Experiments on the effect of suction on the flow due to a rotating disk

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The stability and transition Reynolds numbers for the flow due to a disk rotating in still air were increased by low rates of suction through either a woven wire-cloth or a slitted surface. Observations on the slitted disk at rotational speeds between 550 and 1250 r.p.m. showed that the critical value of the Reynolds number $r^2\omega/\nu$ for instability increased from about 135,000 without suction to nearly 250,000 for a value of the suction parameter a of 0·4. The corresponding values for transition increased from about 275,000 to about 400,000. A given increase in stability Reynolds number required about 75 % more suction than that theoretically predicted for uniform distributed suction, a satisfactory result in view of the limitations of the apparatus.

At higher rates of suction ($0{\cdot}4 < a < 1{\cdot}6$), the reduction in secondary flow allowed transverse turbulent contamination to spread inwards from the rim. Consequently the vortices associated with secondary-flow instability were not found, though disturbances of larger wavelength appeared. Intermittent turbulent flow was spread over a much larger region of the disk and no laminar flow could be obtained above a Reynolds number of 400,000. Owing to this feature of the flow, it was not possible to extend laminar flow to values of the unit Reynolds number (ratio of stream velocity to kinematic viscosity) corresponding to flight conditions on a swept-back wing. It is concluded that the rotating disk is not a satisfactory tool for the investigation of the effects of suction on secondary-flow instabilities such as arise in the case of a swept-back wing, or for the testing of suction surfaces.

1. Introduction

Transition to turbulence in the flow over a smooth disk rotating in still air results from the instability of a secondary-flow profile, as in the flow over a swept-back wing. This instability has been discussed by Gregory, Stuart & Walker (1955).

In the case of a swept-back wing, boundary-layer control by suction should extend the laminar flow range by reducing the magnitude of the secondary-flow velocity, by decreasing the thickness of the boundary layer and by altering the secondary-flow profile to one that is inherently more stable. In the case of a rotating disk, however, this last alleviation would not be expected to occur, as Stuart (1954) has shown theoretically that there is little change in the shape of the velocity profiles with uniform distributed suction.

Attempts to increase the extent of laminar flow on a disk by suction through a woven wire-cloth surface have previously been described by the authors in detail (1953). The present paper briefly refers to this work and reports additional tests with a slitted surface. It was hoped that the tests would prove of value in connexion with the application of a similar surface to a laminar flow swept-back wing, but the difficulties met with earlier in extending laminar flow on a rotating disk were again encountered. This time, however, the difficulties are shown to be fundamental to the disk flow and not to be due to the nature of the porous surface.

2. Apparatus

The basic disk consisted of a slab of dural 3 ft. in diameter, perforated with a large number of $\frac{1}{2}$ in. diameter holes arranged in concentric circles. On one side of the disk a series of concentric narrow protruding lands, machined from the solid, separated each row of holes and held the test skin away from the surface, thus allowing suction everywhere except over the area of the lands.

The porous surface used by Gregory & Walker (1953) was formed by a rolled piece of monel metal woven wire-cloth which was dry-mounted on to a sheet of aluminium perforated with thirty $\frac{1}{8}$ in. diameter holes per square inch and screwed and glued to the lands. As there was little diffusion of the flow through the wire-cloth, which provided the whole resistance to the suction, the distribution of suction corresponded to the holes in the perforated backing sheet. The porosity of the wire-cloth was not particularly uniform, local suction flow variations of the order of $\pm 30\%$ being found, whilst surface waviness up to $\pm 0{\cdot}006$ in. was present over part of the disk.

The disk was mounted flush with, and in the middle of, one of the large faces of a fixed suction box of dimensions 7 ft. $\times$ 7 ft. 6 in. $\times$ 1 ft. The possibility of any static pressure variation over the rear face of the disk arising from its rotation was thus avoided, and uniform suction was obtained by lowering the pressure in the box and metering the flow, due allowance being made for the leakage flow which was measured at the same pressure differential when the surface of the disk was sealed with a sheet of cellophane.

For the experiment with slits, the wire-cloth surface was replaced by a dural skin $\frac{1}{16}$ in. thick. This skin was slitted between the 3 and 14 in. radius circles by seventy-two straight slits, 0·004 in. wide, disposed evenly round the disk and all tangential to the 2 in. diameter circle. In addition, seventy-two short slits, alternating with the long slits, were cut between the 11 and 14 in. radius circles. The flow was controlled partly by strips of Perflec gauze applied as backing, with 0·004 in. apertures very carefully aligned with the slits, and partly by covering all the $\frac{1}{2}$ in. diameter holes in the basic disk by thin film drilled with graded throttle holes so that the velocity into the slits increased linearly with radius except outboard of the 11 in. radius where the velocity was halved. This ensured uniform suction per unit area of disk. The circumferential lands were recessed locally to allow clearance for the backing strips behind the slits and were reduced in their radial thickness so as to offer as little obstruction as possible to the continuity of flow through the slits. Nevertheless, measurements made when the disk was stationary suggested that the velocity into the slits dropped practically to zero where each slit crossed a land. In addition, the velocity distribution along the length of the slits cannot have been very uniform when the disk was rotating, owing to the radial pressure gradients

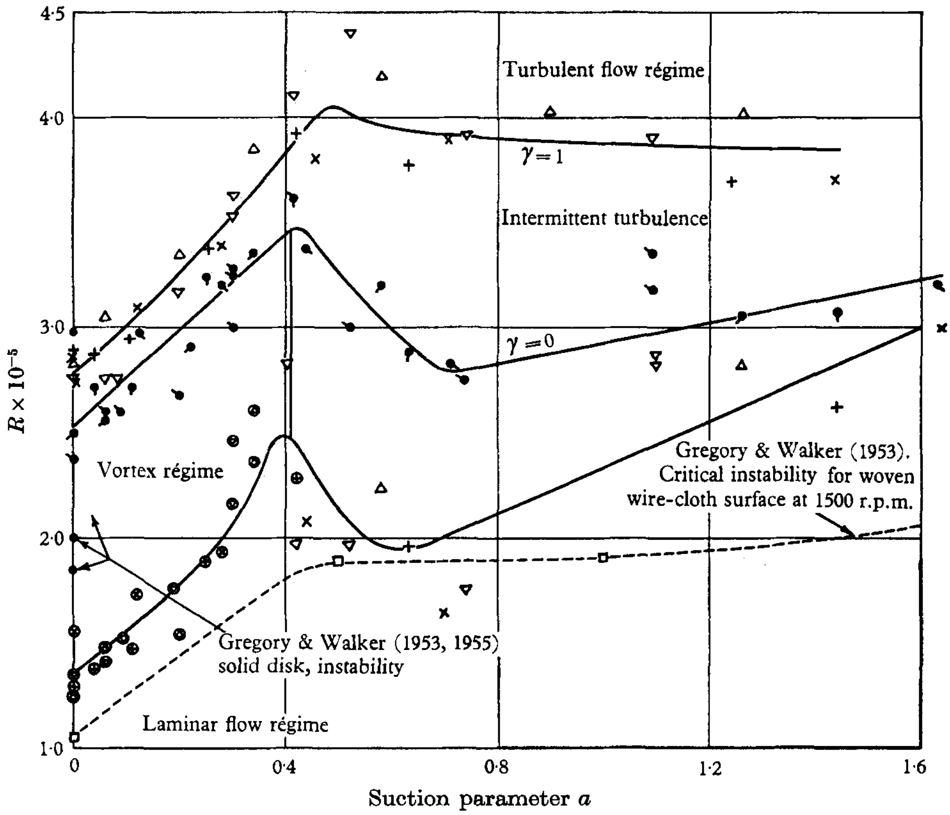


FIGURE 1. Observation of the effect of suction on the state of flow over a slitted rotating disk. γ is the turbulent intermittency factor.

	Disk r.p.m. 550	750	980	1250
First signs of disturbance	×	+	Δ	∇
(Ringed symbols indicate onset of vortex regime)				
$\gamma = 0$, first bursts of turbulence	●	●	●	●
$\gamma = 1$, fully turbulent	×	+	Δ	∇

between successive lands which arose from the use of small throttle holes on the rear face of the disk. None of the difficulties encountered during the tests, however, could be attributed directly to the poor suction distribution.

Steps due to lack of perfect alignment between adjacent sectors of the skin were kept less than $\pm 0{\cdot}0005$ in., though over the circumference, waves of $\pm 0{\cdot}004$ in. were present. The reading of an anemometer probe held close to the rotating surface was therefore by no means steady.

3. Measurements

3.1. *State of flow over woven wire-cloth surface*

The state of the boundary layer on the woven wire-cloth surface of the earlier experiment was determined from the display on an oscilloscope of the signal from a probe microphone connected to a total head tube which was held in the flow close to the moving surface. As the probe was sensitive to noise and to the effects of disk vibration and surface waviness, as well as to the turbulence

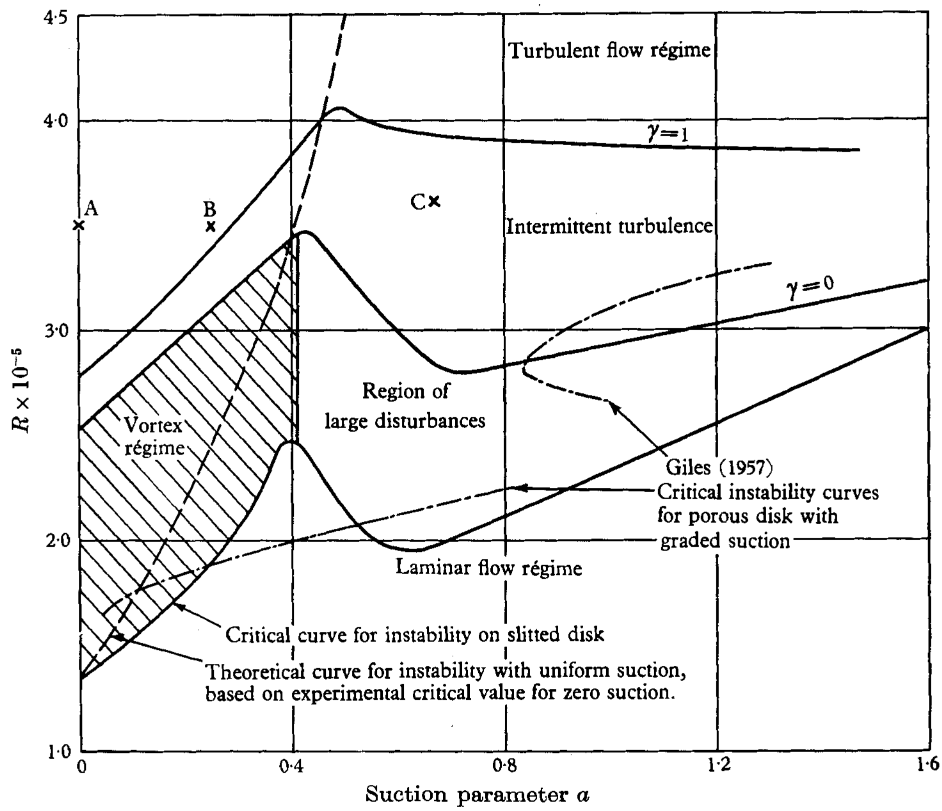


FIGURE 2. Comparison between theory and experiment for the effect of suction on the state of flow over a slitted rotating disk.

in the flow, it was not easy to interpret the signal. The dashed curve included in figure 1 indicates for a rotational speed of 1500 r.p.m. the variation of the critical Reynolds number for stability R (defined as $r^2\omega/\nu$, where r is the radius, ω the angular velocity of the disk and ν the kinematic viscosity) with the value of the suction parameter a (equal to $W_0/\sqrt{(\nu\omega)}$, where W_0 is the mean normal velocity over the face of the disk as far out as suction extends).

The critical Reynolds number was sensitive to rotational speed (or unit Reynolds number at the critical position) owing to the roughness of the disk, and although a value of 190,000 is indicated in figure 1 for a value of a of 1, the value actually varied between 240,000 at 700 r.p.m. and 156,000 at 2000 r.p.m.

at the same rate of suction. For very high values of the suction parameter, the critical Reynolds number *appeared* to be much larger, increasing to 640,000 for $a = 5$ at 1500 r.p.m. Certainly, at Reynolds numbers 100,000 to 200,000 above this suggested critical value, the flow was undoubtedly turbulent, but it could not definitely be said to be stable below this critical Reynolds number as the signal was by no means disturbance-free and some mean velocity profiles that were measured were not at all close to the theoretical laminar form. As the typical frequencies of the vortices arising from cross-flow instability could not be detected when an analysis was made of the noise, it was concluded that transition with high suction quantities was not caused by instability of the cross flow. This is not surprising in view of the small increase with suction in the observed transition Reynolds number compared with the great theoretical stabilizing effect of suction shown by the dashed curve in figure 2. These results, described fully by Gregory & Walker (1953), were confirmed by the additional investigation with the slitted skin during which the cause of the difficulty was elucidated.

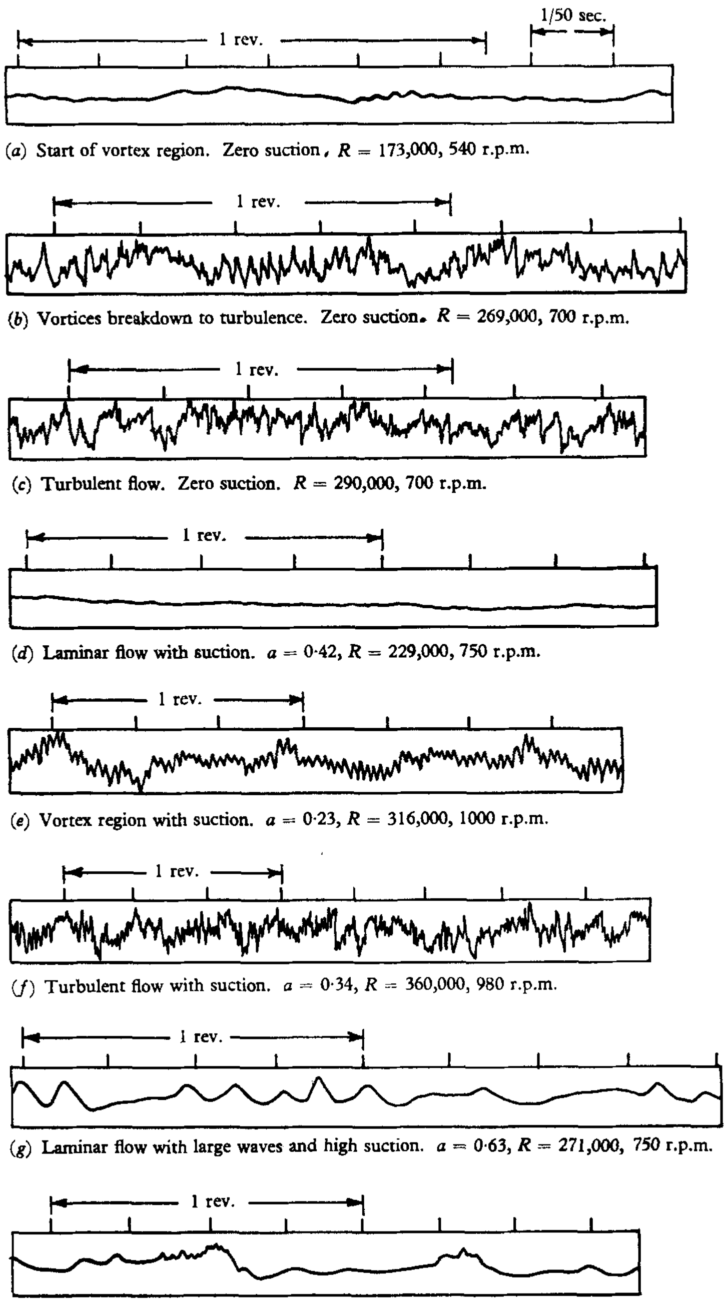
3.2. *State of flow over slitted surface*

In the tests with the slitted skin, the velocity fluctuations were observed using a 'Lintronic' hot-film anemometer probe held about 0·01 in. away from the surface. At given disk rotational speeds and suction quantities, the probe was traversed radially and the positions noted at which the state of the flow appeared to change. The observed Reynolds numbers and values of the suction parameter at which the changes occurred are all plotted in figure 1, and as the observations were not so sensitive to rotational speed as on the woven wire-cloth surface, single curves have been drawn through the points. At low suction quantities, a critical boundary can be drawn for the onset of the vortex pattern associated with instability of the secondary flow: at greater Reynolds numbers, transition sets in rapidly. At suction rates above a value of a of 0·4 the vortex pattern does not appear, but with increasing Reynolds number the laminar flow is disturbed by the presence of a wave of much lower frequency and the eventual transition to turbulent flow is spread over a much wider range of Reynolds number. Oscillograms showing typical traces to be found in the various regions are shown in figure 3.

It was not possible to increase the suction flow above a value of a of 1·6 owing to the high resistance of the slits and a limitation on the suction pressure. Although in the case of the woven wire-cloth surface further increases in suction had apparently extended the region of laminar flow, the performance of the slitted disk at a value of a of 1·6 fell a long way short of that suggested by calculation in figure 2, and it was clear that simple instability of the secondary flow was not the prime cause of transition.

3.3. *Demonstration of the role of transverse contamination*

The explanation which appeared after further investigation was that at high rates of suction transition on the disk was due to a novel self-contamination effect peculiar to the three-dimensional nature of the flow. For two-dimensional boundary-layer flow over a flat plate, it had been shown by Schubauer & Klebanoff (1955) that, provided the boundary-layer Reynolds number was not so low that finite disturbances were damped, a wedge of turbulent flow spread laterally, having a fully turbulent core subtending a half angle of 6·4° and an



(*a*) Start of vortex region. Zero suction, $R = 173{,}000$, 540 r.p.m.

(*b*) Vortices breakdown to turbulence. Zero suction. $R = 269{,}000$, 700 r.p.m.

(*c*) Turbulent flow. Zero suction. $R = 290{,}000$, 700 r.p.m.

(*d*) Laminar flow with suction. $a = 0{\cdot}42$, $R = 229{,}000$, 750 r.p.m.

(*e*) Vortex region with suction. $a = 0{\cdot}23$, $R = 316{,}000$, 1000 r.p.m.

(*f*) Turbulent flow with suction. $a = 0{\cdot}34$, $R = 360{,}000$, 980 r.p.m.

(*g*) Laminar flow with large waves and high suction. $a = 0{\cdot}63$, $R = 271{,}000$, 750 r.p.m.

(*h*) Intermittent turbulence with high suction. $a = 1{\cdot}44$, $R = 321{,}000$, 750 r.p.m.

FIGURE 3. Oscillograms showing the state of flow over slitted disk.

intermittent region with wedge half angle of about $10\frac{1}{2}°$. On a solid disk, the flow in the stationary disturbances generated by instability of the secondary flow travelled downstream and outwards relative to the disk along spiral paths which made an angle of about 14° with the tangential direction (Gregory & Walker 1953; Gregory *et al.* 1955). It was noticed that the centre line of a wedge of turbulence arising from a surface excrescence on a disk lay on a similar

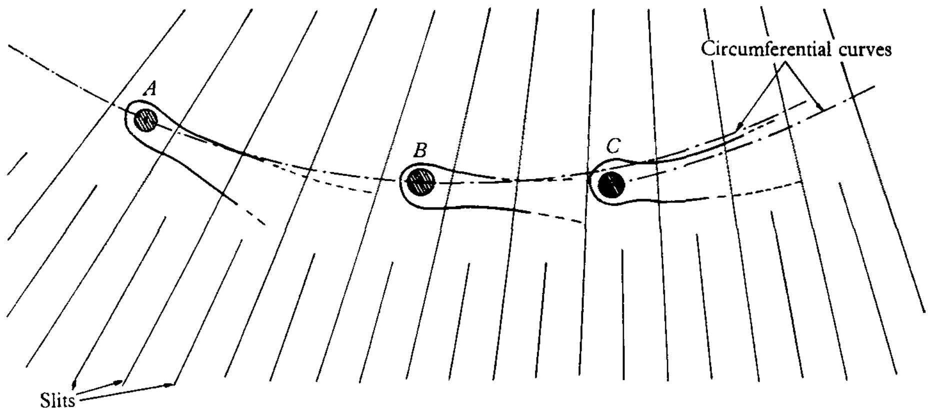


FIGURE 4. Records showing the effect of suction on the spread of the wake of a surface excrescence in turbulent flow, indicated by the sublimation of naphthalene (the position of the three cases in relation to critical conditions is shown in figure 2). *A*: *n*, 750 r.p.m.; *r*, 10 in.; *R*, 350,000; *a*, 0. *B*: *n*, 750 r.p.m.; *r*, 10 in.; *R*, 350,000; *a*, 0·25. *C*: *n*, 750 r.p.m.; *r*, 10·2 in.; *R*, 363,000; *a*, 0·67.

spiral so that the inner edge of the wedge moved outwards along a spiral that eventually made an angle of only a few degrees to the tangential direction when the full spread of the wedge was achieved. As the effect of suction is to reduce the radial outflow it was thought possible that the inner edge of a turbulent wake might lie on a path that would be inclined towards the centre on an inward rather than on an outward moving spiral. This conjecture could not be proved on the disk in a region where suction maintained the flow laminar, since such a region existed only near the centre of the disk at low Reynolds numbers where the postulated flow was not present, presumably because the turbulence was damped out and would not spread laterally at such a large angle. The point was made, however, by experiments in which the naphthalene sublimation technique was used to visualize the wedge of turbulent flow behind a surface excrescence in a *turbulent* boundary layer. Owing to the increased mixing in the wake of the excrescence, a region of increased shearing stress was found extending 2 to 3 in. downstream of the excrescence, and figure 4 shows that at high suction rates the inner boundary to this region becomes parallel to the tangential direction and the disk is therefore self-contaminating.

4. Discussion

4.1 *Discussion on rotating-disk flow*

It appears that at low suction rates ($a < 0·4$) the critical Reynolds number observed experimentally (figures 1 and 2) corresponds to the minimum critical Reynolds number for neutral disturbances of the linearized theory. In view of the large departure of the suction arrangements from that of uniform distributed suction, the stabilization of the flow to a given Reynolds number by means of a suction rate 75 % greater than that predicted with uniform suction is a not unsatisfactory result. Note also that if the velocity profile on the disk is the theoretical one, the observed critical value of the Reynolds number $r^2\omega/\nu$ of 135,000 without suction corresponds to a cross-flow Reynolds number χ ($= v_{\max}\delta/\nu$, where $v_{\max}$ is the maximum value of the cross-flow velocity and δ is the boundary-layer thickness) of about 340. With the suction parameter a equal to 0·4, the observed critical Reynolds number of 225,000 would correspond to a value of χ of 270 if the profiles were those appropriate to uniformly distributed suction, although with suction through discrete slits, the values of χ upstream and downstream of a slit presumably lie above and below this mean value. As expected, there is no stabilization of the cross-flow profile by suction, and the critical value of χ has not been raised.

At high suction rates, the transverse inward spread of the disturbances enables them to reach regions of lower Reynolds number upstream of those at which linear theory would indicate infinitesimal disturbances to be first amplified. There is presumably a balance between the transverse transfer of energy to a disturbance, the energy dissipated by the disturbance and that given to the mean flow. The oscillograms of figure 3 in the order f, h, g (although not taken with a constant value of the suction parameter) show the more rapid decay of the high compared with the low-frequency turbulence as the Reynolds number is reduced. The observed minimum critical Reynolds number clearly has a value which in the linear theory would be appropriate to some degree of damping. Above this minimum, the oscillograms show that finite disturbances of considerable amplitude are present, so that any attempt to calculate the state of the flow would have to be based on the non-linear mechanics of hydrodynamic stability as discussed by Stuart (1958), with the added complications of both boundary-layer growth and transverse energy transfer. At the moment such calculations do not appear to be feasible.

A significant feature in view of the above considerations is that at low suction rates, turbulence finally develops in the disturbed flow very rapidly with increase in Reynolds number, whilst at the higher suction rates where the undistorted flow is stable to infinitesimal disturbances, turbulence develops but slowly in the direction of increasing Reynolds number. This may also be due to the fact that some energy is now spreading inwards instead of all being convected downstream with the disturbances.

Tests with distributed suction on a wholly porous sintered steel disk have also been reported by Giles (1957). In this experiment, the suction chamber rotated with the disk so that the centrifugal pressure gradient led to a graded suction distribution with inflow at the centre and outflow near the rim, even when there was no net flow through the disk. The stabilization achieved is shown in figure 2, the lower curve representing conditions with no net flow, the upper one with a net flow. The suction parameter represents the mean value of suction out to the instability point; variations in the value were obtained by altering the rotational speed. It can be seen that at small rates of suction ($a < 0{\cdot}4$), the rate of increase in stability with suction is less marked than with the slitted disk, although better than that obtained with the woven wire-cloth surface. Limitations imposed by waviness were again present. At high rates of suction there is a slight improvement over the present results, although the increase in stability Reynolds number is nowhere near that suggested by the linear theory. This improvement is due to two effects. With a wholly porous surface, the rate of spread of a wedge of turbulent flow is slightly reduced by suction so that the self-contaminating effect is postponed to larger rates of suction. Such a reduction in wedge angle due to distributed suction has recently been noted in two-dimensional flow, thus confirming earlier experiments by the present authors (Gregory, Walker & Devereux 1948) which suggested this effect and showed that the wedge was completely suppressed by suction quantities of the order of five times those used in the slitted disk experiments, but this suction rate had the additional effect of reducing R_{δ^*} to an extremely small value. The second possible reason for improved results with the porous disk used by Giles (1957) may lie in the fact that the suction rate decreased with distance away from the axis of rotation. The effects of inward transverse transfer of energy would thus be greater nearer the centre where the boundary layer R_{δ^*} is low and disturbances well damped, and less farther out where the boundary layer is more sensitive to the effect. To obtain the maximum extent of laminar flow on a rotating disk it may thus be advantageous to reduce or terminate the suction outboard of the radius at which instability occurs.

Although distributed suction slightly reduces the lateral spread of a wedge of turbulent flow, it is also the most effective way of reducing the outflow on a rotating disk. Calculation shows that the limiting angle at the surface which the flow relative to the disk makes with the tangential direction decreases from 39° 36′ without suction to about 7° at a value of the suction parameter a of 2. Similarly, the angle at a distance from the surface where stationary disturbances generated by instability of the secondary flow are expected decreases from 13° 18′ without suction to about $2\frac{1}{2}$° for a equal to 2. Thus can be seen how the flow over the disk rapidly becomes a self-contaminating 'closed' flow with large suction rates, and extensive laminar motion at high Reynolds numbers is unlikely.

4.2. *Relevance to problem of maintaining laminar flow over swept-back wings with slitted surfaces*

Considering now the case of flow over a swept-back wing, similar difficulties arising from the transverse spread of turbulence are only likely to be encountered right on the leading edge where the main flow is in a spanwise direction, and if a turbulent wedge is present, the whole of the flow outboard of the originating excrescence could be turbulent. Wind-tunnel demonstrations of this possibility are reported by Gregory *et al.* (1955), Gregory (1960), whilst Gray of the R.A.E. had observed the phenomenon in flight tests. It is thus possible that it may be necessary to suck somewhat more in the leading-edge region than would be suggested by considerations of the linear stability theory. Further downstream the difficulty could not arise.

As the hoped-for stabilization with suction was not achieved on the rotating disk, it was not possible to test the effectiveness of the slit arrangement at high Reynolds numbers. At the highest critical instability Reynolds number of 240,000 obtained with a value of a of 0·4, calculation suggests that if the boundary layer is taken to be roughly that appropriate to uniform suction then $R_{\delta*}$ is only 530 and R_{θ} is only 2120 for the tangential main flow, which with H roughly equal to 2 is in a very stable state. (The critical value of $R_{\delta*}$ for $H = 2$ is about 42,000.) The slit Reynolds number was only about 17 under these conditions, and at 1250 r.p.m., the velocity of the disk at the instability point was only 70 ft./sec. All that can be concluded, therefore, is that at this relatively small Reynolds number and value of U/ν, no evidence was found for any effects due to slit contour, due to slit sweep (which could be altered by changing the direction of rotation), due to rapid variations or breaks in continuity of the inflow along the length of the slit, or due to the ends of the additional rows of slits at 11 in. radius. It is possible that the flow was affected by these features but that the indications were masked by the disturbances due to flow turbulence and to waviness and discontinuities in the surface.

The rotating disk can thus no longer be regarded as a satisfactory tool for investigation of the effects of suction on secondary-flow instabilities such as arise on swept-back wings, or for testing suction surfaces.

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