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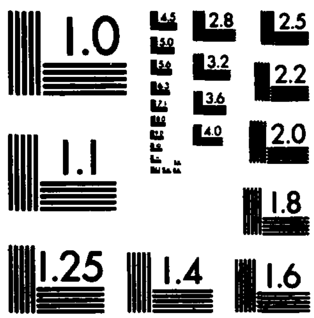
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Visualisation of the flow at the tip of

a high speed axial flow

turbine rotor

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a preliminary assessment of the expected flow phenomena

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The basic flow mechanisms are presented for leakage and boundary layer flows at the tips of axial turbine rotors. Various methods for visualization the flows near a rotating turbine tip are assessed. These include smoke injection, spark tracers, pulsed lasers and fluorescent traces. Experimental results are presented for flow visualization by seeding with fluorescent droplets.

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Contents

Summary

The previous work having relevance to the flow in the region of an unshrouded turbine rotor blade tip was examined and found that although extensive information is available on the effect of leakage flow on the loss mechanisms on the suction side of the blade, an almost complete dearth of detailed information exists on the flow structure and mechanisms in the pressure side corner and tip gap regions which are considered important with respect to blade cooling. It would seem thus both wise and essential to lay a foundation of understanding from simple models and ending with the complex full speed situation.

A logical qualitative prediction of the expected flows is presented. Apart from being complex with various zones of flow behaving almost independently from each other, the effect of upstream tangential unsymmetry (nozzle wakes) was shown to complicate the flow visualisation technique and render the normal type of continuous tracer injection of no use. Thus either an experimental rig is required which has tangentially uniform flow upstream of the rotor or a new type of pulse trace technique is needed. It is suggested that both of these requirements be adopted.

Finally, since the flow in the pressure corner is the most important from a blade cooling point of view, it is suggested that

this area should be studied first followed by the flow within the tip clearance gap.

Introduction

The complex flows in turbomachinery have been characterised, quantified and formulated with increasing sophistication and accuracy by experimentalists, analysts and designers such that the efficiency and temperature/blade life targets have been enhanced and the physics of the flows largely understood. The most recent areas to be quantified experimentally is the flow in between the blades of axial rotors using laser (Refs. 1 & 2) and rotating frame traversing gear (Ref. 3), and the increasing inclusion unsteady or wake effects. (Ref. 4).

A zone of even greater complexity is that occurring at the tip of unshrouded axial flow turbines and compressors. Here a combination of flows produced by the relative motion between endwall and blade tip* and the leakage flow generated by the blade pressure difference adds to the already intricate phenomena of horseshoe vortices, corner vortices and unsymmetrical endwall boundary layers

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* In this report the relative motion will normally be referred to as "endwall motion". This is because conceptually it will most often be easier to consider the rotor blade as stationary and the outer annulus to be moving.

seen in simple linear and annular cascades without rotation and tip clearance. The flows in these relatively simple situations have been described many times and examples are Ref. 5 for a linear cascade and Refs. 6,7 and 8 for an annular cascade. The flows are therefore relatively well understood and documented.

It will be seen that although considerable work has been done on the flow at an unshrouded rotor tip, the emphasis has been on the effect of leakage on losses. Both experimental and predictive techniques have therefore concentrated on the suction side of the blade and also at rotor exit where the loss phenomena appear and may be quantified. Indeed even in the simple cases of Refs. 5 to 8, the major discussion is of the suction side where there are more significant and interesting phenomena.

However, the incentive for this present study lies primarily in turbine blade tip cooling. The relatively thin boundary layers on the pressure side of the blade in combination with the leakage of hot mainstream flow through the clearance gap renders the blade tip a problem area. Thus the flow on the pressure side of the blade is of primary concern and this is where relatively little effort has been expended.

Because of the relatively unknown nature of the flow field, it is proposed that streamwise flow visualisation be used to establish the nature of the flow and the fluid dynamic mechanisms at work. It is suggested in Ref. 9 that flow visualisation plays an important part in revealing flow phenomena and in inspiring theories and solutions to basic problems. Quantification and validation can then follow via the hard data provided by anemometry guided by what has already been seen.

It is further proposed to carry out the visualisation in a situation as representative as possible of that in a real turbine. This is particulary in respect of blade Mach Number, fully rotating rotor blades beneath a stationary outer annulus and in the presence of the periodic effects produced by the upstream nozzle.

The above aspects will make the task difficult. Smoke trace visualisation has classically been done in simple linear cascades or among the stationary blades at low speeds such that mixing does not disperse the injected tracer aerosol particles (Ref. 10). At high speed, aerosol tracers have been used to photographically reveal streamlines where the flow turbulence has been carefully reduced. (Ref. 11). The flow in an axial turbine is highly turbulent, particularly in the tip region and rotor Mach numbers of unity are common. A lot of special difficulties arise not only from blade rotation and intense turbulent mixing but, as will be seen later, from nozzle wake generated periodicity which will place stringent requirements on the flow visualisation techniques.

In the following sections, this report will review what is known of endwall and tip clearance flows which have relevance to flow visualisation and the understanding of the operative flow mechanisms. The expected nature of the detailed flow at a turbine rotor tip will then be qualitatively deduced. This will not only provide a basis for the design and selection of the experimental turbine and flow visualisation equipment, but will provide a guide to the experimentalist in the early stages of study. Since flow visualisation must select either a streamline origin or a streamline termination as the starting point of a trace recording, it will be useful to know where the first trial locations should be attempted. The situation can be likened to the selection of a window in a tall building from which a paper dart must be launched to reach a specific location in a street below on a gusty windy night during a power failure.

In a subsequent report, the flow visualisation techniques will be reviewed and adaptations and suggestions made which relate to the turbine rotor tip situation. The conceptualisation of the experimental turbine needed will be discussed in the light of what the previous reports have shown. A recommendation will be made as to the best type of machine to build and as to how it can be used to step by step provide the knowledge of the flow structure.

Review of tip clearance flow phenomena

The literature describing the tip clearance flow mechanisms will be reviewed in this section. The dominant mechanism is the leakage of fluid through the gap due to the pressure differnece between the suction and pressure side of the rotor blade. It is well accepted, Ref. 12, that the jet of fluid emerging from the gap on the suction side of the rotor blade gives rise to a vortex above the normal secondary flow vortex and in the opposite direction. This is illustrated in Fig. 1. A zone of separated flow exists at the blade tip since the emerging leakage flow cannot follow the sharp corner.

There are relatively few studies dealing with the detailed tip flows occurring within the gap itself. In a simulated tip clearnace effect experiment with water and without endwall motion (Ref. 13), the leakage flow coefficient was measured and shown to be independent of rotor inlet boundary layer, clearance gap and crossflow. The direction of the flow in the gap confirms the indications given in Ref. 14 and is illustrated in Fig. 2.

An analytical model, which included endwall motion, was devised in Ref. 15 and streamline patterns computed for a simple flat tip blade and for various step and winglet tip shapes. A typical flow pattern, shown in Fig. 3, reveals the expected strong flow from pressure to suction side through the gap. This leakage flow in combination with the endwall motion sets up a vortex pattern in the pressure side corner similar to the normal corner vortices seen on the suction side. These vortices are said to agree with those visualised in early work done in an axial compressor (Ref. 16).

The motion of injected cooling flows have been studied in a low speed rotor using an ammonia sensitive paper attached to the rotor blade profile and tip surfaces and ammonia seeding in the injected cooling flows (Ref. 14). Figure 4 shows the limiting traces of the injected flow accross the pressure surface and tip surface. The lines indicate the expected radially outward motion of the pressure surface boundary layer, and the tip clearance flow driven towards the suction surface by the profile pressure difference.

Some attempts have been made to visualise the limiting streamlines on the endwall of axial flow compressors (Ref. 17 and 18) using either lampblack or white oil techniques. These techniques are limited in that they show only average surface phenomena and are unable to reflect any periodic or time dependant motions and nothing of any depth within a flow.

There are no known studies of the phenomena even in linear cascades with stationary walls. An understanding of the intricate flow phenomena in compressors and turbines did not emerge fully fledged and documented from a single rig fully representative of real flow phenomena. It has been built up over decades of painstaking study by many workers in many countries. Both simple and complex experiments have modelled effects, often in isolation of other phenomena, and led to the situation today, where more intricate flow detail is being sought using advanced rigs and sophisticated instrumentation. To therefore attempt to solve the high speed physics of tip clearance flows in one blow may not be feasible, the danger being that a rig is constructed which will not produce results. In the light of the present understanding of the flows and in the light of the history of turbomachinery research, it would seem far safer to build a rig or a series of rigs which could progressively achieve the desired goals. This will be discussed in a later report.

Identification of the major flow regimes at the rotor tip.

Although it has been stated that the flow patterns in the tip region have not been widely studied and are not well understood, certain inferences or predictions can be made based on simple flow patterns and on the major additional driving forces i.e. the leakage flow and the moving endwall. The aim of this preliminary analysis is to provide the soundest possible basis for the design of the experimental turbine, for the selection of the flow visualisation equipment and to guide the experimentalist in the initial stages.

The flows described should not be taken as the actual flow pattern. If this were so, no experiments would be needed. It is also expected that flow visualisation will turn up surprising results and render some of the ideas here unfounded or incomplete.

In a simple annular turbine cascade the dominant inner annulus endwall boundary layer flow patterns are shown in Figure 5 taken from Ref. 19. Apart from small scale separation patterns caused by the leading edge vortices, the most important effect is the tendency for the boundary layer to deviate from the mainstream flow direction and is skewed towards the suction surface. This pattern of skewing and separation is not expected to vary extensively on the outer annulus wall provided there is no tip clearance or endwall motion. However, Refs. 6, 8 & 19 have shown that endwall boundary layer crossflow is much stronger when the simple "real turbine" effect of relative motion between rotor and stator is modelled in the experiment. Also shown was the importance of including the axial endwall gap in the experimental model. The conclusions from the above are that the endwall boundary layer was relatively easily influenced by "real turbine" effects. It is therefore thought that when the "real" effect of endwall motion and tip clearance are included, that these effects will probably dominate completely in determining the endwall flow pattern.

If the rotor blades are considered stationary and the outer casing to be in motion, the endwall moves as shown in Figure 6 from the suction side of the blade towards the pressure side. Reference 13 has given an approximate direction of the leakage flow occurring due to the pressure difference between the pressure and the suction surface and thus is of course from the pressure side to the suction side or in the opposite direction to the endwall motion. As shown in Figure 6 therefore, the moving endwall will force a thin layer of fluid through the clearance gap above the leakage flow and in the opposite direction.

The flow in the gap is therefore subject to an intensive velocity change of the blade speed plus the peak leakage flow velocity across a distance somewhat less than the clearance gap. The flow in the clearance gap is thus a zone of intense shear and the implications of this for the proposed flow visualisation study are that:

a) any tracer on the pressure side of the blade is extremely unlikely to survive the entry into the gap without a degree of mixing that will have any meaning in what is subsequently seen,

b) the flow exiting the gap is unlikely to contain any characteristics which are heavily dependent on the parameters of the flows entering the gap.

Stated more simply, tracing a streamline through the clearance gap will be much more difficult than tracing a streamline into or out from the gap. If tracing such a streamline were possible it would show the leaving flow independent of the inlet flow and thus would reveal no more information than tracing the inlet and exit flow completely separately. It is therefore strongly recommended that no attempt be made at such cross gap visualisation until the flow into the gap is mapped and the flow out of the gap is mapped. Thus the flow visualisation techniques considered will be orientated with this philosophy in mind.

Not only does the gap shear flow seem to be a watershed for flow visualisation, but as already implied, seems to also be a dividing line between zones of flow which are distinct from each other in a radical way. In all, 4 such zones are identified and are sketched in Figure 7. These zones could also be so different in regard to location and origin of flow as to require different flow visualisation techniques. In terms of providing esential information regarding blade cooling, these zones will probably have different importance.

Flow entering the clearance gap - Zone 1

From a heat transfer point of view, Zone 1 is lilkely to be the most important. It is known that the hottest and most difficult part of the blade to cool is the rear half of the tip of the pressure surface. Zone 1 consists of the fluid approaching and entering the pressure surface clearance gap. The type of flow expected in this zone is likely to be determined firstly by the pressure surface boundary layer, which is known to be thin in comparison to the suction surface layer and to flow with a slight radially outward inclination. Secondly, due to the gap, the mainflow in this region will encounter the effect of a line of sinks and thus flow will be towards and into the gap. Some or all of the radial component of the boundary layer fluid could be swept into the gap.

Before attempting to sketch the streamline flows in Zone I it will be helpful to examine, somewhat simplistically and without the periodic effects of the stator blade boundary layers, the flow approaching the rotor leading edge taking account only of the existance of an outer annulus boundary layer. Figure 8 sketches the rotor inlet velocity diagrams for the freestream case and for an outer annulus retardation of nozzle exit velocity C_1, right down to zero on the outer endwall. The rotor incidence is seen to vary from about zero in the mainstream, to high negative values in the boundary layer where, in the limit on the surface, flow is approaching at blade speed with -90o incidence. It should be noted that there is no velocity deficit at the endwall surface. In fact the rotor inlet velocity has roughly blade speed values in the endwall layer and roughly axial velocity values in the free stream.

Since it will normally be convenient to view the rotor tip flows as though the rotor were stationary and the outer casing were moving, Figure 9 translates these rotor inlet vectors and presents them pictorially. The method chosen to present these inlet vectors is specifically chosen to be helpful to the understanding and to be as close as possible to the way the flow will be seen experimentally. This will most probably be viewed from the outside, through a transparent window. The pictorial basis for Figure 9 is therefore to consider the outer annulus wall as being a thin curved transparent sheet moving tangentially above a stationary blade. An alternative viewpoint for describing the flow is to look at the rotor from upstream and somewhere near the axis of rotation. In Figure 10 the inlet flow vectors are shown from that viewpoint.

These highly energetic rotor leading edge stagnation lines ("energetic" meaning there is no decrease of velocity in the "boundary layer") means that no horseshoe vortex will attempt to form on the outer wall. All that will happen is that the stagnation point in the endwall boundary layer will move around further and further onto the suction surface side of the profile.

In Figure 11, leading edge stagnation streamlines are shown which, after stagnation, join the thin pressure surface boundary layer and flow radially outwards to enter the clearance gap. The effect of the endwall boundary layer is that the starting point of streamlines closer to the endwall are tangentially farther away from the leading edge. This tangential distance depends upon the depth of the nozzle endwall boundary layer which varies circumferentially. Therefore the starting points of the group of streamlines will be fairly heavily time dependent.

Apart from these stagnation streamlines which touch the pressure surface, other streamlines also enter the clearance gap via the blade boundary layer. For example, if an origin slightly to the left of point 2 in figure 11 were chosen, this would identify fluid which would be slightly higher up in the blade boundary layer. There would be less radial motion and the streamline would enter gap further towards the trailing edge. There would finally be a point 2' to the left of 2 which would no longer shed a tracer into the gap. There is thus an envelope of streamline origins which send fluid into the gap via the pressure surface boundary layer. They are summarised in Figure 12.

In the above, it has been assumed that any pressure surface boundary layer fluid leaving the blade tip will be drawn into the gap via the blade pressure difference. While this seems a reasonable assumption since the layer is thin and the pressure differences are large, it may not always be so and the shear flow generated by the endwall motion may be such as to overcome the leakage flow, perhaps near the leading and trailing edges where the magnitude of the pressure differences are small. Only experimentation would show which situation were correct. If the shear flow does overcome the leakage flow then the gap velocity distribution would be as shown in Figure 13. If there are zones where the blade boundary layer does not enter the gap, some of the predictions made will be invalid and the streamlines will not enter the gap as shown in Figure 13. The envelope of Figure 12 would be reduced.

Apart from the pressure surface boundary layer fluid, Zone 1 (Figure 7) will feed "free stream" fluid into the clearance gap. Reference 13 has predicted that the fluid in this zone will have a vortex rotation due to the endwall motion. This roation will be aided by the radial movement of the blade boundary layer since it imparts the same rotational direction to the fluid. Although the fluid entering the clearance gap has been referred to as "boundary layer" it is likely that all the remainder of the critical flow entering the gap will be affected by viscous shear flow. The zone is geometrically a "corner" where there are two surfaces which enhance boundary layer growth.

The fluid in this corner zone will not only be drawn into the gap but some will be drawn into the transversely moving endwall boundary layer. Due to the vortex rotation it is not possible to say which streamline approaching the rotor from upstream will enter the gap, which would enter the boundary layer and which would pass right through to exit the rotor. Fluid which is physically closer to the gap could roatate away from the gap and enter the endwall boundary layer. Thus in Figure 14, three streamlines are shown with the same origin but which follow the 3 different paths mentioned. Also sketched is the possible envelope of upstream streamline origins which could feed fluid in any of these 3 directions.

To summarise, there appears to be a triangular shaped envelope upstream of the rotor which could feed flow into the clearance gap or which could originate streamlines of high interest. This envelope will vary depending on the nature of the boundary layer delivered by the nozzle blades. Thus unless the flow visualisation technique is locked to a specific location with respect to the stationary frame, the paths could be difficult to stabilise or to render repeatable. Figure 15 shows 2 possible envelopes, one for the thin boundary layer leaving the nozzle pressure surface corner and the other for the nozzle suction surface corner which is a high loss region with an effectively deep low velocity region including the corner vortex.

It is however normal in flow visualisation to identify a streamline via the passage of flow across a point and the continuous injection of some marker of tracer. Thus visualisation normally implies the flow to be maintained across the origin for at least enough time for the first tracer particle to reach its destination and more often for long enough to make a recording of the trail by some means. The most common practice is to inject microscopic aerosol particles (smoke) and to record the result photographically.

The periodic effects of the nozzle thus render it impossible to lock a normal flow visualisation process to a fixed point on the stationary frame since the flow is continuously varying. This is illustrated very simply in Figure 16 where the flow in a single static linear cascade of straight blades is to be visualised using a tracer origin fixed relative to the blades. This is a very simple dynamic equivalent to the rotor flow when viewed as though the blades were stationary. With the tracer origin at 1, the streamline from an invariant inlet flow draws the tracer along the path shown. If the tracer origin is moved to positions 2 and 3, the curved paths around the vanes are seen. If however, by some means, the inlet flow instead of being invariantly axial, is made to have an oscillating inlet angle as shown in part b of the figure, the result is perhaps unexpectedly different. Path 1 is the simple undulating streamline shed between the vanes where the flow direction is uninfluenced by the blade. Path 2 shows the path cut in half as the shed streamline is cast on the one side and then the other. The blade is seen to control the swing of the direction change and to cut the streamline in two. This line was conceptualised without considering the returding effects of the blade boundary layer. In reality the tracer shed into the boundary layer zones will move more slowly and will tend to elongate the trace on the left of the blade in trace 3 and to shorten it as shown as it moves and is shed on the right of the blade.

An aspect of flow periodicity which should also be pointed out is that of a changing velocity as well as angle. This could elongate segments of the simple waving trace 1 and compact other parts as shown in trace 4.

The implications of the foregoing arguments will be quite profound on flow visualisation with periodic variation of inlet flow. Figure 17(a) illustrates that any attempt to inject a continuous marker into a periodically varying flow at the point of injection will lead to a multitude of streamline destinations being seen in a time exposure. Thus blurring will occur over and above that expected from mixing. If the image is "frozen" via a high speed recordinfg (Figure 17b), then although what is seen is a single or chopped up line, the line is time dependent because it represents a row of particles each having a completely different destination and a completely different approach line than that apparently revealed by the trace.

If however a single short duration tracer were injected into the periodically varying fluid and its path tracked via a time exposure or the superposition of successive exposures, then a true particle trace or streamline will be recorded as shown in Figure 17(c).

The conclusion at this stage is therefore that unless the later review of flow visualisation techniques reveals a satisfactory pulse tracer technique, any argument to operate the test turbine with circumferentially invariant inlet flow is strongly enhanced.

Leakage flow across blade tip - Zone 2

The next most important flow identified in Figure 7 is Zone 2 or the leakage flow across the top of the blade. It has already been argued that this flow is unlikely to depend on the characteristics of the Zone 1 streamlines which form the entering flow. It is therefore not expected to reveal periodic effects except perhaps as the pressure difference across the rotor blade tip changes due to the passing of an upstream or downstream nozzle blade which causes significant profile pressure changes (Ref. 20) at the leading and trailing edge regions depending on the axial blade spacing. Thus once again, periodic effects could render the flow difficult to record and careful thought must therefore be given to axial spacing and to deliberatly include a downstream nozzle row when all the variables are to be included.

As shown in Figures 2, 4 and 6, the work of Refs. 14 & 21 show the strong pressure to suction surface flows in the gap. These flows may be radically changed as suggested in Figure 13 should at any time circumstances create a situation when the leakage flow is overcome by viscous endwall motion which is in the opposite direction. A further factor to consider is that the tip region is seldom flat and is shaped to limit the effects of rubs, to reduce leakage flows via steps and channels and to exhaust internal blade cooling flows.

Due to the narrowness of the gap and the presence of two opposing flows it will be extremely difficult to improve the suggestion as to the flow type in in Figure 6 or to measure radial variations in the gap. It is fortunately not of great importance in terms of blade cooling. Zone 1 would have identified the source of leakage fluid as well as the possible existance of zones of zero leakage. A study of Zone 2 would be far more sensitive to showing zero leakage or any other unexpected phenomena. A useful result would be to identify the chordwise variation of the two zones as shown in Figure 18 via the location of a hot wire probe on the blade tip and detecting the crossover point.

<u>Leakage flow entering the suction corner - Zone 3</u>

A description of the flow in Zone 3 has already been presented in the introduction based on Ref. 12 and described in Figure 1. This zone is likely to be extremely complex due to the existance of the leakage and secondary vortices and the separated flow region. As has already been argued there are unlikely to be any horseshoe vortices. Like Zone 1 the periodic effects are again expected to be important. In Zone 3, the periodic effects will be reflected in:

1) the varying leakage flow strength due to varying blade pressure distribution (axial spacing and downstream stator dependent)

2) the effect of the secondary flow vortex on the leakage flow vortex. The secondary vortex does depend on the inlet boundary layer and therefore on the periodic nozzle exit flow.

It has been stated that a flow visualisation tracer is unlikely to survive the passage from Zone 1 to Zone 3 due to the shear flow in clearance gap. Therefore flow visualisation traces will have to be initiated at the gap exit and progress recorded through the zone.

Flow leaving the gap could follow three general paths.

1) Join the leakage vortex and proceed to rotor exit.

2) Join the endwall shear layer and be returned back through the gap

3) Join the shear flows near the secondary vortex or near other regions and proceed to rotor exit.

Since the flow in a vortex is stable the flow in the leakage vortex may be relatively easy to trace. Figure 19(a) shows some possible streamline paths. Due to the rotation, fluid from the leading and trailing edges could be found anywhere within the vortex and not simply further away or close to the suction surface as would be the case without a vortex. At the exit of the rotor, a possible enlarged envelope is shown in which the streamlines could move due to periodic effects. Figure 19(b) shows possible paths (2 and 3) for leakage flow not involved with the leakage vortex.

Endwall shear layer - Zone 4

The fluid flow in the shear layer moving with the endwall forms Zone 4 of Figure 6. It will have a thickness significantly less than the clearance gap. In this section it will be somewhat simpler to consider the endwall to be stationary and the rotor blades to be moving. It can easily be appreciated that the shear layer will be characterised by intense crossflow and mixing caused by the passage of the blades and the accompanying intense local pressure gradient and local leakage flow movement.

Considering the stationary outer annulus wall as it is in reality, the motion of the fluid near the endwall will be influenced periodically by the following factors:

a) the stationary wall which due to viscous action will oppose any induced motion and create a velocity gradient across the layer

b) the viscous drag of the mainstream fluid which will tend to drag the layer in the direction of motion

c) the channel pressure gradient which will accelerate the fluid according to the direction of the forces

d) the pressure difference across the profile tip which will accelerate the fluid according to the direction of the forces

e) the viscous drag of the leakage flow which will tend to drag the layer in the direction of fluid motion.

In Figure 20 some blade to blade changes of the variables which control the above factors are qualitatively illustrated. Two rotor blade profiles are shown with a thick suction surface boundary layer and a thin pressure surface boundary layer. In the middle of the blade passage the free stream particle trajectory is shown with the inlet and outlet velocity diagrams (No. 1 & 7), the quantities for which are for simplicity assumed to be that for 50% reaction and axial absolute rotor exit. The magnitude of the velocites are taken from the velocity (relative) and pressure distribution diagrams on the right hand side.

Figure 20 also gives local velocity diagrams at various locations to show the lilkely variation in direction and magnitude of the absolute velocity vector which will tend to viscuously drag the endwall boundary fluid. Triangle 2, at a point just outside the suction surface boundary layer and near the leading edge where the local relative velocity reaches its peak value, shows the absolute vector to be high. On the opposite side, triangle 3 shows a lower velocity but inclined at a higher angle. Triangle 4, in the free stream near the suction side blade exit, shows the velocity to be nearly axial as at No. 7. A diagram drawn for the pressure side would be much the same.

Velocity diagram No. 5 is drawn inside the suction surface boundary layer. The low relative velocity produces a high absolute velocity at an acute angle. No other boundary layer diagrams are drawn since they will all be similar due to the comparatively small contribution made by the relative velocity to the final result.

Finally, triangle No. 6 is drawn for a point in the clearance gap where relative vector L is the pressure driven leakage velocity approximated from 2 and 4. This velocity triangle shows a high absolute velocity at a large angle.

The pressure distributions and gradients are also shown in Figure 20. The blade passage pressure gradients drop towards rotor exit as the pressure and suction surface values converge towards the trailing edge, the passage width remaining about constant. The pressure gradient across the blade surfaces will depend also on the blade thickness and thus could remain high even towards the trailing edge.

A particle of fluid in the mainstream between rotor blades will pass through the rotor following a trajectory as shown in the lower half of Figure 20. this particle transits the rotor during the passing of exactly one rotor blade pitch. This particle is thus never "passed" by a rotor blade and the trajectory is smooth. This is of course only if the particle is not in the nozzle boundary layer which could alter the situation.

The trajectory of a fluid particle within the outer wall boundary layer is quite different. Since it moves relatively slowly it will encounter the effects of a number of blade passings. If a fluid particle is considered which enters the rotor just after the passing of a rotor blade, i.e. near the pressure surface, it will be exposed to the effects of the passage pressure gradient and the free stream viscous drag. These forces are shown schematically and a resultant particle direction deduced. Under the action of the freestream fluid for a period of time, the trajectory denoted f_1 will be executed. The particle will then encounter the suction surface boundary layer and due to the viscous forces now swinging round to almost directly oppose the pressure forces, motion will change as denoted by segment b_1. When the particle is covered by the blade tip, the leakage velocity vector and pressure gradient are now in almost the same direction and thus segment l_1 is in the opposite direction to that created by the freestream and a zig zag motion has been established.

The series of actions is now repeated but since the particle has progressed axially, the magnitude of the forces are different. The free stream viscous force is less due to the overall deceleration of the absolute vector and the direction is more towards the axial. The pressure gradient is also less. Segment f_2 is thus shown to be shorter than f_1 but more nearly axial. The second boundary layer segment b_2 is shown larger than b1 since the boundary layer is wider and will influence the particle for a longer time. The next leakage segment l_2 is shown to be not as long as l1 since the pressure force is less. These varying influences will continue to act producing f_3, b3, 13 for as long as a particle remains between the leading and trailing edge of the rotor.

A trajectory will obviously depend on the point of entry into the rotor zone and on its depth in the endwall boundary layer. A particle very close to the surface will move sluggishly, the viscous forces dominating rather than the pressure and will show a much larger number of blade passings. A particle relatively high up in the boundary layer could have a much more enhanced zig zag motion but with fewer blade passings. Particles even higher up in thme endwall layer will probably be caught up in other flows such as the leakage jet or the suction corner vortex and vice versa. Thus some particles could make a few zig zags and then leave the boundary layer altogether.

The above description may only be accurate enough to show that the endwall boundary layer will be a zone of intense periodic mixing. Flow visualisation will most likely be not only difficult but also time dependent. The effects of nozzle boundary layers has not been considered at all.

As in Zone 1, the injection of a continuous tracer in the stationary frame will lead to a blurred result due to successively injected particles following conmpletely different streamlines. The injection of a continuous tracer from the rotating frame will improve the situation but will then be subject to nozzle induced periodicity and resultant spread of trajectories.

Due to the thin nature of the boundary layer, the expected difficulty in visualising the flow and the suspicion that this zone of flow will not play a major factor in blade cooling and heating, this zone should be the last to receive attention. The value of flow visualisation as opposed to flow measurements using wall mounted quick response probes should be considered.

Conclusions

The review of previous work shows that while the effects of tip clearance on suction corner losses have been widely studied and predictive methods developed, there has been a sparse effort put into the pressure side and tip clearance cavity flow zones which are important from a blade cooling point of view. The flow mechanisms are thus only a matter of intelligent conjecture. There is no work of major significance either in flow visualisation or anemometry for even a simple linear cascade, which deals with the detailed flow.

The implications of this barreness for the envisaged study to which this report is directed, is that unless the experimental turbine built is such that it will allow knowledge to be gradually built up starting with a simple case and, as understanding and experience is gained, progressing to more complex and demanding areas, the rig when switched on may throw up such a host of problems that no results are obtainable. At best, the results may not be easily interpreted without the prior understanding gleaned from simpler cases.

A logical analysis of the expected flow based on previous studies has been presented. As expected the flow is likely to be highly turbulent with a high degree of mixing and flow visualisation will be difficult. Zones of flow were identified which could require completely different approaches in basic methodology.

The zones of primary importance and which should be examined first from the point of view of blade cooling and from the point of view of the dearth of previous work, are the pressure side flow entering the gap and the flow in the tip clearance cavity.

In the first and most important zone, the pressure side tip corner flow, the effects of nozzle blade periodicity will render flow visualisation even more complex that it already is due to turbulent mixing and the rotation of the area of interest. The added difficulty arises from flow variations at the site of continuous tracer injection spreading the resulting traces over a wide area. High speed trace recording will not help significantly since the trace then seen does not represent the path of the streamlines. Thus either the experimental rig will have to be such as to have no tangential flow variations at rotor inlet or flow visualisation techniques based on the injection of a tracer pulse rather than on continuous tracer injection will have to be developed and used. As subsequent reports will show, it is believed possible to design an experimental rig which may include or exclude the tangential unsymmetry of the nozzle blades and, at least in theory, pulse trace techniques are possible. Due to the already acknowledged difficulties it is recommended that the test turbine first be used without the effects of the nozzle being present, at low speeds and with a stationary blade rather than a rotating one.

It is finally suggested that a tracer pulse method should receive attention but not to the exclusion of the more conventional continuous injection methods. A tracer pulse method could have application in both types of flow and thus the effort would not be wasted.

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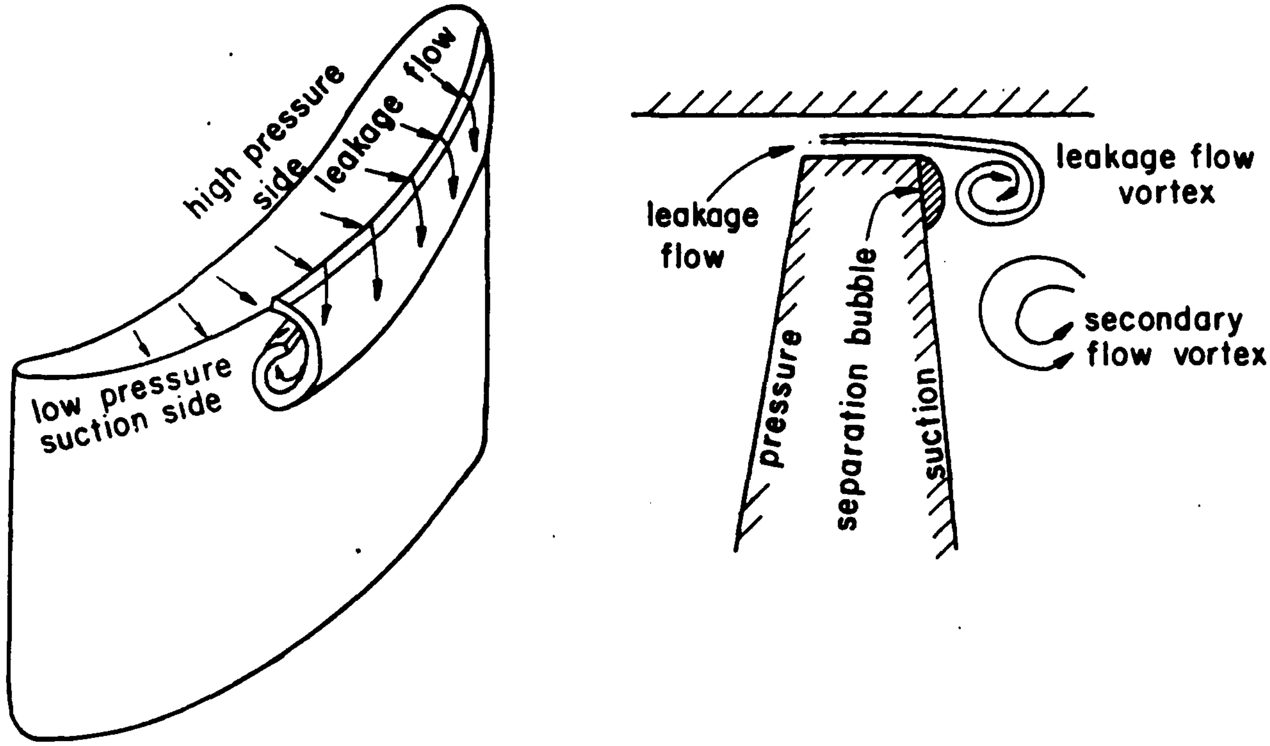


Fig. 1 Suction corner vortex caused by leakage flow.

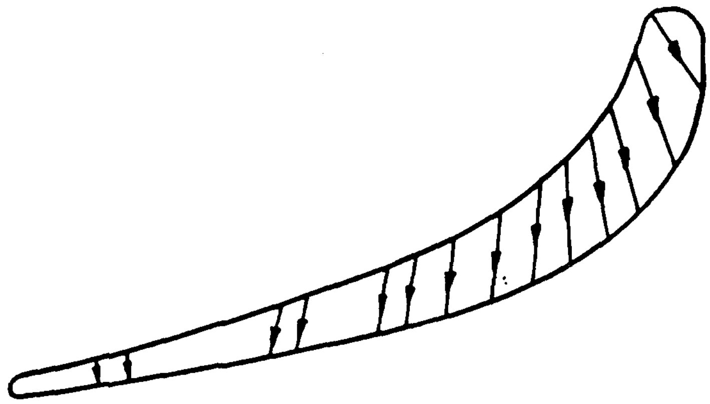


Fig. 2 Direction of leakage flow in the clearance gap at rotor tip.

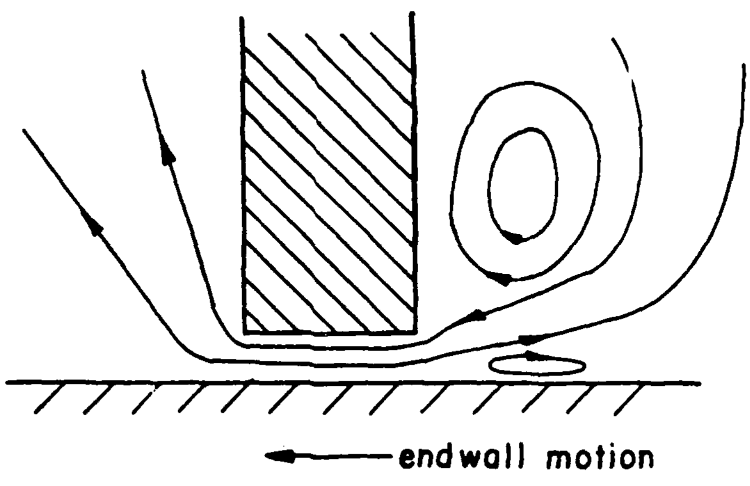


Fig. 3 Computed streamline flow at blade tip.

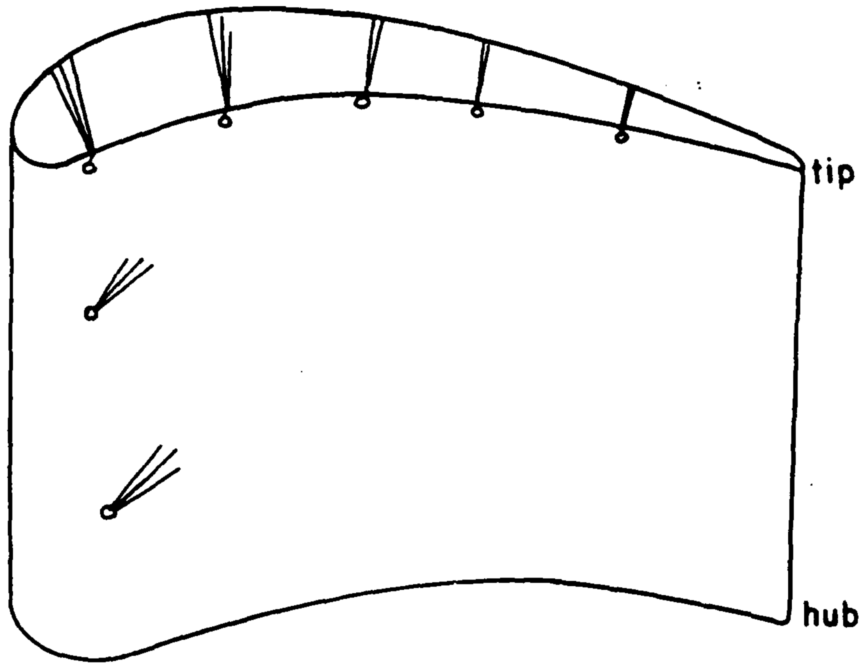


Fig 4 Cooling flow motion in the limiting streamline flow on the pressure surface and tip surface of turbine rotor

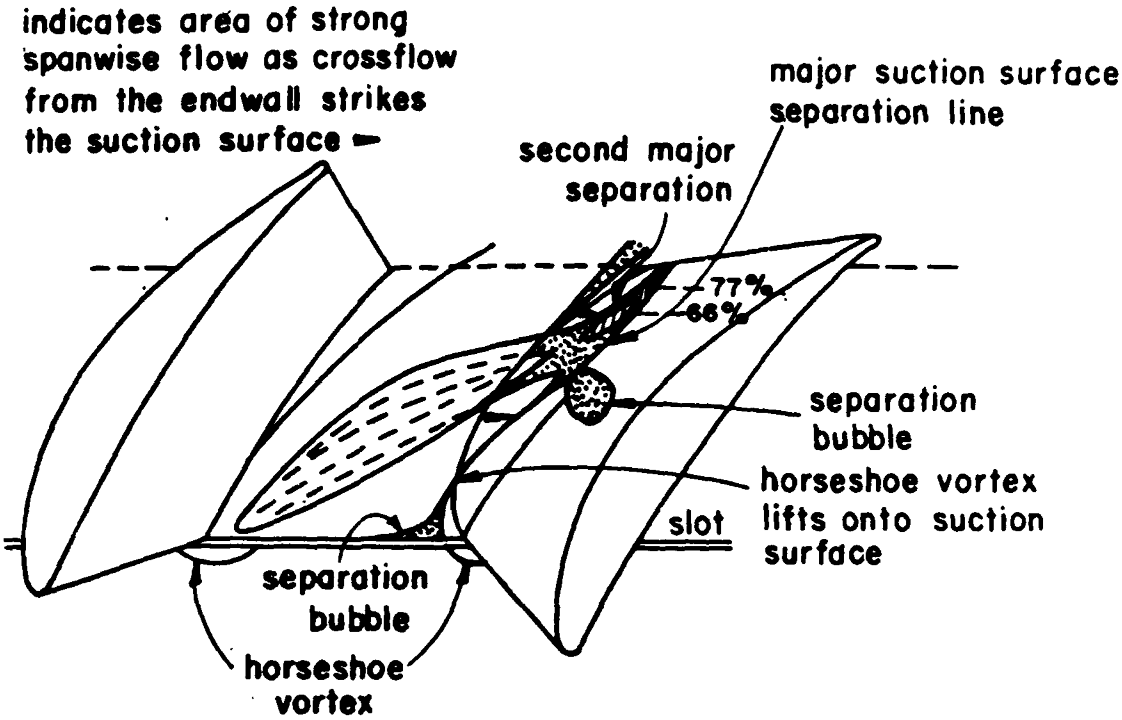


Fig. 5 Interpretation of inner annulus endwall streak lines (Ref. 19, Fig. 9)

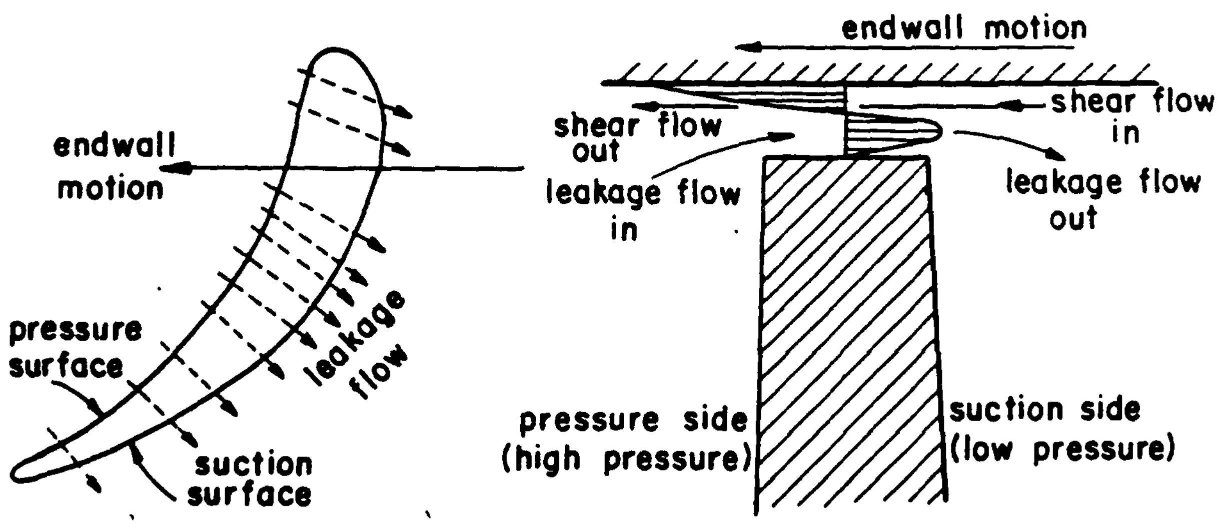


Fig. 6 Flow in rotor blade tip clearance gap

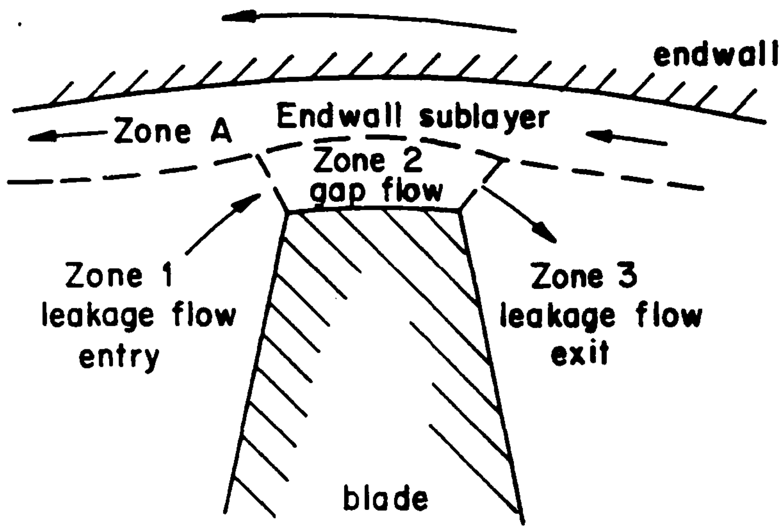


Fig. 7 Zones of flow in the tip region which are expected to be radically different and which could require different flow visualisation approaches.

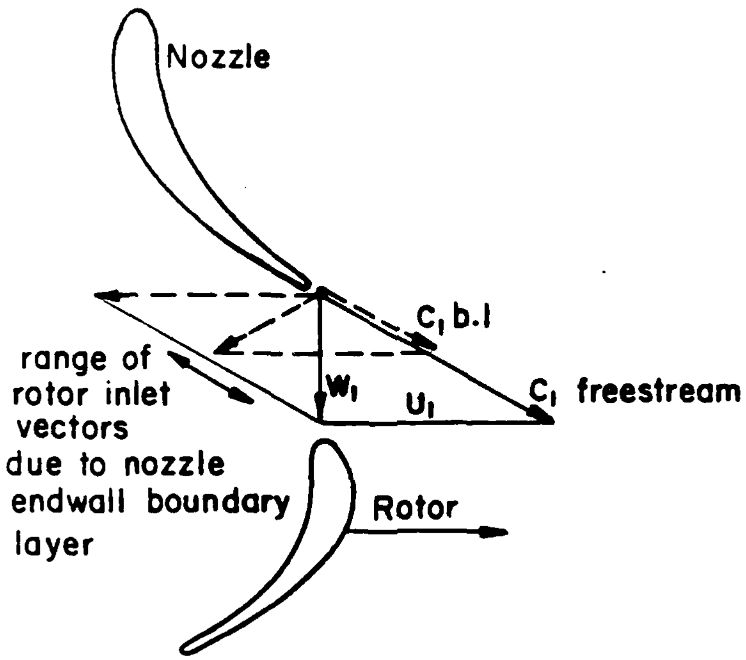


Fig. 8 Rotor inlet velocity diagrams for nozzle velocity varying from freestream value down to zero on the outer endwall surface.

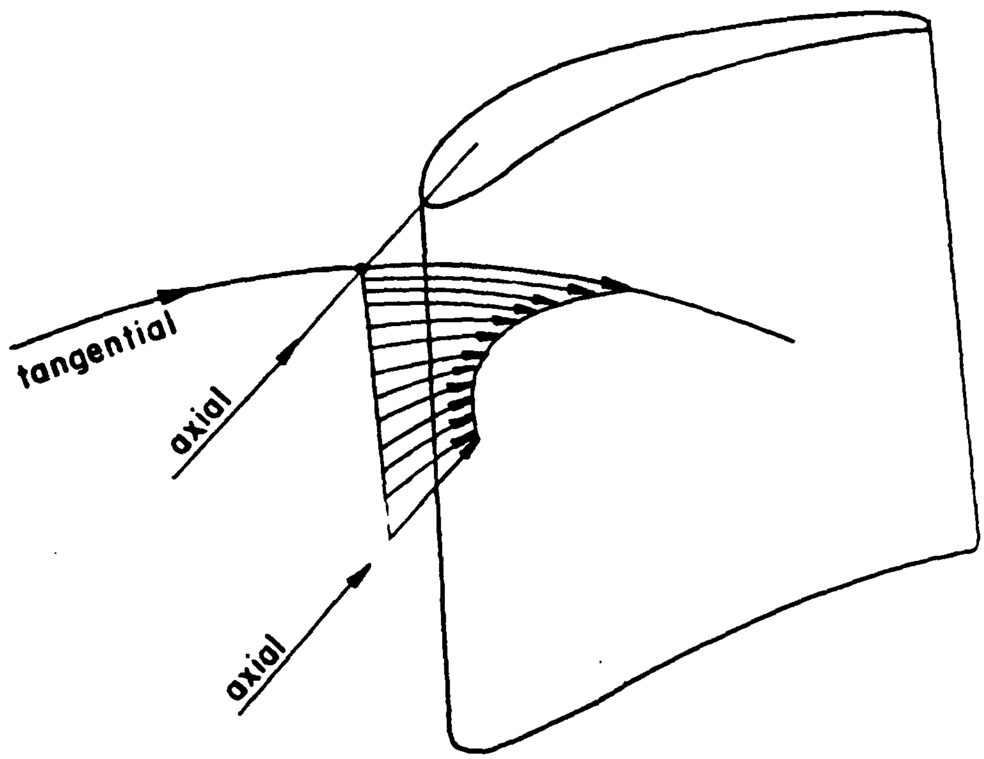


Fig. 9 Rotor inlet vectors seen as though rotor were stationary and endwall was a thin transparent window moving over the blade tip.

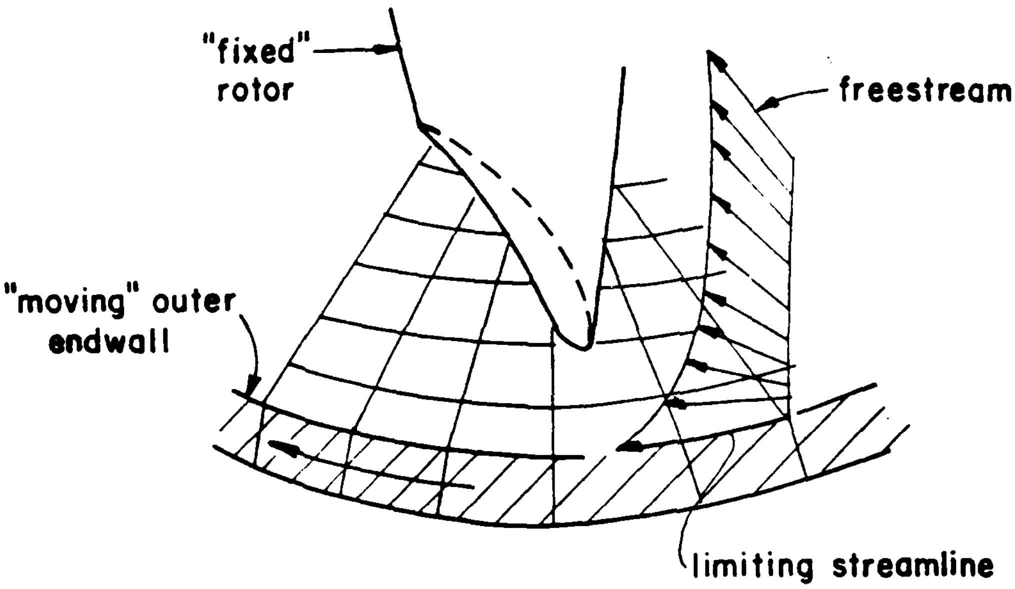


Fig. 10 Rotor inlet vectors seen as though rotor were stationary and endwall were moving at blade tip speed.

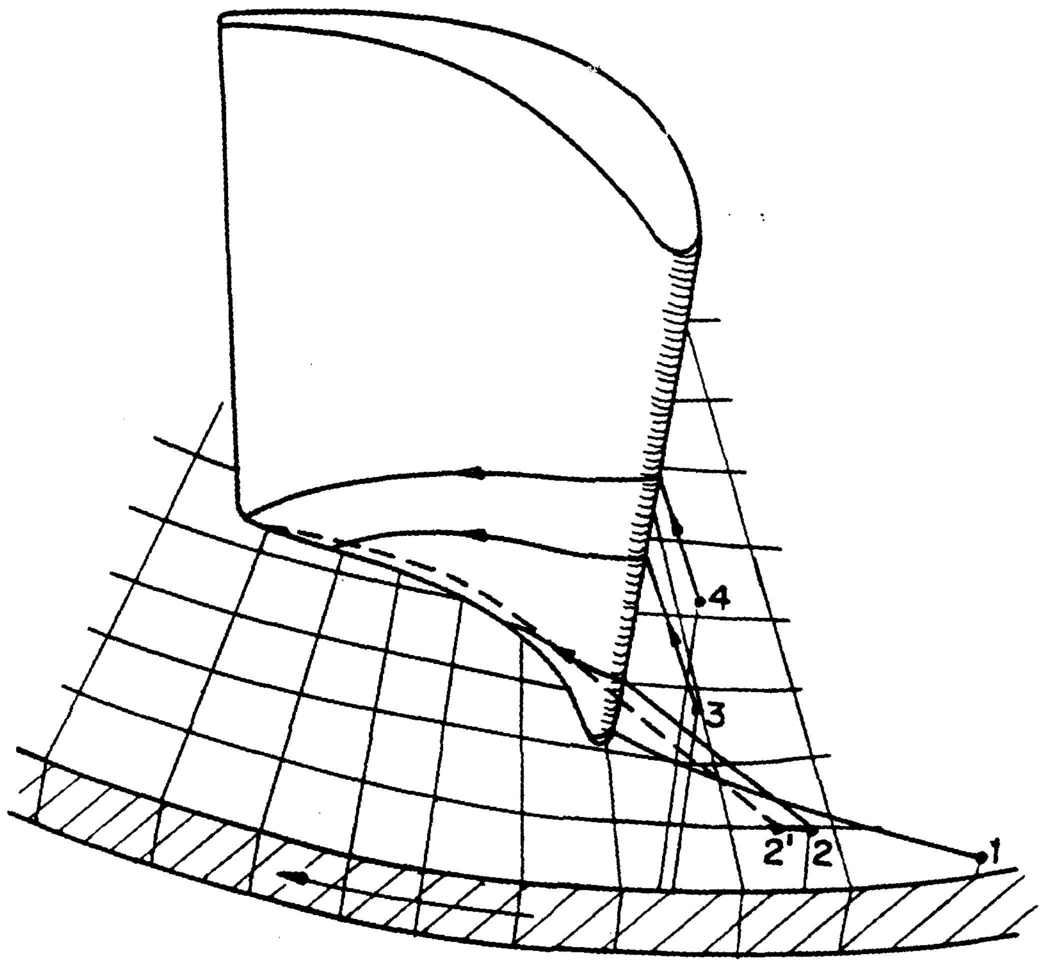


Fig. 11 Leading edge stagnation streamlines which enter the pressure surface boundary layer and, via that path, enter the clearance gap.

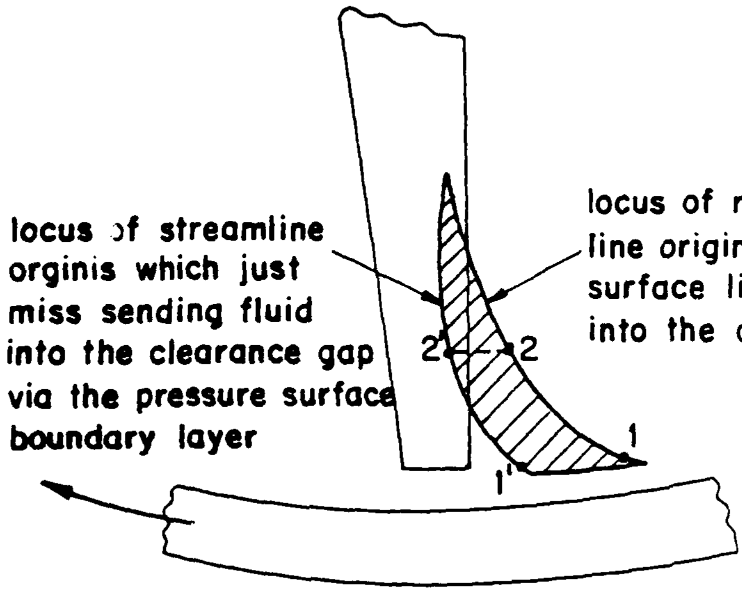


Fig. 12 Envelope of streamline origins upstream of a rotor blade which send fluid into the clearance gap via the radially outwardly migrating pressure surface boundary layer.

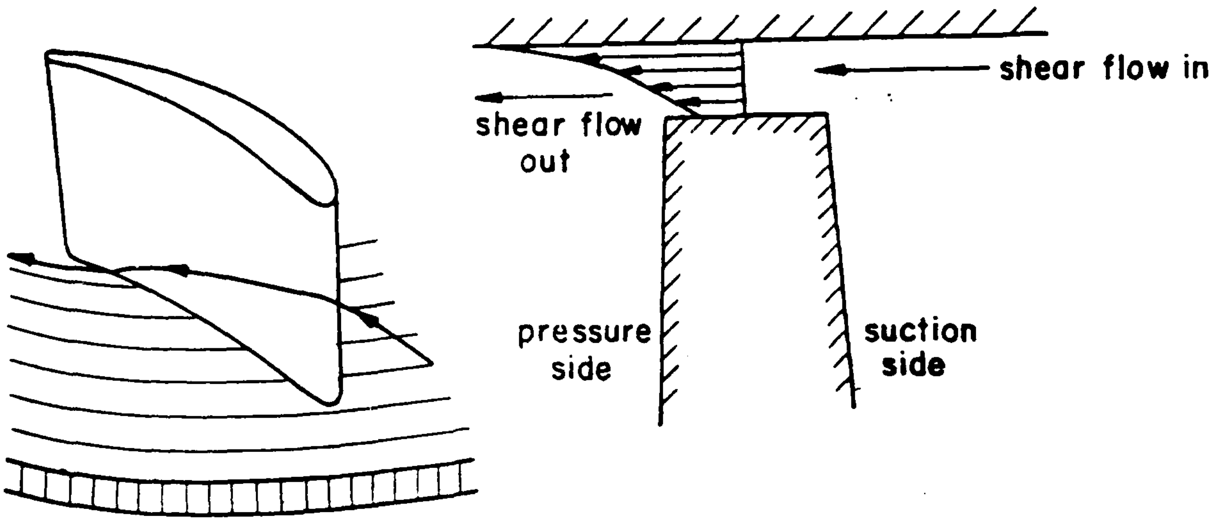
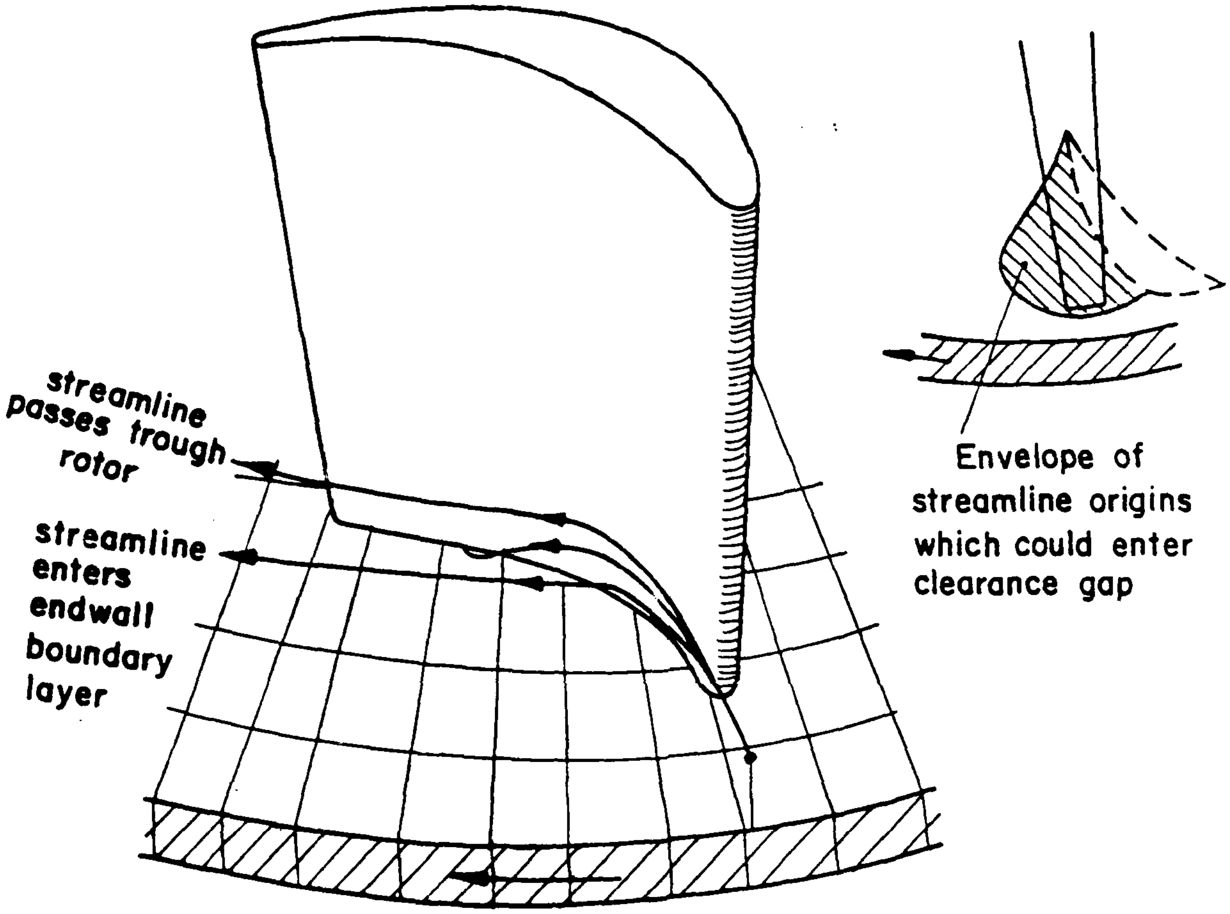


Fig. 13 Flow in tip clearance gap if endwall motion is such as to overcome leakage and resulting effect on pressure surface streamline.



<u>Fig. 14</u> Streamlines for flow outside of the pressure surface boundary layer which could either enter the clearance gap, bypass the rotor or enter the moving endwall boundary layer.

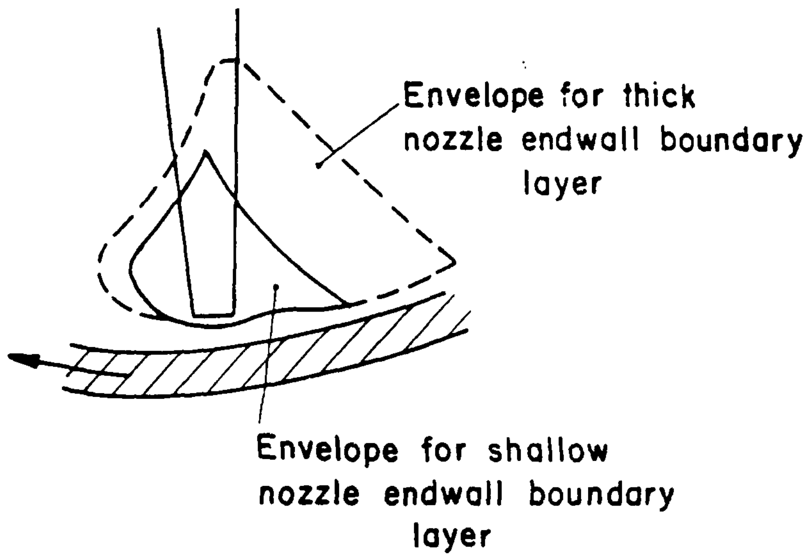
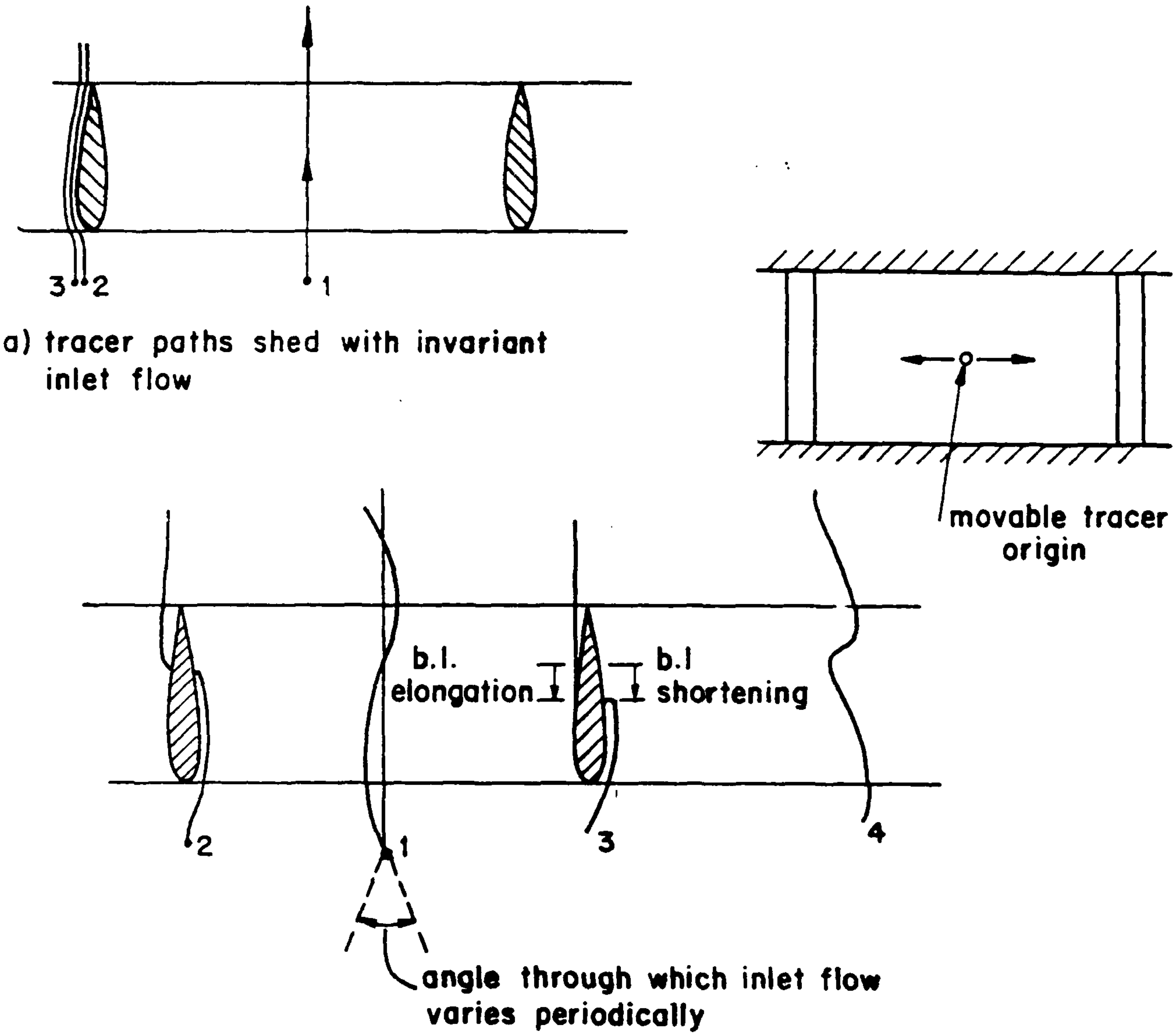


Fig. 15 Expected change of envelope as rotor receives thin or thick endwall boundary layers from the nozzle.



a) tracer paths shed with invariant inlet flow

b) tracer paths shed by inlet flow with oscillating inlet angle

Fig. 16 The effect of flow periodicity on simple tracer type flow visualisation in a stationary linear cascade with straight vanes.

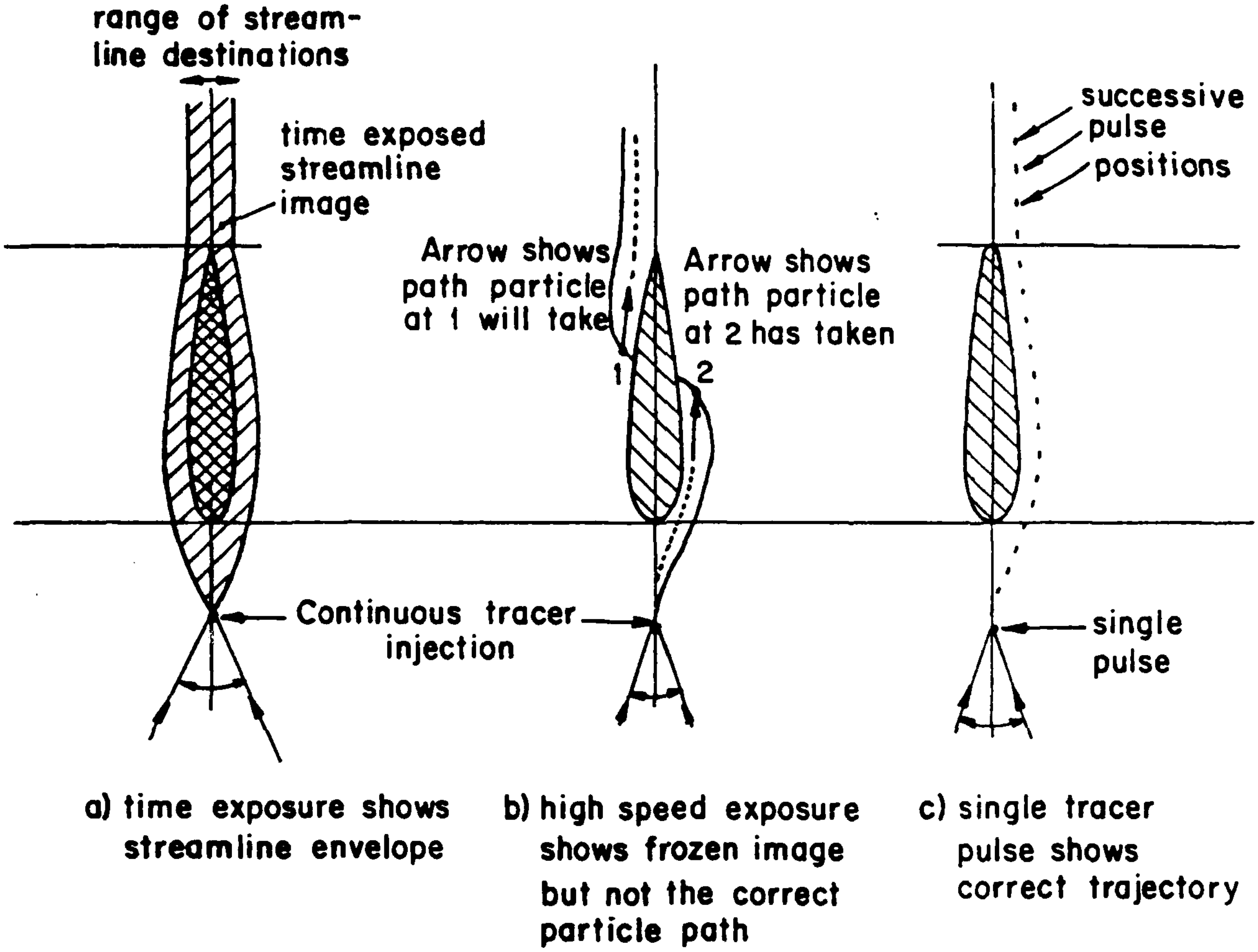


Fig. 17 Angular time variant inlet flow visualisation images.

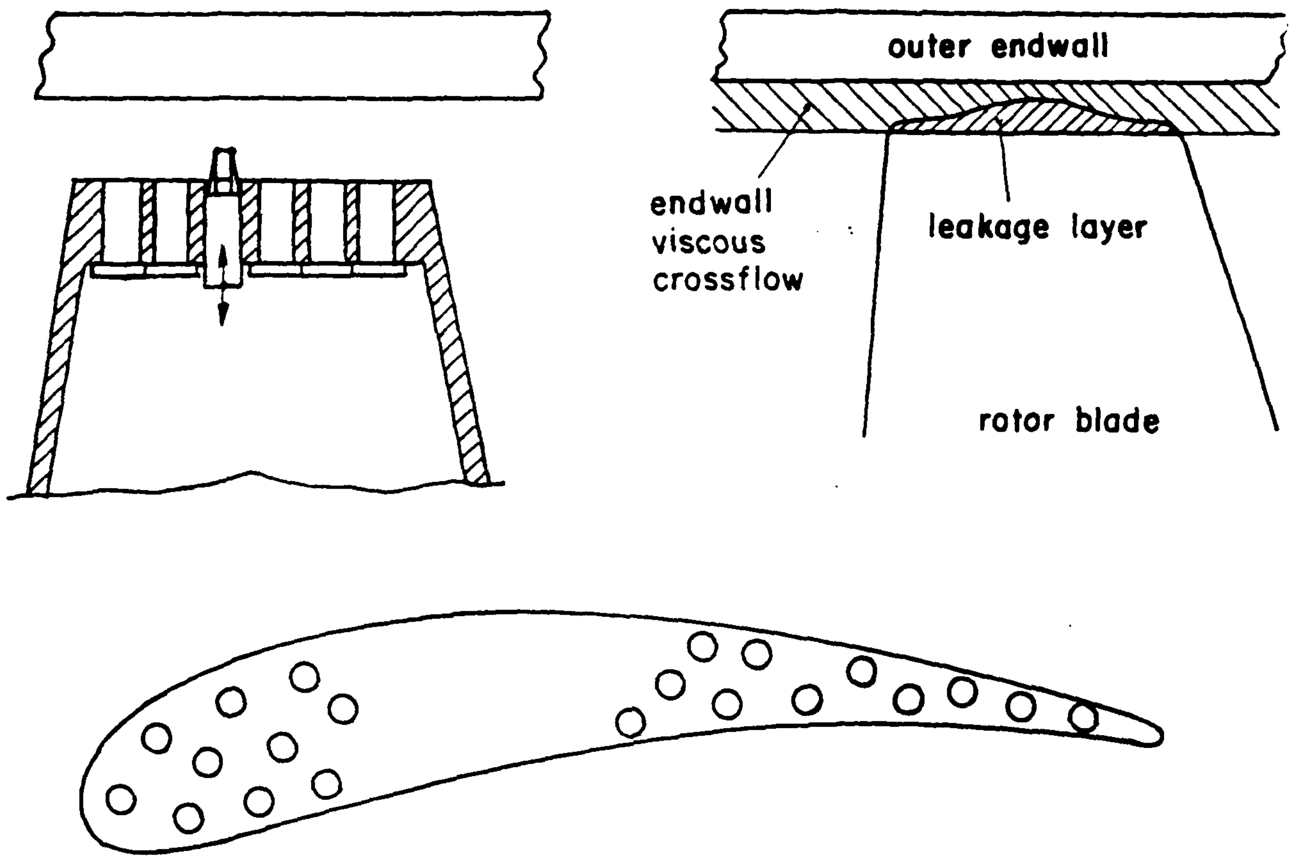


Fig. 18 Indentification of gap flow layer heights via a rotor tip mounted hot wire probe.

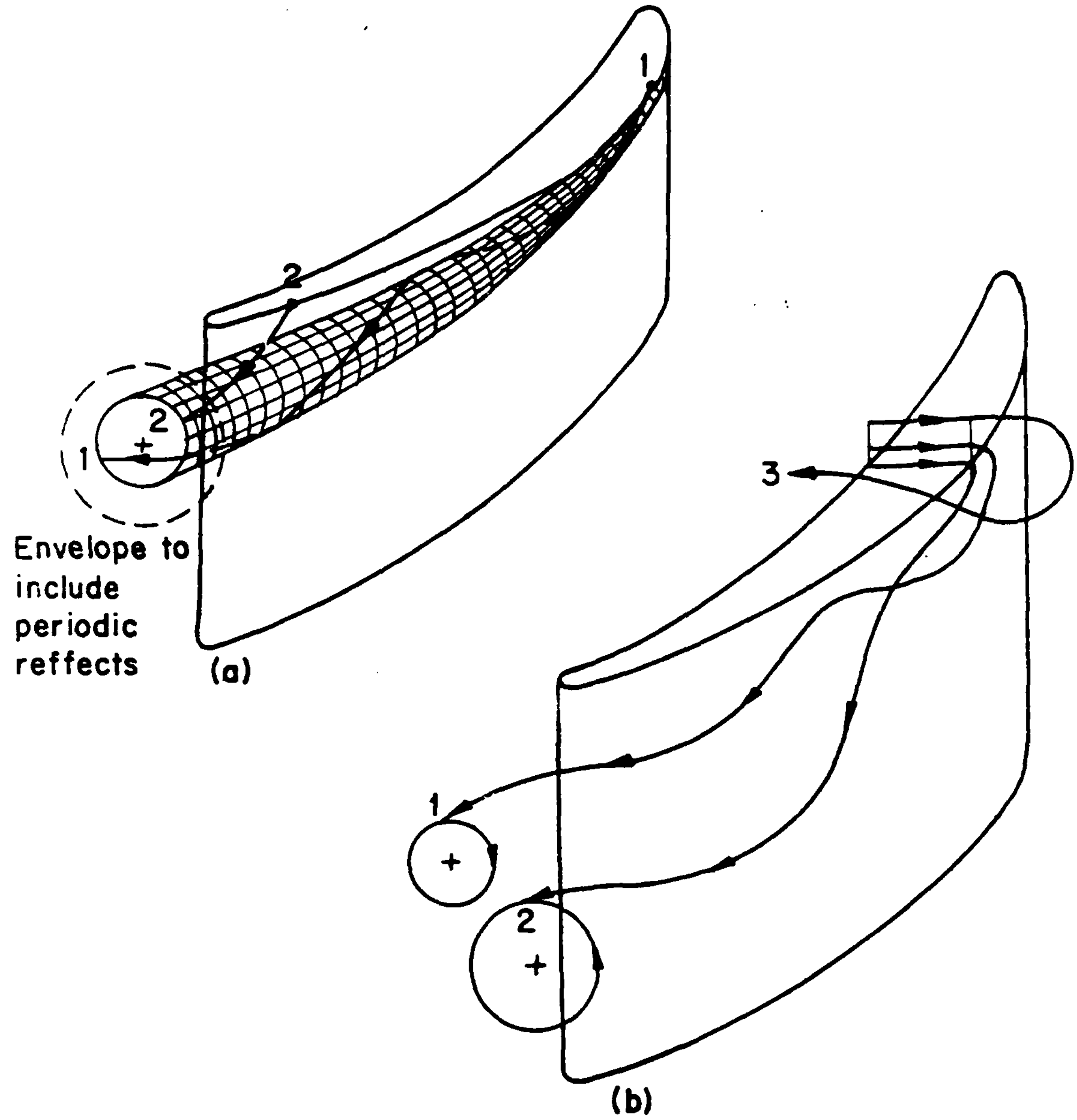


Fig. 19 Possible clearance gap outlet trajectovies.

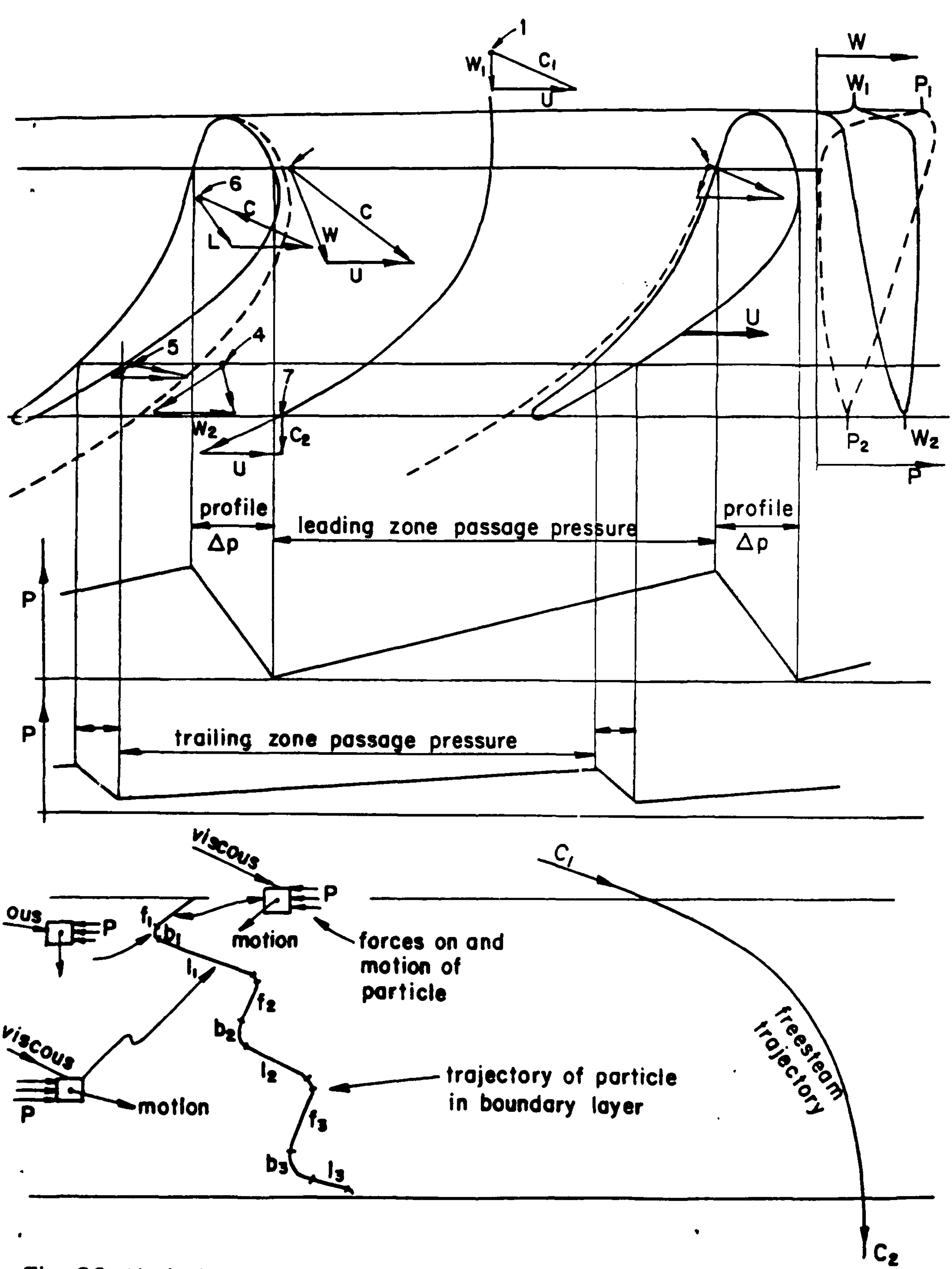


Fig. 20 Variation of factors affecting the rotor endwall boundary layer and a possible trajectory within the boundary layer.