provides important insights: it exposes much of the underlying physics and fine-grain flow structure; it provides variables of a given problem, thus proving useful in guiding numerical studies. Local singularities, such as the physically unrealistic separation point singularities are eliminated by introducing the appropriate local viscous/inviscid interaction details. Nevertheless, these asymptotic solutions have usually been restricted in practice to certain values of the flow parameters, and to simple geometries. It is desirable, therefore, that they be used to suggest approximate analytical approaches of layered type that can provide design information and solutions to laminar and turbulent interactions (and separating flows) over a wide range of conditions, corresponding in principle, with the approximate solutions developed to solve the boundary-layer equations. We note that Stratford's successful method (1959) of separation prediction that was quoted extensively at the conference, utilises a two-layer representation of the flow.

The capability of extending the laminar flow analysis to turbulent flows was discussed; but we should be cautious about modelling laminar and turbulent shock/boundary-layer interactions in two dimensions by essentially similar techniques. In laminar flow, for instance, shock waves are developed near the outer edge of the boundary layer resulting from a mutual interaction between the viscous layer and the outer flow. In turbulent flow, on the other hand, the separation shock and the separated region are embedded well within the thickness of the undisturbed turbulent boundary layer due to the fuller mean Mach number profile. The describing of the turbulent interaction by a laminar model, modified to incorporate a larger and more complex viscosity, is not considered the correct physical approach (see Holden, 1975).

In his Prandtl memorial lecture[1], Prof. Schlichting reminded us that theory must lead to predictions of facts that can be verified experimentally, and as a consequence can be useful in practical design. Some proposals were forwarded at the conference that good basic laminar flow experiments, other than in hypersonic flow, were necessary to confirm the ideas expressed in the multi-layered analysis. However, we should remember that fully laminar separated flows are of practical importance, only where flight Mach numbers are greater than 12, and where highly-cooled wall conditions exist. The important practical problems are the effect of pressure gradient, leading-edge bluntness and surface curvature, on the occurrence and the properties of separated flow in the laminar boundary-layer interaction regions, none of which were addressed at the meeting.

In the numerical analysis presented, provided viscous/inviscid interaction effects are included, the boundary-layer equations (with $\partial p/\partial y \sim 0$) were considered adequate to obtain engineering solutions of high Reynolds' number separating flows, over a wide range of practical conditions up to reasonably high Mach numbers. Nevertheless, in hypersonic flows, $\partial p/\partial y$ terms are probably important near to separation and re-attachment, while for acceptable accuracy on curved bodies, it is desirable to add first order longitudinal and/or transverse curvature terms.

Several finite difference programs are now available[8], that can cope with separating flows, but few showed comparison with experimental results. These finite difference schemes appear to be generally superior to integral methods and free from the spurious super-to-subcritical jumps and saddle-point singularities. The displacement thickness effects, properly included, appear to have the largest significance in treating the separation singularity. If, for example, in the "inverse" problem, the displacement thickness is prescribed to be a regular function of wetted length (Catherall and Mangler, 1966) or, alternatively, the wall shear stress is given[7], solutions of the laminar boundary-layer equations may be obtained through and beyond separation and re-attachment.

There still appear to be some unresolved difficulties. The success of many numerical schemes seems sensitive to the choice of independent variables and co-ordinate systems. Moreover, it is unclear why some investigators manage to obtain solutions to the Navier-Stokes' equations at high Reynolds' numbers while others continue to have substantial difficulties with instabilities. Ghia[6] considered that the reason for the difficulty in computing high Reynolds' number flows using Navier-Stokes' equations, was the two different time and two different length scales in the problem, for the viscous and the inviscid regions respectively. It appears important to choose the relaxation factors in an iterative numerical scheme, or the time steps in ADI* schemes, such that both time scales in the viscous and inviscid flows are given proper representation simultaneously.

However potent these above mentioned numerical solutions appear to be, they usually work satisfactorily only for well-understood problems. Both analysis and experiment will always be needed when we are confronted with new problems and unknown phenomena, and where we must initially obtain a physical insight into the flow structure and the relevant scaling parameters.

4. TURBULENT SEPARATION

In a wide-ranging review[12] of 2D separations in incompressible and compressible turbulent flows, Sirieix considered especially those flows about rearward and forward-facing steps, ramps, bases and in interactions between boundary layers and externally-produced shock waves. Sirieix noted that although a satisfactory comprehension of the global nature of turbulent 2D separated flows has been established, the structure of the turbulence is not well understood, particularly in separated shear layers and about re-attachment zones where non-equilibrium conditions prevail. The rate of entrainment of inviscid fluid into an attached turbulent boundary layer is substantially different from the entrainment when the boundary layer is separated; and when it re-attaches. Clearly, we require to know more about the changing turbulence levels and zones of intermittency and their effect on entrainment rates. Such changes in structure of the turbulent boundary layer are not usually reflected in the near-equilibrium turbulence models currently in use. Nevertheless, measurements of turbulence quantities in separated flows may present difficulties, according to Chu and Young[13]. They found that hot wire measurements of turbulent shear stress were not reliable when the boundary layer was close to separation, nor did the interpreted mean flow velocity profiles from the hot wires show agreement with profiles determined from pitot tubes and local wall static pressures. There is clearly a requirement for redundant measurements in a separation experiment, where intrusive and non-intrusive instrumentation results can be compared critically.

In incompressible, boundary-layer flows, at least, weak interaction problems can be solved satisfactorily with a good choice of calculation methods existing between integral (e.g. Head and Patel, 1969) and differential (e.g. Bradshaw et al, 1967) methods, provided the static pressure distribution is available. One may introduce lag terms (Green et al, 1973) or other terms corresponding with extra rates of strain (Bradshaw, 1974) to provide very satisfactory comparison with experiments when the compressible boundary layer is not in local equilibrium in strong (but not separating) pressure

*alternating-direction-implicit

gradients. To predict separation, Stratford's method (1959) was considered at the meeting to be a conservative but easily applicable and reliable criterion.

When the static pressure distribution along the wall is unknown, and we have a strong interaction such that the separation induces gross changes in the (original) external flow field, the external flow reacts back on the viscous flow in a manner not readily predictable at the outset. Here, separation is not a local boundary-layer problem, but a phenomenon that depends on the global flow field, where the latter (and hence the pressure field) are themselves dependent on the viscous and turbulent shearing forces, and are not given in advance. As a consequence, Liepmann argued that the computation of the point of zero shear on the basis of boundary-layer theory, with a prescribed pressure distribution is not the essential part of the separation problem. Simpson[14], in measurements with a laser velocimeter within a highly-separated incompressible aerofoil-type flow, concluded that neglect of the normal stress terms in the momentum and turbulence energy equations is not justified, and that the intermittent separation viewpoint of Sandborn (1968) is relevant.

Between the flow cases of the attached boundary layer and the fully separated one, we have the small bubble case, envisaged in papers on shock/boundary-layer interaction, where the boundary layer re-attaches after the small region of separation. A number of methods has been developed[22,23,25], to predict such flows, that involve variants of the boundary-layer equations coupled with the external flow. These have then been compared against solutions of truncated Navier-Stokes' equations, in which the turbulence modelling was, perhaps, the weakest feature. Boundary-layer theory is a perturbation procedure that enables the correction of a potential flow for relatively small viscous effects. When non-trivial normal pressure gradients are observed in the Navier-Stokes' solutions, then the boundary-layer approaches used for these same flows must fail, and are seriously deficient in predicting the details of the interaction regions[25].

There was insufficient material on strong interactions, and these are the real practical problems. The stalling of relatively high aspect ratio wings at low speeds, shock stall and the onset of buffetting at transonic speeds were not considered in detail (neither were these subjects in the 3D flow régime). However, there were some papers on quasi-steady[27,30] and unsteady[26,28,29] shock/boundary-layer interactions.

There has been substantial discourse on the effect of Reynolds' number on the occurrence of separation in 2D turbulent flow, beginning perhaps with Kuehn's (1959) and Roshko's and Thomke's (1969) earlier investigations. It will be remembered that for $R_{\delta_0} < 10^5$ the incipient separation angle at a wedge compression corner, α_i, was demonstrated by Kuehn to decrease with increasing Reynolds' number, while at $R_{\delta_0} > 10^6$ and $<10^7$, Roshko's and Thomke's results showed an increase. These trends were consistent up to Mach numbers of at least 5. Stollery[20] reflected on Elfstrom's method (1972) - see Appendix - that provides an explanation of this trend reversal, and who obtained quantitative estimates of the incipient separation angle. On the other hand, Bogdonoff's interpretation of Settles' (1975) work disputed the above qualitative trends in α_i with Reynolds' number. He discussed incipient separation experiments at Mach 2.9, where measurements were made in a high stagnation pressure blowdown wind tunnel environment, with test boundary layers on the floor of a long working-section using a wedge, and upon an axially symmetric model with a flare. Both sets of these measurements showed that in the range $10^4 < R_{\delta_0} < 10^7$, the incipient separation angle was virtually invariant with Reynolds' number, at a value between 15° and 18°. The differences between these latter results and those from previous experiments were attributed to differing mainstream turbulence levels from facility to facility, wherein only a small Reynolds' number range was usually available, and the haphazard approach by some experimenters to the end-wall problem.

The effect of increasing Reynolds' number is to reduce the oncoming boundary-layer thickness, but do the boundary-layer profiles also change substantially, and if so, do these changes affect the region of interaction between shock waves and the viscous flow? Clarification is needed of any dependency on the undistorted boundary-layer profiles, by analysis and from experiments.

Some claims were made that the use of a laser velocimeter provided all of the relevant information to determine a given flow field, and that variations in static (and pitot) pressures were not required to be measured. Young considered that we are interested in the mean static pressure distributions in their own right, to provide forces on an immersed body, for instance. Rainbird proposed that the velocity measurements alone are not sufficient and that we still require pitot pressures to show regions of total pressure loss. In rolled-up shear layers, for example, a knowledge of only mean velocity components does not provide a complete picture and cannot distinguish clearly the viscous and inviscid parts of the flow field.

In the main, we see that computations of turbulent flow are still essentially empirical, to bridge between sets of experimental results. Any extension of such computations is not safe, to flow cases where there are no measurements, and calculation methods, therefore, must be applied with caution.

5. THREE-DIMENSIONAL SEPARATION

Smith[31], in his excellent review paper, categorised three-dimensional flow separations in terms of their causes. These he considered to be: (1) obstacles protruding from a wall; (2) blowing perpendicularly from a wall; (3) shock waves; (4) external flows with streamwise and transverse adverse pressure gradients over smooth walls; and (5), salient edges. Some important examples of the first of these are the separation of a fuselage boundary layer by the wing or other lifting surface, and about excrescences in general[illegible] [see the discussion on large and small protuberance flows respectively by Peake et al (1972) and by Gaudet and Winter (1973)]. The second item relates to the local body flow in proximity to propulsion or control jets emitting from a surface. Little has been reported on the effects of normal or tangential blowing on 3D separation. Work on interactions between shock waves and boundary layers in three dimensions has been intensive since Green's review of the subject in 1970, but much of the recent experimental research has been concerned with the mean flow details about supercritical swept wings and within intakes at off-design conditions. Six of the papers at the meeting,[35,36,37,40,41,42] all dealt with 3D shock/boundary-layer interactions, indicating the concern that aircraft, missile and propulsion designers advance about these important flows. Of course, the above flows could be included in category (4), where separation is induced on a body by varying degrees of longitudinal and circumferential adverse pressure gradient. Smith's review[illegible] concentrated on these latter flows with smooth walls, and flows from sharp edges, category (5). Such flows are found on and about bodies of revolution at high angles of attack[illegible], over the surfaces of swept wings[illegible], over the upper surfaces of slender or delta planforms beneath the primary vortex structures[illegible], and indeed, about most aircraft and missile configurations. Water channel flows about a multitude of 3D bodies were superbly illustrated in Werlé's film[illegible].

Our design aim must be to bring together a prediction of 3D separation lines, coupled with a model of the separated viscous shear layers as they leave the surface. In most practical examples, we still try and blend an inviscid flow solution with an appropriate boundary-layer procedure, rather than exploiting the conceptual simplicity of the more general Navier-Stokes' equations*. Unfortunately, for the general case we are still unable to model the turbulence structures adequately in 2D flows (let alone in 3D) and the concomitant free shear layers springing from 3D separation lines, to provide a rational design procedure. When the viscous, streamwise derivative terms are small in comparison with the viscous normal and circumferential derivatives, an approximate system of parabolic equations obtained from the steady Navier-Stokes' equations may, however, be used for laminar flows about sharp cones (McRae, 1975) or blunted cones[32]. Apparently, the equations are valid for both the inviscid and viscous regions when leeside separations are present, although internal shocks in the cross-flow cannot be predicted. The method in Paper 32 did not indicate the development of the free shear layer from the 3D separation line, however.

In the classical aircraft, the art of design has been to eliminate separation ahead of the trailing-edge, usually because increases in drag and flow unsteadiness are introduced with essentially 2D separations on unswept wings of relatively large aspect ratio. With increases in speed, and range of angle of attack, over which smaller aspect ratio, swept-back lifting wings and bodies are required to operate, extensive regions of 3D separated flow are predominant, and we require new and suitable flow models. On wings with sharp, swept leading-edges, for example, 3D separation occurs at the salient edges, and is virtually independent of the oncoming boundary-layer properties at the high Reynolds' numbers of practical interest to us. The boundary-layer fluid departs from the surface to form rolled-up viscous shear layers whose scale is usually many times the local boundary-layer thickness (in contrast with the separation caused by a swept shock wave[illegible]). In the limit of infinite Reynolds' number, or for practical purposes, at high enough Reynolds' numbers, the coiled viscous shear layer may be modelled approximately by a coiled inviscid flow vortex sheet. In other words, viscosity causes the separation, the location is determined by the edge geometry, after which the flow may be modelled by inviscid means[illegible]. The slender wing and strake are examples of these flows. Maskell and Küchemann's philosophy (1955,1956) of controlled flow separation by a salient edge was the essential ingredient that launched the aerodynamic design of the slender wing and of Concorde, the flow field remaining qualitatively invariant with attitude and with Mach number. On the other hand, the modelling of the secondary separations has not been successful thus far.

On bodies, the location of separation is not known a priori, and we must attempt to calculate its position via 3D boundary-layer theory. The separation line is given from the calculation when the limiting streamlines (i.e. *surface shear* stress trajectories) merge into an envelope (Maskell, 1955) - see the computation by Peake and Galway, 1965. Correspondingly, a numerical instability is encountered in the calculation as the physical location of the separation is approached. Geissler[33] used these phenomena to calculate 3D separation line positions in an incompressible laminar boundary layer on a 6:1 ellipsoid at incidence, but no comparison with experiment was shown. The boundary layer was computed by an implicit finite difference technique utilising a streamline co-ordinate system, making no assumptions of small cross-flow. The co-ordinate system was the projection on to the surface of the inviscid flow equipotentials and their orthogonals, the external flow being computed by a singularity procedure. Hence the assumed non-interactive nature of the viscous and inviscid flow fields will probably produce some errors in the calculation of the leeside viscous flow, where the departing of the viscous shear layers from the surface will modify the inviscid flow pressure distribution (see Peake et al, 1972).

Close to a 3D separation on an "infinite" swept wing, Elsenaar et al[34] found that the calculation of the incompressible turbulent boundary layer was particularly sensitive

*Even with the continuation of the startling growth in our computer technology, it is not considered that the complete time dependent Navier-Stokes' equations for complex flow fields will be solved in a routine manner for at least a decade (Chapman et al, 1975); if then.

to the local pressure distribution. The calculation was a finite difference method due to Wesseling and Lindhout (1971) that employed semi-empirical shear stress relations (suitably modified from the experimental measurements) as input to the turbulent kinetic energy equation. Convergence problems were encountered in the calculation near the 3D separation line.

In the experiments[34], the development of the 3D boundary layer upstream of separation showed a marked decrease in mixing length and a substantial difference between the directions of shear stress and velocity gradient. Simpson suggested that all six production terms of the turbulence energy equation for three dimensions should be retained as separation is approached (see discussion after Paper 34 in the Conference Proceedings).

In regions of 3D separated flow produced by shock waves, and in areas of high heat transfer rates along a re-attachment line emanating from an attachment point, our ability to predict the consequences is unsatisfactory (Korkegi, 1971). In general then, we are unable yet to model the viscous flow phenomena encountered in 3D attachment and separation regions that will yield rational design procedures. But from the pioneering work of Sears (Collected Papers, 1974), Maskell (1955,1961), Küchemann (1956,1969), Legendre (1965,1966), Lighthill (1963) and others, we do possess some understanding of conditions close to attachment, separation and re-attachment in 3D flow fields. It is clear that in any 3D separated flow, the limiting streamline that is characteristic of a 3D separation line, has one feature common to all flows. It is a barrier across which the limiting streamlines on either side of it cannot pass (see Papers 40 and 41).

Bachalo and Holt[35], Peake and Rainbird[40], Oskam et al[41] and Yoshihara and Zonars[42] all dealt with aspects of swept shock waves interacting with turbulent boundary layers. Swept-back wedges were used in Papers 35, 40 and 41, whereas Paper 42 dealt with swept wing flows influenced substantially by the adjacent fuselage. The development of the viscous flow in the swept interaction region leading eventually to 3D separation when the imposed adverse pressure gradients become sufficiently steep, is a gradual, progressive and relatively steady (in comparison with 2D separations) process, in which the flow leaves the 3D separation line as a free shear layer that rolls up into a vortex within the depth of the original undisturbed boundary layer. Such vortices were viewed using vapour screen techniques by Bertram and Henderson (1969). There appears to be no sudden eruption of viscous vortical fluid from the test surface. In fact, the occurrence of incipient separation is particularly elusive, unless the formation of an envelope of limiting streamlines (Maskell, 1955) that happens to coincide with parallelism of the limiting streamlines with the calculated (or visualised) shock wave in the external flow, is adopted as the incipient separation criterion. With the potential utilisation of non-intrusive measurement techniques such as the laser anemometer, perhaps a clearer understanding of conditions away from the surface can be obtained to define incipient separation by means other than at the surface. Incipient separation in 3D occurs at a lower overall pressure ratio than in 2D flows, at corresponding Mach numbers (Korkegi, 1973).

The control by blowing, of a shock-induced 3D separation was attempted in Paper 40. It was shown that the optimum direction of a supersonic wall jet was roughly along the line of 3D separation, rather than normal to it. This result may be pertinent to the slender protuberance geometry used to generate the shock wave, and may not necessarily carry over to the swept wing problem. More work is essential on how to control 3D separations with active means in a general case.

6. CONCLUSIONS AND RECOMMENDATIONS

In laminar, separating flows, we noted the emergence of matched asymptotic or "multiple deck" analysis as a worthwhile approach to understanding viscous-inviscid interactions and separation.

In turbulent flows approaching separation, weak interaction problems can be solved satisfactorily with a good choice of boundary-layer calculation methods available, of the integral and differential type. Where there is strong coupling between the viscous and inviscid domains, and where non-trivial normal pressure gradients and normal stresses exist, boundary-layer calculations fail, in which only an undisturbed potential flow pressure distribution is assumed.

In three-dimensional separating flows, the calculation of laminar viscous/inviscid interactions appears successful utilizing simplified versions of the Navier-Stokes' equations. There are no suitable calculation procedures in turbulent flow to predict overall flow fields containing viscous vortices emanating from three-dimensional separation lines. Elsenaar et al's extensive measurements (that included Reynolds' stresses) in the turbulent boundary layer on a swept wing, provide a suitable data base against which to compare incompressible 3D turbulent calculation methods up to separation.

We were concerned at the inordinate amount of effort being expended in the definition of the initial onset of separation. We are of the opinion that, at least for most of the three-dimensional cases we have examined, the initial onset of separation (involving only the inner parts of the approaching boundary layers) is not a particularly notable event and does not signal large changes in the external flow field or, therefore, in the overall aerodynamics of the flight vehicle.

The collection of papers at the meeting provided some additional insight into the fundamental aspects of 2D separation in laminar and turbulent flows. However, the time has now arrived where, with the constraints of budget and fuel costs, real, practical problems must be the focus of our work. We must direct research into the measurement of turbulence quantities in three-dimensional flows, particularly in the presence of dominant 3D separations and the ensuing re-attachment zones. We must try and understand the physics of 3D flow separations, for such problems are the main cause of concern in the aerodynamic design of aircraft, missiles and propulsion systems. The control of these separations is a subject barely breached in studies to date. Apart from the obvious advantages of fixing 3D separations at sharp edges, how beneficial are leading-edge notches, vortilons, suction and blowing boundary-layer control in three-dimensions?

Non-intrusive instrumentation, such as the laser velocimeter, offers great promise in improved flow diagnosis. Notwithstanding, comparisons with alternative measuring devices must still be done to provide redundant measurements, while static and pitot pressures are still required to determine forces on a configuration and to indicate immediately, where the regions of energy loss occur in a flow.

It is clear that a specification should be formulated to set up respective 2D and 3D boundary-layer experiments, to remove the ongoing doubts that exist whenever comparisons are made between virtually all of our present measurements and theories. Sufficient redundant measurements must be incorporated as cross-checks. The experiment should be planned, with a view to that which is required in the theory, and the two must interact.

In terms of configuration, an axisymmetric cowl for 2D flows at zero angle of attack, and at incidence for 3D flows, could be a suitable basic model. Either the external or internal surfaces could be used. Alternatively, the right-circular cone facilitates the measurement problem, by providing the opportunity to use one axial measurement station, if the combined viscous and external flow fields remain conical. In such a controlled experiment, we might envisage the measurement of the following parameters:

1. at the wall: mean and fluctuating static pressures; shear stress from surface pitot, strain-gauge balance and hot film gauges; surface temperatures using thermocouple, hot film and infra-red techniques; surface flow visualisation; precise definition of transition.

2. in the viscous and external flow fields: mean static and mean pitot pressures; fluctuating static and pitot pressures; mean yaw and pitch angles from pneumatic and hot wire probes and laser velocimeter; mean stagnation temperature and fluctuations; velocities, mean and fluctuating, with laser velocimeter and hot wires; Reynolds' stress terms from velocimeter and hot wires; intermittency measurements and conditional sampling; flow visualisation.

The external flow fluctuation levels as well as the mean flow details must be adequately defined. The experiment should also make provision for tests through a wide range of varying Reynolds' number to change the relative scale of the oncoming boundary layer with respect to the interaction region. Finally, a Stanford-type appraisal could be organised to check promising calculation procedures against the experimental results. Clearly, the foregoing requires substantial effort and expense, but is it not time that a complete and unambiguous set of experimental results were available?

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SESSION I - LAMINAR SEPARATION

Laminar Separation by L. Crocco — 2

Laminar Separation at a Trailing Edge by J-P. Guiraud and R. Schmitt — 3

Laminar Separation - A Local Asymptotic Flow Description for Constant Pressure Downstream by A.F. Messiter — 4

Dependence of Laminar Separation on Higher Order Boundary-Layer Effects Due to Transverse Curvature, Displacement, Velocity Slip and Temperature Jump by A. Wehrum — 5

Evaluation of Several Approximate Models for Laminar Incompressible Separation by Comparison with Complete Navier-Stokes' Solutions by K.N. Ghia, U. Ghia and W.A. Tesch — 6

SESSION II - TURBULENT SEPARATION

SESSION III - THREE-DIMENSIONAL SEPARATION

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APPENDIX

Elfstrom's method is, in fact, valid only in high Mach number and/or in very high Reynolds' number flows, where the characteristics of the outer (i.e. the essentially inviscid) portion of the boundary layer dominate the flow development. A full discussion of the method and its qualifications is presented in Elfstrom's Ph.D. thesis, Sept. 1971, at the University of London, entitled "*Turbulent Separation in Hypersonic Flow*".

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14. Abstract

This report contains an evaluation and appraisal of the subject with recommendations for future research. Current knowledge and understanding of the fluid physics of 2D and 3D flow separation and reattachment, particularly for turbulent flows, is limited. It is necessary that high quality, carefully planned 2D and 3D boundary layer experiments be conducted to obtain dependable experimental data to enhance our basic knowledge, and for use in verification, validation and development of theoretical prediction methods. These complete, unambiguous data sets should include detailed documentation of all measurable quantities, both mean and fluctuating, at the wall, in the viscous boundary layer and in the external flowfield. Emphasis should be placed on redundant measurement techniques to ensure high data reliability.

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