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**BEHAVIOUR OF SEPARATION BUBBLES IN SHARP-EDGED GAPS
OF FINITE DIMENSIONS**

by

Nathalie Hétu

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Master of Engineering (Aerospace)

Department of Mechanical and Aerospace Engineering
Ottawa-Carleton Institute
for Mechanical and Aerospace Engineering

Carleton University
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BEHAVIOUR OF SEPARATION BUBBLES IN SHARP-EDGED GAPS
OF FINITE DIMENSIONS

submitted by

Nathalie Héту, B.A.Sc. Eng.

in partial fulfilment of the requirements for
the degree of Master of Aerospace Engineering

Thesis Supervisor

Chairman, Dept. of Mechanical and Aerospace Engineering

Carleton University
April 1993

ABSTRACT

Measurements are presented for the nominally two-dimensional flow in a sharp-edged gap with finite length and height, and complemented with extensive flow visualization. Eight clearances were examined with height to length ratios varying from 0.19 to 0.81. The geometry of the gap is seen to have a significant influence on both the streamwise and transverse dimensions of the two-dimensional separation bubble present at the inlet of the gap. The height and length of the bubble remain a constant proportion of the gap height for various values of the height to length ratio. However, in a slightly diffusing clearance gap, the flow remains separated throughout. The Reynolds number, based on the gap height and the velocity inside the gap, was varied from 150000 to 325000 and found to have no influence on the flow in the gap.

The discharge coefficient was calculated at four clearances. Results show a correlation between the value of the discharge coefficient and the gap height to length ratio. An existing model of the flow through a two-dimensional gap with a leading edge separation bubble is examined in light of the present data, and expanded to evaluate the discharge coefficient at various clearances. A second expression is suggested, which improves the prediction, and the discharge coefficients evaluated in this manner are compared to those calculated from measurements made in the tip gap of a planar cascade of turbine blades. The results suggest that the prediction model developed in the present two-dimensional clearance space can provide reasonable estimates of the discharge coefficient in actual tip gaps.

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NOMENCLATURE

C_D	= discharge coefficient : m_{actual} / m_{ideal}
C_L	= loss coefficient : $1 - C_{p_{tot}}$
C_L'	= mass averaged loss coefficient (see eq. 5.3)
C_p	= pressure coefficient (see eq. 5.1)
$\tilde{C}_p$	= pressure coefficient defined by Roshko & Lau (see eq. 2.1)
$C_{p_{dyn}}$	= dynamic pressure coefficient : q / q_{gap}
$\tilde{C}_{pm}$	= coefficient of reattachment pressure rise defined by Roshko & Lau (see eq. 2.3)
$C_{p_{max}}$	= maximum pressure coefficient
$C_{p_{min}}$	= minimum pressure coefficient
$C_{p_{tot}}$	= total pressure coefficient (see eq. 5.2)
h	= height of bluff plate above splitter plate
H	= boundary layer shape factor
I_r	= reverse flow intermittency
L	= gap length
L_b	= bubble length
$\dot{m}$	= mass flow rate
P_e	= exit static pressure
P_{min}	= minimum static pressure
P_o	= undisturbed free stream static pressure
P_{ps}	= blade pressure side static pressure
P_{ref}	= reference static pressure at gap outlet
P_{ss}	= blade suction side static pressure
P_{TOT}	= total pressure
q	= dynamic pressure
q_{gap}	= ideal gap dynamic pressure
Re_{gap}	= Reynolds number based on the gap velocity and the gap height
t	= blade tip thickness
$\bar{U}_e$	= area average exit flow velocity
U_{gap}	= ideal gap velocity

U_{max}	= maximum velocity
U_∞	= undisturbed upstream velocity
u_{rms}	= root-mean-square value of the fluctuating streamwise velocity component
u'^2, v'^2, w'^2	= normal Reynolds stresses
$u'v', u'w', v'w'$	= shear stresses
V_N	= velocity normal to blade chord
V_T	= velocity tangential to blade chord
x	= streamwise direction
x_i	= reattachment distance
x_{rs}	= reseparation distance
y	= transverse direction
$Y_{1/2}$	= gap half-width
z	= direction normal to endwall
α	= pitch angle
δ	= boundary layer thickness
δ_v	= vorticity thickness (see eq. 2.4)
ρ	= density
Θ	= detachment angle
Θ_s	= separation momentum thickness
τ	= gap height
τ_b	= bubble height
τ_s	= height of separated region
σ	= contraction ratio (used in eq. 6.1)
η	= z/τ in equation 6.2
Λ	= constant in equation 6.2

CHAPTER 1

INTRODUCTION

Separated-reattaching flows are common around all types of bluff bodies. In fact, they are the dominant feature of atmospheric flow over buildings and a critical factor in the design of bridges. Separation bubbles are also present in a wide range of devices which operate with fluids. They can be found in diffusers, due to the presence of an adverse pressure gradient, and in engine inlets. Separation bubbles are known to form at the leading edge of blunt plates, and are therefore a frequent occurrence in heat exchangers which typically consist of an array of plate segments aligned parallel with the flow. Separation bubbles are of particular concern when they occur on airfoils. They greatly influence high angle of attack performance and constitute a major consideration in the design of wings with laminar flow over a large portion of their surface. Leading-edge stall has also occasionally been blamed on bursting of the separation bubble located immediately downstream of the suction peak, especially at low Reynolds numbers.

The presence of separation bubbles on compressor and turbine blades reduces the efficiency of turbomachines by distorting the flow, and thus the loading, on the blades. They have also been observed in the clearance space present between the casing and the blade tip in the rotating blade row of turbomachine stages. The clearance exists to prevent rubbing of the blades against the annulus wall but the clearance flow also causes a significant drop in the efficiency of the stage. Part of the fluid travelling through the stage ends up crossing the clearance space from the pressure side to the suction side of the blade, in a direction more or less normal to the camber line, instead of following the blade contour and contributing to the useful output of the turbomachine. The separation bubble is located on the blade tip and it has been credited with enhancing the heat transfer to the tips of turbine rotor blades, thereby decreasing blade life in high temperature gas turbines. On the other hand, the separation bubble should reduce the mass flow rate through the gap, which may be beneficial.

The presence of a separation bubble in the tip gap of turbomachine stages prompted the undertaking of this work. The flow in the tip gap is highly complex and three-dimensional and

cross-flows undoubtedly influence the bubble. The purpose of this research was not to model the gap flow but rather to study the separation bubble in its simplest form in order to understand the mechanisms which influence and control its size and characteristics. The present geometry is that of an idealized, two-dimensional tip gap. It presents a large frontal area to the incoming flow and a gap with a sharp-edged inlet which represents the low radius of curvature of the blade tip and fixes the separation point. The gap height is adjustable, allowing the investigation of the influence of the endwall on the separation bubble. As well, the flow in the gap is two-dimensional and incompressible.

Having identified the factors which control the separation bubble in the tip gap, the next step is to attempt to manipulate the bubble. This may be achieved by injecting spent cooling air at an appropriate rate and location, or by diverging the gap in order to influence the location of the reattachment point. The height of the clearance gap may also partly control the size of the bubble. The scope of the present work is restricted to identifying some of the factors which control the separation bubble and examining the effect of the height of the clearance gap on the size of the bubble.

The following chapter contains a fairly thorough literature review which covers separation bubbles found in a variety of geometries. Flow visualization was performed, in a water flume, in both constant area clearance gaps and diffusing gaps. Various inlet gap heights were used to gain qualitative information on the influence of the endwall. These results are presented in the third chapter. In order to allow more precise measurements using various probes, the experiment was repeated with air as the working fluid. Chapter four describes the apparatus and instrumentation used in this subsequent experiment. Static pressures were measured along the walls and the flow was traversed with a seven-hole probe across various planes. The boundary layer was traversed with a flattened Pitot probe, the free-stream streamwise turbulence intensity was measured and oil flow visualization was also performed with this apparatus. The results of this investigation are discussed in the fifth chapter. Subsequently, an evaluation of existing prediction schemes was conducted in the light of these measurements, and a method was presented to predict the discharge coefficient of a clearance gap depending on its aspect ratio. This discussion can be found in Chapter six. Finally, conclusions are drawn in the last chapter, and recommendations are made as to the direction of further research.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

In its broadest sense, the separation bubble can be defined as the region of flow between a separation and a reattachment point, bounded on one side by a solid surface and on the other by a free shear layer. Flow separation can occur as the fluid attempts to turn a sharp corner or it can be caused by an adverse pressure gradient acting on the fluid travelling along a solid surface. Only two-dimensional separation will be considered here.

To understand the cause of separation consider a laminar boundary layer flowing along a solid surface with a pressure gradient impressed upon it. In the case of a favourable pressure gradient, the momentum equation reveals that the curvature of the velocity profile must be negative at the wall and remain as such up to the edge of the boundary layer. A zero pressure gradient is accompanied by a velocity profile with zero curvature at the wall followed by negative curvature at the outer edge of the boundary layer. An adverse pressure gradient, on the other hand, generates a velocity profile with positive curvature at the wall. The profile must have negative curvature at the edge of the boundary layer in order to merge with the free stream such that an inflection point must exist somewhere in-between. This profile is very unstable and as it travels into the adverse pressure gradient, the point of inflection moves away from the wall (White, 1974). The fluid very close to the wall is decelerated and loses energy until it can no longer proceed into the adverse pressure gradient and separates from the surface. Once the flow has broken away from the wall, a region of backflow is established to satisfy continuity. Normal velocities are quite high here, ensuring significant interaction with the free stream flow. Also, the boundary layer assumptions are now violated so that the boundary layer equations can no longer be used in this region. In two-dimensional steady flow, vanishing surface shear stress and flow reversal accompany separation but in unsteady two-dimensional flow, the surface shear stress can change sign with flow reversal but without separation (Simpson, 1989). Therefore, in two

dimensional steady boundary layer flow, the separation point can be thought of as an interface between regions of forward and reverse flow.

Separation can also occur at a sharp corner. Infinite acceleration is required for the flow to make a sudden turn. Since this is physically impossible for the flow to achieve, it separates from the surface at the sharp corner.

Once separation has taken place, a free shear layer is established in the flow. The free shear layer grows through entrainment of free stream fluid and increases its static pressure until it becomes high enough to permit reattachment to the surface. The shear layer has received a large amount of attention in the literature and will be examined more closely later in this chapter. At the reattachment point, the time-averaged wall shear stress vanishes and a new boundary layer begins to grow on the surface downstream of reattachment. It will either be laminar or turbulent depending on the state of the free shear layer at reattachment. The recirculating fluid contained between the separation point, the free shear layer, the reattachment point and the solid surface forms the separation bubble.

In their study using blunt flat plates, Ota et al. (1981, referred to by Djilali & Gartshore, 1991) varied the Reynolds number based on plate thickness and observed three flow régimes. At the lowest Reynolds number, they observed laminar separation followed by laminar reattachment. Instabilities appeared in the shear layer near the separation point when the Reynolds number was increased, thereby provoking transition in the shear layer and leading to turbulent reattachment. Further increases in the Reynolds number moved the transition region closer to the separation point until the flow could be considered to basically undergo turbulent separation with turbulent reattachment. The last type of separation bubble has received the most attention by researchers in the literature.

Research on separation bubbles has been conducted on a number of different geometries such as airfoils, forward and backward-facing steps, square and bevelled bluff plates with splitter plates in their wakes and blunt plates as shown in Figure 2.1. The purpose of these various geometries was to create the separation bubbles on a large enough scale to allow measurements to be made within them, and also to isolate the external factors which might influence the shear layer

Figure 2.1 Various geometries which exhibit two-dimensional separation bubbles.
Taken from Djilali & Gartshore (1991) and Cherry et al. (1983).

behaviour. Castro & Haque (1987) have found that the reattachment length, defined as the distance between the separation and reattachment points, is largely set by the obstacle geometry and the entrainment needs of the shear layer in the case of the backward-facing step, the bluff plate with splitter plate and the blunt plate. The separation bubbles on each of these geometries will be examined in greater detail in the following sections. A brief review of suitable instrumentation for measurements in this flow is also included.

2.2 INSTRUMENTATION

Traditional instrumentation used in air flows such as Pitot probes, multi-hole pressure probes (3, 5 and 7-hole probes) and single hot-wire probes are not adequate for measurements in the highly agitated, reverse-flow region inside the separation bubble. The single hot-wire probes are unable to determine flow direction and for angles between the flow direction and the axis of the probe exceeding about 20° , the port pressures on the leeward side of the probe are less sensitive to changes in flow direction (Yaras & Sjolander, 1990). It is therefore necessary to turn to more complex instrumentation in order to obtain precise data on the flow in the separation bubble.

Although the single hot-wire probes cannot be used to measure flow direction, they are useful in obtaining values of mean velocity and fluctuations in the mean flow direction. Detailed information on the operating principles of hot-wire anemometers is plentiful and readily available; therefore, only a brief description will be given here. Thermal anemometers measure fluid velocity by sensing changes in heat transfer from a small, electrically heated sensor wire placed in the flow (Goldstein, 1983). The sensor wires are usually manufactured from platinum or tungsten and typically have a diameter of 1 to 5 μm with a length of 0.5 to 2 mm (Richards, 1977). The anemometer can be operated in the constant-current mode or in the constant-temperature mode, the latter being most widely used. In this case, a feedback loop is added to the circuit to maintain the resistance of the sensor, and hence its temperature, constant. An increase in the velocity of the fluid flowing past the sensor wire will increase the convection heat transfer from the wire, causing it to cool. Since the resistance of the wire is a function of its temperature, the effect will be a reduction in resistance and, therefore, in voltage across the wire. The feedback loop then acts to increase the voltage across the wire, thus increasing the current

through the wire and heating it until the system regains equilibrium. This occurs very quickly and measurements of the variations in current are used to calculate variations in heat transfer rate and flow velocity. The hot-wire probe is only sensitive to velocities normal to its axis. In order to measure two velocity components, a second wire is often placed at 90° to the first one to create a cross-wire or X-probe. More information on this probe is given in Goldstein (1983).

Non-linearities in the relationship between current and heat transfer limit the use of these probes to regions where the turbulence intensity is below 20%. In more turbulent areas, such as in the reverse-flow vortex, the non-linearity leads to measurements of the mean flow magnitude which are too large (Gaster, 1967). Therefore, hot-wire measurements can only be counted on to describe the gross features existing in this flow (Djilali & Gartshore, 1991). Although not too useful for measurements in the separation bubble, thermal anemometers can be used quite well in the flow outside the shear layer.

A frequently used device for measurements in the separation bubble is the pulsed-wire anemometer. It measures velocity or skin friction by timing the flight of a heated tracer of air between a pulsing wire and one of two sensor wires (Devenport & Sutton, 1991). Details of the geometry and the capabilities of this probe for measurements in three-dimensional highly turbulent flows are given by Dianat & Castro (1984) and Castro & Dianat (1985); therefore, only a short description will be given here. The standard velocity probe consists of a central pulsing wire with two parallel sensor wires on either side, as seen in Figure 2.2a. The sensor wires are placed on a plane perpendicular to the pulsing wire. Tungsten is commonly used to manufacture the 9 μm diameter pulsing wire and the 2.5 μm diameter sensor wires. A short electrical pulse is used to quickly heat the central wire and the time taken for the heat tracer to reach one of the sensor wires is monitored, thus yielding a measure of the velocity. The probe can be oriented to enable the wires to be sensitive to any chosen velocity component. More details are given by Bradbury & Castro (1971).

In their study, Castro & Haque (1987) used a modified pulsed-wire velocity probe in which the sensor wires were placed in a plane at about 30° of yaw with respect to the pulsing wire axis. They present results of a detailed yaw response calibration for both the standard probe, whose sensor wires are in the plane perpendicular to the axis of the pulsing wire, and the modified probe.

The calibration shows that, in the standard probe, the viscous wake of the upstream sensor wire increased the velocity vector measured at the downstream sensor wire above the expected value by a quantifiable amount. As well, measured values of velocity for yaw angles between about $\pm 20^\circ$, taken with respect to the downstream sensor wire, were higher than the value of velocity at zero yaw angle with the standard probe. Placing the sensor wires on an inclined plane resolved this problem by removing the upstream wire from the path of the velocity vector sensed by the downstream wire. With this new configuration, the ratio of the velocity at a non-zero yaw angle to the velocity at zero yaw angle is equal to the cosine of the angle. Furthermore, since the wires were closely spaced, the probe could respond to velocity vectors at angles up to 80° .

Figure 2.2 a) Pulsed-wire anemometer, b) Pulsed-wire skin friction probe.

Taken from Djilali & Gartshore (1991) and Devenport & Sutton (1991).

Wall shear stress measurements can be taken using a pulsed-wire skin-friction probe shown in Figure 2.2b. This probe consists of three parallel tungsten wires mounted approximately 0.05 mm from the wall. The pulsing wire has a $9\ \mu\text{m}$ diameter and is centered between the two $5\ \mu\text{m}$ diameter sensor wires; the typical distance between wires being 0.5 mm. The three wires are welded to prongs mounted in a 5 mm diameter circular plug mounted flush with the wall (Dianat & Castro, 1989). Skin-friction measurements are obtained from velocity measurements taken in the viscous sublayer, under the assumption that both quantities are proportional to each other. In

the region very near the wall, the viscous shear dominates and the velocity profile can reasonably be presumed linear. Values of the fluid's viscosity and the distance of the sensor wire from the wall can then be used with the average velocity given by the probe to evaluate the wall shear stress. In regions of high wall shear stresses, the wire spacing can be increased in order to obtain a more precise measure of velocity. The skin-friction probe must be calibrated since the relationship between either velocity or skin-friction and the reciprocal of time of flight is nonlinear. This is due to thermal diffusion of the heat tracers for which more details are given by Bradbury (1976).

According to Simpson (1981) laser anemometry appears to be the instrument of choice in the future for accurate, continuous and simultaneous measurement of all three velocity components. Further details on the number and arrangement of the beam(s) are given in his review.

The mean and fluctuating velocity in the separation bubble can also be measured with a split-film probe shown in Figure 2.3. Split-film anemometers are constructed in much the same way as hot-film anemometers (Goldstein, 1983). A conducting film, usually platinum or nickel, is deposited on the surface of a Pyrex or quartz substrate. The substrate is an electrical insulator chosen for its strength and low thermal conductivity to reduce conduction losses to the supports. The conducting film is chosen for its electrical properties. Since the sensitive portion of the anemometer is placed on the surface, a superior frequency response to that of the hot-wire is attainable. Typical dimensions are as follows: a 6-mil diameter rod, a film thickness of 1000 Å, a total sensor length of 200 mils and an active sensor length of 80 mils defined by gold-plating the extremities of the sensor.

In the split-film anemometer, the conducting film is split along the axis of the rod at two stations located 180° apart as shown on Figure 2.3. Therefore, there are actually two separate sensors on the substrate. The operation of these anemometers is based on the non-uniform distribution of the heat-transfer coefficient from a heated cylinder in cross-flow. The heat transfer from a cylinder in cross-flow depends on the state of the boundary layer: laminar or turbulent, attached or separated (Holman, 1986). For Reynolds numbers based on diameter less than 5×10^4 , the maximum heat transfer occurs at the stagnation point. It decreases as the laminar boundary layer grows, reaching a minimum at approximately the point of separation. Turbulent

Figure 2.3 Split-film anemometer (Spencer & Jones, 1971).

eddy motion in the separated flow then acts to increase the heat transfer. A short description of the operation of split-film anemometers follows and the reader is referred to Olin & Kiland (1971) and Spencer & Jones (1971) for further details.

The split-film sensors can be used in two different configurations: one with the plane of the split normal to the main flow direction, the other with the plane of the split parallel to the main flow direction (Kiya & Sasaki, 1983). With the plane of the split normal to the main flow direction, this probe is able to detect reversals of the local flow direction. It can therefore be used to measure the mean and fluctuating streamwise velocity components as well as the reverse-flow intermittency, defined as the fraction of time during which the flow is in the upstream direction. The second configuration is useful in measuring the transverse fluctuating velocity component. Each split film element is electrically heated to the same constant temperature using two separate control systems. For the probe operated in the first configuration and Reynolds numbers based on diameter less than 5×10^4 , the heat flux to the upstream split film containing the stagnation line is greater than that to the downstream sensor, thereby enabling the sense of the component of the velocity vector normal to the sensor to be calculated. Olin & Kiland (1971) have determined a simple quadratic correlation between the heat flux ratio of the downstream sensor to the upstream sensor and the effective flow velocity direction. The effective velocity is defined as the component of the velocity vector influencing the sensor heat transfer; the contribution of the component parallel to the sensor axis is negligible. Spencer & Jones (1971) show that the sum of the heat fluxes yields the magnitude of the velocity normal to the sensor. Therefore, by

summing and dividing the heat fluxes from the two film elements, it is possible to completely determine the velocity vector in the plane normal to the sensor axis. As is the case for other anemometers, the split-film probe must be calibrated. The calibration procedures are provided by the manufacturer, Thermo-Systems Inc.

Measurements of total pressure in low-turbulence level regions, such as the low-velocity region in the front part of the bubble, can be made through the use of a flattened Pitot tube (Storer & Barton, 1991). One of the main advantages of the flattened Pitot tube as opposed to the more conventional circular model is the improved spatial resolution. The value being measured by the Pitot tube is essentially the one which exists at its geometric center. Flattening a tube of any diameter moves its geometric center closer to its edges, thus enabling measurements closer to a wall for example. As well, to acquire total pressure data very close to a wall, the radius of the circular Pitot probe must be equal to, or less than, the distance between the wall and the closest measurement station of interest, thereby establishing the probe's cross-sectional area. If a flattened Pitot probe is used to make these same measurements, it would have a height equal to the diameter of its circular counterpart but its width would be greater, resulting in an overall larger cross-sectional area. The advantage of the greater cross-sectional area is a decrease in response time. As the total pressure in an air flow decreases for example, the probe adjusts by releasing some air. This can be done more quickly through a greater cross-sectional area, thereby increasing the probe's response time over that of the standard circular Pitot tube. However, the flattened tubes are hard to manufacture and kinks can easily appear in the mouth area. As well, the total pressure measurements at the wall from these probes can be used as those from Preston tubes to obtain wall shear stress values, but calibration data for flattened Pitot tubes as Preston tubes only exist for a limited number of height to width ratios and are not quite as reliable as those for circular Pitot probes. Finally, flattened Pitot probes are most often smaller than their circular counterpart and would therefore be subjected to a lesser velocity gradient across their height. Consequently, the pressure gradient across their height would also be smaller, resulting in less streamline deflection due to the presence of the probe. However, wall proximity and shear corrections are not as well established as for circular probes.

2.3 SEPARATION BUBBLES ON AIRFOILS

The majority of airfoil applications involve chord Reynolds numbers on the order of 10^6 to 10^7 (Schmidt & Mueller, 1989). However, there are circumstances under which airfoils are required to operate at Reynolds numbers less than 10^6 . Wings of remotely piloted vehicles typically operate with chord Reynolds numbers between 30000 and 200000 (Schmidt, 1986 as referred to by Schmidt & Mueller, 1989) and blades of small axial-flow fans used to cool electronic equipment in the unpressurized compartments of high-altitude aircraft can be required to operate at chord Reynolds numbers as low as 3000 (Clayton & Massey, 1967 as referred to by Schmidt & Mueller, 1989). The formation of a separation bubble depends on the existence of an adverse pressure gradient steep enough to cause laminar separation. The Reynolds number must also be low enough such that transition in the laminar boundary layer does not take place upstream of the point where separation would occur if the layer had remained laminar; otherwise, laminar separation bubble formation will be precluded (Tani, 1964). In the above-mentioned cases, the laminar boundary layer on the suction surface of the airfoils is more stable with respect to turbulence at these lower Reynolds numbers, but it is unable to remain attached under the influence of the adverse pressure gradient following the suction peak. It therefore separates from the surface and transition occurs in the free shear layer which reattaches at a certain distance downstream, depending on the order of magnitude of the chord Reynolds number. For large Reynolds numbers, on the order of 10^5 , the free shear layer reattaches very closely behind the separation point, forming a bubble with a length of the order of 1% chord (Gaster, 1967). An increase in incidence or a reduction in Reynolds number to about 5×10^4 may cause the shear layer to reattach much further downstream, forming a bubble with a length of the order of the airfoil's chord, or it may inhibit reattachment completely, leading to stall. This phenomenon is known as bubble bursting. It is accompanied by a decrease of the peak velocity on the suction surface of the airfoil, an increase in drag and a reduction in lift, all undesirable effects. The presence of the separation bubble affects the pressure distribution over the airfoil. A short bubble has a small, local effect while a long bubble can be responsible for a large alteration of the airfoil's pressure distribution or stall.

The transitional separation bubble, whether long or short, is made up of two distinct sections as shown in Figure 2.4. Immediately downstream of the separation point, there is a region of

laminar flow in which the fluid moves very slowly. The speed of the reverse-flow in this region is on the order of a few percent of that at the edge of the shear layer (Schmidt & Mueller, 1989). This region is followed by one where the fluid is much more agitated with velocities reaching 20% of the free stream value. Figure 2.5 shows a typical surface pressure distribution along the chord of the airfoil. Consider a streamtube enclosing the airfoil. As flow moves over the nose of the airfoil, the streamlines get pushed closer together which reduces the area available for the passage of the air. The velocity increases and the pressure decreases down to the value at the suction peak. An adverse pressure gradient region exists downstream of the suction peak since the airfoil surface curves back down, thereby increasing the area available for the passage of the air in the streamtube. Separation generally takes place in this adverse pressure gradient region as indicated in Figure 2.5. The wedge-shaped region of laminar fluid in the separation bubble displaces the external flow, once again reducing the flow area in the streamtube and increasing the velocity of the fluid within it. This generally reduces the adverse pressure gradient in that region to roughly zero. The surface pressure gradient remains fairly steady at zero while transition in the shear layer is taking place. Once transition is complete, the large turbulent shear stresses energize the shear layer by entraining fluid from the external stream which causes its pressure to rise (Arena & Mueller, 1980). The streamlines curve back towards the airfoil surface, where the shear layer reattaches, reducing the displacement effect of the bubble which therefore decreases the velocity of the external fluid contained in the streamtube. The fluid in the separation bubble underneath this section of the shear layer is much more agitated with reverse-flow velocities of the order of 20% of the external velocity.

A study by Gleyzes et al. (1980) conducted on a 200 mm chord LC 100 D ONERA profile yielded mean velocity profiles inside and downstream of the separation bubble which exhibit the major characteristics of the separation bubbles formed on any airfoil. The mean velocity was measured with a hot-wire anemometer, therefore no measurements are reported inside the bubble between the location where the mean velocity reached zero and the wall. The velocity is expected to be negative in that region. Above the reverse-flow, a layer of intense shear develops. Reattachment seems to occur at $x/c = 11\%$ followed by a rapid change in the mean velocity profile close to the wall, while the outer part of the profile changes more slowly towards a turbulent profile. A complete turbulent profile does not appear until $x/c = 65\%$. Weibust et al. (1987) present velocity profiles obtained downstream of a separation bubble on an airfoil. As in

Figure 2.4 Transitional separation bubble on an airfoil.
Taken from Schmidt & Mueller (1989).

the profiles presented by Gleyzes et al. (1980) along the chord, the velocity near the wall changes more rapidly than that in the upper part of the boundary layer.

2.3.1 Factors affecting the separation bubble

Any factor which affects boundary layer separation will invariably affect the separation bubble. The Reynolds number, the angle of attack, the surface roughness, the freestream turbulence level and other freestream disturbances can all be counted as influencing factors.

Experiments conducted by various authors have all concluded that in the range of Reynolds numbers where separation bubbles exist, a shortening of the bubble is observed for increases in the Reynolds number. Arena & Mueller (1980) report measurements made on a model airfoil which had a cylindrical leading edge followed by a constant thickness section and a wedge-shaped trailing edge flap. This configuration ensured that separation would take place near the leading edge and that the separation bubble would be reasonably thick. They found that for any set angle of attack and flap deflection angle, increases in the chord Reynolds number generate reductions

Figure 2.5 Typical surface pressure distribution through a transitional separation bubble on an airfoil. Indent shows location of bubble at airfoil leading edge.

in the lengths of both the laminar and turbulent sections of the separation bubble. Variations in the lower range of the Reynolds number, from about 1.5×10^5 to 3×10^5 , produced larger changes to the length of the separation bubble than variations in the higher range, up to about 4.5×10^5 . In all cases however, the length of the turbulent section of the bubble decreased more than that of the laminar section. These results are echoed by Weibust et al. (1987) whose experiment on a 15% thick laminar wing section also showed that the magnitude of the suction peak increases as the chord Reynolds number grows from 4×10^5 to 1.5×10^6 .

The value of the angle of attack is also an important parameter influencing the length of the leading edge separation bubble. Kraemer's 1961 measurements taken on a Göttingen 801 airfoil section, presented by Tani (1964), show the bubble shortening with an increase in angle of attack at a constant chord Reynolds number. The investigations of Arena & Mueller (1980) shed more light on the effect of the angle of attack. They found that as the angle of attack increases, at a constant Reynolds number, the minimum pressure peak moves marginally closer to the stagnation point which has the effect of also moving the separation point slightly upstream. The onset of

transition also occurs closer to the leading edge but the reattachment point moves downstream forming a longer separation bubble. Their measurements show that this behaviour persisted until the stall condition was achieved. The pressure distributions on the suction surface presented by Weibust et al. (1987) for three values of angle of attack also show a slight movement upstream of the separation point with increases in the angle of attack. The reattachment location is not shown but the pressure distribution indicates that the favourable pressure gradient region where reattachment takes place has also moved slightly upstream. It appears from these results that the bubble has shortened very slightly with an increase in angle of attack. However, the uncertainty in the above measurements is quite high and more experiments are necessary to accurately determine the trend in bubble length with angle of attack.

The amounts of surface roughness and free stream turbulence affect the separation bubble through their influence on the transition Reynolds number in the upstream boundary layer. Recall that a laminar separation bubble will not be formed if transition to turbulence occurs upstream of the separation point. The stability of a boundary layer relies on its ability to damp out disturbances. Surface roughness disrupts the laminar layer and reduces the transition Reynolds number based on displacement thickness. Furthermore, the momentum integral equation shows that an increase in the friction coefficient between the fluid and the surface accelerates the rate of growth of the boundary layer as measured by the momentum thickness. It is therefore clear that an increase in surface roughness promotes earlier transition and may even cause transition to occur upstream of the separation point, thereby precluding the formation of a separation bubble.

Turbulence in the free stream also reduces the transition Reynolds number. The boundary layer grows by entraining free stream fluid. If this fluid has a high level of turbulence, it will be transferred to the boundary layer and transition will occur for a lesser value of displacement thickness Reynolds number. For a high enough level of free stream turbulence, transition may occur upstream of the separation point, and once again the formation of a separation bubble may be impeded. An increase in the free stream turbulence intensity also has the effect of shortening the laminar portion of the free shear layer (Arena & Mueller, 1980).

2.3.2 Bursting

In developing codes to model the flow around an airfoil, it is of great interest to possess the ability to predict the occurrence of a separation bubble as well as its length, i.e. long or short. This has paved the way for the development of so-called bursting criteria. Since the formation of a separation bubble is directly related to the behaviour of the boundary layer, it seems appropriate to characterize the flow by a Reynolds number based on local conditions in the boundary layer (Tani, 1964). Therefore, a Reynolds number based on the boundary layer displacement thickness at separation and on the velocity just outside the boundary layer at the same location was formed. In the study presented by Tani, four different airfoils were tested at various values of free stream Reynolds number and angle of attack. The angle of attack was varied in a constant free stream Reynolds number flow, and the displacement thickness Reynolds number was reported for the highest incidence at which a short bubble was observed and the lowest incidence at which a long bubble was observed for each airfoil. The ratio of the bubble length to the displacement thickness at separation was also reported for two of the airfoils. The results suggest that the displacement thickness Reynolds number at the separation point is above 500 when a short bubble is present and less than 500 in the presence of a long bubble. Characteristic values of the bubble length to displacement thickness ratio are 10^2 and 10^4 for short and long bubbles respectively.

The data by Owen & Klanfer (1953, as referred to by Tani, 1964) for bubbles on airfoils support the existence of a critical displacement thickness Reynolds number separating short and long bubbles put forward by Tani. A physical explanation for the existence of such a Reynolds number was suggested by Maekawa & Atsumi (1948, as referred to by Tani). They conjectured that reattachment would not occur unless sufficient energy was supplied to maintain the circulating motion of the separated fluid, which attracts the separated shear layer towards the surface, against dissipation. Pursuing that idea, they suggested that the boundary layer Reynolds number at separation must be greater than a certain value for the separated flow to become sufficiently unstable for the circulating motion to be energized. This is due to the fact that at high Reynolds numbers, an instability develops in the separated shear layer and creates turbulence, which is considered a prerequisite for reattachment. The abrupt drop observed in the displacement thickness Reynolds number at separation when a long bubble is formed can be reasoned from the fact that the breakdown of the short bubble brings about a radical readjustment of the pressure

distribution (Gault, 1955, as referred to by Tani). The above criterion is not meant as a condition for the breakdown of a short bubble, but rather only as a statement that the displacement thickness Reynolds number is generally above 500 for short bubbles and below 500 for long bubbles.

Tani (1964) discusses a second criterion which determines whether or not a short bubble will burst. The criterion, proposed by Crabtree (1957), is based on the assumption that there exists a maximum possible value of pressure recovery in the turbulent entrainment process leading to flow reattachment. This is based on an analysis made by Norbury & Crabtree (1955, as referred to by Tani) of the simplified bubble flow model shown in Figure 2.6. In this model, it is assumed that the turbulent entrainment process and the corresponding pressure recovery occurs only in the region ABRT, and that the velocity along the streamline AB falls from the value at A to that at B without any loss of energy. As well, it is assumed that on the average, there is zero mass and momentum transfer across TV and negligible shear stress along the airfoil surface VR. Velocity profiles were given for the regions across AT and BR respectively as shown in Figure 2.6. Applying the equation of continuity and the momentum theorem to the region ABRV yields an expression for the pressure recovery, which in this case, is the pressure difference between the regions BR and AV normalized by the dynamic pressure at the transition point, taken as point T. Applying the equation for the conservation of energy to that same region with no work done and zero heat transfer shows that the pressure recovery is directly related to the sum of the velocity difference and the losses between AT and BR. The maximum value of pressure recovery is attained when no losses are generated in that region.

A short bubble will burst due to an increase in incidence for example, because the pressure at its reattachment point has increased such that the pressure recovery taking place in the separated shear layer is no longer large enough to raise the pressure from its value at transition to the one now present at the former reattachment location. According to Tani (1964), the situation just prior to the breakdown of a bubble is that the first criterion is fulfilled, displacement thickness Reynolds number above a certain critical value, and the second criterion (Crabtree criterion) is about to be violated.

In order to analyze laminar separation bubbles, Gaster (1967) set up a pressure distribution along a flat plate similar to the one found around an airfoil, beginning with a favourable pressure

Figure 2.6 Flow in the vicinity of a separation bubble. Model by Norbury & Crabtree (Tani, 1964).

gradient up to a suction peak followed by an adverse gradient in pressure. While attempting to correlate the data, he pointed out that the momentum thickness varies slowly near separation (since skin friction, which is directly related to the gradient of the momentum thickness, is small), and is therefore a better choice as a length parameter for the Reynolds number than the rapidly changing displacement thickness. As mentioned in the paper by Tani (1964), the pressure recovery in the shear layer bounding the bubble plays an important role in determining whether a long or short bubble will be formed. Gaster proposes $\left(\frac{\theta_s^2}{\nu}\right) \left(\frac{\Delta U}{\Delta x}\right)$ as a non-dimensional parameter describing the pressure distribution in the region of the bubble. The subscript s refers to conditions at separation while ΔU is the rise in velocity over the length of the bubble Δx . This is Thwaites' pressure gradient parameter commonly used to calculate the pressure distribution in attached laminar boundary layers. The rationale for applying this parameter to the flow in the region of the bubble is as follows: The fluid is practically static under the separated laminar shear layer, giving rise to a constant pressure region. Had the shear layer not separated from the surface, the pressure along the surface would have been that calculated by Thwaites' parameter. In the event of detachment, the separation streamline takes on a shape which enables the establishment of a region of zero pressure gradient on the surface. Therefore, it is assumed that the pressure distribution calculated by Thwaites' parameter appears along the separation streamline, enabling the use of this parameter in the flow around the separation bubble. Gaster conjectures that if the momentum thickness Reynolds number at separation and the pressure rise

over the bubble do in fact control bubble behaviour, then bursting should yield a unique relationship between them. This hypothesis was backed up by experimental data obtained for a number of short bubbles prior to bursting. A plot of the momentum thickness Reynolds number at separation versus the proposed pressure gradient parameter showed a convincing correlation.

Figure 2.7 Pressure distribution on an airfoil surface: a) short bubble; $Re_{chord} = 6.36 \times 10^4$. b) long bubble; $Re_{chord} = 4.52 \times 10^4$. Gaster (1969).

In the same paper, Gaster presents plots of the pressure distribution [$C_p = (P - P_\infty) / (\frac{1}{2} \rho U_\infty^2)$] for seven values of chord Reynolds numbers, two of which have been reproduced in Figure 2.7. A short bubble can be seen for the four highest values of upstream velocity. As the flow velocity is further reduced, bursting of the short bubble into a long bubble is seen to occur. In the presence of a long bubble, the value of the pressure coefficient at the suction peak decreases drastically, the favourable pressure gradient where reattachment takes place is weaker and the location of reattachment is located much further downstream. It is also apparent that the transition region is longer in the long separation bubbles.

2.4 BUBBLES ON BLUNT PLATES AND BLUFF PLATES WITH SPLITTER PLATES

The flow around a blunt rectangular plate is the simplest. De Brederode (1975, as referred to by Ruderich & Fernholz, 1986) found that the flow was nominally two-dimensional with this geometry when the aspect ratio formed by the tunnel width and the thickness of the plate was

greater than 10; therefore, it is possible to eliminate three-dimensional effects at least in the vicinity of separation. This geometry also has the advantage of having a fixed separation point and an extremely thin separating shear layer compared with the overall scale of the bubble, due to the strong favourable pressure gradient on the front face (Djilali & Gartshore, 1991). Another contributing factor to the thinness of the separating shear layer is the relatively small height of the front face: there is very little length for boundary layer growth along the front face from the stagnation point to the sharp corner where separation occurs. Having a thin separating shear layer renders the influence of the upstream boundary layer on the separation and reattachment of the flow negligible.

For all the blunt plate and bluff plate with splitter plate geometries shown in Figure 2.1, the streamwise length of the plate was much greater than the bubble length thereby ensuring that reattachment would occur, and that there would be no interaction between the shear layers on either side of the body. The central splitter plates located in the wake of the bluff plates prevent vortex shedding and lead to an extensive region of separated flow (Castro & Haque, 1987). The purpose of the models with a backward-facing step and a splitter plate preceded by a rounded forebody was to reduce the detachment angle of the separating streamline to zero. The effect of surface curvature, present in the experiments conducted on airfoils, was also eliminated in the above geometries.

2.4.1 Factors affecting the reattachment length

The state of the free stream has a large influence on the length of the separation bubble. In the experiment by Kiya & Sasaki (1983) on a blunt flat plate, the free stream turbulence level was reduced from 0.4% to 0.2% by enclosing the intake of the tunnel with glass-wool screens. This resulted in a 5% longer separation bubble. Cherry et al. (1984) and Djilali & Gartshore (1991) report a similar trend in bubble length with freestream turbulence in their experiments on blunt plates. Increasing the turbulence intensity of a smooth stream to 9.6% more than halved the length of the separation bubble in the first study while a 44% drop in bubble length was recorded by Djilali & Gartshore for an increase in turbulence intensity from 1% to 6.5%. This behaviour is expected since a more turbulent free stream encourages earlier transition in the separated shear layer. The shortening of the bubble has also been attributed to an increased spreading rate of the separated shear layer (Djilali & Gartshore, 1992).

The blockage ratio is also an important parameter affecting the distance to reattachment. Djilali & Gartshore (1991) compiled data obtained by various researchers on blunt plates under low free stream turbulence conditions and similar Reynolds number which showed that the reattachment length decreases with increasing solid blockage. Kiya & Sasaki (1983) attempted to eliminate the blockage effect by fitting false boundaries to the wind tunnel walls which were curved according to the blockage-free streamline, flared by an amount equal to the displacement thickness of the boundary layer along those walls and joined smoothly to the bellmouth entrance of the test section. The value of bubble length which they report is lower than that given for 2% blockage. It is about equal to that measured at 2.5% and 3.8% blockage suggesting that perhaps not all blockage effects were, in fact, eliminated (Djilali & Gartshore, 1991). Since the exact shape of the separation bubble is not known, it is not really possible to determine the shape of the blockage-free streamline and curve the tunnel walls accordingly. Therefore, the solid blockage, which originally amounted to 5%, might have been only reduced by 1 or 2%, instead of eliminated. For the geometry with a bluff front plate and a splitter plate, an increase in either blockage or free stream turbulence also led to a decrease in reattachment length, as shown by Ruderich & Fernholz (1986) and Castro & Haque (1987).

The Reynolds number of the flow is another important factor influencing the reattachment length. As previously mentioned, a short bubble will burst into a long one when the Reynolds number decreases below a critical value dependent on geometry. In the studies conducted on blunt plates and bluff plates with splitter plates, a range of Reynolds numbers has been identified within which the surface pressure distribution and the reattachment length are constant. In the case of the blunt plate, the Reynolds number is based on the upstream velocity and the thickness of the plate. Cherry et al. (1984) noticed a weak progressive elongation of the bubble when the Reynolds number was reduced below 3×10^4 but no variations in either bubble length or pressure distribution for increases in the Reynolds number from 3.2×10^4 to 6.0×10^4 . The reattachment length was determined from surface oil flow visualization. Ota & Itasaka (1976) determined the reattachment location on their blunt plate by three different methods. The tuft probe exploration appears to be the most accurate method of the three. It concluded that the reattachment length remains constant for Reynolds numbers above 3.8×10^4 , increases while the Reynolds number decreases to 3×10^4 . A further reduction in the Reynolds number to 2.1×10^4 brings about a sharp decrease in the reattachment length to a value slightly greater than that measured at a

Reynolds number above 3.8×10^4 . The constant bubble length found here was somewhat shorter than that reported by Cherry et al. This is most probably due to both the higher turbulence level in the free stream and the higher amount of blockage in the experiment by Ota & Itasaka. There does not appear to be any explanation for the fact that the elongation of the bubble begins at a higher value of the Reynolds number in this study. Further research into the factors that influence the reattachment length is required before this question can be answered.

In the bluff plate/splitter plate geometry, the Reynolds number is based on the free stream velocity and the height of the bluff plate above the splitter plate, h in Figure 2.1. Castro & Haque (1987) report that the flow was sensibly Reynolds number independent for Reynolds numbers from 7.17×10^3 to 2.39×10^4 whereas Ruderich & Fernholz (1986) consider this behaviour to occur as of a Reynolds number equal to 1.4×10^4 . Photographs of the smoke-flow visualization performed by the latter authors show single large coherent structures in the shear layer at a Reynolds number of 1.5×10^3 and the roll-up of the separated shear layer into spanwise vortices at 2.2×10^3 . Once the Reynolds number reaches about 1.4×10^4 , the turbulence structure in the mixing layer is finer and transition in the shear layer occurs very close to the separation point at the sharp edge. This suggests that the reattachment length would remain constant as of that Reynolds number.

The angle of separation of the limiting streamline relative to the streamwise direction also influences both the pressure distribution and size of the separation bubble. Djilali & Gartshore (1992) attached various triangular front pieces to the leading edge of a blunt flat plate to alter the separation angle. Their experiment was run in the Reynolds number independent flow regime, 5×10^4 , and results show that decreasing the separation angle does not change the characteristic shape of the pressure distribution but induces an earlier pressure recovery, a shift of the pressure distributions towards the leading edge and a corresponding shortening of the bubble length. As well, the pressure just downstream of separation decreases and the pressure dip following separation becomes more pronounced at separation angles of 60° and 45° . At a separation angle of 45° , the reattachment length was 50% shorter and the pressure just downstream of separation was 10% less than for the plain blunt plate with a separation angle of 90° . The authors conjecture that this is due to the lower radius of curvature of the separating shear layer.

2.4.2 Description of the bubble through flow visualization

Ruderich & Fernholz (1986) performed extensive flow visualization on the surface of the splitter plate located in the wake of a bluff plate. Figure 2.8 shows the oil-flow pattern they obtained at a Reynolds number, based on U_∞ and the fence height (height of the bluff plate above the splitter plate, h), equal to 1.4×10^4 . The grid lines are located roughly 4.8 fence heights apart. The picture displays a few regions where oil has accumulated: a narrow, nearly straight spanwise strip located about 2.3 fence heights downstream of the bluff plate and a circular region at either end of this strip, in the corners between the plate and the sidewalls. The accumulation of oil in a circular pattern is due to the presence of a corner vortex on each side. It is a weak vortex with a small amount of rotation in the direction such that the flow travels downstream on the side of the vortex where it faces the tunnel sidewall. This vortex has previously been observed downstream of a backward-facing step by de Brederode & Bradshaw (1972, as referred to by Ruderich & Fernholz). The narrow, spanwise strip of oil has been identified as a limiting streamline. The fluid between the bluff plate and the limiting streamline moves very slowly in the streamwise direction. Downstream of this streamline, there is a reverse-flow region bounded on the splitter plate by a curved reattachment region. Recirculation takes place in the reverse-flow region in a direction such that the fluid on the splitter plate travels upstream to the limiting streamline, moves up normal to the plate and flows back downstream towards the reattachment point as shown in Figure 2.9. The flow velocity is much greater in the reverse-flow region than in the region upstream of the limiting streamline. The streamlines in the reverse-flow region converge slightly towards the centerline due to interaction with the flow on the sidewalls. Reattachment occurs at 17.2 ± 0.5 fence heights downstream of the separation point on the centerline and at approximately 15 fence heights near the sidewall. The oil flow visualization gives a picture of the mean flow and the width of the reattachment region indicates the amount of fluctuation in the instantaneous reattachment location. Flow visualization conducted on the tunnel sidewall revealed that part of the flow between the bluff plate and the limiting streamline is recirculating in a direction such that it moves downstream on the splitter plate but upstream at a small distance above it. There appears to be a streamline bounding this recirculating region which connects the limiting streamline on the splitter plate to the top of the bluff plate and along which the flow travels in the upstream direction.

Figure 2.8 Oil flow pattern on a splitter plate in the wake of a blunt plate.
Taken from Ruderich & Fernholz (1986).

Figure 2.9 Schematic of the flow above a splitter plate in the wake of a blunt plate.
Taken from Ruderich & Fernholz (1986).

2.4.3 Loci of mean streamlines in and near the separation bubble

Castro & Haque (1987) present a locus of mean streamlines obtained in the flow behind a bluff plate/splitter plate geometry. The streamfunction at any y -location above the plate is calculated by integrating the velocity profiles from the wall to the desired y -location and the mean streamlines are drawn as lines of constant streamfunction as shown in Figure 2.10. Their results support the observations of Ruderich & Fernholz (1986). The small recirculating region between the bluff plate and the limiting streamline is detected by the calculations and velocities as large as 30% of the free stream value are seen in the reverse-flow region.

Figure 2.10 Locus of mean streamlines in the flow behind a bluff plate/splitter plate geometry. Taken from Castro & Haque (1987).

The experiments conducted on blunt plates did not reveal the presence of any reattachment line, referred to above as the limiting streamline. The locus of mean streamlines deduced from pulsed-wire measurements by Djilali & Gartshore (1991) show the reverse-flow region beginning as of the separation point and bounded by the mean separating streamline originating at the sharp edge and ending at the reattachment location. The mean separation streamline is taken as the one for which the value of the streamfunction is zero. Once again, the mean velocity profiles taken inside the bubble show that the reverse-flow velocity attains about 30% of the free stream velocity. Similar measurements were conducted by Ota & Itasaka (1976) on a blunt plate using both a flattened Pitot tube and a 3-hole probe and the calculated flow field generally agrees with that of Djilali & Gartshore.

The height of the separation bubble can also be estimated from the above loci. For the bluff plate/splitter plate arrangement of Castro & Haque (1987), the separating streamline rises up from 1 to about 2.5 fence heights, from the separation point to 0.4 reattachment length, and falls with further downstream distance until it impinges on the splitter plate surface at the reattachment location. For the blunt plate model, the rise in the separation streamline is not as large. The data of Djilali & Gartshore (1991) yield a maximum bubble height of half the plate thickness at a location about 40% of the bubble length downstream from separation while Ota & Itasaka report a maximum bubble height of 0.7 plate thickness at the same streamwise location. As expected, both sets of data show the separating streamline falling to zero thereafter.

2.4.4 Secondary separation bubble

The results of Kiya & Sasaki (1983) hint at the existence of a secondary separation bubble, immersed in the main one, in the downstream vicinity of the separation line. The reverse-flow intermittency is defined as the fraction of time during which the longitudinal velocity near the surface is negative. It was measured with a split-film sensor. A plot of the reverse-flow intermittency, I_r , versus streamwise distance shows I_r very nearly equal to 1 from about 16% to 70% of the reattachment length followed by a sharp drop to 0 at 140% reattachment length. It has a value of 0.5 at the reattachment point where the time-mean longitudinal velocity at the surface is zero. This illustrates the variation in the instantaneous location of the reattachment point.

The most interesting feature of this plot is the behaviour of the reverse-flow intermittency immediately downstream of separation. The measurements begin at a streamwise location equal to 5% of the reattachment length and show a sharp increase in I_r from about 0.67 to very nearly 1 at 16% reattachment length. The time mean longitudinal velocity at the surface is nearly zero at 5% reattachment length. It is these relatively low values of the reverse-flow intermittency in the upstream portion that suggest the possible presence of a secondary separation bubble immersed in the main one at that location. Other measurements of the reverse-flow intermittency made on a blunt circular cylinder (axis parallel to the flow direction) by Kiya et al. (1991) show a sharp dip from the separation edge to about 6% reattachment length followed by a fairly constant region up to about 25% reattachment length. A sharp rise came next, followed by a constant region through the main part of the bubble and a subsequent fall to reattachment. Once again, the

authors conjecture that the upstream dip in the intermittency function suggests the intermittent formation of a secondary separation bubble immersed in the main one.

2.4.5 Surface pressure distribution through a separation bubble

The surface pressure distribution through the bubble is common to most two-dimensional geometries (Cherry et al., 1983). There is suction at separation followed by a further reduction in pressure through the transition region to a minimum value and then a rather sharp increase in pressure up to reattachment. The pressure increase continues for a short distance downstream of reattachment before settling at a constant value.

Ota & Itasaka (1976) present static pressure distributions normal to the plate surface at various streamwise locations inside and downstream of the bubble. The measurements, made with a static pressure tube, extend as far as two plate thicknesses above the plate surface, thus well above the separating streamline, and 16 plate thicknesses downstream of the separation point, that is to say about 2.5 bubble lengths past the reattachment point. All the values of static pressures reported are less than those in the upstream uniform flow. The pressure profiles, at stations located one and two plate thicknesses downstream from the separation point, show constant static pressure in the direction normal to the plate, from the surface up to the separating streamline, followed by an increase in pressure with further normal distance. This represents roughly the first half of the bubble. At the last two stations before reattachment, three and four plate thicknesses downstream of separation, the region of constant static pressure normal to the plate surface extends beyond the separating streamline but begins a short distance above the plate, after an initial small reduction in pressure from the value on the surface. The more upstream of these profiles shows an increase in pressure with normal distance as of about one half plate thickness above the separating streamline, whereas the latter does not exhibit any pressure variation past the separating streamline. This reflects the diminishing influence of the separation bubble on the flow above it, with downstream distance. The pressure profile becomes nearly uniform as of six plate thicknesses downstream of separation, or about 1.4 plate thicknesses past the reattachment point.

As stated previously, there exists a strong similarity in the shape of the pressure distributions through separation bubbles on various geometries. In view of this, Roshko & Lau (1965)

attempted to produce a universal correlation of mean surface pressure data. They proposed a pressure coefficient defined as:

$$\tilde{C}_p = \frac{C_p - C_{p_{\infty}}}{1 - C_{p_{\infty}}} = \frac{P - P_{\infty}}{\frac{1}{2}\rho U_{\infty}^2}, \quad (2.1)$$

where C_p is a usual pressure coefficient equal to:

$$\frac{P - P_{\infty}}{\frac{1}{2}\rho U_{\infty}^2}, \quad (2.2)$$

and $C_{p_{\infty}}$ is the minimum pressure coefficient usually measured at separation; the subscript ∞ refers to undisturbed conditions upstream. When plotted against the streamwise distance normalized by the reattachment length, this parameter collapses data from blunt plates and bluff plates with splitter plates at various Reynolds numbers onto a single curve (Roshko & Lau, 1965; Cherry et al., 1983; Castro & Haque, 1987; Ruderich & Fernholz, 1986). The data obtained in the present experiment is plotted with these coordinates in Chapter 5. The surface pressure data obtained on a splitter plate preceded by a long, rounded and slender forebody (Roshko & Lau; Cherry et al.) falls below that of the other geometries when plotted as suggested by Roshko & Lau. Both studies speculate that this may be due to the boundary layer being thicker at separation in the latter geometry. The agreement in the rest of the data confirms that the parameters $\tilde{C}_p$ and x/x_r take into account the effects on the flow of blockage, aspect ratio and free-stream turbulence (Ruderich & Fernholz, 1986). However, the effects of strong imposed favourable pressure gradient are not embodied in those parameters (Devenport, 1985 as referred to by Castro & Haque). The Roshko-Lau coordinates also collapse on a single curve all the data collected by Djilali & Gartshore (1992) on blunt plates with various separation angles and the data of Ruderich & Fernholz from a flat plate/splitter plate geometry. This shows that the effect of the separation angle is also taken into account by these coordinates.

Roshko & Lau also defined a coefficient of reattachment pressure rise, from the minimum to the maximum static pressure:

$$\tilde{C}_{pm} = \frac{C_{p_{\text{sep}}} - C_{p_{\text{rec}}}}{1 - C_{p_{\text{rec}}}} \quad (2.3)$$

This parameter had a constant value of 0.39 for the blunt plate and bluff plate/splitter plate models tested by Cherry et al. (1983); it is very close to the averaged value 0.41 from the blunt plates with various separation angles of Djilali & Gartshore (1992). However, a somewhat lower value, 0.34, was obtained for the backward-facing step of Cherry et al. (1983). The step was preceded by a long, rounded forebody to produce a zero separation angle. This behavior is not unexpected as Tani (1964, as referred to by Djilali & Gartshore, 1992) noted that the pressure recovery was lower for thicker boundary layer at separation. The constancy of the coefficient of reattachment pressure rise in their experiment prompted Roshko & Lau to conjecture that the flow configuration established in each case is the one which corresponds to a certain value of this parameter. Continuing along these lines, Cherry et al. noted that the constancy actually indicates the importance of the separation dynamic pressure in controlling the recovery to reattachment.

2.4.6 Separation bubbles behind backward-facing steps

The separation bubbles formed downstream of backward-facing steps are very similar to the ones just discussed. The one major difference is that the upstream boundary layer now has an influence on the separation and reattachment of the flow since it is no longer negligibly thin in relation to the overall scale of the bubble. Another difference is that the mean streamlines at detachment are almost parallel to the incoming free stream whereas in the previous geometries, the separation streamlines, and the neighbouring ones, were at a large angle to the free stream direction (Simpson, 1981). This is certainly one of the reasons the reattachment length is shorter in this case than it is for the blunt plates and the bluff plates/splitter plates, as indicated by the measurements of Cherry et al. (1983) and Bradshaw & Wong (1972). One of the characteristics of this flow is that after separation, the free shear layer grows within the original boundary layer instead of within essentially inviscid free stream fluid, as in the other geometries. It is therefore much easier for conditions upstream to influence the separation bubble since their history travels with the boundary layer. According to Bandyopadhyay (1991) however, the shear layer grows largely independently of the incoming boundary layer. Just downstream of separation, this free shear layer is thin enough that it is not affected by the presence of the wall and the separating streamline is only slightly curved. It remains fairly straight up to the reattachment zone, where

it curves sharply downward and impinges on the wall. At this point, the shear layer splits and some fluid is deflected upstream while the rest continues downstream. The fraction of shear layer mass flow which is deflected upstream depends on the initial boundary layer thickness; with a thin initial boundary layer, at least half the shear layer may be deflected upstream and used to supply the entrainment (Bradshaw & Wong, 1972). The structure of the free shear layer will be discussed at greater length in a later section.

There is a small corner eddy and a large recirculating region below the shear layer. These two structures rotate in opposite directions suggesting the presence of a reattachment line, as with the bluff plate/splitter plate models, although none seems to have been reported. The corner eddy rotates such that the fluid on the reattachment surface travels downstream whereas the sense of rotation in the recirculation region is such that the fluid travels upstream on the reattachment surface. The maximum measured backflow velocity in that region is usually over 20% of the free stream velocity (Simpson, 1981).

In this geometry, the reattachment length is normalized by the step height. A strong dependence on the Reynolds number, based on upstream free stream velocity and step height, exists for this ratio with Reynolds numbers less than 6000 (Simpson, 1989). As well, similarly to the blunt plate and the bluff plate/splitter plate models, high free stream turbulence levels and low aspect ratio test sections (width/step height < 10) reduce the reattachment length (Eaton & Johnston, 1981 as referred to by Simpson, 1989). On the other hand, an increase in the Reynolds number based on the momentum thickness at separation seems to increase the reattachment length (Simpson, 1989). This is a new factor which was not present in the geometries dealt with earlier, and which illustrates part of the influence of the incoming boundary layer. The following section deals with separation bubbles which are formed in the wake of obstacles fully-immersed in the boundary layer. Clearly, in this class of flow, the oncoming boundary layer has an even greater influence on the separation bubble.

2.4.7 Behind obstacles fully-immersed in the boundary layer

Experiments conducted on two-dimensional obstacles, such as fences, fully immersed in the oncoming boundary layer have shown the presence of two separations and reattachments (Tillman, 1945; Plate & Lin, 1964; Petryk & Brundrett, 1967 as referred to by Bradshaw & Wong, 1972).

The first separation takes place upstream of the obstacle with reattachment to the front face of the obstacle followed by separation from the obstacle and a second reattachment further downstream. The length of the second separation region is strongly affected by the initial inclination of the dividing streamline and therefore by the details of the first separation region which makes it impossible to distinguish between the influence of the obstacle and that of the upstream boundary layer (Bradshaw & Wong, 1972).

The study by Schofield & Logan (1990) sheds some light on the upstream separation region and its influence on the downstream one. They found that as the undisturbed flow approaches the object, an upstream pressure field is created by the obstacle which retards the boundary layer. For small obstacle height to boundary layer thickness ratios, the upstream pressure increase acts mostly on the low momentum boundary layer fluid near the wall and separation occurs far upstream of the object. For larger ratios, the upstream pressure field acts on fluid with higher average momentum thereby causing separation to occur closer to the object. Results by Good & Joubert (1968) showed that the form of the pressure distribution over the front face of an obstacle changed very little with h/δ meaning that the location of the stagnation streamline, and hence the separation streamline, is fixed on the front face of the object. Therefore, the slope of the separation streamline is seen to increase with larger obstacle height to boundary layer thickness ratios. The size and shape of the downstream separation bubble is directly influenced by the slope of the separation streamline because it determines the shape of the streamlines over the obstacle. For example, the length of the bubble increases with larger obstacle height to boundary layer thickness ratio because the slope of the separation streamline is steeper over the object.

The streamwise length of the obstacle is another factor which greatly affects the separation bubble. Once separation has occurred, an internal shear layer develops over the object. It travels downstream, growing until reattachment. Entrainment into this shear layer is from the fluid both above and below it. If the obstacle is a block with large streamwise dimension for example, its very presence below the shear layer will restrict entrainment from that side of the layer by reducing the amount of fluid present in that region. This also causes the pressure on top of the block to be reduced, since less mixing takes place, and attracts the layer closer to the block surface. This results in either the downstream bubble being shorter or, in the limit, to the flow reattaching to the block and separating again at the trailing edge.

After reattachment, the mean velocity profile adjusts to equilibrium conditions unevenly. The flow near the wall reaches equilibrium much more rapidly than the outer layer. However, the profile near the wall continues to accelerate as the outer flow approaches equilibrium and overshoots its equilibrium position. It takes quite a long distance downstream of reattachment for the entire profile to reach equilibrium implying that the presence of the obstacle and the separation bubble constitutes quite a large perturbation to the flow. This behaviour is similar to that of the reattaching turbulent shear layer on blunt plates or bluff plates with splitter plates as discussed in the following section. The recovery of these shear layers to an ordinary attached turbulent boundary layer also requires quite a large distance.

2.5 SHEAR LAYERS

The free separated shear layer begins at the separation edge and grows as it travels downstream. It eventually reattaches to the wall and continues to grow as an attached boundary layer. It is bounded on its lower side by a region of recirculating fluid, which makes up the body of the separation bubble, and on its upper side by essentially inviscid free stream fluid. The center of the shear layer is defined as the location where the rms value of the streamwise velocity fluctuations reaches a maximum (Kiya & Sasaki, 1983; Djilali & Gartshore, 1991; Ruderich & Fernholz, 1986). It is also in the vicinity of the position where the velocity profiles have an inflexion point. The derivative of the profile, dU/dy , reaches a maximum at the inflexion point which probably explains why Kiya et al. (1991) defined the center of the shear layer as the location where the magnitude of dU/dy is a maximum. From their experiment on a blunt plate, Kiya & Sasaki report a maximum streamwise turbulence intensity of 20% in the first 40% of the separation bubble, with an increase to 25% downstream of 0.6 reattachment length. A plot of the position of the shear layer center from the separation point to almost twice the reattachment length shows the shear layer rising to a constant height in the first half of the bubble and remaining at that position thereafter. Ruderich & Fernholz (1986), in their experiment with a bluff plate/splitter plate model, found that the locus of the shear layer center in the first half of the bubble falls on the mean dividing streamline. Their results also show the height of the shear layer center remaining fairly constant as far as 2.5 reattachment lengths downstream of separation.

2.5.1 Shear layer growth and comparison with plane mixing layer

The growth of the shear layer is usually measured in terms of the increase in its vorticity thickness defined by Brown & Roshko (1974, as referred to by Ruderich & Fernholz, 1986) as:

$$\delta_v = \frac{U_{\max} - U_{\min}}{\left(\frac{\partial U}{\partial y}\right)_{\max}} \quad (2.4)$$

where all quantities are taken at the same streamwise location. The velocities $U_{\max}$ and $U_{\min}$ are present at the edges of the shear layer while $(\Delta U/\Delta y)_{\max}$ is in the vicinity of its centerline. The vorticity thickness is commonly normalized by the reattachment length and plotted versus x/x_r . The data by Castro & Haque (1987) and Ruderich & Fernholz (1986) on bluff plate/splitter plate geometries show a large growth rate in the first 20% of the bubble. Through the next 80%, the shear layer appears to grow linearly. The data by Kiya et al. (1982) on a blunt plate, of Dianat & Castro (1989) in a separated boundary layer on a flat plate, and of Ruderich & Fernholz (1986) indicate a growth rate roughly equal to that present in a plane mixing layer, whereas that of Castro & Haque points to a slower growth rate. Past the reattachment location, the growth rate increases markedly, as evidenced by the measurements of Castro & Haque and Ruderich & Fernholz, due to the decreasing values of $(\Delta U/\Delta y)_{\max}$ (Ruderich & Fernholz). Djilali & Gartshore (1991) obtained velocity profiles at a few streamwise locations inside and downstream of the separation bubble on a blunt plate, from which they calculated the vorticity thickness. Their data shows the shear layer growing at essentially the same rate as that of Ruderich & Fernholz over the first half of the bubble. However, in the second half, the growth rate decreases noticeably before increasing sharply downstream of reattachment. The variation in growth rate through the bubble may not be genuine. The linear increase reported by Castro & Haque, Ruderich & Fernholz and Kiya et al. was inferred by fitting a straight line through the data points and assuming that uncertainty in the measurements was responsible for the points which did not fall directly on the line. Many more velocity profiles must be obtained before a sound conclusion can be reached about the behaviour of the shear layer growth rate through the separation bubble. It is the opinion of Castro & Haque, however, that there is no reason why the shear layer should grow linearly in this complex flow.

2.5.2 Reynolds stresses in the shear layer

In turbulent shear layers, the Reynolds shear stresses are defined as $u'v'$, $u'w'$ and $v'w'$, the time average product of the x-, y- and z-components of the turbulent fluctuating velocity. The normal Reynolds stresses are u'^2 , v'^2 and w'^2 . In free shear layers bounding reverse-flow regions, the choice of the non-dimensionalizing velocity greatly influences the apparent behaviour of the Reynolds stresses with downstream distance. Either the undisturbed upstream velocity, U_∞ , or the velocity difference across the layer, $\Delta U = U_{\max} - U_{\min}$, can be used. If the latter is chosen, both the normal and shear Reynolds stresses reach a maximum at reattachment and fall thereafter as evidenced by the data of Ruderich & Fernholz (1986) and Castro & Haque (1987). On the other hand, if U_∞ is used to normalize the fluctuating quantities, u'^2/U_∞^2 and w'^2/U_∞^2 reach a maximum about halfway through the bubble before dropping abruptly, while the transverse normal stress and the shear stresses reach their maximum near 80% of the bubble and slowly decrease with further downstream distance. In both cases, the normal stresses downstream of reattachment fall to a value below their initial one while the shear stress $u'v'$, although dropping in that region, still remain above its initial value at separation. No data was reported for $u'w'$ and $v'w'$. The variation in trends of the stresses depending on the normalizing velocity is due to the fact that the velocity difference across the layer varies with streamwise distance while U_∞ is constant. The velocity difference is greatest near the center of the reverse-flow region, where the magnitude of $U_{\min}$ is largest, and falls towards reattachment.

Many authors have compared the growth rate and magnitude of the stresses in the separated shear layer to those in the plane mixing layer. Castro & Haque (1987) show that the turbulence structure of the separated shear layer is different, in several ways, from that of a plane mixing layer. The normal stresses, taken with respect to the maximum velocity difference across the layer, are higher than their plane mixing layer counterparts up to reattachment, while the shear stress $u'v'/\Delta U^2$ is about the same in the first half of the bubble and rises thereafter. Djilali & Gartshore (1991) report that the maximum value of $u_{\min}/\Delta U$ seen just upstream of reattachment is higher by 20 to 40% than the plane mixing layer value, as also observed by Ruderich & Fernholz (1986), and state that the turbulence structure of the reattaching layer is very different from that of a plane mixing layer. In spite of this it appears that the consensus view is that "a mixing layer bounding a separation bubble with a thin initial laminar boundary layer is not greatly

different from a plane mixing layer" (Chandrsuda & Bradshaw, 1981 as referred to by Castro & Haque).

Bandyopadhyay (1991) gives an explanation for the rapid decrease of the Reynolds stresses downstream of reattachment. He suggests that the effect of convex curvature of the dividing streamline only acts very near the point of reattachment, since the streamline is known to curve sharply downwards only once it approaches reattachment, and although it can more or less account for the drop in the stresses in that region, it cannot explain the continuing drop downstream. This is attributable, he speculated, to the sudden appearance of the small scales after the disintegration of the eddies at reattachment. This phenomenon, observed in his experiment, is documented in his paper.

2.5.3 Shear layer unsteadiness

A low-frequency unsteadiness was identified in the shear layer by Kiya & Sasaki (1983, 1985), Cherry et al. (1984) and Djilali & Gartshore (1991) on blunt plates, by Kiya et al. (1991) on a blunt circular cylinder, by Castro & Haque (1987) on a bluff plate/splitter plate geometry and by Eator. & Johnston (1980, 1982 as referred to by Castro & Haque, 1987) in the flow behind a backward-facing step. The origin and nature of this unsteadiness are still unclear but it is of large scale, meaning that it is felt everywhere in the separation bubble, although more so in the upstream region, near the separation edge. This unsteadiness is accompanied by a low frequency oscillation of the shear layer in the direction normal to the reattachment surface, hereinafter referred to as flapping of the shear layer. The flow in a separation bubble is characterized by a second frequency associated with the shedding of large scale vortices as mentioned in the previous section. Kiya et al. (1990) speculate that the large scale vortex shedding and the low frequency flapping motion are inherent properties of separation bubbles formed by separation from a salient edge.

The low frequency unsteadiness was discovered through measurements of the fluctuations in surface pressure; the flapping results in a peak in the rms pressure spectra. The motion of the shear layer is accompanied by velocity and pressure fluctuations. When the shear layer moves from its time-mean position towards the reattachment surface, for example, the velocity at its lower edge increases because of an increase in curvature, especially near the separation line. This

results in positive rms velocities. Assuming that the pressure at the surface is about equal to that at the shear layer's lower edge, it then becomes lower than the time-mean value, resulting in a negative cross-correlation between the velocity and pressure fluctuations. As explained by Kiya & Sasaki (1983), the flapping motion may change the location along the normal to the reattachment surface of the center of the large vortices present in the shear layer. The velocity fluctuations associated with this motion are weaker than or comparable to those caused by the vortex itself, especially in the downstream part of the bubble where the vortices are quite large. However, near separation the vortices have cross-sectional dimensions at least comparable to the spatial extent of the flapping such that the velocity fluctuations caused by the shear layer motion are more easily identified. This explains why the flapping is felt most in the region near separation.

Cherry et al. did simultaneous smoke flow visualization and surface pressure measurements very near the time-mean reattachment point. The results show a positive departure from the mean in the surface pressure occurring when the pressure tap is located below a shear layer trough between the vortical structure which has just been shed and the one forming behind it. Vortex shedding will be treated in the next section. Kiya & Sasaki (1983) cross-correlated the surface pressure fluctuations at 20% and 100% of the time-mean reattachment length. For the pressure tapping located at the time-mean reattachment point, decreases in pressure were taken to mean that the tapping was located within the separation bubble while increases implied that the tapping was downstream of the reattachment line. Fluctuations in the surface pressure at $x/x_r = 0.2$ were associated with the flapping of the shear layer as explained above. The authors found a negative correlation between these two pressures which was rationalized as follows: When the shear layer moves inwards from its time-mean position, it causes a decrease in the surface pressure at $x/x_r = 0.2$. The negative correlation implies that the pressure at $x/x_r = 1.0$ increased while the upstream one decreased, indicating that the tapping was now outside the bubble. This means that the inward motion of the shear layer is accompanied by a shrinkage of the bubble while the outward motion comes with a lengthening of the bubble. The shortening-lengthening process of the bubble was also observed in the present flow visualization study as documented in Chapter 3.

Further evidence of the movement of the instantaneous reattachment point, and therefore of the large scale unsteadiness, was given by Djilali & Gartshore (1991) whose measurements

indicate that the instantaneous location of zero wall shear stress wanders up and downstream in a region surrounding the time-average reattachment point. Recall that the time-averaged wall shear stress vanishes at the reattachment point. Eaton & Johnston (1982, as referred to by Kiya & Sasaki, 1985) suggested that the unsteadiness was probably caused by an instantaneous imbalance between the entrainment of fluid from the recirculation region by the shear layer and the reinjection rate of fluid into the bubble at the reattachment line. They conjectured that an unusual event might cause a short-term breakdown of the spanwise vortices in the shear layer which would temporarily decrease the entrainment rate while the reinjection rate remained constant. This would cause an increase in the volume of recirculating fluid which would move the shear layer away from the wall and increase the short-time average reattachment length. In view of the observations by Cherry et al. and the correlations by Kiya & Sasaki, it seems possible that the decrease in the reinjection rate is caused by the shedding of vortices from the reattachment region while the entrainment remains constant. This would result in a reduction in the volume of recirculating fluid which attracts the shear layer towards the surface and decreases the bubble length. Since the frequency of the unsteadiness differs from that of the vortex shedding, it is probable that this is a cumulative effect and the shedding of a few vortices is required before a significant motion of the shear layer can be detected. The influence of the flow in the reattachment region on the separation bubble was also pointed out by Kiya & Sasaki (1985) who indicated that the fairly constant periodicity of the low-frequency unsteadiness demonstrated a feedback of disturbances from the reattachment zone to the shear layer near the separation line.

Correlation by Kiya & Sasaki (1985) of the velocity fluctuations at 20% of the bubble length with the surface pressure fluctuations along the mid-span of the bubble conclude, as before, that the bubble shrinks when the shear layer moves towards the surface. This and the other correlations also show that the low-frequency unsteadiness is not a local effect, but is felt throughout the entire bubble.

2.5.4 Shear layer vortices

The flow visualization study by Lane & Loerhke (1980) on a blunt plate identified the three régimes of flow mentioned in Section 2.1. For very low Reynolds number based on plate thickness, from 100 to about 300, a laminar separation bubble was observed. The shear layer became unsteady near a Reynolds number of 380 and regular, two-dimensional rolls formed within

it. Further increases in the Reynolds number caused the bubble to shrink until a Reynolds number of about 500 where it reaches a constant length up to the end of the measurements at a Reynolds number of 1100.

Very similar results were reported by Sasaki & Kiya (1991). The flow on the blunt plate was visualized using hydrogen bubbles and the same three régimes were identified although they report the appearance of the first instability wave near a Reynolds number of 320. The bubble length also reached its maximum value at this Reynolds number. The wave propagates downstream with no spanwise deformation and no shear layer roll-up is observed because viscous forces are still dominant. As the Reynolds number increases to 380, the shear layer begins to roll up and large vortices are formed. The spanwise vortex filaments have a Λ -shape downstream of reattachment. The bubble reaches a constant length, about 70% of the maximum value, as of a Reynolds number of 400, until the end of the reported results at a Reynolds number equal to 800.

The shrinkage is associated with the onset of the separated shear layer roll-up which was accompanied by a transformation of the two-dimensional rolls into a more three-dimensional random structure. Cherry et al. (1984) also observed that the onset of transition in the shear layer was marked by the rapid development of three-dimensionality and that the shear layer approached some asymptotic three-dimensional state with downstream distance.

In the higher range of Reynolds numbers, the visualization reveals hairpin-like structures formed by the amalgamation of two or three rolled-up vortices in the middle of the bubble, from $x/x_r = 0.3$ to 0.8. An earlier study by Kiya & Sasaki (1985) also concluded that the shear layer vortices have a hairpin shape and furthermore, that the ends are counterrotating so as to lift fluid between them, away from the plate surface. These authors also conjectured that the growth of these vortices was hampered by the presence of the plate surface (Kiya & Sasaki, 1983). Both these studies were conducted at a much higher Reynolds number, 2.6×10^4 , but the shear layer structure appears to be quite similar to that at a Reynolds number of 400, suggesting that once a shear layer has been established with transition occurring close to the separation point, further increases in the Reynolds number no longer have any effect. These vortices generate a spanwise non-uniformity of the velocity field which feeds back upstream and apparently deforms the vortex filaments near the separation line. As well, since the amalgamation does not occur uniformly

across the span, the shape and arrangement of the vortices becomes less and less regular as disorders are superimposed at every amalgamation.

The shear layers formed over bluff plate/splitter plate geometries and from sharp-edged two-dimensional orifices bear a striking resemblance to those over blunt plates. Clark & Kit (1980) conducted a study on the latter geometry at Reynolds numbers for which laminar flow was present at the exit of the orifice with transition occurring shortly thereafter. They found that the free shear layer initially rolls up into circular transverse vortices whose axes are parallel to the separation edge. A two-dimensional vortex pairing process occurs downstream, creating a single vortex 1.5 times larger than the initial one. Three-dimensionality, identified as variations along the span, results from induction between neighboring vortex tubes present during coalescence. The axes of vortex tubes bend and deviate from the transverse direction and some segments sometimes end up aligned in the streamwise direction as in a horseshoe, or hairpin, shape. Again in this geometry, the coalescence process does not occur uniformly across the span. The authors describe two patterns of vortex coalescence, either twisting or interlocking, and state that both these mechanisms can take place at different locations along the span at the same moment. Therefore, as many as five original pre-coalescent vortices may become intimately involved before eventually breaking down with complete disintegration of their structure into incoherent turbulence.

Ruderich & Fernholz (1986) also observed the two-dimensional vortex pairing process on the bluff plate/splitter plate geometry. Increases in the Reynolds number from 1.2×10^3 to 2.4×10^4 did not reveal any major changes in the shear layer structure, only a refining of the turbulence structure. They do report, however, that the spanwise size of the coherent structures is larger on the high speed side of the shear layer. This is conjectured to be due to the different interaction mechanisms between the shear layer and the outer flow on one side, and the reverse flow on the other side. The side which mixes with the reverse flow is subjected to much stronger interaction which leads to shorter spanwise size.

The smoke flow visualization by Cherry et al. (1984) illustrates the unsteady shedding of vorticity from the bubble. Spanwise correlations were very low showing that various phases of the vortex shedding process can be present across the span at one time. It appears that the vorticity is shed from the bubble as a series of more-or-less discrete turbulent structures. A

characteristic vortex shedding frequency has emerged in various studies (Hillier & Cherry, 1981; Eaton & Johnston, 1982; Kiya & Sasaki, 1983) conducted on differing geometries. The values agree fairly well with each other thereby strongly suggesting a universal nature of two-dimensional separation bubbles downstream of a sharp corner (Kiya & Sasaki, 1983).

The vortex shedding has an influence on the entire bubble. Cherry et al. (1984) suggest that the shedding of a vortex from the reattachment region probably influences the roll-up of the next shear layer disturbance since a large amount of the bubble vorticity will have been discarded. As well, Kiya & Sasaki (1983) observed that the fluid in the separation bubble moves intermittently back and forth corresponding to the formation and shedding of large scale vortices.

2.5.5 Downstream of reattachment

Downstream of the turbulent reattachment point, a sub-boundary layer, whose mean velocity profile follows the log law, begins to grow up through the reattached shear layer at the same rate as in the case of a change in surface roughness (Bradshaw & Wong, 1972). The re-development of the mean velocity profile through the entire shear layer begins with the development of the linear law in the viscous sublayer, achieved partly through the new internal boundary layer, and continues with a slow build-up of the log law via an undershoot followed by an overshoot of the mean velocity profile (Ruderich & Fernholz, 1986). The outer layer structure requires a very long distance to relax to the state of an ordinary turbulent boundary layer. In fact, Simpson (1989) states that, in the flow behind a backward-facing step, even at a distance of about eight reattachment lengths downstream of separation, the outer part of the reattached shear layer still has most of the characteristics of the free shear layer. Using the same geometry, Bandyopadhyay (1991) found that at 5.8 reattachment lengths from separation, large structures still appeared nearly periodically and while some were of the turbulent boundary layer type, the majority were similar to those in the reattaching transitional flow. From their experiment on a blunt flat plate, Ota & Itasaka (1976) also found a very slow redevelopment of the boundary layer taking place downstream of reattachment.

The flow behind a bluff plate/splitter plate geometry demonstrated a sharp decrease in the maximum values of the shear and streamwise normal stresses downstream of the reattachment point (Ruderich & Fernholz, 1986). In fact, these were halved after a distance of 0.7 reattachment

length. Ruderich & Fernholz attribute this to the presence of the wall while Bradshaw & Wong (1972) believe that it may be due to a splitting of the large eddies in the free shear layer. These are known to carry a large fraction of the shear stress and the authors reason that if the eddies split when they impinge on the reattachment surface, part of the shear stress will be entrained by the separation bubble while the rest will proceed downstream. However, in the review by Eaton & Johnston (1981, as referred to by Bandyopadhyay, 1991), the authors state that the majority of workers disagree that eddies are torn in two since measurements far downstream of reattachment indicate that the free shear layer structure persists in the outer part of the boundary layer. This is reinforced by Ruderich & Fernholz who show that the relaxation of the turbulent structure downstream of reattachment is slow and that as far as three reattachment lengths from reattachment, the turbulent profiles along the normal remain between those characteristic of a mixing layer and those of a turbulent boundary layer. Ota & Narita (1978) compared the streamwise variations of the turbulence characteristics in the reattaching boundary layer to those in a turbulent boundary layer on a flat plate as far as four reattachment lengths from separation and concluded as the others, that an extremely long distance was needed to reach the fully-developed turbulent boundary layer state. Further research is clearly required in this part of the flow before a clear image can emerge.

2.6 FLOW IN A TURBOMACHINERY TIP CLEARANCE

2.6.1 Introduction

The flow in the clearance space is very complex, involving vortices and separated regions, and has been investigated by a large number of researchers. In this review, interest is focused mainly on the separation bubble which forms at the inlet of the clearance gap. Flow separation occurs from the sharp edge at the pressure side corner of the blade while reattachment takes place on the blade tip. The geometry of the clearance gap, be it convergent, divergent or of uniform height, the Reynolds number of the flow in the gap, the size of the clearance height and the radius of the pressure side corner all influence the separation bubble as discussed in the following section.

2.6.2 Separation bubble in tip clearance

A widely used configuration to study the flow in the clearance space is a rectilinear cascade of blades with a gap between the blade tip and the endwall simulating the clearance space. The blades are often modelled on sections of existing turbine or compressor blades. For the flow in the clearance space, the streamwise direction is nearly normal to the camber line, from the pressure side to the suction side of the blade.

Figure 2.11 Tip clearance flow geometries by Rains (1954): **a)** idealized flow, **b)** actual flow. Taken from Moore & Tilton (1988).

Rains (1954) appears to be the first author to have suggested the existence of a separation bubble on blade tips. Consideration of the flow through the tip gap of a compressor blade led him to propose the two flow models presented in Figure 2.11 (taken from Moore & Tilton (1988)). The first model is based on incompressible potential flow theory with the flow separating at the inlet of the gap and remaining such until the exit while the second model involves reattachment to the blade tip and flow mixing following the vena contracta. The majority of studies on tip clearance flows corroborate Rains' second model with reattachment occurring on the blade tip, although there are some conditions under which the flow in the clearance gap does not reattach and more closely resembles the first model. Aside from the separation bubble which forms on the blade tip, a second bubble has been identified on the endwall. Through oil flow visualization, Sjolander & Amrud (1987) found a pair of small, nearly two-dimensional bubbles on the endwall. They speculated that the bubble on the blade tip tended to create a convergent-divergent passage in the clearance space and that the resultant adverse pressure gradient toward the outlet of the gap caused the tip wall separation bubble. The flow visualization of Moore & Tilton (1988) also revealed a separation bubble on the endwall, within the clearance space. However, the laminar separation line and the turbulent reattachment line begin at about 15% chord from the leading edge and extend all the way to the trailing edge forming one long transitional bubble as opposed to two small, separate bubbles. The bubble extends about 21% of the gap length in the streamwise direction, with separation occurring at approximately 35% of the way into the tip gap and reattachment taking place near 56%. These two studies appear to be the only ones in the literature reporting the existence of the endwall separation bubbles.

2.6.3 Effect of clearance height

Storer & Barton (1991) examined the flow in the tip gap of a compressor cascade, with and without reattachment to the blade tip, by varying the blade tip to clearance height ratio, t/τ . Their results suggested that the flow was unlikely to reattach if this ratio was less than about 1.5. They also concluded that the reattachment length was insensitive to Reynolds number and that it scaled on the gap height, τ . As the clearance height was reduced such that t/τ increased above 2, a vena contracta was observed at about 1τ from the pressure side corner followed by a reattachment region which extended to about 2.5τ from the corner. This flow picture remained fairly constant for values of t/τ of 2.5, 3.3 and 5. In these measurements, the static pressure in the separation region remained essentially constant with changes in the tip clearance, therefore, it is assumed that

the local Reynolds number at the point of separation is also assumed constant. This indicates that the reattachment length is not controlled by the Reynolds number, but is dictated by the inertia of the fluid entering the gap and by the pressure forces present in the gap. Gearhart (1966) considered a much smaller clearance ($t/\tau = 1.4$) in tests on shrouded underwater propulsors and also found flow reattachment to occur at 2.5 tip gap heights from the pressure side corner. Graham (1986) varied the tip clearance height on a water flow turbine cascade model scaled to give Reynolds numbers corresponding to high pressure axial turbine blades for small Pratt & Whitney Canada gas turbines (Moore et al., 1989). Once again, separation occurred from the pressure side corner of the blade and velocity profiles obtained near the gap exit show the flow having reattached to the blade tip for the three set clearances, $t/\tau = 2.5, 3.5$ and 5.2 . These results are consistent with those of Yaras & Sjolander (1990) who report reattachment to have occurred on the blade tip for clearances from $t/\tau = 1.79$ to 6.56 . The reattachment location is not available from Graham's measurements, but for the largest clearance, the velocity profile was obtained at about 2.5τ into the gap and reattachment had already taken place. Storer & Barton (1991) also examined the velocity profile at the exit of the tip gap. They report that when reattachment occurred on the blade tip, due to an increase in t/τ , the exit velocity profile became much more uniform and the low velocity region near the blade tip disappeared.

The static pressure variation along the endwall and the blade tip is also of interest. Storer & Barton report that the static pressure in the separation region did not change significantly when the gap height was altered, which suggests that, to a first approximation, the flow speed adjacent to the separated shear layer did not change. Therefore, this implies that the mass flow rate through the gap would have to vary with clearance. However, the constancy in the static pressure could also occur if the curvature of the streamlines bounding the separation region varied with t/τ such that the pressure drop across the shear layer varied with the velocity, and therefore the pressure, adjacent to it. It then is not possible to predict the variation of the mean flow rate through the gap without more measurements. Other studies, however, have found that as the blade thickness to gap height ratio decreased, the static pressure on the blade tip at the gap inlet became more negative (Gearhart, 1966; Bindon (1986 as referred to by Moore et al., 1989); Sjolander & Amrud, 1987). This is also consistent with the data of Yaras et al. (1990) which shows the maximum pressure difference across the gap increasing as t/τ decreases from 5.0 to 3.0 . The pressure variation along the blade tip followed the same pattern for the three clearances set by

Bindon, $U/\tau = 4.4, 7.4$ and 11.0 . The minimum value is found at the corner of the pressure surface at the gap inlet. This is followed by a slight recovery in the first 0.2τ of the blade tip and a constant region until 0.75τ . The pressure then begins to rise as the wake mixes out, up to about 2.5τ , where the mixing is complete, and remains constant thereafter until the end of the gap. Moore & Tilton (1988) obtained the static pressure distribution along both the blade tip and the endwall for $U/\tau = 7$. They also report the lowest pressure occurring at the corner on the blade tip followed by a slight rise up to 1.3τ . They do not mention any constant region but this could be due to the low number of measurement stations in that area. They only show two data points so they may not have captured a potential constant pressure region. The pressure along the endwall shows the flow accelerating rapidly as the tip gap is approached and continuing to accelerate until about 1.3τ through the gap while the pressure on the blade tip rises slightly. Downstream of this, the pressure on both surfaces starts to rise rapidly reaching approximately the same value at the tip gap exit, thereby revealing straight streamlines at that plane. The pressure rise is also evidence of mixing in the last section of the gap.

Surprisingly little attention has been given to the height of the separation bubble which, in effect, determines the size of the vena contracta in the gap. Graham (1986) examined the variation in the extent of the low velocity fluid located in the wake of the bubble normal to the blade tip as the clearance was reduced. He noted that this region was significantly reduced whereas the speed and extent of the main flow remained fairly unchanged. Correlating the extent of this low velocity fluid behind the bubble to its height suggests that the bubble becomes smaller as the clearance is reduced. However, the apparent reduction in the extent of this region could also be due to the fact that the measurement plane is located at the gap outlet which is increasingly further from the reattachment region. Therefore, more mixing can take place in the gap and a more uniform velocity profile would result at the outlet. The results of Yaras et al. (1990) also show that the zone of separated fluid did not extend as far into the gap in the direction normal to the blade tip for the smaller clearances. They attributed this to the constraining effect of the endwall and noted that the bubble height was not a constant fraction of the gap height. In fact, in a subsequent paper, Yaras & Sjolander (1990) state that the bubble occupies the largest fraction of the clearance at $U/\tau = 4.92$. On the other hand, in his experiments with a uniform tip clearance, Shalnev (1958, as referred to by Gearhart, 1966) varied the Reynolds number and noted that the height of the bubble remained a constant fraction of the tip clearance height.

2.6.4 Effect of gap geometry and endwall motion

The formation of a separation bubble on the blade tip can be prevented by rounding the pressure side corner. Rains (1954, as referred to by Gearhart, 1966) suggested using a radius approximately equal to the gap height. This yields a contour which is more rounded than the free streamline contour obtained by the potential flow solution for flow through a two-dimensional orifice, indicating that the fluid will not tend to separate from the blade end (Gearhart, 1966). Gearhart noted that it was possible for the clearance gap to present a convergent or a divergent channel to the flow moving from the blade pressure side to the blade suction side. Such a geometry could happen when the casing wall has either a conical or spherical contour and the blades are tipped accordingly, resulting in a clearance channel with curved walls parallel to each other. Any movement of the center of either the casing or the rotor from their designed coaxial positions would alter the geometry of the clearance gap. Deflection of the blade due to its loading could also have the same effect. A convergence angle of as little as 3.5° produced noticeable changes in the pressure coefficient on the blade tip. The maximum negative pressure coefficient, which occurs at the tip clearance inlet, had a smaller magnitude than that of the uniform gap and became more negative as the clearance height increased. This indicates a weaker separation bubble at the gap inlet for this geometry. The maximum negative pressure coefficient for a gap with a divergence angle of 2° had the greatest magnitude but, contrary to both the convergent gap and the gap with uniform height, an increase in clearance height had no effect on the pressure coefficient. As well, the mass flow rate through the clearance gap appears to be greatest for this geometry even though the exit mean velocity is least.

When the turbomachine is in operation, the rotor blades move with respect to the casing wall. This is most often simulated by using a moving belt as the endwall in a rectilinear cascade of blades. Gearhart (1966) and Graham (1986) both found that for very small clearances, there was no flow through the tip gap. The reasons put forward by the two authors to explain this behaviour differ since Graham used a turbine cascade while Gearhart used one typical of compressors. Graham states that as the clearance is reduced for a certain belt speed, the belt boundary layer occupies a relatively increasing proportion of the gap space and the pressure-driven gap flow is drawn in the direction of the moving belt through viscous effects. It is eventually almost parallel to the moving belt. The strength of the tip clearance vortex also diminishes as the endwall speed increases. At tight clearances, $U/\tau = 10.4$, the secondary and scraping flows tend to stagnate on

the tip suction surface, thereby raising the pressure above the stationary wall case. This reduces the loading at the tip and Graham noted that, for this clearance, the leakage flow was effectively reduced to zero. For larger clearances, the leakage flow was reduced, though not annulled, and the leakage vortex weakened with endwall motion. The same conclusions were reached by Yaras & Sjolander (1991) on a planar cascade of turbine blades. They report that endwall motion was accompanied by a global reduction of the driving pressure difference, leading to a decrease in mass flow through the gap. For very tight clearances, $t/\tau = 29$, Gearhart attributes the cessation of flow through the clearance gap to the belt boundary layer stagnating on the pressure face of the blade and restricting the flow around the blade end corner which occurs in the case of greater clearances. In fact, his results for $t/\tau = 14$ show quite the opposite behavior; the mass flow through the tip clearance gap increases considerably with endwall motion.

Gearhart (1966) also examined the effect of the relative motion on the separation bubble and noted an appreciable reduction in the length of the bubble. He attributes this to the effect of the vorticity in the moving belt boundary layer. The measurements of Yaras & Sjolander (1991) indicate a reduction in the bubble height as well, with an increase in endwall speed.

2.6.5 Effect of compressibility on the gap flow

In gas turbine engines, the turbine rotor blades operate with large pressure ratios across the tip gap; therefore, regions of supersonic flow can arise in the tip clearance gap, at least over part of the blade chord. The features of compressible flow such as overexpansion to supersonic Mach numbers, shock formation within the tip gap and the shock boundary layer interaction have not yet been thoroughly investigated. Moore et al. (1989) and Moore & Elward (1992) appear to be the only ones to have looked at compressible tip gap flows. They used a water table analogy in which the flow passed through a narrow channel, thereby modelling a tip gap and its mirror image. The endwall of the turbine is modelled as a plane of symmetry or an inviscid wall.

Moore et al. (1989) examined the effect of varying the back pressure on the pressure distribution on the endwall. For the subsonic flow case, the measurements revealed a minimum pressure at about 2 tip gap heights from the inlet and a pressure rise due to flow mixing, by 3 tip gap heights. This is similar to the pressure distributions measured in cascades by Moore & Tilton (1988) and Bindon (1986) on the endwalls of turbine tip gaps. Reducing the back pressure further

in the water table experiment caused the minimum pressure to decrease and its location to move upstream until the flow reached Mach 1. The following shock patterns are an interpretation of the flow based on the surface waves of the water in the water table and is only approximate. At Mach 1, a normal shock is established in the middle section of the channel with oblique shocks emanating from the inlet corners, as shown in Figure 2.12a. The oblique shocks are associated with overexpansion as the flow turns the sharp corner. The normal shock in the middle section sits at 1.7 tip gap heights and is interpreted as a Mach reflection from the endwall. It is followed by an oblique shock which reflects back to the blade tip at about 2.4 tip gap heights. The flow is subsonic on the centerline downstream of the normal shock. As the back pressure is further reduced, the Mach reflections move downstream and the Mach number reaches a maximum value of 1.8 on the centerline. Figure 2.12b shows the shock pattern for this velocity. The oblique shocks from the inlet corners undergo regular reflection at the centerline. There is a relatively small pressure rise on the centerline, such that the flow remains supersonic along the gap. A complex pattern of weak oblique waves fills the channel downstream.

Figure 2.12 Shock patterns in the channel: a) Mach = 1, b) Mach = 1.8.

The results of Moore & Elward (1992) suggest that the oblique shock does not start from the sharp corner. As the flow accelerates into the channel, it separates at the sharp corner and, for Froude numbers (ratio of flow velocity to wave speed) greater than 1.3, it curves back to intersect the wall between 0.4 and 1.4 tip gap heights from the inlet. The Froude number is analogous to the Mach number since the velocity of a wave moving on the free surface is considered analogous to the speed of sound in a gas. The oblique shock begins at the reattachment point, causing the flow to become parallel to the sidewall, as shown in Figure 2.13. As the freestream Froude number increases, the flow intersects the wall closer to the channel inlet yielding a shorter bubble.

For Froude numbers between 1.0 and 1.3, the free streamline becomes parallel to the wall and no reattachment occurs.

Figure 2.13 Compressible flow in the tip gap: Moore & Elward (1992).

These results seem to support the argument put forth by Norwood (1961, as referred to by Moore & Elward, 1992) that the phenomenon of reattachment is a compressibility effect. Norwood used a two-dimensional model of a flapper valve and set the incoming flow velocity along the horizontal. The geometry of the valve was like that of a two-dimensional slit except that it was followed by a wall inclined at 22.5° to the horizontal, effectively creating a tip gap with a sharp inlet corner and a linearly increasing height. He noted that the jet followed the horizontal in the subsonic and just supersonic flows but jumped to the inclined wall at a relatively constant ratio of back pressure to stagnation pressure. This suggested that the Mach number was the dominant characteristic parameter for flow development and that reattachment was a compressibility effect. He also visualized the flow using Shadowgraph pictures and observed a separation bubble at the edge of the orifice, on the inclined wall, as well as an oblique shock starting at the end of the bubble.

The presence of shocks in turbine tip gaps is potentially detrimental to the turbomachine. The heat transfer is already high on the pressure side of a turbine blade tip, and the shock boundary layer interaction may enhance it, leading to higher blade temperatures and thus, shorter blade life.

2.6.6 Flow models

Relatively few models have been suggested for the flow in the clearance gap. As previously mentioned, Rains proposed the two incompressible models of Figure 2.11 which seem to be the first to have appeared in the literature. Considering flow through the tip gap of a compressor blade, he noted that the pressure gradient across the blade was much greater than that along the blade and concluded that the tip gap flow direction could be taken as normal to the camber line of the blade. The exit velocity U_e is calculated by applying Bernoulli's equation from just upstream of the gap inlet to the outlet plane. The contraction coefficient, σ , is based on calculations for flow at rest entering a slot where the centerline of the slot models the bottom endwall (Milne-Thomson, 1968, as referred to by Moore & Tilton, 1988). The contraction coefficient has the value $\pi/\pi+2 = 0.611$. No experimental confirmation of this potential flow theory has been provided.

Moore & Tilton (1988) proposed an incompressible flow model based on Rains' second model which included a vena contracta and mixing from the vena contracta to the exit plane. Again the flow path is considered to be normal to the camber line. Bernoulli's equation is applied from the region upstream of the gap inlet up to the vena contracta, and the momentum equation is applied on a control volume from the vena contracta to the exit plane, as shown in Figure 2.12. Combining equations yields an expression by which it is possible to calculate the exit pressure coefficient from a knowledge of the minimum pressure coefficient present in the gap, usually found at the vena contracta, and the contraction ratio. In this model, it is assumed that the contraction ratio has the value 0.611 suggested by Rains, that the flow at the exit plane has reached fully mixed-out conditions and that the flow in the separation bubble recirculates such that it does not contribute to the momentum. The model does not account for the separation bubble on the endwall downstream of the vena contracta and it is limited to predicting only the magnitude, and not the rate, of the pressure rise from the vena contracta to the exit plane. Nonetheless, the results calculated from the equations agreed quite well with those obtained from experiment. Moore et al. (1989) applied this model to data obtained by Bindon (1986) on blade tips and found good agreement.

Figure 2.14 Model of the flow in the gap; Moore & Tilton (1988).

Moore & Tilton (1988) also considered the effect of mixing in the gap on the discharge coefficient, defined as the ratio between the actual exit flow rate, and the ideal flow rate obtained from Bernoulli's equation using the measured overall pressure difference. In the absence of mixing, the static pressure at the exit plane would be the same as that at the vena contracta yielding a discharge coefficient of about 0.61. However, mixing is accompanied by a pressure rise which causes an increase in the discharge coefficient to 0.84. The authors also defined a discharge coefficient, from their momentum analysis, dependent only on the contraction ratio. The contraction ratio suggested by Rains yielded $C_d = 0.844$. The closeness of the two values of the discharge coefficient reinforces the assumption that incompressible flows in flat tip gaps with sharp entrances exhibit a vena contracta with a contraction ratio of about 0.61.

Heyes et al. (1991) used the model proposed by Moore & Tilton (1988) but represented the tip gap exit flow by a combination of an isentropic jet and a wake. In agreement with Moore et al. (1989), they found that any mixing that takes place over the tip increases the discharge coefficient. As well, it was suggested that mixing was likely to increase as the gap length to height ratio increased although this was not substantiated by any measurements.

Yaras et al. (1990) suggested a model for the flow in the tip gap based on kinetic energy rather than on momentum. The tangential velocity of the fluid before it is accelerated into the gap

is calculated from the total and static pressures on the pressure side of the blade and assumed to remain constant as the flow crosses the gap, since the pressure gradient parallel to the blade mean line is small. The velocity normal to the blade mean line is calculated from the blade midspan pressure difference at the chordwise position being considered, since measurements by Yaras et al. on the endwall have shown that it is a good approximation to the driving pressure seen by the flow near this wall. The discharge coefficient is the ratio of the actual total mass flow rate to $\int \rho V_n dA$ in the gap. The agreement with experimental values of the distribution of the mass flow rate and the velocity vector in the tip gap along the chord is good using this method. However, Yaras et al. (1990) found that it could be improved by using the midspan pressure difference distribution shifted 20% rearward along the chord to calculate the velocity normal to the blade mean line in the above flow model. The rearward shift in the midspan pressure distribution was suggested by the static pressure measurements made on the endwall. Indeed, these showed that the maximum pressure differences seen on the endwall along lines nearly normal to the chord line were very similar in magnitude and trend to the pressure differences measured at the midspan on the blade, except that the endwall curve is shifted rearward along the chord by about 20% chord. These results are encouraging since they show that although the flow in the gap is fairly complex, it can still be reasonably well predicted by a relatively simple model.

As previously mentioned, Yaras & Spolander (1991) investigated the effect of relative wall motion on the gap mass flow rate in a planar cascade of turbine blades. Although the discharge coefficient partly represents the area blocked by the tip separation bubble and the tip wall boundary layer and also accounts for the mass dragged back over the tip by the moving endwall, it does not account for the reduction in driving pressure difference. That was incorporated into the model through a pressure reduction coefficient. As the relative endwall speed increased, the reverse flow in the boundary layer more than offset the reduced blockage by the separation bubble and produced a net reduction in the discharge coefficient. Using single average values of the discharge coefficient, the pressure reduction coefficient and the pressure difference which would exist near the blade tip in the absence of clearance, very reasonable agreement between measured and predicted distributions of tip gap flow vectors and gap mass flow rate along the chord were obtained.

CHAPTER 3

FLOW VISUALIZATION

The purpose of the flow visualization study was to observe both the formation of a laminar separation bubble at the entrance of a gap, and the influence of the gap size and geometry on the dimensions of the separation bubble. Laminar separation bubbles are created when a laminar boundary layer separates from the surface on which it is flowing, becomes turbulent and reattaches to the surface. The region of recirculating fluid between the separation and reattachment points constitutes the separation bubble. A water flume was used to conduct this study, and separation was initiated from a sharp corner at the entrance to a gap. The free shear layer reattached further downstream and the separation bubble was observed using ink injected into the flow. Several tests were done with the surface on which the separation bubble was established being placed at various distances from another flat surface facing it, thereby making the above-mentioned gap. The flow visualization was primarily used to observe any changes to the dimensions of the bubble under these various conditions. However, differences in other aspects of its behaviour were also looked out for. The observations made here should help establish some of the parameters which govern the bubble geometry and suggested the measurements that should be taken when the experiment was repeated using air as the working fluid.

3.1 APPARATUS

The apparatus consisted of a plexiglass box mounted inside a flume as shown in Figure 3.1. The water is pumped from a large underground tank to a reservoir from which it flows through the adjoining plexiglass channel. This channel is 17 feet long, 6.2 inches wide and 1 foot high. The water is then emptied into a second reservoir which returns it to the underground tank. The discharge tank is equipped with a 90° V-notch weir which was used to measure the flow rate required to calculate the Reynolds number. The weir equation was taken from Gerhart & Gross(1985), and used with a discharge coefficient of 0.58. A large gate valve placed upstream

Figure 3.1 Experimental set-up for flow visualization study

controlled the flow of water into the first reservoir and an adjustable gate placed at the end of the channel was also used to control the speed of the flow. The maximum flow rate used in this study was about 0.61 ft³/sec., corresponding to a velocity of 3.2 ft/sec. inside the gap, with a typical gap height of 4.56 inches.

Figure 3.2 Diffusing gap configurations:
a) $\theta=0^\circ$, b) $\theta=7.5^\circ$, c) $\theta=15^\circ$.

The 1/4 inch plexiglass box was 12 in. long, 12 in. high and 6.125 in. wide. It was located at a position 9.5 ft from the start of the flume and could be moved vertically as desired. The size of the opening formed between the bottom of the box and the floor of the flume will be referred to as the gap height. The length of the box in the streamwise direction constitutes the gap length. Gap heights of 1.5 in., 3 in., 4.56 in. and 6 in. corresponding to gap height to length ratios of

12.5%, 25%, 38% and 50% were used. It was also of interest to observe the flow when the gap acted as a diffuser in the streamwise direction. Therefore, the plexiglass box was manufactured such that the upstream wall could remain normal to the flow while the bottom of the box moved to any position between 0° and 30° measured from the horizontal axis. Figure 3.2 illustrates how the diffusing gap was obtained. Subsequent observations were made for diffusion angles of 7.5° and 15° at gap heights of 1.5 in., 3 in. and 6 in. The uniformity of the gap height along the length and the value of the diffusion angle were measured with an angled water level.

The ink ejection apparatus can be seen in Figure 3.3. The brass tube at the bottom of the reservoir was connected to a plastic tube of 2mm inside diameter via a piece of flexible Tygon tubing. Preliminary tests showed that the streak of ink emerging from this plastic tube was quite thick; therefore, a very small piece of brass tubing of 0.025 in. inside diameter was fitted in the bottom of the plastic tube. This resulted in a very thin stream of ink entering the flow. The flow of ink was controlled by a small valve placed on the brass tubing immediately below the reservoir. It was found that a good flow of ink could be obtained with the reservoir located about 8 in. above the free surface. The motion of the ink ejector was restricted in the streamwise sense but some flow induced vibrations could be seen when the mean flow velocity was high. Another consequence of high mean flow velocity was the more rapid diffusion of the ink trace.

Figure 3.3 Ink ejection apparatus

3.2 EXPERIMENTAL PROCEDURE

As the water flowed through the flume and under the box, it separated at the sharp upstream corner and reattached to the bottom surface of the box some distance downstream. The area bounded by the free shear layer and the bottom of the box between the separation and reattachment points is referred to as the separation bubble. This is illustrated in Figure 3.4. The depth of the water in the flume, measured from the floor of the plexiglass channel, was varied to observe its effect on the bubble behaviour. For water depths close to the gap height, also measured from the floor of the plexiglass channel, it was apparent that variations in the water depth of the order of 0.5 in. brought about changes in the transverse and streamwise dimensions of the separation bubble. These were probably due to a change in the detachment angle of the separation streamline. As the free surface of the water in the flume dropped towards the bottom of the plexiglass box, the detachment angle diminished which reduced both the above-mentioned bubble dimensions. However, when the free surface of the water was more than 2 in. above the bottom of the box, the bubble dimensions became independent of further increases in the water depth. All experiments were run at conditions for which the bubble dimensions were independent of the depth of the water.

Figure 3.4 Flow terminology

Black and red Pelikan drawing ink diluted with water was used to visualize the flow. The best concentration found was about 22 drops of ink for every 10cc of water. The ink was injected into the flow from several positions upstream of the gap in an attempt to mark the separation streamline. The best position found was on the centerline of the flume about 1 in. upstream of the front wall of the box and about 1.5 in. higher than the bottom of the box. From this position, the ink was seen to touch the sharp upstream corner of the gap as it flowed past it, this being the expected path of the separation streamline.

It was also attempted to inject ink directly inside the bubble through the 0.05 in. diameter static taps placed along the floor of the box. These were intended to give a rough idea of the pressure distributions inside and downstream of the separation bubble. This technique did not provide any additional information because as soon as the ink entered the recirculating flow in the separation bubble, it spread out in all directions forming a haze which masked all the details of this region. The boundaries of the hazy region could have provided the streamwise and transverse dimensions of the bubble, but these were already available by the previous method.

Photographs were taken using a Canon A-1 camera mounted with a single-ring zoom lens, model FD 70-210mm f/4. The camera was used in the manual mode at a shutter speed of 1/500 second and an aperture of f/4. All photographs were taken on Kodak Ektachrome, ASA 400, colour slide film. A white cardboard was placed behind the flume at the level of the separation bubble. Two 150W indoor floodlights were shone towards the cardboard from either side of the bubble, giving a contre-jour effect which acted to make the ink trace appear darker in the photographs. Several photographs of the ink trace were taken once steady flow conditions were obtained in the flume upstream of the gap. These were useful in showing the unsteadiness which exists in separating and reattaching flows.

The slides were projected onto a digitizing table connected to a personal computer. Using the streamwise length of the box and the gap height to establish the scale on the x and y axes enabled the coordinates of any point in the gap to be obtained simply by pointing to it with the digitizer. The length of the separation bubble was taken as the streamwise distance from the sharp corner of the box where separation takes place to the downstream point where the ink trace first makes contact with the bottom of the box. The maximum height of the bubble was taken as the

maximum normal distance from the bottom of the box to the edge of the ink trace. Since the ink entered the shear layer bounding the bubble when it flowed under the box, the height measurements are obviously taken somewhere within the shear layer although it is not known precisely where.

3.3 DISCUSSION

The first case studied was a gap of constant height. Using the Blasius solution for the laminar boundary layer to obtain the Reynolds number based on the momentum thickness, it was concluded that the boundary layer on the floor and side walls of the flume remains laminar up to the test section. Its thickness varied between about 8% and 24% of the flume width as the velocity decreased. For the smallest clearance height and upstream flow velocities less than about 0.3 ft/sec., the boundary layer on the floor of the flume was thick enough to reach the shear layer bounding the separation bubble. This did not seem to affect the dimensions of the bubble, although shear effects were apparent in the ink trace. In this experiment, the Reynolds number based on gap height and average velocity inside the gap at each clearance was varied by changing the upstream velocity of the flow. At the highest velocities, two bathtub vortices located a short distance upstream of the box on either wall of the flume, were apparent and provided proof of the three dimensionality of the flow. They were continually present, often sucking air from the free surface and releasing it into the flow. The air bubbles would then flow through the gap beyond the separation bubble. As the upstream velocity was reduced, the vortices released less air bubbles and began to appear intermittently. Both appeared and disappeared roughly at the same moment. As the flow became quite slow, the vortices were no longer visible at any time and stopped releasing air bubbles into the flow. In most instances, the outline of the separation bubble resembles the bottom half of an ellipse which would have been cut along its major axis. This is shown in Figure 3.4.

3.3.1 Constant gap height configuration

The Reynolds number is based on an average flow velocity inside the gap and the gap height unless otherwise indicated. The average flow velocity in the gap was calculated from the continuity equation using the flow velocity and the height of the water in the flume upstream of

the test section. This Reynolds number is considered significant because it represents conditions in the gap. The free shear layer originating from the separation point grows in the gap flow and eventually undergoes transition. The location of transition is invariably affected by the gap Reynolds number and it has a large influence on the streamwise and transverse dimensions of the separation bubble. Therefore, it seems reasonable to examine the bubble dimensions obtained in this experiment with respect to the gap Reynolds number. The non-dimensional ratio of the average bubble length to gap height is plotted against the Reynolds number at each gap height in Figure 3.5. The averages of the ratios of bubble length or height to gap height in this figure are time-mean values evaluated from the measurements on all the photographs taken under the same flow conditions. The average values listed in Table 3.1, however, are averages taken over the range of Reynolds numbers at any given gap height. As discussed later, it was found preferable to non-dimensionalize the bubble length with the gap height rather than with the gap length. The range of Reynolds numbers at which the flow visualization was conducted varied with the gap height as shown in Table 3.1.

<i>Gap height (inches)</i>	<i>Reynolds number range</i>	<i>Avg. bubble length Gap height</i>	<i>Absolute bubble length (inches)</i>
1.5	6.5×10^3 to 4.7×10^4	2.80	4.2
3.0	3.4×10^4 to 9.8×10^4	1.76	5.3
4.6	4.9×10^4 to 1.1×10^5	1.40	6.4
6.0	4.8×10^4 to 1.1×10^5	0.95	5.7

Table 3.1 Constant height gap

Referring to Figure 3.5, it appears that the average bubble length to gap height ratio either increases or decreases with the Reynolds number depending on the value of the gap height to

Figure 3.5 see caption on following page

Figure 3.5 Variation of bubble width and length with Reynolds number at zero inclination angle. a) $\tau/L = 0.125$, b) $\tau/L = 0.25$, c) $\tau/L = 0.38$, d) $\tau/L = 0.50$.

length ratio. A straight line has been drawn through the data points to show these trends. The slope of this line is greatest at the smallest gap height. As the gap height increases with respect to the gap length, the rate of increase of the bubble length to the gap height ratio with the Reynolds number diminishes until the slope becomes negative at the largest gap height. The rate of change with Reynolds number is small at the intermediate gap height to length ratios of 25% and 38% but it is more pronounced for the smallest and largest gap heights. It is important to note at this point that there is a large uncertainty in the measurements; therefore, there is also considerable uncertainty in the apparent trends.

The average bubble length to gap height ratio and the absolute bubble length obtained from Table 3.1 were both plotted against the gap height to length ratio in Figure 3.6. It appears that as the gap height increases, the absolute bubble length increases as well; however, it does so at a lower rate, such that the ratio of bubble length to gap height actually decreases. Figures 3.7 to 3.10 are photographs of the separation bubble at the average conditions mentioned above which serve to clearly illustrate the trend of increasing bubble length with increasing gap height. In Figure 3.7, red ink was injected directly into the bubble through the static taps on the floor of the box while black ink flowed from the upstream ink ejector. The other pictures were taken with the ink coming only from the upstream ink ejector.

Figure 3.6 Variation of the non-dimensional and absolute bubble length and width with the gap height at zero inclination angle.

The ratio of bubble height to gap height appears to remain fairly constant with increases in the Reynolds number but it is greatly influenced by the value of the clearance height as shown in Figures 3.5 and 3.6. Table 3.2 lists the average of this ratio, taken over the range of Reynolds numbers at each gap height, with the minimum and maximum values observed for each clearance. Note that the average bubble height to gap height ratio is nearly equal for three of the four gap heights, that is to say the smallest and the two largest clearance heights. It is at a clearance height of 25% of the gap length that this ratio is greatest. Figure 3.6 shows the actual value of the average bubble height quickly increasing with the first increase in gap height. As the gap height is increased further to 6", the increase in actual bubble height becomes much milder. Figures 3.7 to 3.10 confirm this trend. This suggests that the dimensions of the gap influence the bubble. More specifically, it is conjectured that the proximity of the endwall acts to reduce the height of the bubble. It is probable that as the distance between the endwall and the bottom of the box increases, the bubble will heighten, eventually attaining a natural height. After this point, further increases in the distance will not affect the bubble.

<i>Gap height (inches)</i>	<i>Avg. bubble height Gap height</i>	<i>Maximum ratio</i>	<i>Minimum ratio</i>
1.5	0.28	0.32	0.24
3.0	0.42	0.50	0.30
4.6	0.31	0.42	0.22
6.0	0.28	0.37	0.23

Table 3.2 Constant height configuration

The behaviour of the fluid downstream of the reattachment point is very similar at all clearances. The ink begins to spread out into the clearance gap, in the reattachment region. The slope of a line tangent to the ink trace, drawn from the floor of the flume towards the reattachment point, is about 42° in the gaps of Figures 3.7 to 3.10. The ink eventually mixes out and fills the entire gap height near the outlet plane. This is indicative of flow mixing in the gap, from the reattachment region to the outlet, and will be discussed at greater length in Chapter 5.

Figure 3.7 Gap height = 1.5 inches; $L_b / L = 0.3$.

Figure 3.8 Gap height = 3 inches; $L_b / L = 0.45$.

Figure 3.9 Gap height = 4.6 inches; $L_0 / L = 0.5$.

Figure 3.10 Gap height = 6 inches; $L_0 / L = 0.4$.

It also forms an integral part of the flow model presented by Moore & Tilton (1988), as discussed in Chapter 6

Velocity measurements were taken by Graham (1986) in a water flow cascade. Using a hot-film probe, the clearance gap between the blade tip and the endwall was traversed near the suction surface of the blade. These measurements reveal a region of higher velocity in the lower half of the channel and an extensive upper area moving more slowly. This upper area is in the wake of the separation bubble observed at the entry to the gap, just inside the edge between the pressure surface and the tip surface. As the clearance between the blade and the endwall was reduced, a decrease in this lower velocity region, thereafter referred to as the bubble-wake region, was also observed. Graham's experiment is similar to the present one in that both geometries involve separation from a sharp edge located at the entry of a constant area gap, and flow reattachment inside the gap. For comparison purposes, Graham's data will be expressed in terms of gap quantities. The thickness of the blade is used to non-dimensionalize the clearance height, while the extent of the bubble-wake region is non-dimensionalized by the clearance height. Graham's experiments were run at clearances of 9.85%, 14.18% and 19.7% of the blade thickness for which the bubble-wake region took up 10.8%, 28% and 40% of the clearance height respectively. Assuming the bubble-wake region can be correlated with the maximum bubble height, these numbers agree very well with the data obtained in the present flow visualization study: as the clearance height was increased from 12.5% to 25% of the gap length, the bubble height increased from 28% to 42% of the gap height.

The study by Lane & Lochrke (1980) on blunt flat plates in a water flume and this one contain some common features which allow some degree of comparison. Common features include the fixed laminar separation point and the fact that the flow reattaches to a surface which extends directly downstream from the separation point, parallel to the streamwise direction. As well, both studies involve transitional separation bubbles. However, there are quite large differences in the blockage ratio and in the Reynolds number of the flow adjacent to the separation bubble. These differences are expected to affect the streamwise and transverse dimensions of the bubble due to their influence on the detachment angle of the separating streamline and on the location of the transition point in the separated shear layer bounding the bubble. Therefore, bubble dimensions obtained from this study cannot be compared to those from

the present experiment, but variations in the bubble dimensions with changes to the gap geometry are expected to be similar.

In the study reported by Lane & Loehrke, the flume wall was far enough away from the blunt plate that it was believed not to have any influence on the separation bubble. Their experiment was conducted at Reynolds numbers based on upstream velocity and gap height from 3300 to 6000. The authors noted that the reattachment length of the flow remained constant as they lengthened the plate, yielding plate length to gap height ratios of 1.44 and 1.82. The present experiment was run at Reynolds numbers based on gap height and gap velocity from 6000 to 110000. As the gap height was reduced from 6 in. to 1.5 in., thus increasing the gap length to gap height ratio from 2 to 8, the average reattachment length of the flow, taken over the range of Reynolds numbers at a given gap height, decreased from about 5.7 in. to 4.2 in. The difference in the behaviour of the bubble length with an increase in gap length to gap height ratio between the present study and that of Lane & Loehrke is thought to be due to the increased proximity of the adjacent wall to the bottom of the box. Since the dimensions of the gap in the present experiment were varied by changing the gap height, and since there seems to be evidence showing that the bubble length becomes independent of the gap length at a large enough gap height, it was decided to non-dimensionalize all quantities using the gap height.

The behaviour of the static pressure inside and downstream of the separation bubble was examined by means of an array of Pyrex tubes attached to the static taps lining the bottom surface of the box. With the Pyrex tubes opened to the atmosphere, the water rose to a height proportional to the static pressure present at that tap location. Evidently, this method could only be used to measure gauge pressures greater than atmospheric; therefore, no readings were taken when the flow velocity was great enough to cause negative gauge pressures. The water columns were constantly oscillating, thereby prompting an average value of the height over time to be estimated. Measurements taken for a gap height of 1.5 in. indicate greater pressure fluctuations along the gap centerline as the Reynolds number increases. The static pressure inside the bubble increases steadily towards the reattachment point where it reaches a value very close to that present at the gap outlet. It then remains fairly constant, increasing slightly along the rest of the gap.

3.3.2 Bubble unsteadiness

Unsteadiness in the separation bubble was noted throughout the experiment. The bubble seemed to lengthen and heighten at times immediately prior to bursting but it reattached very quickly, apparently forming a bubble smaller than the original one. This small bubble grew swiftly to an average size before repeating the cycle. In this context, bursting is said to occur when the separated shear layer fails to reattach to the surface during a brief moment. Two examples of this behaviour, for a gap height to length ratio of 50%, are shown in Figures 3.11 and 3.12. Figure 3.11 shows the separation bubble much longer and slightly larger than average in the transverse direction while Figure 3.12 shows the bubble at its average length and height. Figure 3.12 also shows a very irregular bubble outline with the ink being concentrated at the inlet of the gap; this displays heavy recirculation occurring at the inlet with instabilities further downstream. Near the end of the bubble in this same picture, the ink forms a triangle pointing toward the bottom of the flume. Moments later, this triangular formation is no longer apparent. It is probable that this is a vortex about to be shed from the reattachment region of the bubble. The occurrence of vortices being shed downstream from the reattachment zone was shown by Hillier & Cherry (1981a, as referred to by Kiya & Sasaki, 1983) and confirmed by Kiya & Sasaki (1983) in their experiment with a blunt flat plate. It is believed that results from Kiya & Sasaki's experiment can be compared with those of the present experiment since, in both cases, separation took place at a sharp corner and transition to turbulence in the free shear layer occurred a short distance downstream of separation.

Hillier & Cherry also observed a low-frequency unsteadiness in the separation bubble accompanied by the shedding of a vortical structure from the reattachment zone. The low-frequency unsteadiness was also found by Eaton & Johnston (1982, as referred to by Kiya & Sasaki, 1985) in the separation bubble behind a backward facing step, and by Kiya & Sasaki (1983, 1985) in the separation bubble on a blunt flat plate. Eaton & Johnston suggested that the unsteadiness was caused by an imbalance between the entrainment rate from the recirculation zone and the reinjection of fluid into the bubble near the reattachment line. Assuming that the bubble length is determined by the balance between the entrainment rate and the reinjection rate, following Kiya & Sasaki (1985), the instantaneous imbalance could cause the enlargement or shrinkage of the bubble noted above. Eaton & Johnston associated the entrainment rate with the spanwise vortices in the shear layer. A short term breakdown of the spanwise vortices would

Figure 3.11 Gap height = 6 inches; Reattachment length greater than average.

Figure 3.12 Gap height = 6 inches.

decrease the entrainment rate while the reinjection rate remained constant, thus causing an increase in the volume of recirculating fluid and moving the shear layer away from the wall. This would increase both the bubble's length and height. This conjecture seems reasonable but it does not explain the rapid shrinkage of the bubble and the subsequent increase to an average size observed in the present study. Kiya & Sasaki (1983) imagined that very weak regular vortex shedding occurs from the main body of the separation bubble but is hindered in such a way that a large amount of vorticity is accumulated within the bubble. This would be accompanied by a large increase in the bubble length and an outward motion of the shear layer. An extremely large vortex would then be shed from the bubble when a sufficient amount of vorticity had been amassed. There would subsequently be a rapid shrinkage of the bubble and an inward motion of the shear layer. In their subsequent paper, Kiya & Sasaki (1985) mentioned that the shedding of these large vortices was actually quite a rare event. They also endorsed Eaton & Johnston's explanation of the physics of the flow and further suggested that the fairly constant periodicity of the low frequency unsteadiness indicates a feedback of disturbances from the reattaching zone to the shear layer near the separation line; these disturbances would be responsible for changes to the spanwise vortices.

The present flow visualization study shows that the values of the bubble's height and length at any instant hover around a mean value; these variations could be due to the behaviour of the spanwise vortices as explained by Eaton & Johnston. On the other hand, the large growth of the bubble leading to bursting and the formation of a smaller bubble is probably due to the vorticity amassed in the bubble as conjectured by Kiya & Sasaki (1983).

3.3.3 Diffusing gap configuration

Flow visualization was also performed with the floor of the box inclined at 7.5° and 15° from the streamwise direction such that the gap essentially behaved as a diffuser. It was repeated for inlet gap heights of 1.5 in., 3 in. and 6.1 in. The most obvious consequence of this change of geometry was the failure of the separated shear layer to reattach. It is therefore not possible to speak of a separation bubble in this case. The region of separated fluid extends along the entire length of the gap as shown in Figure 3.13. The distance between the ink trace and the bottom of the box measured along the y-axis will be referred to as the height of the separated region.

Figure 3.13 Inlet gap height = 6 inches; Inclination angle = 15° .

Table 3.3 shows the range of the Reynolds number based on the gap velocity and the gap height at the inlet used with the various values of inlet clearance height to streamwise gap length ratio for both inclination angles. It also includes the value of the average height of the separated region non-dimensionalized by the inlet gap height for each configuration. For all these configurations, the height of the separated region non-dimensionalized by the inlet gap height remained constant for all values of the Reynolds number, within the uncertainty of the measurements. At the 7.5° inclination angle, the average ratio of the height of the separated region to the inlet gap height remains constant at 0.51 as the clearance height increases to 25.5% from 12% of the gap length. This implies that the separated region has actually increased in height since it occupies the same proportion of the gap. This can be seen in the graphs of Figure 3.14. Increasing the gap height to 50% causes a reduction in the extent of the separated region to 36% of the inlet clearance height. However, the actual height of the separated region still increases slightly. On the other hand, at the 15° inclination angle, the ratio of the height of the separated region to the height of the gap at the inlet decreases from 0.5 at the smallest clearance

to 0.39 as the clearance increases to 25% of the streamwise gap length. This value then increases very little to 0.41 as the inlet gap height reaches 50% of the gap length. In terms of dimensional values however, increases in the clearance height are accompanied by increases in the height of the separated region. This can be seen clearly in the photographs of Figures 3.15 and 3.16. The height of the separated region for the diffusing gap configurations and the height of the separation bubble in the constant gap height configuration both increase as the clearance height increases. In the previous section, this behaviour was associated with the relative proximity of the floor of the flume to the separation bubble and it is believed that the same conjecture applies to the diffusing gap geometry.

<i>Gap height (inches)</i>	<i>Inclination angle = 7.5°</i>		<i>Inclination angle = 15°</i>	
	<i>Re number range</i>	<i>Average τ_s τ</i>	<i>Re number range</i>	<i>Average τ_b τ</i>
1.5	2.8×10^4 to 3.7×10^4	0.51	1.1×10^4 to 3.3×10^4	0.50
3.0	5.1×10^4 to 7.6×10^4	0.51	4.3×10^4 to 6.0×10^4	0.39
6.1	9.6×10^4 to 1.2×10^5	0.36	6.2×10^4 to 8.2×10^4	0.41

Table 3.3 Diffusing gap configuration

Once again in these tests, the Blasius solution shows that for the smallest gap height and velocities less than about 0.3 ft/sec., the boundary layer thickness is large enough to seriously interfere with the free shear layer forming at the corner of the box although no sign of this is apparent from the photographs. It would therefore seem that, at times, the entire gap is filled with vortical fluid from either the boundary layer on the floor of the flume or the free shear layer. For the two largest clearances tested, the boundary layer was much thinner and, as a result, the edge was far from the separated shear layer.

a) inclination angle = 7.5°

b) inclination angle = 15°

Figure 3.14 Variation of the non-dimensional and absolute bubble width with the gap height.

Figure 3.15 Gap height = 1.5 inches; Inclination angle = 15° .

Figure 3.16 Gap height = 3 inches; Inclination angle = 15° .

To summarize, diverging the gap by 7.5" or 15" prevents the separated shear layer from reattaching and results in the height of the separated region being between about 36% and 50% of the inlet clearance height for all cases.

3.4 CONCLUSIONS

A few tentative conclusions may be drawn from this flow visualization study. In the constant-height gap configuration, both the length and the height of the separation bubble are significantly influenced by the proximity of the wall facing the surface on which the bubble is formed. As the distance between the wall and the bubble increases, the average streamwise and transverse dimensions of the bubble also increase. This suggests that the wall has a constraining effect on the bubble. As the wall is moved away from the bubble, its influence diminishes and presumably becomes nil at a large enough distance. Further measurements are required to confirm this.

The average bubble height and length, non-dimensionalized by the gap height, appeared to increase, decrease or remain constant with increases in Reynolds number, depending on the value of the gap height to length ratio. However, the data have a high level of uncertainty, and it seems probable that in this range of Reynolds numbers, the bubble is controlled mainly by the geometry of its surroundings.

A certain amount of unsteadiness in the separation bubble was noted throughout this flow visualization study. It was observed that, at times, the bubble would grow in the streamwise and transverse directions to values much larger than average. It then appeared to burst and the shear layer would quickly reattach forming a small bubble which swiftly grew to its average size. Flow mixing was also evident downstream of the reattachment point.

Slightly inclining the bottom surface of the box counterclockwise from the streamwise direction inhibited reattachment, and all increases in the gap height had the effect of increasing the extent of the separated region in the transverse direction. In this configuration, there appeared to be no influence of the Reynolds number on the extent of the separated fluid.

CHAPTER 4

DESCRIPTION OF WIND TUNNEL EXPERIMENT

In order to document the flow in and around the separation bubble, the setup described in Chapter 3 was reproduced in the test section of a wind tunnel. Static taps were used for surface pressure measurements while a seven-hole probe provided three-dimensional information on the flow field outside the separation bubble, and through the shear layer. Oil flow visualization was conducted on the walls of the clearance gap, thereby supplying data on the flow inside the separation bubble. This chapter describes the apparatus and the instrumentation used in this study, as well as the procedure followed in making the measurements.

4.1 EXPERIMENTAL RIG

The experimental setup using air as the working fluid is shown in Figure 4.1. The air is supplied by a centrifugal fan driven by a 40 HP DC motor. The maximum output of the fan is a flow rate of 4 kg/sec at a maximum pressure rise of 48 cm of water. Much care is taken to minimize swirl. The air enters the fan through a bellmouth inlet and exits into a straight conical diffuser with an area ratio of 2.72 and an equivalent cone angle of 14° . From the diffuser, it flows through a honeycomb screen with cells of 9.5 mm width and 76 mm depth before entering the settling chamber. Three screens in the settling chamber reduce the turbulence. The air then flows through a transition section at the outlet of the settling chamber, which provides a constant area conversion from a circular to a square cross-section.

The transition is followed by a long channel with a cross-section of 0.366 m square, and a rectangular shaped body, 0.275 m long and 0.366 m wide. The rectangular body is placed in the channel to partially obstruct the flow, thereby forcing the air to flow through the clearance space between the top wall of the channel and the upper surface of the rectangular body. This clearance

space will be referred to as the two-dimensional clearance gap, and described in terms of its height to streamwise length ratio, τ/L . It is intended to represent, approximately, the tip gap found in rotating turbomachines, at a certain chordwise position. The upper surface of the rectangular body represents the tip surface of the blade, between the pressure and suction sides, while the top wall of the channel represents the casing of the turbomachine. The test section still remains, however, only a two-dimensional idealization of a tip gap. The channel continues downstream of the clearance gap and exhausts to the atmosphere. It has a total length of 2 m. The top and side walls are constructed of 19 mm thick plexiglass while the bottom surface is 12 mm aluminum. Angle iron is used to bolt the top and bottom walls to a 25 mm thick particle board side wall, which essentially provides the main support to the test section. The rectangular body slides vertically into the channel through an opening in the bottom wall, located 1 m downstream of the transition, and bolts into the side wall. It can be placed at different vertical positions in the channel in order to study the effect of the τ/L ratio on the flow in the clearance gap. The edge of the rectangular body, at the inlet of the clearance gap, is made of aluminum and sharpened to ensure flow separation from this corner.

Figure 4.1 Experimental setup for wind tunnel experiment.

2 OF/DE 2

PM-1 3 1/2" x 4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO EQUIVALENT

4.2 INSTRUMENTATION

4.2.1 Static pressure taps

Well static pressure taps were widely used in this study, both on the upper surface of the rectangular obstruction and on the top wall of the channel. All taps had a 0.5 mm diameter for a depth of 2 mm from the flow surface, before increasing to a 3.2 mm diameter through the remaining thickness to the material. The increase in diameter is used to reduce the response time.

The spacing of the static taps on the top wall of the channel, with respect to the rectangular obstruction is shown in Figure 4.2. The transverse rows of taps provide a picture of the two-dimensionality of the flow, whereas the streamwise rows cover a distance from about 0.44 gap lengths upstream of the clearance gap to about 72% of the gap. The streamwise rows of taps were placed at an equal distance on each side of the centerline to permit the mounting of the traverse gear on the top wall, thereby allowing probe traverses across the clearance gap, on the centerline. A static tap was placed on the centerline, at the outlet of the clearance gap, to provide a reference pressure for the flow measurements in the gap.

Figure 4.2 Static tap locations on endwall. Dashed lines represent tip wall and all dimensions are in mm.

Figure 4.3 shows the tap locations on the lower surface of the clearance gap. This is, in fact, the upper surface of the rectangular obstruction, hereinafter referred to as the tip wall. The taps are closely spaced along the centerline, providing a high resolution of the streamwise variation of the flow inside the separation bubble, and under the developing boundary layer downstream of reattachment. Here as well, the transverse rows serve to illustrate the two-dimensionality of the flow.

Figure 4.3 Static tap locations on tip wall. All dimensions are in mm.

4.2.2 Seven-hole probe

A seven-hole probe was also used extensively in this research, to document the flow in the clearance gap, outside the separation bubble. It consists of seven stainless steel hypodermic tubes arranged with one center tube and six surrounding ones, as shown in Figure 4.4. The tube bundle is then contained in a brass casing. The space between the tubes is filled with solder and the probe tip is tapered at 30° from the axis. The probe tip diameter is 2.4 mm which is quite small compared to the size of the clearance gap. The overall probe dimensions and the tip geometry is shown in Figure 4.4.

The probe was used in the non-nulling mode to measure the three-dimensional velocity vector, as well as the dynamic and total pressures. It was calibrated up to 50° of flow misalignment with the probe axis in 5 degree steps by Yaras as outlined in Yaras (1990). The calibration was checked at the beginning and again at the end of the measurements.

4.2.2.1 Error sources in seven-hole probe measurements

The main error in these measurements is identified by Yaras (1990) as the curve-fitting to the calibration data. The checks on the calibration suggest accuracies of $\pm 1.5^\circ$ for the measured flow angles, and $\pm 4\%$ actual dynamic pressure for the measured dynamic and total pressures.

Another error inherent to all measurements made with an intrusive method is the influence on the flow due to the presence of the instrumentation. Wakes are shed behind the apparatus and streamlines are displaced, thereby disturbing the pressure and velocity fields in the flow. In the case of seven-hole probes, for example, a pressure gradient is established as the flow accelerates over the tip, causing the holes surrounding the center hole to sense a higher pressure. However, this error is usually rectified through calibration. The current trend to minimize the size of probes is an attempt at reducing these effects on the flow.

Multi-hole probe measurements will be in error if the probe is located near enough to a solid surface that flow acceleration occurs in the region between the probe and the wall. The velocity gradient induces a pressure gradient which is sustained through streamline curvature towards the wall, and therefore towards the probe. Sitaram et al. (1981) studied wall proximity effects on five-hole probes and their results show that the probe tends to read higher than actual velocity, but that the error is less than 1% when the probe is two or more diameters away from the wall.

Problems of spatial resolution arise when the probe is used in flows with high velocity and/or pressure gradient regions because pressures from different ports are not measured at the same physical location. The magnitude of this error is proportional to the magnitude of the gradients (Yaras, 1990). Large gradients were not present in the region of the flow where the seven-hole probe was used in this study.

Figure 4.4 Seven-hole probe port numbering, tip geometry and coordinate system.
 α is the pitch angle; β is the yaw angle.

4.2.3 Hot-wire anemometer

A hot-wire anemometer was used to find the turbulence intensity in the flow upstream of the test section. The platinum plated tungsten wire, manufactured by DISA, had a 5 μm diameter and a length of 1.25 mm. It was placed at about 1.7 tip gap lengths upstream of the test section, at an equal distance from both side walls, and well outside the endwall boundary layer. The anemometer was operated in the constant-temperature mode, at 260°C. Since the relationship between current and heat transfer is non-linear, the hot-wire is calibrated in its operating range, and used in conjunction with a linearizer to make the measurements within this range.

4.3 DATA ACQUISITION SYSTEM

The data acquisition system consists of two pressure transducers, a 48 port Scanivalve, and an electronic measurement system manufactured by Sciometric Instruments and controlled by an IBM-PC compatible micro computer, through its serial port. The electronic system included a Model 901 CPU with an Intelligent Serial Interface (M 901) and a Model 81 Electronic Measurement System (M 81).

Two different pressure transducers were used: a Rosemount variable capacitance differential pressure transducer and a Baratron differential pressure transducer. Both convert pressure differences into analog voltage signals. The Rosemount transducer possesses an input range of ± 0.5 psi corresponding to a full scale output range of ± 2.5 volts DC, while the Baratron transducer possesses an input range of ± 1 psi and a full scale output range of ± 10 volts DC. The calibration of each transducer, against inclined manometers, was checked both at the beginning and end of the measurements and found to be quite stable. The Rosemount transducer was used to set and monitor the flow in the wind tunnel, whereas the pressures of interest in the test section were measured with the Baratron transducer. Since the wind tunnel operates at a steady pressure difference, the Rosemount transducer provides a reference pressure. The analog output signals from both transducers are transmitted to the M 81 Electronic Measurement System.

The M 81 is activated by the M 901 which is controlled by the personal computer through an RS232 serial interface port. The software which controls the data acquisition system and

processes the data was written by Yaras (1990) in Turbo Pascal Version 3.0. It was modified for three-hole probe measurements, and upgraded to run with Turbo Pascal Version 5.0 by Whitehouse (1993). Further modifications were made in the upgraded code in order to enable seven-hole probe measurements, as described in Appendix A. This software also determines the optimum range for the analog input signal of each data point, in order to provide the maximum possible resolution for the digitization of each signal. This is done by sampling the data for 10 seconds without any amplification. These samples are then used to select the best range to be employed during the actual sampling period. The M 81 uses an integrating analog-to-digital converter with a 12 bit-plus-sign and a dual slope. The integration eliminates high frequency noise, while the 12 bit-plus-sign provides a resolution of 0.024% of the selected range. Four ranges are available to read the input signal: ± 5 volts, ± 0.4 volts, ± 0.03 volts and ± 0.005 volts.

The communication rate between the PC and the M 901 is 2400 bps. Since the transfer of data to the computer is quite slow, all the data acquired during one sampling period is stored in the 24000 bytes random access memory (RAM) on the M 901. Since the data acquisition system can only read one quantity at a time, it samples the transducers sequentially; two samples per second are obtained from each transducer. Once the data has been transferred to the computer at the end of the sampling period, it is processed following the method devised by Yaras (1990). The pressures are grouped in cycles of "reference pressure - test section pressure - reference pressure", and each test section pressure is normalized by the average of the reference pressures acquired in the same cycle. The individual non-dimensional test section pressures are then averaged over a sampling period. This method was found to minimize the effects of the small amount of drift in the wind tunnel operating point, as opposed to non-dimensionalizing averaged quantities, and gives good repeatability in the data.

The pressures were measured using a 48 port Scanivalve. These ports are connected to pressure sensors, such as static taps and multi-hole probes, via flexible plastic tubing. Air fills the tubing and the internal volume of both the Scanivalve and the transducer, until a state of pressure equilibrium is reached. A finite time is required to achieve equilibrium every time the Scanivalve steps to a different port. Therefore, a waiting period is established prior to each sampling period.

The amount of waiting and sampling time necessary to obtain accurate long term average values was determined in the following manner. The pressure from the Scanivalve was sampled for 150 seconds, immediately after it stepped from a high pressure port to a low pressure port. The waiting time was chosen as the time required for the transient in the pressure to die out. A running time average was calculated starting at the end of the transient, and the sampling time was chosen as the time required for the average to become constant. This procedure was repeated for both the wall static pressure measurements and the seven-hole probe measurements, resulting in a 20 second wait and a 70 second sampling time for the wall pressures, and a 35 second wait followed by a 45 second sampling time, for the seven-hole probe pressures. The sampling times in particular, are very conservative.

4.4 DESCRIPTION OF MEASUREMENTS

4.4.1 Operating point

This experiment was run at a gap Reynolds number of 250000. The Reynolds number is based on the gap height and on an ideal gap velocity determined using the total pressure 1.7 tip gap lengths upstream of the test section, and the wall static pressure at the outlet of the gap. Typically, gas turbine engines operate at a chord Reynolds number of the order of 10^5 (Graham, 1986). The on-going research of the flow in the tip gap of a planar cascade of turbines blades, conducted in the Turbomachinery laboratory at Carleton University, is done at a Reynolds number of 4.3×10^5 based on the blade chord and the undisturbed upstream velocity. For the clearances investigated by Yaras (1990), this translates to a gap Reynolds number ranging from 1.3×10^4 to 4.7×10^4 . This range of Reynolds number could not be used in the present experiment, because it required operating the fan at too low an rpm value. Therefore, the gap Reynolds number was increased until the fan operated at a reasonable range within its operating range. Static pressure measurements were also carried out at a lower Reynolds number, 150000, to investigate possible Reynolds number effects on the flow. As well, due to the limitations of the data acquisition system, the 7-hole probe measurements in the smallest clearance gap were also carried out at a Reynolds number of 150000, and those in the largest gap were carried out at a Reynolds number of 325000.

4.4.2 Boundary layer traverses

The boundary layer on the top wall of the channel, hereinafter referred to as the endwall, was traversed at about 1.7 tip gap lengths upstream of the gap inlet, on the centerline, in clearance gaps of $\tau/L = 19\%$ and 31% . A flattened Pitot probe was used to measure the total pressure in the boundary layer, and referred to the endwall static pressure in the same plane. The advantages and shortcomings of these probes are discussed in Chapter 2. The probe used in this experiment had a width of 0.05 inches and was 0.02 inches high. The pressures were sampled for 45 seconds, following a 35 second wait, as was the case with the seven-hole probe measurements. The Pitot probe was traversed in 0.1 mm steps for the first 2 mm from the endwall, then in 0.5 mm steps for the next 8 mm.

The datum position, where the probe first contacts the endwall, was determined aerodynamically. With the wind on, the head of the Pitot probe was brought increasingly closer to the endwall. From the point where the probe first makes contact with the wall, the total pressure remains constant while the probe bends slightly as it is further pulled towards the endwall. The datum position is the one at which the total pressure first becomes constant.

In the smaller gap, $\tau/L = 19\%$, the incoming boundary layer is about 7 mm thick, with a displacement thickness of 0.75 mm and a momentum thickness of 0.53 mm. It is a turbulent layer with a shape factor of 1.4. The incoming boundary layer is also turbulent in the larger clearance gap, $\tau/L = 31\%$, although somewhat thicker at 9 mm. The endwall boundary layer was also traversed at the inlet and outlet of the clearance gap, as well as at the position where the endwall static pressure reaches a minimum. The boundary layer thinned as the flow accelerated into the gap, but thickened again towards the outlet. The boundary layer on the tip wall, at the gap outlet, was also traversed, and determined to be very thin.

The endwall boundary layer was not traversed at the other clearances because it was deemed thin enough that its influence on the flow in the gap was considered inconsequential. This is further discussed in Chapter 5.

4.4.3 Hot-wire anemometer measurements

The turbulence intensity is defined as the ratio of the root-mean-square velocity fluctuations

to the mean velocity. It was calculated using the AC and DC outputs from the anemometer, which represent the root-mean-square value of the fluctuations, and the mean value of the velocity, since the anemometer output was linearized. The value of the turbulence intensity increased with the mean flow velocity in the tunnel. Measurements were made at $\tau/L = 35\%$, over a wide range of mean flow velocities. The hot-wire can only sense velocities normal to its axis; therefore, since it is placed perpendicular to the incoming flow, it can only measure streamwise fluctuations, as transverse fluctuations do not noticeably alter the magnitude of the velocity vector. At the higher velocities, the streamwise turbulence intensity settled at $0.75\% \pm 0.05$ but, at the upstream velocity used in the experiment at this clearance, it had a value of $0.53\% \pm 0.07$. As the gap height was reduced, thereby increasing the area blockage in the tunnel, the upstream flow velocity was kept more or less constant by increasing the fan rpm, which probably also increased the turbulence intensity. Nevertheless, the incoming free stream in this experiment can still be considered very smooth since, from the discussion of Section 2.4.1, it appears that streams with turbulence intensities greater than about 5% were considered turbulent, whereas smooth streams had turbulence intensities lower than 1%.

4.4.4 Static tap measurements

The wall static pressure measurements were carried out at a gap Reynolds number of 250000. The measurements were done at various clearances: $\tau/L = 19\%$, 24%, 28%, 31%, 35%, 43% and 81%. However, the Reynolds number used in the largest gap was 325000, and measurements were only done along the streamwise rows of taps on the endwall and on the reattachment surface. The static pressure at each tap is referred to that at the gap outlet, on the endwall, and the difference is normalized by the ideal gap dynamic pressure. Repeatability tests give an accuracy of ± 0.025 to the pressure coefficient.

4.4.5 Seven-hole probe traverses

The seven-hole probe was traversed on the centerline, across three planes normal to the endwall: the inlet and outlet planes, as well as the plane at the streamwise position at which the static pressure on the endwall reaches a minimum. The latter plane is expected to be close to the location of the maximum height of the bubble. A traversing gear, fitted with a stepper motor was used to move the probe, thereby enabling it to be positioned with an accuracy of ± 0.1 mm. The datum position was established using a ruler and is estimated accurate to within ± 0.2 mm.

Seven-hole probe measurements were carried out in three different gap clearances: $\tau/L = 19\%$, 31% and 43% . A traverse of the outlet plane was also done for $\tau/L = 81\%$. The pressure at each of the seven ports on the seven-hole probe, was referred to the gap outlet static pressure on the endwall, and non-dimensionalized by the ideal gap dynamic pressure. The gap Reynolds number was reduced to 150000 for the measurements in the smallest clearance gap because the pressure differences were too large to be read by the data acquisition system. It was set to 250000 for $\tau/L = 31\%$ and 43% , but increased to 325000 at $\tau/L = 81\%$ because, in this case, the pressure differences were too close to the resolution of the data acquisition system at the lower Reynolds number.

All the seven-hole probe traverses began 5 mm, about 2 probe diameters, from the endwall. The data at this location was not used in the reduction, due to the proximity of the probe to the wall. The inlet and outlet planes were traversed in 2.5 mm steps in the smallest gap, 4 mm steps in the gap with $\tau/L = 31\%$, and 5 mm steps at $\tau/L = 43\%$. Steps of 6 mm were used across the outlet plane in the largest gap. Inside the clearance gap, the probe was not traversed across the entire gap height because it entered a reverse-flow region near the bottom surface of the clearance space, in which accurate measurements were no longer possible. Therefore, it was traversed using the same step sizes as for the inlet and outlet planes, from the endwall up to just inside the reverse-flow region.

The seven-hole probe yields the three-dimensional velocity vector as well as the total and static pressures. The seven-hole probe measurements were reduced using the Pascal program, SHP_TRV.RE2, written by Yaras (1990). The program outputs the pitch and yaw angle of the velocity vector with respect to the probe axis, as shown in Figure 4.4, the three components of the velocity vector normalized by the magnitude of the velocity, and the total and dynamic pressure coefficient defined as follows:

$$C_{P_{tot}} = \frac{P_{tot} - P_{ref}}{q_{gap}} \qquad C_{P_m} = \frac{q}{q_{gap}}$$

where q and P_{tot} are the dynamic and total pressures felt at the probe.

CHAPTER 5

RESULTS AND DISCUSSION

The flow in the two-dimensional clearance space was investigated for several values of the gap height to length ratio. This involved static pressure measurements on the endwall and on the surface beneath the separation bubble, as well as seven-hole probe traverses across the gap height, on planes perpendicular to the endwall. The inlet and outlet planes, together with the plane at the streamwise position where the static pressure on the endwall reaches a minimum, were chosen for this purpose. The combination of these measurements with the results from extensive flow visualization provides a very clear picture of the flow inside the clearance gap, and of the influence of the gap geometry.

5.1 FLOW VISUALIZATION

Oil flow visualization was considered the best method for use in the wind tunnel for a number of reasons. First, it very clearly shows the direction of the flow, and it also gives an indication of the amount of shear present at the surface. As well, any separation or reattachment lines are easily recognizable. Another very useful quality of this technique is that the patterns drawn on the oil covered surface by the air flow remain once the wind tunnel is shut off. Therefore, the visualization is not restricted to wind on conditions, as is the case with smoke flow visualization, for example. The model can be removed from the test section to be photographed, and measurements can be taken directly off the surface, thus yielding results of greater accuracy. Two types of application were used, oil film and oil dots, as described below.

5.1.1 Procedure

The mixture used for visualization consisted of commercially available Crisco vegetable oil and white art color powder. Motor oil was initially used, but proved to be too viscous; the shear

forces in the flow were too small to draw clear patterns on the oil-covered surface. The amount of powder necessary to produce distinct patterns was found by trial and error.

In order to create a sharp contrast and enhance the flow visualization, the surface below the separation bubble was covered with a thin sheet of black vinyl. The upstream edge of the vinyl sheet was set so as to not influence the radius of curvature of the edge from which the flow separates. The downstream edge of the sheet was flush with the end of the surface.

The oil film method was used on all the wind tunnel walls. As the name implies, it consists of completely covering the surface on which flow visualization is to be performed with a thin, uniform coat of the oil mixture. As the air flows along the surface, shear forces redistribute the oil coverage, resulting in some areas where the oil has been scoured away, others where it has accumulated and others where it has simply moved in the direction of the air flow. This method is especially useful to identify if, and where, the boundary layer has separated from the surface. The other visualization technique consists of placing small dots of oil on the surface of interest. The drops must be very small, and sufficiently distant from each other, in order not to act as a disturbance to the boundary layer. They are sheared in the direction of the flow as the air passes over the surface, and the distance they travel is a qualitative indication of the magnitude of the shear forces present in the flow at the surface. The direction of the shear stress is also quite clear with this method.

In the present study, the most vivid flow patterns were obtained with the surface below the separation bubble divided into two sections along the streamwise centerline, as shown in Figure 5.1. One half was completely covered with oil, while drops were scattered on the other. The flow visualization was performed by operating the wind tunnel for a few minutes until a clear flow pattern became visible. This surface was then removed from the test section, enabling the quantities of interest to be more easily measured and photographs to be taken.

5.1.2 Characteristics of the flow inside the clearance gap

The oil flow visualization upstream of the test section did not uncover any boundary layer

separation in the incoming flow, on either the top or side walls; however, many interesting characteristics of the flow on the surface below the separation bubble were discovered.

The most unexpected flow characteristic revealed by the visualization was the existence of a boundary layer separation downstream of the sharp edge, as seen in Figures 5.1 and 5.2. The clearance gap is created by blocking a large area of the wind tunnel with a surface normal to the flow, as described in Chapter 4. Therefore, it seems likely that a boundary layer grows on this perpendicular surface, separates at the sharp corner while entering the gap, but that part of it reattaches almost immediately, forming a small separation bubble, and continues downstream to this second separation line, hereinafter referred to as the reseparation line. Upstream of the spanwise reseparation line, the flow is very unsteady but generally moves in the downstream direction, while a region of reverse-flow exists downstream of this line. Thus, the forward and reverse flows converge at the reseparation line. There exists a region of extremely high shear immediately downstream of the reseparation line, as evidenced by the fact that the oil has been completely scoured away. Visual inspection conducted with the air on revealed that the oil dots just past the sharp edge are smeared in the downstream direction while those close to the second separation line basically have not been smeared at all. This shows that the shear forces decrease from the sharp edge to the reseparation line, as expected in a boundary layer moving towards separation. It must be noted that although partial reattachment apparently occurs immediately downstream of the sharp edge, part of the boundary layer fluid still makes up the free shear layer which only reattaches further inside the gap, thereby constituting the upper bound of the separation bubble. In effect, the small separation bubble very near the sharp edge seems immersed in the main separation bubble.

As seen in Figures 5.1 and 5.2, the reseparation line is fairly straight, spanwise across the box surface, but curves upstream as it nears the side walls where it ends in a corner vortex. The flow in the vortices is counterrotating such that it travels downstream on the side of the vortex which is adjacent to the sidewall. Downstream of the vortices, along each side wall, the visualization shows some three-dimensional effects in the flow which extend to no further than about 10% of the total channel width.

Figure 5.1 Oil dot and oil smear flow visualization; $\tau/L = 24\%$.

Figure 5.2 Oil smear flow visualization; $\tau/L = 35\%$.

The free shear layer reattaches downstream of the reattachment line at a distance dependent on the gap height to length ratio. The reattachment line is easily spotted on the oil smeared surface: it is the spanwise line of high shear between the reverse-flow and forward-flow regions as shown in the photographs. Reverse flow exists from the reattachment line to the reattachment line, while forward flow is established downstream of the reattachment region. Figure 5.3 contains a schematic of the flow on the surface below the separation bubble, as described below, and a side view of the flow along the gap, on the centerline. The reattachment line is curved such that it is closer to the sharp edge along the side walls, and further away in the center region. However, the flow is symmetrical about the streamwise centerline. The exact position of the reattachment line is difficult to identify from the oil flow visualization photographs. It is therefore more accurate to refer to the reattachment region, which is the high shear area containing the reattachment line. The oil dot visualization of Figure 5.1 shows the flow near the reattachment region, on either side of the centerline, curving slightly towards the centerline as it proceeds in either the upstream or downstream direction. Further from the reattachment region, however, the flow path straightens out. This curvature in the flow path is believed to be due to the three-dimensionality of the reattaching shear layer caused, in part, by the presence of the sidewalls.

The oil flow pattern described above has also been observed on a splitter plate located in the wake of a blunt plate by Ruderich & Fernholz (1986), as reported in Chapter 2. The similarity of the flow on the surface below the separation bubble in these two different geometries, suggests that the mechanisms which control the flow and its reattachment downstream of separation, such as entrainment of free stream fluid by the separated shear layer, and the interaction with the reverse-flow region beneath the shear layer, are largely independent of the geometry. Some of the characteristics noted above were also found on other geometries. The corner vortices have been reported behind a backward-facing step by de Brederode & Bradshaw (1972, as referred to by Ruderich & Fernholz). As well, the existence of a secondary separation bubble, immersed inside the main one, very near the separation line is conjectured by Kiya & Sasaki (1983) from their measurements on a blunt plate.

a)

b)

Figure 5.3 Schematic diagram of the mean flow: a) on the tip wall,
b) side view along the gap.

The oil flow pattern reported by Ruderich & Fernholz bears a striking resemblance to the one from the present experiment. In their study, as in the present one, the flow separates from a sharp edge and reattaches at some distance downstream. The reattachment region is curved and constitutes the downstream bound of a reverse-flow region, which extends upstream to a nearly straight, spanwise reattachment line located a short distance from the sharp edge. Furthermore, this line ends at the sidewalls in two corner vortices. The flow travels downstream between the sharp edge and the reattachment line as well as downstream of the reattachment region. In both cases, the flow velocity is much greater in the reverse-flow region than in the forward-flow region upstream of the reattachment line. There exists, however, a major difference in the flow from the sharp edge to the reattachment line between these two studies. Ruderich & Fernholz and Castro & Haque (1987) identified a small vortex behind the blunt plate in which the flow moves downstream along the splitter plate, towards the reattachment line, and back upstream at a small distance above the splitter plate. From the present flow visualization on the sidewall, no recirculation is apparent. Rather, as previously mentioned, it seems more probable that the flow separates from the sharp edge, but that part of it reattaches almost immediately creating a very small separation bubble. The flow then proceeds downstream to the reattachment line where it separates from the surface and joins the free shear layer bounding the main separation bubble. The main separation bubble can then be thought of as made up of two sections: a forward-flow region at the front end of the bubble, followed by a reverse-flow region up to the reattachment line. It is bounded by the separated shear layer on one side, and by the wall on the other side.

5.1.3 Effects of τ/L on the flow inside the gap

The oil flow visualization was performed in gaps with height to length ratios, τ/L , of 0.19, 0.24, 0.28, 0.31, 0.35 and 0.43 to determine the influence of the clearance gap geometry on both the reattachment length and the location of the reattachment line. The results in Table 5.1 show that as the size of the gap increases, both the reattachment and the reattachment lines move downstream. The reattachment region is the band of high shear flow where the forward and reverse flow regions diverge, in Figure 5.2, and the location of the reattachment point is considered to be at its center. The reattachment point is also considered to be at the center of the reattachment line. In Table 5.1, the location of both the reattachment and the reattachment points

was measured from the sharp edge, along the centerline. The results have been non-dimensionalized by the gap height and, given about a 10% uncertainty in the measurements, it appears that while the reattachment length scales on the clearance gap height, $x_r/\tau = 2.3$, the distance to the reseparation point does not. The same conclusion concerning the reattachment length has also been reached by Storer & Barton (1991) in their study of the flow in the clearance space of a compressor blade tip.

τ/L	x_r (inches)	x_{rs} (inches)	x_r/τ
0.43	10	2.1	2.1
0.35	8.5	2.1	2.2
0.31	7.8	1.8	2.3
0.28	7.1	1.8	2.4
0.24	6.2	1.4	2.4
0.19	5	1.1	2.4

Table 5.1 Variation of the reattachment and reseparation lengths with τ/L .

The results from the flow visualization performed in the flume, as described in Chapter 3, show the length of the bubble increasing with the gap height, but not as a constant fraction of the clearance space. This may be attributed to a few factors. First, there was no quantitative way to pinpoint the reattachment point; therefore, an estimate of its location was made based on the apparent path of the ink trace. As well, only a limited number of photographs were taken for each flow condition and may not have reflected mean conditions. This creates a large uncertainty in the data obtained from the experiment conducted in the flume, but is not solely responsible for the differing conclusions. Another factor is the fact that the incoming free stream turbulence in the flume decreased as the gap height increased. As mentioned in Chapter 2, an increase in free stream turbulence encourages earlier transition in the free shear layer and leads to a shortening of the bubble. The inconsistency in the level of free stream turbulence could also be partly responsible for the variation in the bubble length to gap height ratio.

Further flow visualization was conducted in the wind tunnel using tufts, to determine whether the free shear layer would eventually fail to reattach as the gap height to gap length ratio continued to increase. A tuft placed at the exit plane of the gap was used to observe if reattachment had occurred. In the case of full reattachment taking place inside the gap, the tuft consistently pointed in the direction of forward flow. As the gap height to length ratio was increased to 0.48, the shear layer only partially reattached to the surface, as evidenced by the back-and-forth motion of the tuft. It is probable that at this ratio, part of the reattachment region had reached the exit of the gap. Further increases in the gap height resulted in the reattachment region continuing to move downstream until the shear layer finally remained completely separated, at about $\tau/L = 0.62$. At this ratio, the tuft consistently pointed in the upstream direction. The tuft probe exploration also revealed that further increases in the gap height to length ratio produced the reverse effect. In fact, for $\tau/L > 1$, the separation bubble reattached inside the gap. These observations are partially compatible with those of Storer & Barton (1991), who stated that full reattachment could only be achieved in clearance gaps with a height-to-length ratio smaller than 0.40, and that the flow would remain separated in gaps with τ/L ratios greater than 0.67.

According to the results of Storer & Barton, the flow should have only partially reattached at the largest clearance tested in the flume. However, it appears from the visualization that the flow was fully reattached in that case. This may be due to the fact that the incoming free stream turbulence in the flume was higher than that in their wind tunnel. Although Storer & Barton do not report values of the free stream turbulence intensity, they do present plots of the turbulence intensity in the clearance gap. The flow outside the separation bubble had almost zero turbulence intensity which indicates that the incoming free stream must also have been very smooth. Therefore, their results, as the present ones from the wind tunnel experiment, apply to situations in which the turbulence intensity of the incoming flow is very low.

5.2 WALL STATIC PRESSURE MEASUREMENTS

The static pressure was measured on the endwall, and on the surface below the separation

bubble, in gaps with height to length ratios equal to 0.19, 0.24, 0.28, 0.31, 0.35, 0.43 and 0.81. The exact position of each static tap was given in Chapter 4; therefore, only a brief reminder follows. On the endwall, the streamwise rows of taps began near 0.44 gap length upstream of the gap inlet, and extended to about 72% of the gap. The two transverse rows of taps covered 83.5% of the gap width, and provided information on the two-dimensionality of the flow. They were located at 0.08 gap length upstream of the gap inlet and 0.3 gap length into the gap respectively. The surface below the separation bubble was instrumented with a streamwise row of static taps along the centerline, which covered the entire length of the gap. There were also two transverse rows of taps located at 24% and 78% of the gap length into the gap, which spanned 87.4% of the gap width.

All pressure measurements were reduced to a non-dimensional pressure coefficient defined as follows:

$$C_p = \frac{P - P_{gap\ exit}}{\frac{1}{2}\rho U_{gap}^2} \quad (5.1)$$

where $\frac{1}{2}\rho U_{gap}^2$ is an ideal gap dynamic pressure determined from the total pressure upstream of the test section, and the static pressure on the endwall at the exit of the gap. Repeatability tests give an accuracy of ± 0.025 to the pressure coefficient.

5.2.1 Static pressure on endwall

The variation in the static pressure coefficient along both rows of transverse taps on the endwall, as shown in Figure 5.4, is less than ± 0.02 , within the uncertainty of the measurements. This suggests that the flow near the endwall, both upstream and inside the clearance gap, is uniform across the width. The two-dimensionality of the flow is also apparent in the measurements along the two streamwise rows of taps on the endwall. These were located on either side of the centerline, and the value of static pressure measured along both rows was nearly identical.

Figure 5.4 Static pressure variation on endwall, in the transverse direction; open symbols for upstream row, closed symbols for downstream row.

Figure 5.5 shows the static pressure variation in the streamwise direction for all clearances. Well upstream of the gap, the pressure varies only slightly. From continuity, as the flow nears the gap inlet, it must accelerate in order for the mass flow rate to remain constant through the constrained area. This is apparent in the sharp pressure drop which begins a short distance upstream of the gap inlet and continues into the gap. The further decrease in static pressure inside the gap is due to the presence of the separation bubble. As discussed in the previous section, the flow separates at the gap inlet and reattaches to the surface inside the gap. Between the separation and reattachment points, the separation bubble grows in a direction normal to the surface, reaches

Figure 5.5 Static pressure variation on endwall, in the streamwise direction.

a maximum height, and shrinks as it nears reattachment. The bubble essentially blocks part of the gap area, such that even once inside the clearance space, the flow continues to feel increasingly constrained, and therefore accelerates. This presumably persists until the separation bubble attains its maximum height, which is the point where the endwall static pressure should reach a minimum. The separation bubble is, in fact, forming a converging-diverging passage inside the gap. The flow in the forward part of the gap is similar to the flow entering a two-dimensional slot where, based on symmetry, the centerline of the slot is the endwall (Rains, 1954). Therefore, the shear layer can be considered to form a vena contracta inside the gap. Downstream of the vena contracta, the static pressure on the endwall increases as the flow decelerates towards the reattachment point, and eventually levels out beyond the reattachment region.

Measurements of the endwall static pressure in the streamwise direction were made at two gap Reynolds numbers, 150000 and 250000, in the gap with $\tau/L = 19\%$, but at 250000 in all other clearances. As shown in Figure 5.5, the gap Reynolds number has no influence on the static pressure variation described above. The difference in the pressure coefficients remains within the uncertainty of the measurements, except at near zero values of C_p where the magnitude of the pressure difference is very close to the resolution of the data acquisition system. This behaviour is not unexpected since it had already been observed by various authors on other geometries. As mentioned in Chapter 2, Cherry et al. (1984) and Ota & Itasaka (1976) both reported constant bubble lengths in their experiments on blunt plates, for a certain range of Reynolds numbers. The flow was also described as sensibly Reynolds number independent in the bluff plate/splitter plate geometry by Castro & Haque (1987) and Ruderich & Fernholz (1986).

5.2.1.1 Effect of τ/L on the endwall static pressure

As long as the flow reattaches to the surface inside the gap, the size of the clearance does not influence the general trend, in the streamwise static pressure on the endwall. As shown in Figure 5.5, in all cases where there is reattachment inside the gap, the static pressure reaches its minimum value inside the gap at a streamwise distance of 1.1 ± 0.1 tip gap heights before increasing again. However, at $\tau/L = 81\%$, the flow remained separated throughout the gap and the static pressure along the endwall decreased continually.

In this experiment, the gap Reynolds number was kept constant as τ/L increased from 0.19 to 0.43; thus U_{gap} was larger in the smaller gaps. A decrease in the gap height implies an increase of the blockage ratio, which is accompanied by an increase in the static pressure upstream of the gap, for a given value of the total pressure. In order to keep the gap Reynolds number constant, the total pressure needed to be increased. However, the increase in the upstream static pressure, due to the greater blockage ratio, more than offset the increase in the gap dynamic pressure, such that the value of the pressure coefficient upstream of the gap increased as the gap closed up. However, the situation is reversed once inside the gap, where the values of C_p from the inlet to the vena contracta, are consistently lower in the smaller gaps. As well, the flow undergoes greater acceleration into the gap at smaller τ/L ratios. This is apparent in the rate of decrease of the static pressure, which is greatest at $\tau/L = 0.19$.

The oil flow visualization revealed that the separation bubble lengthened as the gap height was increased. Figure 5.5 shows that opening the gap pushes the point where the pressure coefficient reaches its minimum value further downstream. Since this is thought to be the location at which the separation bubble reaches its maximum height, the experimental results show the separation bubble lengthening, with its crest also moving downstream, as the gap height increases.

The increase in the endwall static pressure downstream of the bubble crest is due to an increase in the effective area, as the flow moves towards the reattachment region. The rate of this pressure increase is a function of the distance between the reattachment point and the vena contracta; a longer distance producing a lower rate of pressure increase. Since this distance grows as the gap height increases, the greatest rate of pressure increase occurs at the smallest τ/L ratio.

5.2.1.2 Comparison with published studies

The variation of the static pressure along the endwall in compressor and turbine tip gaps has been investigated by various authors, and resembles that in the present experiment. Separation bubbles have been found in these gaps and the general trends in the pressure are similar in all cases: the pressure decreases in the first part of the gap, reaches a minimum, and increases thereafter to a constant value. The measurements by Storer & Barton (1991) on the endwall

within the clearance space of a compressor blade tip and those by Heyes et al. (1991) in the clearance space of an axial turbine cascade both indicate a fairly sharp decrease of the static pressure up to about 1.5 clearance heights into the gap followed by a slower increase towards the exit. The endwall minimum pressure occurs slightly further downstream than in both the present experiment and that of the turbine cascade flow by Moore & Tilton (1988). Moore & Tilton measured the minimum pressure on the endwall at 1.3 tip gap heights into the gap while the present data shows this occurrence at 1.1 tip gap heights. Moore & Tilton attributed the subsequent rise of the endwall static pressure to flow mixing in the tip gap, from the point where the bubble reaches its maximum height to the exit.

5.2.2 Static pressure on tip wall

The flow on the surface below the separation bubble shows more three-dimensionality than that on the endwall. The upstream transverse row of static taps is located a short distance downstream of the reattachment line, in the reverse-flow region. As the clearance gap height increases, the reattachment line moves further downstream, becoming increasingly closer to, but not reaching, the first transverse row of taps. This is apparent in the measurements of Figure 5.6 which show a greater variation across the span in the larger clearance gaps, but a symmetry about the streamwise centerline all the same. The reattachment region also moves downstream as the clearance gap height increases. In the smallest gap, $\tau/L = 19\%$, reattachment occurs well ahead of the downstream row of transverse taps, but as of $\tau/L = 31\%$, the taps are within the reattachment region, and in the largest gap, they are fully immersed in the separation bubble. The variation in the static pressure coefficient across the span is quite large at all clearances, up to a maximum of ± 0.08 , indicating high three-dimensionality even downstream of reattachment. As was the case further upstream, the flow in this region is symmetric about the streamwise centerline.

Figure 5.7 shows the static pressure variation in the streamwise direction, along the centerline, on the surface below the separation bubble. The location of the reattachment and the reattachment lines are indicated by upward and downward pointing arrows respectively. As on the endwall, the trends are similar at all clearances, and measurements done at a gap Reynolds

number of 150000 in the smallest gap, again indicated no Reynolds number influence on the flow. The measurements shown in the figure were done at a gap Reynolds number of 250000. A favorable pressure gradient exists in the upstream section of the gap, encouraging forward flow from the inlet to the reseparation line. Downstream of reseparation, the static pressure decreases to a minimum value within a short distance, before increasing sharply and eventually levelling off. The adverse pressure gradient extends throughout the reverse-flow region and the static pressure does not start to level off until well past the reattachment region. Comparing the values of static pressure on the surface below the separation bubble to those on the endwall, it is apparent that flow curvature is present in the gap. The higher pressure occurs on the endwall, indicating that the streamlines curve towards the surface below the bubble, as expected.

Figure 5.6 Static pressure variation on tip wall, in the transverse direction: open symbols for upstream row, solid symbols for downstream row.

5.2.2.1 Effect of τ/L on the static pressure on the tip wall

The magnitude of the pressure coefficient at the inlet is smaller in the larger gaps, indicating a smaller static pressure difference across the gap, as shown in Figure 5.7. Similarly to the flow along the endwall, the minimum value of the pressure coefficient occurs further downstream in the larger gaps. This is undoubtedly linked with the downstream motion of the reattachment line as the gap height increases. As well, the rate of increase of the static pressure is lower in the gaps with larger τ/L ratios. The difference between the minimum pressure coefficient and that at reattachment, is constant at 0.61 ± 0.02 for all clearances; however, the streamwise distance between these two points increases as the gap grows, leading to a lower rate of pressure rise in the larger gaps. The static pressure continues to rise as the flow mixes out past the reattachment region, and eventually levels off to a constant value. In the larger gaps, the pressure coefficient does not reach a constant value before the exit, thereby suggesting that the mixing was incomplete. The static pressure coefficient at the gap exit is greater for larger clearance heights, as was the case at the inlet.

At $\tau/L = 81\%$, the flow remains separated throughout the clearance gap. Moving downstream from the inlet, the pressure below the separated shear layer decreases to a minimum value before increasing gradually towards the gap exit. Tuft flow visualization has shown that reverse flow exists in the separated region. As the reverse flow mixes with the forward flow above it, the magnitude of the velocity in the reverse-flow region will tend to be reduced. This is believed to be one factor responsible for the rise in static pressure below the separated region. Another, is that the flow curvature likely decreases with downstream distance, and the pressure on the surface below the separated region rises towards the one present on the endwall.

5.2.2.2 Correlation of wall static pressure measurements

The static pressure on the surface to which the flow reattaches collapses on a single line for all clearances, when plotted using the Roshko & Lau coordinates defined in Chapter 2. Briefly, Roshko & Lau (1965) proposed to plot the pressure coefficient, $\bar{C}_p$, defined as:

$$\bar{C}_p = \frac{C_p - C_{p_{\text{min}}}}{1 - C_{p_{\text{min}}}},$$

Figure 5.7 Static pressure variation on the tip wall, in the streamwise direction:
up and down arrows indicate reattachment and reseparation respectively.

versus the streamwise distance, x , normalized by the reattachment length, x_r , defined as the distance between the separation and reattachment points. Figure 5.8 compares the data from the present experiment, to those from published studies. Ironically, apart from the data of Roshko & Lau (1965), all other data collapse perfectly with the present one up to about 1.2 reattachment lengths. This discrepancy is believed to be due to the use, by Roshko & Lau, of the pressure coefficient at separation, rather than the minimum value, in the calculation of $\hat{C}_p$, as well as to an increase in precision in later studies. The pressure coefficient, $\hat{C}_p$, calculated in the different clearance gaps of this experiment, collapses along the entire distance for which measurements were taken, but, past 1.2 reattachment lengths, its value is greater than that found in published studies.

The collapse of the data in the present experiment is evidence that the coordinates defined by Roshko & Lau take into account the effect of the clearance height to length ratio on the flow inside the gap, and that the reattachment length is a basic length scale of separated reattaching flows. In fact, these coordinates take into account the influence of the geometry in general, and of the separation angle. The data measured on blunt plates fitted with different forebodies which varied the separation angle from 45° to 90° (Cherry et al. (1983), Djilali & Gartshore (1992), Hillier et al. (1983)), and on a splitter plate again preceded by either different triangular forebodies which set the separation angle at either 90° , 60° or 30° , or by a semi-elliptical forebody which gave a separation angle of 0° (Cherry et al. (1983), Ruderich & Fernholz (1986), Castro & Haque (1987)), all collapsed on a single curve when plotted in these coordinates. Ruderich & Fernholz also varied the blockage ratio in their study and found that the pressure coefficient defined by Roshko & Lau took this effect into consideration as well. Since the data in the individual studies mentioned above collapsed amongst itself, only the results from one geometry in each experiment are shown in Figure 5.8.

5.3 SEVEN-HOLE PROBE MEASUREMENTS

The seven-hole probe was traversed across the inlet and outlet planes, and at the vena

Figure 5.8 Streamwise pressure variation, streamwise along the tip wall, plotted in Roshko-Lau coordinates.

contracta, in gaps with $\tau/L = 19\%$, 31% and 43% , but only across the outlet plane at $\tau/L = 81\%$. All traverses were done on the centerline of the test section. By traversing the inlet and outlet planes of the clearance gap, it is possible to calculate the losses which occur inside the gap and determine which percentage of the total pressure loss seen at the outlet they account for. It also makes it possible to isolate which characteristics of the exit flow were developed within the gap, and which ones were already present at the inlet. The probe was also traversed along the plane of the vena contracta, since the measurements could be used to extract the contraction ratio.

The probe was traversed using step sizes between 1 and 5 mm depending on the height of the clearance gap and the desired resolution. The pressures were measured with respect to the endwall static pressure at the gap outlet, and normalized by the ideal gap dynamic pressure.

5.3.1 Description of the flow inside the clearance gap

Figure 5.9 shows the two-dimensional velocity vectors along the clearance gap at all three clearances for which traverse were made. They are plotted at each measurement station, across the three traverse planes. The flow enters the clearance gap with very little curvature near the endwall. Moving down across the inlet plane towards the sharp edge, the pitch angle of the velocity vector increases drastically as the flow separates from the corner and enters the gap. The variation of the pitch angle of the velocity vector across the gap, is plotted at each traverse plane, for each clearance, in Figure 5.10. The height from the tip wall is non-dimensionalized by the gap height in these figures. The collapse of the pitch angle curves in Figure 5.10a indicates that the influence of the flow separation across the inlet plane is similar at all tested clearances.

It is apparent in Figure 5.9 that the fluid accelerates into the vena contracta from the inlet, and decelerates towards the outlet. The flow between the endwall and the crest of the separation bubble, at the vena contracta, is largely uniform although slightly pitched away from the endwall. The velocity increases slightly at the edge of the shear layer, but this is followed by a sharp decrease further inside the shear layer, and within the separation bubble. The magnitude of the pitch angle increases abruptly in the same region, which indicates a high degree of streamline curvature. The behaviour of the flow across this plane is similar at each clearance.

a)

b)

c)

Figure 5.9 Two-dimensional velocity vectors normalized on the gap velocity:

a) $\tau / L = 19\%$, b) $\tau / L = 31\%$, c) $\tau / L = 43\%$.

Figure 5.10 a) inlet plane

Figure 5.10 b) vena contracta

c) outlet plane

Figure 5.10 Pitch angle variation across the gap, at all clearances.

At the outlet plane, the flow patterns shown in Figure 5.9 differ from one clearance gap to another. In the largest gap, the velocity vectors near the tip wall are noticeably pitched and of small magnitude while those near the endwall remained virtually unchanged, except slightly in magnitude, from their value at the vena contracta. The flow in the bottom section of the gap is in the wake of the separation bubble and contains some shear layer fluid, which explains its small magnitude and higher pitch. In the smallest gap, on the other hand, the flow is essentially parallel to the endwall across the outlet plane, except very near the tip wall where it is slightly pitched. There remains only a small core of fluid near the endwall, at the outlet plane, which proceeds at uniform velocity, while the velocity across the rest of the gap decreases continually towards the

tip wall. The shear layer fluid has spread out across the gap since the outlet plane is further from the separation bubble at this clearance, thus giving considerable length for mixing. The variation of the pitch angle across the outlet plane, for the case where the flow does not reattach inside the gap, is also included in Figure 5.10c for comparison. As in the $t/L = 43\%$ clearance, the flow near the endwall is essentially parallel to it, but the magnitude of the pitch angle increases sharply in the free shear layer which is curved towards the tip wall.

Streamwise velocity profiles are presented in Figure 5.11. Once again, the distance from the tip wall is non-dimensionalized by the gap height and the streamwise velocity by the gap velocity. At the inlet plane, the profile dips near the tip wall due to the increase in the pitchwise component of the velocity near separation. At the vena contracta, the streamwise velocity inside the separation bubble decreases at the same rate for all clearances, indicating a very similar structure in the bubble irrespective of the gap height. As well, the decrease begins at roughly the same height in the gap, thereby establishing evidence that the height of the separation bubble is a fairly constant proportion of the gap height. The data in the upper section of the gap, near the endwall, collapse onto a single curve at the outlet plane. The location at which the profiles begin to diverge is a direct indication of the extent of the mixing which has occurred in the gap.

Mixing between the low velocity fluid in the wake of the separation bubble, and the higher velocity fluid near the endwall, takes place in the clearance gap, from the vena contracta to the outlet plane. The oil flow visualization revealed that reattachment occurs further downstream in the larger gaps, and the static pressure data showed the same trend in the location of the vena contracta. Therefore, the flow in the smaller gap benefits from a longer mixing distance, which enables it to attain a more uniform velocity profile at the outlet plane, as shown in Figure 5.9.

5.3.2 Discharge coefficient and contraction ratio

The discharge coefficient is defined as the ratio of the actual mass flow rate to the ideal value at the exit of the clearance gap. The ideal mass flow rate was calculated using the gap velocity, extracted from the ideal gap dynamic pressure defined in Section 5.3, and assuming a uniform velocity profile across the exit plane. The actual mass flow rate was calculated by

Figure 5.11 a) inlet plane

Figure 5.11 b) vena contracta

c) outlet plane

Figure 5.11 Streamwise velocity profile across the gap at all clearances.

numerically integrating the velocity from the 7-hole probe measurements across the exit area. The decrease in velocity through the boundary layer on the endwall was neglected, and a uniform velocity profile was assumed for a distance of 7 mm (about 2.9 probe diameters) from both the endwall and the tip wall in these calculations. The error in the mass flow rate introduced by this assumption is less than 3%.

The contraction ratio, σ , is calculated at the vena contracta. It is defined as the area required to pass a mass flow rate at this plane equal to that measured at the exit plane, normalized by the area of the gap. It therefore gives the location of the limiting streamline, below which all fluid recirculates inside the separation bubble and, consequently, the maximum height of the bubble with respect to the gap height.

As the gap height increases with respect to its length, the contraction ratio remains constant at about 0.70, but, as shown in Table 5.2, the discharge coefficient, C_D , decreases. It is defined as the ratio of the actual to the ideal mass flow rate. The flow visualization conducted in the flume also yielded approximately 0.7 as the value of the contraction ratio, at most clearances. As mentioned in the previous section, the flow mixes out to a more uniform velocity profile at the outlet, in the smaller gaps. The increase in C_D in the smaller gaps shows that the greater uniformity of the profile results in the area average velocity being closer to the ideal value.

τ/L	C_D	σ	C'_f
0.81	0.70	N/A	0.16
0.43	0.69	0.70	0.22
0.31	0.78	0.71	0.25
0.19	0.82	0.70	0.27

Table 5.2 Variation of C_D , σ and C'_f with τ/L .

In Figure 5.12, it can be seen that the discharge coefficient decreases as τ/L increases, when the shear layer reattaches inside the gap, but when the flow remains separated through the gap, it increases to a value about equal to the contraction ratio.

Moore & Tilton (1988) presented a model of the flow in the tip gap with a vena contracta and assumed fully mixed-out conditions at the outlet. They predicted a discharge coefficient of 0.84. In the present experiment, the discharge coefficient reached a value of 0.82 in the smallest gap, but the flow had only experienced partial mixing. Since the observed trend in the discharge coefficient is to increase with mixing, it appears reasonable that it might reach or surpass a value of 0.84 at fully-mixed out conditions.

Figure 5.12 Variation of the discharge coefficient with clearance height.

5.3.3 Loss coefficient

The loss coefficient is calculated from the total pressure coefficient obtained in the reduction of the seven-hole probe data. The total pressure coefficient is defined as:

$$C_{p_{\text{total}}} = \frac{P_{\text{total}} - P_{\text{gap exit}}}{\frac{1}{2}\rho U_{\text{gap}}^2} \quad (5.2)$$

and the total pressure loss coefficient is simply $C_l = 1 - C_{p_{\text{total}}}$. The variation of the loss coefficient across the clearance gap at the vena contracta and at the outlet plane, is plotted in Figure 5.13. The loss coefficient is essentially zero across the inlet plane, outside the separated shear layer and the endwall boundary layer. This implies that all the losses which show up at the downstream planes were entirely generated within the gap. The flow in the top half of the gap, at the vena contracta, experiences no loss. Moving down into the shear layer, however, the loss coefficient increases drastically due to the decrease in velocity. The limiting streamline is within the shear layer, at $\tau/L = 0.3$, such that the fluid above it, which proceeds to the outlet, has already experienced some loss since the inlet. At the outlet plane of the smallest gap, some losses have spread out all the way to the endwall, whereas there remains a no-loss region near the endwall, in the two larger gaps. Part of the total loss at the outlet is generated from the reattachment process which is dominated by viscous effects: the free shear layer entrains fluid above it, thereby raising its energy sufficiently to enable reattachment. The loss coefficient at the outlet, from the tip wall to roughly 40% of the clearance height, decreases as the gap height increases, due to the rise in velocity in that region, caused by the increased mixture.

The mass averaged loss coefficient is used to compare the amount of losses at any given plane, between clearances. It is calculated from the loss coefficients of Figure 5.13, as follows:

$$C_l' = \frac{1}{\dot{m}} \int C_l \, d\dot{m} \quad (5.3)$$

where $\dot{m}$ is the mass flow rate across the given plane. The results are presented in Table 5.2 and

a)

b)

Figure 5.13 Loss coefficient across the gap: a) vena contracta, b) outlet plane.

show that the mass average loss coefficient at the outlet is greater in the smaller clearance gaps, where the exit velocity profile is more uniform. This was expected since mixing is an entropy generating process which increases the uniformity of the outlet velocity profile.

Heyes et al. (1991) presented a model of the tip leakage flow in linear turbine cascades in which they include the effect of mixing over the blade tip. They make the assumptions that isentropic flow occurs from the inlet up to the vena contracta, and that mass is conserved from there to the gap exit. Their results show that for a given value of the contraction coefficient, any mixing that occurs over the tip serves to increase the gap discharge coefficient, as well as the expected loss for that clearance. They also state that, in general, the amount of mixing is likely to increase as τ/l decreases, for a given cascade and tip geometry. These conclusions agree perfectly well with the ones from the present experiment.

5.4 CONCLUSIONS

The present experiment was conducted at constant Reynolds number based on the ideal gap velocity and the gap height, as the gap height to length ratio was varied. This kept the ideal mass flow rate constant throughout. As τ/l increases, this experiment shows that both the height and length of the separation bubble scale on the gap height. The increase in bubble length with respect to the gap length results in a smaller streamwise distance between the vena contracta and the exit plane, which leads to less mixing taking place in the gap, and therefore, a less uniform velocity profile at the exit. Since the uniformity of the exit velocity profile is the dominant feature of this flow, the discharge coefficient also decreases.

More pertinent to blade designers, however, is the behavior of the mass flow rate over the tip when the gap geometry is varied while the pressure difference across the gap remains constant. In their investigation into the losses present in a planar cascade of turbine blades, Yaras & Sjolander (1989) concluded that the overall losses due to the tip leakage flow scaled on the mass flow rate through the gap, and that the losses generated inside the gap were relatively unimportant

Therefore, reducing the mass flow rate over the tip is of primary importance. The two-dimensional clearance gap used in this study can be more or less considered a large scale model of a two-dimensional tip clearance space. For a set gap height and pressure difference, reducing the discharge coefficient leads to a reduction in the actual mass flow through the gap. Figure 5.10 shows that this can be achieved by decreasing the gap length, or blade thickness. On the other hand, for a constant gap length and pressure difference, the same figure shows that increasing the gap height reduces the discharge coefficient. However, the increase in the ideal mass flow due to the larger area more than offsets the reduction in the discharge coefficient, resulting in a greater actual mass flow through the gap. Therefore, it appears that gains can be achieved by either closing up the gap or thinning the blades.

The flow visualization in the flume revealed that the shear layer did not reattach when the gap formed a mildly divergent passage in the streamwise direction, as discussed in Section 3.3.3. Since Figure 5.12 shows that the value of the discharge coefficient is quite low when the shear layer remains separated, some gain may also be achieved by slightly diffusing the blade tip clearance gap, depending on the increase in the ideal mass flow which may result from a greater exit area.

CHAPTER 6

EVALUATION OF FLOW MODELS

The best parameter to characterize the flow through the tip clearance of a turbomachinery rotor, is the discharge coefficient of the gap. A lower discharge coefficient is preferable since the tip leakage losses scale on the mass flow rate through the gap. Few models of the gap flow, involving the separation bubble, exist in the literature. In the present chapter, the models put forth by Moore & Tilton (1988) and Yaras et al. (1990) will be examined in light of the present experimental results. As well, a fourth order polynomial is presented to define the exit velocity profile, given the aspect ratio of the gap, τ/l .

6.1 MODEL BY MOORE & TILTON

6.1.1 Description of model

The model of the flow in the clearance gap used by Moore & Tilton (1988) is shown in Figure 6.1. Potential flow is assumed from upstream of the test section to the vena contracta, and a control volume analysis is carried out from there to the outlet of the gap. The inlet plane of the control volume, at the vena contracta, spans the entire clearance height, and therefore includes the separation bubble. However, the flow below the limiting streamline is recirculating and does not contribute to the net mass flow rate through the control volume. Indeed, the location of the limiting streamline is determined by calculating the area required at the plane of the vena contracta to accommodate the mass flow measured at the outlet plane. The static pressure is assumed to be uniform across the area, at both the outlet plane and the vena contracta. The flow enters the control volume at the vena contracta, with a uniform velocity profile between the endwall and the limiting streamline, and mixes out to uniform conditions at the outlet plane. The uniform outlet velocity profile implies that the mixing process is complete. Total pressure losses at the outlet are considered to be generated by flow mixing in the control volume.

Figure 6.1 Model of the flow in the gap; Moore & Tilton (1988).

Moore & Tilton (1988) applied Bernoulli's equation to the flow into the gap, up to the vena contracta, and the continuity and streamwise momentum equations across the control volume. They obtained the following expression for the discharge coefficient as a function of the contraction ratio, σ :

$$C_D = \frac{\sigma}{1 - 2(\sigma - \sigma^2)^{1/2}} \quad (6.1)$$

Their experimental results yielded 0.61 for the contraction ratio, which gave a value of 0.84 to the discharge coefficient. In the case where no mixing occurs in the control volume, the discharge coefficient is equal to the contraction ratio; this arises when the shear layer does not reattach inside the gap.

6.1.2 Effect of τ/L on the discharge coefficient

In the analysis by Moore & Tilton, the aspect ratio of the gap, τ/L , has no explicit influence on the discharge coefficient. However, the results from the present experiment indicate a direct correlation between the discharge coefficient and the gap height-to-length ratio. It appears that the aspect ratio of the clearance gap affects the discharge coefficient by establishing the amount of mixing that takes place from the vena contracta to the outlet plane. A greater amount of

mixing will occur in gaps with a shorter separation bubble with respect to the gap length. Moore & Tilton present the limiting case, where the mixing is completed when the flow reaches the outlet plane.

The data from the present experiment provides a value of 0.70 for the contraction ratio, at all clearances, contrary to the value of 0.61 obtained by Moore & Tilton. Using this value in the above expression for the discharge coefficient gives $C_D = 0.92$. This ideally represents the value that the flow in this experiment would reach, if it mixed out fully in the gap.

As mentioned above, the aspect ratio of the gap establishes the amount of mixing that takes place inside the control volume. By the same token, it also influences the shape of the outlet velocity profile. In the case of incomplete mixing, the velocity profile is deficient in the wake of the separation bubble with respect to the fluid near the endwall, and therefore, the profile is non-uniform. Figure 6.2 shows a second model of the flow in the clearance gap, with the non-uniform outlet velocity profile. Figure 6.3 shows the outlet velocity profiles measured in the present experiment at $\tau/L = 19\%$, 31% and 43% . Also included are curve fits to the data using the following fourth order polynomial:

$$\frac{U}{U_{gap}} = (2\eta - 2\eta^3 + \eta^4) + \frac{\Lambda}{6}\eta^2(1-\eta)^3 - 0.10\eta^2 + \frac{20-\eta}{60}(1-\eta)^2 \quad (6.2)$$

where $\eta = z/\tau$ and Λ is a constant.

Figure 6.2 Model of the flow in the gap; non-uniform velocity profile.

Figure 6.3 Comparison of experimental outlet velocity profiles and profiles calculated from equations 6.2 and 6.3.

The Polhausen polynomial, which describes profiles of laminar boundary layers, provided the starting point for the above polynomial. It was used solely for its geometric characteristics, with the edge velocity being replaced by the ideal gap velocity in the present case. The final expression was determined through trial and error. Similarly to the Polhausen polynomial, the profile is manipulated through the use of a single parameter, Λ . Equation 6.3 gives Λ as a function of the aspect ratio of the clearance gap, determined through curve-fitting the experimental data, as shown in Figure 6.4.

$$\Lambda = -30 + 55(\tau/L) + 139(\tau/L)^2 \quad (6.3)$$

The uniform outlet velocity profile used in the continuity and momentum equations, for the control volume analysis by Moore & Tilton, was replaced with the profile described by equation 6.2. An expression for the discharge coefficient was derived with these new results, following the procedure outlined by Moore & Tilton with the model shown in Figure 6.2. This gave C_D as a function of the contraction ratio, σ , and Λ , as presented in equation 6.4.

$$C_D = \frac{\sigma}{\left[1 + 2 \frac{P_{\min} - P_r}{\rho U_{\max}^2} \right]^{\frac{1}{2}}} \quad (6.4)$$

where

$$\frac{P_{\min} - P_r}{\rho U_{\max}^2} = \frac{\sigma^2}{(0.78 - \Lambda/360)^2} \left[0.64 - 0.0025\Lambda + \frac{41\Lambda^2}{118800} \right] - \sigma.$$

The discharge coefficient, given by equation 6.4, was calculated for each clearance using both the contraction ratio suggested by Moore & Tilton, 0.61, and that found in the present experiment, 0.70. As shown in Table 6.1, the discharge coefficient is overpredicted with respect to the experimental values, at all clearances, with either value of the contraction ratio. Therefore, although the model gives the correct trend in the discharge coefficient with the aspect ratio of the gap, it appears to overestimate the losses, and thus C_D . Recall that in the case of zero mixing losses, the discharge coefficient was equal to the contraction ratio. Table 6.1 also includes

calculated values of the discharge coefficient for a gap with an aspect ratio of 0.14. This is the gap size used by Moore & Tilton, and their experimental value is used for comparison. Once again, the model overpredicted the discharge coefficient.

Figure 6.4 Λ vs τ/L , as given in equation 6.3. Points shown are experimental data.

Since the velocity defined by equation 6.2 is normalized by the ideal gap velocity, it can be simply integrated over the exit area to yield the discharge coefficient as a function of Λ .

$$C_D = \frac{\bar{U}_{exit}}{U_{gap}} = 0.7 - \frac{\Lambda}{360} \quad (6.5)$$

The results of this integration are included in the third column of Table 6.1. The discharge coefficients calculated in this manner are closest to the experimental values; however, this simply reflects the accuracy of the curve fit to the present data. Moore & Tilton conducted their study

τ/L	$C_{p_{ex}}$	$\bar{U}_{out} / U_{ref}$	$C_p (\sigma=0.70)$	$C_p (\sigma=0.61)$
0.14	0.844	0.832	0.912	0.838
0.19	0.818	0.818	0.907	0.834
0.31	0.779	0.777	0.880	0.813
0.43	0.686	0.724	0.823	0.767

Table 6.1 Comparison of experimental and calculated discharge coefficients.

in a blade tip gap with an aspect ratio of about 0.14. The discharge coefficient evaluated from equations 6.3 and 6.5 is quite close to their experimental value, the difference being only 1.4%. Therefore, it appears that these equations may not be limited to the present geometry.

As the outlet velocity profile becomes less uniform, the agreement between the experimental and calculated discharge coefficient worsens, reaching a 5.2% difference in the largest gap. The range of applicability of equation 6.3 is $0.11 \leq \tau/L \leq 0.43$, as determined by visual inspection of the velocity profile shape given by equation 6.2. A few profiles are drawn in Figure 6.5 for illustration purposes. For gap aspect ratios smaller than 0.11, the profile shape indicates an initial decrease in the velocity with distance from the endwall, followed by an increase near the tip wall, which is not a proper reflection of the real gap flow. In gaps with $\tau/L > 0.43$, the velocity becomes negative near the tip wall, indicating the presence of separated flow.

6.2 MODEL BY YARAS AND SJOLANDER

6.2.1 Description of model

The model by Yaras & Sjolander (1992) is an improved version of the one developed by Yaras et al. (1990) for the flow in the tip clearance of a turbine blade. It is essentially a two-dimensional model based on kinetic energy, as previously described in Chapter 2. A more complete description will be presented here, along with the modifications by Yaras & Sjolander

Figure 6.5 Outlet velocity profiles from equations 6.2 and 6.3.

Figure 6.6 Gap flow model from Yaras et al. (1989)

(1992), and the results are compared to the ones from the present experiment. Figure 6.6 shows the flow over the blade tip at a certain chordwise position, as used in the gap flow model. The assumptions made in developing this model will be discussed in turn. First, all the fluid entering the gap is assumed to be at the undisturbed free stream total pressure. The total pressure measurements made across the inlet plane in the present experiment validate this assumption, at least in the case of two-dimensional clearance gaps. Second, the tangential velocity of the fluid before it is accelerated into the gap, at point A in Figure 6.6, is assumed to be given by the pressure side static pressure as:

$$V_T = \left[\frac{2}{\rho} (P_o - P_{ps}) \right]^{1/2}$$

It is also assumed that V_T remains constant as the flow crosses over the tip, since the pressure gradient parallel to the blade mean line, or approximately the chord line, is small. Therefore, only the normal component of the velocity vector is increased by the pressure difference driving the flow into the gap. The flow over the tip can then be considered two-dimensional in the normal direction. Since most of the fluid experienced no loss as it passed through the gap, it is assumed

that the velocity normal to the chord can be calculated from Bernoulli's equation, using the blade midspan pressure difference at the chordwise position being considered:

$$V_N = \left[\frac{2}{\rho} (P_{ps} - P_{ss}) \right]^{\frac{1}{2}}$$

This pressure distribution is essentially that which would occur on the blade tip profile in the absence of clearance. It is also the pressure difference experienced by the fluid near the endwall, where most of the leakage mass flow occurs. The ideal mass flow rate is evaluated by considering that V_N is uniform over the gap height, and integrating $\rho \tau V_N$ along the chord. The gap discharge coefficient is calculated to match the measured total mass flow rate.

6.2.2 Comparison of results

The measurements by Yaras et al. (1989) were done at three clearances. Although the tip gap height to length ratios were not identical to the ones used in the present experiment, the values are close enough to allow a comparison of the discharge coefficients. The data is presented in Table 6.2. The first column contains the discharge coefficient measured in the present experiment. The second column lists C_D taken from Yaras & Sjolander (1992). The values are larger than those quoted by Yaras et al., because the discharge coefficients in the earlier paper applied to mass flow rates calculated from the component of velocity normal to the blade mean line; they were recalculated in the later paper using the component of velocity normal to the chord line, to be consistent with the model. The discharge coefficients predicted by equations 6.3 and 6.5 are given in the third column, while the fourth column holds C_D given by equation 6.4, using $\sigma = 0.70$.

It can be seen that, as in the present experiment, the discharge coefficient calculated by Yaras & Sjolander decreases as the aspect ratio of the gap increases. This trend is also correctly reflected by equations 6.4 and 6.5. However, the data by Yaras & Sjolander shows C_D decreasing to a minimum value before increasing again. They attributed this behaviour to the size of the separation bubble with respect to the gap. Total pressure plots of their experimental data indicated that the bubble filled a larger spanwise fraction of the gap as the clearance was increased, thereby essentially blocking the inlet to the gap. Contrary to this observation, the present data indicates

a constant contraction ratio as the gap height increases, but a continuous increase in the bubble length. This behaviour is reflected in the continuous decrease of the discharge coefficient which is not attributed to a blocking effect of the separation bubble at the inlet, but rather to incomplete mixing in the downstream portion of the clearance space. However, the increase in the discharge coefficient for the largest gap used by Yaras et al., is within the 10% uncertainty in the measured mass flow rates, given by these authors, and may therefore not be genuine.

τ/L	$C_{D_{eq}}$	C_D	$C_D (eq. 6.5)$	$C_D (eq. 6.4)$
0.19	0.818			
0.20		0.878	0.815	0.901
0.29		0.718	0.784	0.882
0.31	0.779			
0.43	0.686			
0.51		0.736	N/A	N/A

Table 6.2 Comparison of discharge coefficients.

The discharge coefficients calculated by Yaras & Sjolander (1992) are similar to the ones measured in the present two-dimensional gap, although the decrease in C_D as τ/L increases from 0.2 to 0.3, is much sharper. In the smallest gap, C_D is about 7% larger than the present value, whereas it is about 8% smaller than the present value in the gap with $\tau/L = 0.3$. A direct comparison cannot be made with the data from the largest gap used by Yaras et al., since a gap of similar dimensions was not used in the present study. Nevertheless, it appears that the discharge coefficient calculated by Yaras & Sjolander, at this aspect ratio, would be greater than the one expected from the present trend in the experimental data. These differences are undoubtedly linked to the three-dimensionality of the flow in the cascade of turbine blades studied by Yaras & Sjolander.

Overall, the discharge coefficients predicted by equation 6.5 are closer to the value calculated by Yaras & Sjolander than those predicted by equation 6.4. The difference in discharge coefficients is less than 10% for both $\tau/L = 0.20$ and 0.29 . No values of C_D are predicted for the largest gap, since it is outside the range of applicability of equation 6.3. The closeness of the results further recommends the use of equation 6.5 to estimate the discharge coefficient in actual tip gap flows.

6.3 CONCLUSIONS

The gap flow models presented by Moore & Tilton (1988) and Yaras & Sjolander (1992) have been examined in the light of the present measurements made in a two-dimensional clearance gap. The model by Yaras et al. (1990) was developed primarily to predict the mass flow rate distribution in the gap, along the chord, as well as to predict the magnitude and direction of the resultant velocity vectors. The discharge coefficient was evaluated to match the measured total mass flow rate, and is not actually predicted by the model. Nonetheless, the values of C_D suggested by the measurements of Yaras et al. are only slightly different from those calculated from the present data. This may be the result of neglecting the losses generated in the gap by applying Bernoulli's equation across the blade tip, as well as to the three-dimensionality of the tip gap flow.

The model developed by Moore & Tilton was independent of clearance size and assumed complete mixing at the outlet of the gap. The discharge coefficient predicted by this model represents a maximum value. The model was expanded to include incomplete mixing to a non-uniform velocity profile. In all cases, C_D was overpredicted compared to the experimental value, suggesting that this model overestimates the losses generated in the clearance gap.

Simple integration of the polynomial describing the outlet velocity profile over the area, as shown by equation 6.5, together with equation 6.3, yields values of the discharge coefficient that are very close to the experimental values. However, this simply reflects the accuracy of the curve fit to the present data. Nevertheless, these equations were applied to the geometry used by Moore & Tilton, and predicted the discharge coefficient to within 1.4% of the experimental value. As

well, this method yielded values which matched the discharge coefficients calculated by Yaras et al., in two of their clearance gaps, to within 10%. This suggests that equations 6.3 and 6.5 can provide reasonable estimates of the discharge coefficients in actual tip gaps, although a greater number of comparisons are required to assess the applicability of this method.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The present experiment has examined some of the factors that control the reattachment of a separated shear layer in a clearance gap, thus forming a two-dimensional separation bubble. The study began with flow visualization conducted in a flume. More precise measurements were then obtained by repeating the experiment in a wind tunnel. Finally, existing models for this flow were evaluated in light of this experimental data. The main conclusions drawn from this study are described below.

The flow visualization in the flume indicated that the proximity of the endwall to the surface on which the bubble was formed greatly influenced the average streamwise and transverse dimensions of the bubble. The separation bubble appeared to grow in both these directions as the gap height to length ratio increased. A certain amount of unsteadiness in the reattachment location was also noted throughout this study. At times, the bubble seemed to grow to values much greater than the average, in both directions, before bursting. The free shear layer would then quickly reattach forming a small bubble which swiftly grew to its average size. Evidence of such unsteadiness has also been found in the literature, where it was attributed to the presence of vortices in the shear layer, and to an accumulation of vorticity within the bubble. It was also conjectured to indicate a feedback of disturbances from the reattaching zone to the shear layer near the separation line.

The effects of creating a slightly diffusing clearance gap, 7.5° and 15° , as opposed to one with a constant cross-sectional area, were briefly investigated in the flume. This variation in the geometry resulted in the flow remaining separated throughout the gap. Increases in the inlet gap

decrease was noted in the ratio of the average height of the separated region to the inlet gap height. Furthermore, there did not appear to be any Reynolds number influence on the transverse extent of the separated fluid, and flow mixing between the separated fluid and that on the other side of the shear layer was minimal. The divergent gap was not examined in the wind tunnel because of lack of time.

The quantitative data from the experiment in the air flow channel revealed that the height of the separation bubble remains a constant proportion of the gap height with increases in the aspect ratio of the gap. The visualization conducted in the flume had also generally indicated this behavior. Both studies yielded values of the bubble height to the clearance height ratio near 0.30. On the other hand, the qualitative data from the flume showed the ratio of the bubble length to the gap height decreasing with increases in τ/L , whereas the data from the air flow experiment indicated that this ratio remained constant. The discrepancy is undoubtedly due to the difficulty in defining a reattachment point for the flow in the flume. Nevertheless, both studies show the bubble length increasing with respect to the gap length as τ/L increases, resulting in a smaller streamwise distance between the vena contracta and the exit plane. This leads to less mixing taking place in the gap, downstream of the vena contracta, and therefore, a less uniform velocity profile at the exit. The results from the air flow experiment showed that the uniformity of the exit profile is the dominant feature of this flow; therefore, the discharge coefficient is lower in the larger clearance gaps, where less mixing occurs.

The clearance gap in this experiment can more or less be considered a large scale model of a two-dimensional tip clearance space. For this reason, the trend in the discharge coefficient with the aspect ratio of the gap is believed have some application to the flow in tip gaps. The losses due to the tip leakage flow in a planar cascade of turbine blades scale on the mass flow rate through the gap (Yaras & Sjolander, 1989). Therefore, gains can be achieved by reducing the discharge coefficient of the tip gap. The present results indicate that this might be done by either closing up the gap or thinning the blades. As well, the discharge coefficient is quite low when the shear layer remains separated through the gap. This behaviour was observed in the largest clearance gap used in the air flow channel, as well as in the mildly divergent gaps used in the flume. Since increases in the inlet gap height lead to larger mass flow rates in the tip clearance,

the results suggest that some gain may be achieved by slightly diffusing the clearance gap, depending on the increase in the ideal mass flow which may result from a greater exit area.

The model proposed by Moore & Tilton (1988) for the flow through a two-dimensional gap with a leading edge separation bubble was examined in light of the present data. The model assumed complete mixing at the outlet of the gap, and was independent of clearance. It was therefore expanded to include incomplete mixing at the outlet, by substituting non-uniform exit velocity profiles. This procedure took the aspect ratio of the gap into account, since the shape of the profile is a function of the gap size. It was found that this model overpredicted the discharge coefficient compared to the experimental value, which suggested that the losses generated in the clearance gap were overestimated. However, it was also found that an expression for the discharge coefficient could be generated by integrating the velocity profiles over the exit area. The discharge coefficients calculated in this manner closely matched those from the present experiment, as well as that obtained by Moore & Tilton in their study. Further comparisons were made with the discharge coefficients calculated by Yaras & Sjolander (1992), and the predicted values were within 10% of the experimental ones. This discrepancy was expected due to the three-dimensionality of the flow in the Yaras-Sjolander cascade of turbine blades. However, the results suggest that the prediction model for C_D , developed in the present two-dimensional clearance space, can provide reasonable estimates of the discharge coefficient in actual tip gaps.

7.2 RECOMMENDATIONS FOR FUTURE WORK

As noted in the introduction, the purpose of this research was to identify some of the factors which influence the occurrence and size of the separation bubble, the longer term goal being to control the bubble found in the tip gap of turbomachine stages. More specifically, the influence of the proximity of the endwall to the tip wall, on the separation bubble, needed to be documented. This has been achieved in the present work, but several of the factors affecting the bubble, which have been uncovered during the course of this research, require further investigation.

This work showed that increasing the height-to-length ratio of the gap caused the bubble to lengthen until the free shear layer no longer reattached to the surface inside the gap. However, as this ratio continued to grow, the shear layer eventually began to reattach inside the gap once more. This may be related to the reduction in the frontal area of the rectangular body normal to the flow. A boundary layer grows along this surface, and forms a very small separation bubble at the leading edge of the clearance gap. The possible influence of this boundary layer on the characteristics of the free shear layer at separation, as well as other mechanisms which could conceivably cause the free shear layer to reattach in the gaps with very large height-to-length ratios, remain to be investigated.

It would also be of interest to obtain quantitative measurements in a slightly divergent clearance gap, in order to calculate the discharge coefficient and determine if this geometry leads to a decrease in the gap mass flow rate. Furthermore, the three-dimensional effects of cross-flows on the separation bubble needs to be documented, since this experiment was conducted in an essentially two-dimensional flow. This flow was also incompressible and, as mentioned in Chapter 2, it has been suggested by other authors that compressibility effects may be important in determining where or whether reattachment occurs. This area definitely requires greater research, especially if the results are to be applied to real turbomachinery flows in which the turbine rotor blades operate with large pressure ratios across the tip gap, which can lead to regions of supersonic flow in the clearance gap.

As also mentioned in the introduction, once the factors which control the separation bubble have been identified, the next step is to attempt to manipulate the bubble. Work in this area could include changes in the geometry of the clearance gap to attempt to either promote or inhibit reattachment of the free shear layer. Further research could also include an injection in the clearance gap.

Finally, additional research is needed to develop a more general model to predict the discharge coefficient of the flow in the clearance gap. The equations presented in Chapter 6 could be further developed to increase their range of applicability, although this would entail a greater number of comparisons to be made with data from several other experiments.

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APPENDIX

APPENDIX A

The PASCAL program by Whitehouse (1993) and Yaras (1990) was written for data acquisition using a three-hole probe. A few procedures were therefore added to the TRAVERSE unit in order to perform measurements with a seven-hole probe. As well, a few other procedures were added to the same unit for the static tap measurements.

The Reynolds number in this experiment was based on the clearance gap height. Since this quantity varied throughout the study, a menu option was added to set the characteristic length in the Reynolds number.

A copy of the full program can be found in Whitehouse (1993); therefore, only the units which have been modified are included in this Appendix.

[illegible]


```

-----
  Procedures for traveling with a
  seven-hole probe
  BY
  Nicholas Hahn
  -----
  These procedures dealing with the
  reduction program shipfile are
  written by M. I. Yaras
  -----

```

```

procedure Pr-RedFileOverUp;  Over up the
                             file to be input in the PHH reduction
                             program
var YorN: boolean;

```

```

begin
  if PreRedFileName = '' then
    OutFileMenu Pr-RedFileName;
  if FileExists Pr-RedFileName then
    begin
      WriteLn(PreRedFileName, ' already
      exists. ');
      Write ' Over write file (Y/N) = ';
      bcdMenu YorN;
      if not YorN then
        OutFileMenu Pr-RedFileName;
      end;
      Assign Pr-RedFile, Pr-RedFileName;
      Rewrite Pr-RedFile;
    end;
end;

```

```

procedure DataFile InputShipvar;
  Outfiletext: Vll, Hll, Integer;
  P, Q, p, Probe_Array;
  ( Writes seven-hole probe data to an
  output file with the following format: )
  ( First line 111 V* H* Inpctr Inf
  (                Jcntr P1 Jcntr P2
  ( Second line 122 Jcntr P3 Jcntr P4
  (                Qcntr P5 Qcntr P6 Qcntr P7
  ( Third line 133 V* H* Patm Tm p1
  (                Cp2 Cp3 Cp4 Cp5 Cp6 Cp7
  var i: integer;
  begin
    RunScreen('Writing to data file');
    Write Outfile, '111 Vll, Hll,
    Hll, 3, 3, Inpctr, 3,
    InitP: 9: 3;
    for i := 1 to 2 do
      Write Outfile,
      '122 Jcntr P1 Jcntr P2
      Jcntr P3 Jcntr P4
      Jcntr P5 Jcntr P6 Jcntr P7
      Write Outfile,
      '133 V* H* Patm Tm p1
      Cp2 Cp3 Cp4 Cp5 Cp6 Cp7
      Write Outfile,
      Hll, 3, 3, Patm, 5, 3,
      Tm, 5: 3;
    for i := 1 to Probe_Holes do
      Write Outfile, '144 Y, 1, 1, 1,
      Write Outfile,
    end;
end;

```

```

procedure ShipRedDataFile/var;
  Y In File Array;

```

```

  Write the data file in the PHH
  reduction program.  The file
  is the file shipfile.  The
  file is the file shipfile.
  The file is the file shipfile.
  The file is the file shipfile.
  The file is the file shipfile.

```

```

var i: integer;

```

```

begin
  Write Pr-RedFile, '111 Vll, Hll,
  Hll, 3, 3, Inpctr, 3,
  InitP: 9: 3;
  for i := 1 to 2 do
    Write Pr-RedFile,
    '122 Jcntr P1 Jcntr P2
    Jcntr P3 Jcntr P4
    Jcntr P5 Jcntr P6 Jcntr P7
  end;
end;

```

```

pr - PHH Probe File Over Up

```

```

begin
  Write Pr-RedFile, '111 Vll, Hll,
  Hll, 3, 3, Inpctr, 3,
  InitP: 9: 3;
  for i := 1 to 2 do
    Write Pr-RedFile,
    '122 Jcntr P1 Jcntr P2
    Jcntr P3 Jcntr P4
    Jcntr P5 Jcntr P6 Jcntr P7
  end;
end;

```

```

  Write ' Data file shipfile is
  already exists.  Over write
  file (Y/N) = ';
  bcdMenu YorN;
  if not YorN then
    OutFileMenu Pr-RedFileName;
  end;
  Assign Pr-RedFile, Pr-RedFileName;
  Rewrite Pr-RedFile;
end;

```

```

var i: integer;
begin
  Write Pr-RedFile, '111 Vll, Hll,
  Hll, 3, 3, Inpctr, 3,
  InitP: 9: 3;
  for i := 1 to 2 do
    Write Pr-RedFile,
    '122 Jcntr P1 Jcntr P2
    Jcntr P3 Jcntr P4
    Jcntr P5 Jcntr P6 Jcntr P7
  end;
end;

```

```

  Write ' Data file shipfile is
  already exists.  Over write
  file (Y/N) = ';
  bcdMenu YorN;
  if not YorN then
    OutFileMenu Pr-RedFileName;
  end;
end;

```

```

pr - PHH ShipFile Over Up

```

```

  Write the data file in the PHH
  reduction program.  The file
  is the file shipfile.  The
  file is the file shipfile.
  The file is the file shipfile.
  The file is the file shipfile.
  The file is the file shipfile.

```

```

var i: integer;
begin
  Write Pr-RedFile, '111 Vll, Hll,
  Hll, 3, 3, Inpctr, 3,
  InitP: 9: 3;
  for i := 1 to 2 do
    Write Pr-RedFile,
    '122 Jcntr P1 Jcntr P2
    Jcntr P3 Jcntr P4
    Jcntr P5 Jcntr P6 Jcntr P7
  end;
end;

```

```

  Write ' Data file shipfile is
  already exists.  Over write
  file (Y/N) = ';
  bcdMenu YorN;
  if not YorN then
    OutFileMenu Pr-RedFileName;
  end;
  Assign Pr-RedFile, Pr-RedFileName;
  Rewrite Pr-RedFile;
end;

```

```

var i: integer;
begin
  Write Pr-RedFile, '111 Vll, Hll,
  Hll, 3, 3, Inpctr, 3,
  InitP: 9: 3;
  for i := 1 to 2 do
    Write Pr-RedFile,
    '122 Jcntr P1 Jcntr P2
    Jcntr P3 Jcntr P4
    Jcntr P5 Jcntr P6 Jcntr P7
  end;
end;

```


END

17-12-93

FIN