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# Flow Separation — Problems and Possibilities

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ABSTRACT

This paper is a discussion of those flow regions in which separation, occuring from sharp corners, is followed by reattachment, to form nominally two-dimensional "separation bubbles". New measurements, taken with a pulsed wire anemometer, are reported for the separated region near the leading edge of a blunt flat plate. Mean streamlines are deduced from the velocity profiles and a comparison between the locations of the separation streamlines as measured and as predicted by a simple potential model supports the assumption that the flow separates tangentially from the plate leading edge and that it is essentially two-dimensional.

A simple momentum integral method is devised for use in separation bubbles and is tested for laminar flows in a sudden symmetric expansion. Reasonable agreement with more complicated calculation methods is obtained, suggesting that such simple methods have a useful place in predicting the mean flow fields of separation bubbles.

## 1. Introduction

In nominally two-dimensional flow, two types of flow separation can be identified: separation from smooth surfaces and separation from abrupt corners. The first can occur only in an adverse pressure gradient whereas the second often occurs in a favourable pressure gradient. When the boundary layer at separation is thin, as may well be the case in a favourable pressure gradient, the outer or potential flow streamlines are commonly assumed to be tangential to the upstream surface, giving a useful condition for calculations of the outer flow. The well-known "wake-source" model of Parkinson and Jandali (1970) uses this approximation in calculating pressure distributions around a normal flat plate for example.

Details of the flow in separated regions are difficult to measure or predict and are often summarized in a few empirical constants, used in models which describe pressure distributions or overall fluid forces. Drag co-efficients, base pressure co-efficients, non-dimensional pressure gradients at separation and various forms of Reynolds stress modelling constants are examples of such empirical summaries.

In this paper, which deals deliberately with the simplest cases, attention is restricted to two-dimensional flows which separate at sharp corners and which reattach some distance downstream of separation. Simple descriptions and measurements are made of the mean flow characteristics. In particular the flow close to the leading edge of a blunt flat plate (Dziomba, 1985) has been examined experimentally in some detail, and a second case, the flow over a backward facing step, has been used to test calculation procedures. The objective is to provide dependable experimental data describing two-dimensional separation bubbles and to devise and test calculation procedures based on simple assumptions.

## 2. The Blunt Flat Plate - Measurements

Experimentally, a flow separation region is difficult to make convincingly two-dimensional, as Dziomba (1985) has shown. For the present measurements, the blunt plate shown in Figure 1 was used. The large "fences" were necessary to give reasonable two-dimensionality, as demonstrated by the surface flow visualization studies done in the authors' laboratory by Dziomba. The model spanned the full width of the large wind tunnel at the University of B.C. and gave an overall tunnel blockage of 5.6%. A tapered "tail" was added to the trailing edge of the plate to reduce or eliminate the effect of vortex shedding on pressure and velocity measurements near the separation bubble.

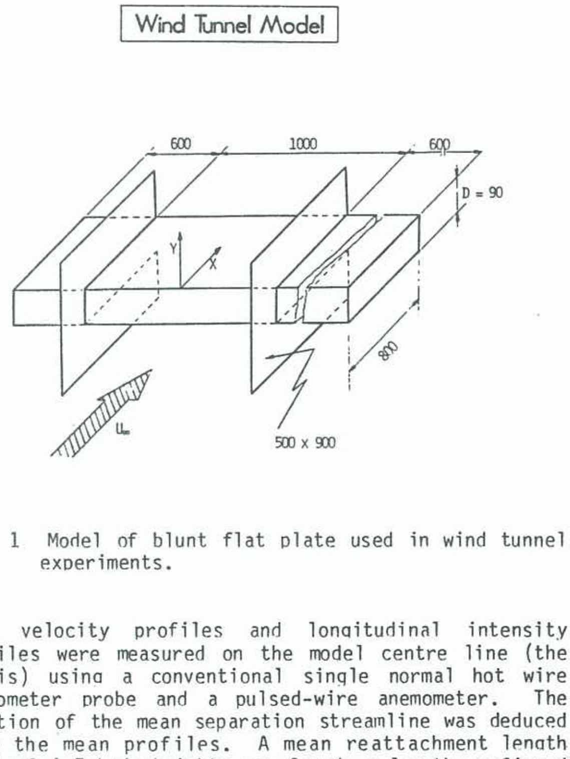


Fig. 1 Model of blunt flat plate used in wind tunnel experiments.

Mean velocity profiles and longitudinal intensity profiles were measured on the model centre line (the x-axis) using a conventional single normal hot wire anemometer probe and a pulsed-wire anemometer. The position of the mean separation streamline was deduced from the mean profiles. A mean reattachment length ($X_R$) of 4.7 body heights was found, a length confirmed by later measurements of wall shear stress in the separated region. This compares very well with values from various sources reported by Cherry et al (1984) who summarize the sensitivity of the reattachment length to both aspect ratio and blockage. Little effect of Reynolds number was found in the present studies over the range $2.5 \times 10^4 < Re < 9 \times 10^4$ (based on plate thickness).

Surface pressure distributions were also measured and were found to be very sensitive to model inclination and to nearby obstructions such as traverse gear components. Figure 2 shows the mean pressure co-efficient distribution on the plate surface and compares the values of $C_p$ to those of Cherry et al (1984). Some uncertainty exists in reported values of $C_p$ because of the experimental difficulty of unambiguously identifying the free stream static pressure $p_\infty$. In the present case, this was measured 10 D ahead of the body and 7.5 D off the centre line (where D is the body frontal height). A different value of $p_\infty$ would shift the $C_p$ curve up or down.

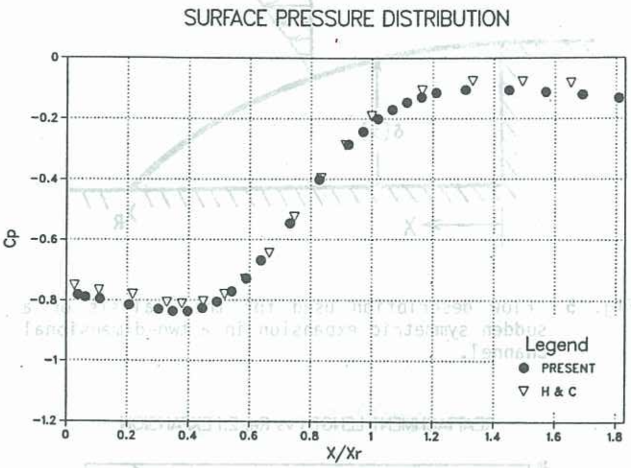


Fig. 2 Surface pressure distribution on the blunt flat plate. Data from present experiments and from Cherry et al (1984).

Frequency spectra taken from a conventional hot wire anemometer placed near the maximum mean velocity position above the separation bubble showed distinct frequency peaks whose value decreased approximately linearly with distance from separation. These agree well with similar measurements made by Cherry et al (1984) and suggest that the curved shear layer separating from the leading edge of the plate has largely conventional turbulent structure unaffected by the wall. The linear dependence of frequency on position stops abruptly at a point about half way between the separation and reattachment positions, measured peak frequencies becoming less distinct and generally constant for distances further downstream. This again supports the findings of Cherry et al and suggests a departure from conventional shear layer behaviour at this streamwise location. At about this same location, the pressure recovery begins and intermittent reattachment starts to occur, as described later. These features are, of course, closely inter-related.

The time averaged profiles and streamlines are deceptive, in that they disguise a large degree of unsteadiness present in the actual flow. The extent of this unsteadiness is illustrated by measurements of the forward flow fraction $\gamma$ in Figure 3, taken very close to the surface of the plate with a pulsed wire shear stress probe. Note that the position at which $\gamma = 0.5$ corresponds, within the accuracy of measurement, to the reattachment point, as expected, but that flow reversals occur to a point approximately 1.5 $X_R$ downstream of the leading edge, and that there is no position at which $\gamma = 0$, that is, at which the flow is always reversed in direction. It is clear that the concept of a reattachment line or distance is somewhat misleading because reattachment occurs in a region rather than at a line. Evidence of a reverse circulation effect appears very close to separation, where $\gamma$ rises sharply. Conventional measuring devices such as pitot tubes and normal hot wire anemometers would not be accurate in a large region of this flow.

## 3. The Blunt Flate Plate - Analysis

The turbulent structure within the separation region has been examined by Kiya et al (1983) and by Cherry et al (1984) among others. Here, attention is focussed on

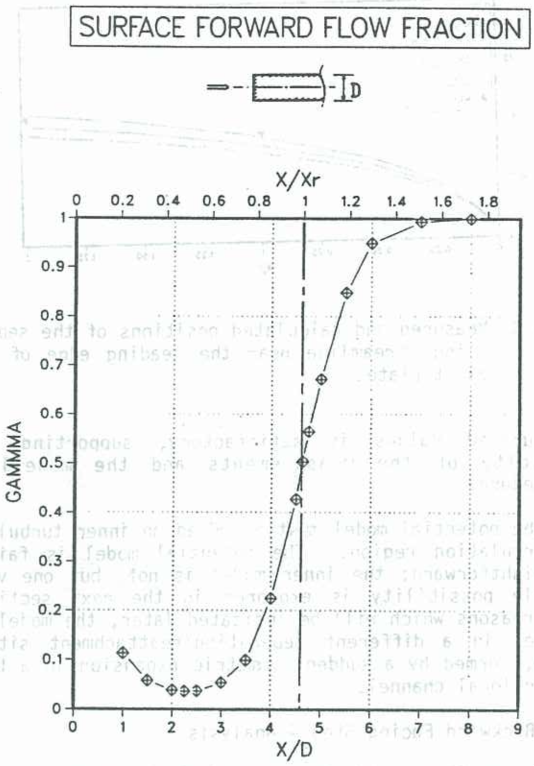


Fig. 3. Forward flow fraction measured very close to the surface of the blunt flat plate.

the mean flow characteristics, making simple assumptions to model the potential flow region.

The boundary layer on the front of the plate is very thin, particularly near separation, and can be ignored for most practical purposes. Separation from the front of the plate can then be described by an outer potential flow and an inner turbulent region, the separation of the potential flow occuring tangentially to the front face.

To explore the validity of this model, a potential flow field has been constructed which describes the external flow separating tangentially from a vertical fence, representing the front face of the plate. The wake source model devised by Jandali and Parkinson (1970) has been used in which a single source of appropriate strength is placed so that separation occurs at the correct place with the correct angle and with an assumed value of the pressure co-efficient. A Schwarz-Christoffel transformation of this flow simplifies potential calculations. In this case, for a physical plane z and a transform plane $\zeta$, the relationship

$$z = K \sqrt{\zeta^2 - 1}$$

results in a semi-infinite or half plane in $\zeta$.

The position in space of the separating streamline is dependent on the velocity at separation or the pressure co-efficient at separation, as shown in Figure 4. For some distance downstream from separation, the potential model should predict the position of the measured separation streamline, provided the separation pressure co-efficients are similar. The two data points in Figure 4 are deduced from measured velocity profiles and describe the mean separation streamline position for a measured separation pressure co-efficient of about -0.80. Some uncertainty must exist in the measured value because of the uncertainty about "free stream" static pressure as already noted. In view of this uncertainty, the agreement between measured and

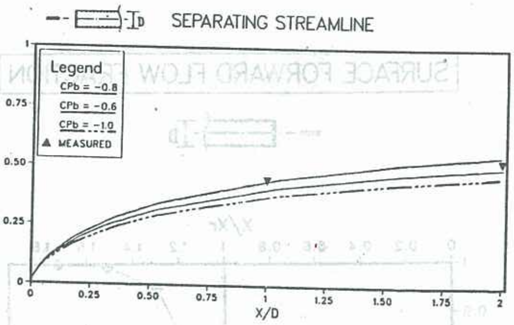


Fig. 4 Measured and calculated positions of the separating streamline near the leading edge of the blunt plate.

calculated values is satisfactory, supporting the validity of the measurements and the modelling procedure.

To the potential model must be added an inner turbulent recirculation region. The potential model is fairly straightforward; the inner model is not, but one very simple possibility is explored in the next section. For reasons which will be indicated later, the model is tested in a different separation/reattachment situation, formed by a sudden symmetric expansion in a two-dimensional channel.

## 4. Backward Facing Step - Analysis

An inner flow model has been devised and tested for laminar 2D separation bubbles forming behind a backward facing step located in a symmetric expansion. For laminar flow, the separation streamline is taken to be indentical to the line of zero velocity, which lies close to it. In addition, the fluid momentum in the backflow region has been ignored (following the widely used "FLARE" approximation) as has the shear stress beneath the bubble. Velocities above the bubble have been represented by a polynomial of third or fourth order, and momentum integral methods have been used. This is probably the simplest inner flow model that could be devised, yet the essential momentum and mass integral constraints are maintained through the use of corresponding integrals in the procedure.

The variables of this inner flow model are illustrated in Figure 5, and are essentially four in number: $\delta$ the inner bubble width; $U_0$ the centre-line velocity; the outer shear layer shape factor; and $p$ the local pressure. The equations needed to find these unknowns, as functions of streamwise distance x, are: momentum integrals over the inner bubble, and over the outer shear layer, and an integral continuity equation applied over the entire flow. As usual, the equation of motion, here in very simple form is used along the line $y = \delta$, to link the pressure gradient and the shear stress on that line. The shear stress at $y = \delta$ must be known, and for laminar flow this is related directly to the velocity gradient in the shear layer above this point. Suitable boundary conditions placed on the polynomial define its co-efficients to ensure symmetry at the centre-line and zero velocity at $y = \delta$. As noted by Acrivos and Schrader (1982) the boundary layer equations for this flow show that the x co-ordinate can be non-dimensionalized to include Reynolds number so that reattachment distances (for example) will always be directly proportional to Reynolds number. This relation follows from the present use of boundary layer integrals as well.

Results for laminar flow are shown in Figure 6, compared to other calculated results of Macagno and Hung (1967) Acrivos and Schrader (1982) and Kwon, Pletcher and Lewis (1984). Method A of Figure 6 uses a third order polynomial, method B uses a fourth order polynomial, to represent the shear layer velocity distribution.

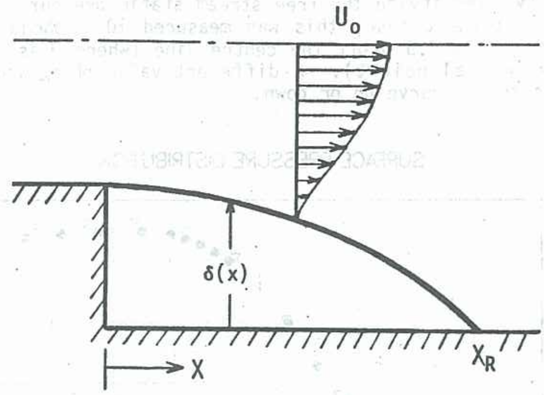


Fig. 5 Flow description used for the analysis of a sudden symmetric expansion in a two-dimensional channel.

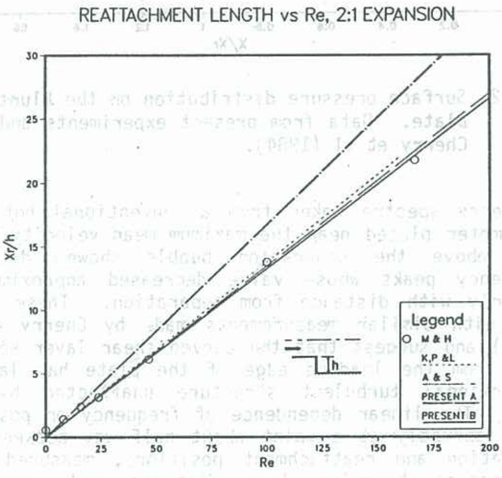


Fig. 6 Reattachment lengths from the present momentum integral method and from other more detailed calculations.

The present calculations require no iteration and the three ordinary differential equations can be solved in one downstream marching procedure using (for example) a Runge Kutta routine.

This is very much simpler than the other calculations represented in Figure 6, although of course the more exact solutions give more detail of the flow and are necessary as a basis of comparison. Pressure distributions along the channel bed are found from the present calculations and again show reasonable agreement with the more exact calculated results, as shown in Figure 7.

The simple methods used successfully in the laminar case can be carried over directly to the turbulent separation / reattachment problem provided some empiricism is introduced into the expression for the shear stress along the line $y = \delta$. From previous comments, and other work, it appears that a shear layer with essentially conventional structure develops over the first half of the separation bubble. This implies a linear variation of effective viscosity in the shear layer over this part of the region.

Once reattachment starts, at about $x = x_R/2$, the pressure starts to rise and the turbulent structure departs abruptly from that of a normal mixing layer. It should

PRESSURE RISE ALONG 5:2 EXPANSION

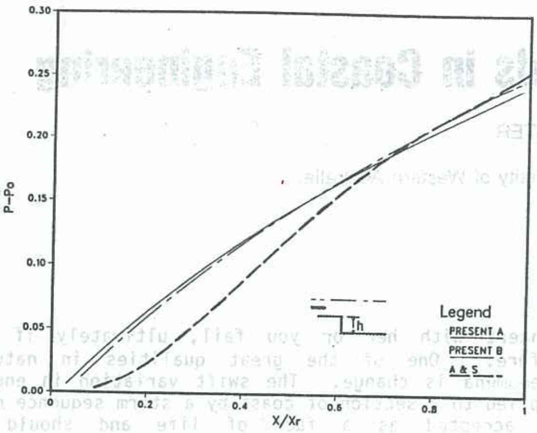


Fig. 7 Pressure rise for a 5:2 sudden expansion, calculated by present methods and by Acrivos and Schrader (1982).

not be difficult to find empirical expressions for the shear stress in this region which will provide reasonable agreement between the results of the present model and measured reattachment lengths and pressure variations in symmetric expansions. Whether the same model and empirical expressions will be adequate for predictions in other cases, such as the blunt flat plate, can then be examined. Some changes in calculation procedure will be necessary however, as described in the next section.

## 5. Concluding Discussion

Although the analytical model described in the previous section may have fairly broad applicability, the method of solution appropriate for internal flows governed largely by continuity constraints, cannot be used without modification for external flows governed by equations of elliptical type. For the latter application, which includes the blunt flat plate flow, iterations are required to adjust and match the inner and outer solutions. Simple downstream marching methods are not adequate for the elliptic nature of external flows, or even for internal flows in which the step height or upstream boundary layer are small compared to the initial channel height.

When separation / reattachment occurs and iterative methods are necessary, an inverse formulation of the problem should be adopted in which the displacement thickness from the inner solution is used to calculate the pressure distribution rather than the other way around (see Williams, 1984). Although the iterations complicate the procedure considerably, the application of momentum integral methods is still much simpler than the iterative solution of finite difference versions of the differential equations.

Because separation bubbles are inherently complicated by tendencies to three-dimensionality, unusual turbulence structures and large scale unsteadiness, integral models may be particularly appropriate for engineering calculations or for the starting conditions used in more detailed calculations.

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