Int. J. Heat Mass Transfer. Vol. 19, pp. 1189–1195. Pergamon Press 1976. Printed in Great Britain

FLOW BEYOND AN ISOLATED ROTATING DISK

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(*Received* 5 *April* 1976)

Abstract—Visualization and flow measurements were performed for the flow field radially beyond the rims of isolated flat circular disks rotating in their own planes. The investigation included effects of disk thickness and speed of rotation. Flow in the near-rim region has similarities to that of the near-wake region of bluff-tailed bodies, with vortices being found there. In the same region there is a large negative radial gradient of whirl velocity. Further from the disk rim the flow becomes a jet with straight mean streamlines. The relative degree of swirl in the far-jet varies with disk thickness and speed.

NOMENCLATURE

θ,	angle of yaw;
t,	thickness of disk;
ω,	angular velocity;
r,	radial distance from axis;
r_0,	disk radius;
Re_R,	Reynolds number at rim;
ν,	kinematic viscosity.

INTRODUCTION

THE ROTATING disk provides an attractive fluid mechanical problem: it has a three-dimensional boundary layer whose laminar motion can be found as an exact solution of the Navier–Stokes equations [1, 2] and which presents an interesting stability problem [3]. Such theories, and some elaborations involving the presence of other moving or stationary surfaces nearby, e.g. [4], do not consider disks with a finite overall radius. Real disks are always of finite radius, and in consequence two questions arise: how does this affect the flow on the disk surfaces, and what happens to the fluid flowing outwards on the disk surface when it reaches and passes the rim? Experimental investigation of overall rotating disk friction has shown that rim width has a very considerable effect on the overall friction coefficient [5]. This has led experimenters to use very thin disks—even of thin paper—to measure disk friction. In heat-transfer experiments it has been found necessary to fit guard heaters at the disk rim to compensate for large heat losses [6]. Clearly, such edge effects are associated with the fluid motion at the rim. Chanaud, in experiments with a single disk rotating at one speed [7] found evidence of vortices at the rim and a radial jet with swirl extending beyond this. The object of the present paper is to present data for rotating disks of various thicknesses and speeds, the effects of variations of these not having been reported previously.

The terms and coordinates used in this paper are illustrated in Fig. 1. Only plane, smooth-surfaced disks were used. The possible variations of shape of the rim are legion. Straight, solid rims were used except in one part of the flow visualization studies.

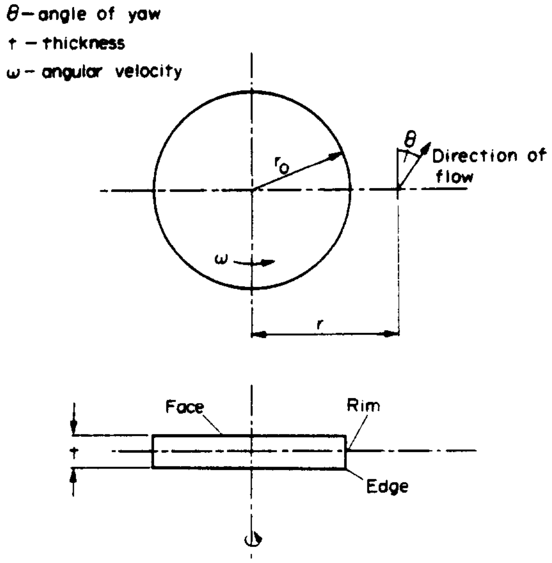

FIG. 1. Coordinates and terms used in describing the flow beyond a rotating disk.

EXPERIMENTS

The objects of the experiments were firstly to obtain some knowledge of the order of velocities and the pattern of flow in the near-disk jet, and secondly to study questions of particular interest, such as the effects of disk thickness and radius, the effect of the rim flow on flow on the disk faces and the effect of disk speed.

The human hand is a crude but useful anemometer, sensitive to both heat transfer (low velocities) and dynamic pressure (high velocities). Using it to "feel" the jet coming from a rotating disk, two features of the flow are immediately apparent: first, the jet flowing radially from the disk is very weak, even when the disk is rotating fast—the speed of the airflow falls below 10% of the rim speed quite close to the rim—and is felt to die away as the hand is moved away from the rim. Secondly, the flow is felt to be irregular, or "lumpy"—the hand is sensitive only to frequencies below 1 Hz or so, but in this region a number of irregular pulses can be felt.

Flow visualization

Because the flow velocities were reasonably low, flow visualization was attempted, using both titanium tetrachloride and paraffin smoke. It was immediately seen that the flow in the disk-edge jet was turbulent. This was observed over the complete range of disk sizes and speeds used—about 4–25 cm in radius, and 100–2700 rev/min. The existence of the turbulence is hardly surprising in view of the intrinsically unstable flow configuration.

Visualization of the flow on the disk faces, particularly near the edge, showed it to be completely regular right up the disk edge and unaffected by the rim flow to within a boundary-layer thickness of the edge. At the edge, the pattern of flow was seen to change rapidly. The flow became irregular, considerable entrainment occurred, and the flow spread rapidly in the axial direction. Vortices were seen to form just above the edge. The vortices were more readily seen on thick disks than on thin disks, where the vortices seemed to interfere with each other. Also, it was easier to see the vortices at low disk speeds than at high speeds, either because of the greater difficulty of smoke visualization at high speeds or because of some change in the flow pattern, such as a reduction in vortex size. The vortices appeared to be about four times as long in the direction of flow as they were wide across the main direction of flow.

The vortices formed at each edge could be seen very clearly in a modified configuration. A hollow rotating disk was constructed from two solid metal disks with a modest gap (about 3 mm) between them. One disk had a small hole at its center and a short brass tube soldered axially to this. Laboratory gas was supplied to the inter-disk gap from a stationary tube which was a close sliding fit in the brass tube. The rim of this disk configuration was, of course, different from a solid rim: with a radial outflow of gas from the rim slot, one might expect a reduced tendency of the airflow from the disk faces to form vortices on passing the edges. With a relatively large gas supply rate to the disk core a smooth, steady diffusion flame could be stabilized on the rim of the rotating disk. As the gas flow rate was reduced, the disk speed being held constant, the flame reduced in size, became very noisy and could be clearly seen to be composed of many discrete vortices at the disk edge. Each vortex seemed to be distorted somewhat by the high rate of change of velocity in the tangential direction at the disk edge. Further reduction of the gas flow soon resulted in flame blow-out. The same sequence of phenomena was observed when the gas supply was held constant and the disk speed progressively increased.

Flow measurements

Because the flow beyond the rotating disk has rather small velocities, while spreading out as a large disk of its own, it is very sensitive to disturbances, which can deflect the flow from a planar-symmetric form quite easily. A nearby stationary surface, or natural convection from a disk-driving electric motor, for example, can cause considerable deflections. Care was taken to eliminate such sources of difficulty. Measurements were made with disks rotating in a vertical plane. Thermal anemometers and yaw-meters were used for measurement after appropriate calibration. The yaw meters had a sensitivity of ±0.5° arc.

The rapid spread of the disk flow in the axial direction just beyond the rim is dramatically illustrated in Fig. 2, which shows velocity isopleths in the region radially beyond a thin rotating disk. For the conditions pertaining in this experiment, measurements of velocity profiles at a set of neighboring radii provided an estimate of the mean axial velocity associated with entrainment in the near-rim region of 12.5 ft/s (from continuity considerations); the axial inflow velocity towards the laminar boundary layer on the disk face under the same conditions was 0.4 ft/s. Chanaud [7] also remarked upon the very rapid axial growth of the disk flow immediately beyond the rim with his disk on which the boundary layers were turbulent.

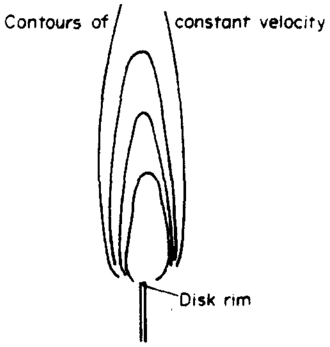

FIG. 2. Velocity isopleths in the near-disk jet for a disk radius 86 mm and thickness $t = 0.8$ mm rotating in air at 1820 rev/min. The laminar disk surface boundary-layer thickness ~ 2 mm.

The most extensive set of measurements was taken with a series of disks 10.7 cm in radius and several different thicknesses. The angle of yaw was measured in the center plane at different radii and disk speeds. Figure 3 illustrates the effect of a ten-fold increase of speed on the flow from a disk of one thickness; at low speeds an inflection was observed in the angle of yaw close to the rim, but this disappeared as the speed was increased. Figure 4 illustrates the effects of thickness at lower disk speeds and higher disk speeds separately; at low disk speeds the angle of yaw close to the rim fell progressively as the disk thickness increased, as found at higher disk speeds also but with a smaller range of yaw angle. Mean flow lines are illustrated in Fig. 5 for two different disk thicknesses. The curvature of the lines close to the rim and the straightening of the flow lines at larger radii can be seen. The radius to which curvature persists appears greater for wider disks. The same figure shows a graph of the initial rate of change of angle of yaw with respect to radius as a function of the reciprocal of rim width (on a logarithmic scale). Experiments with thin disks fitted with T-rims (idealized flywheels) indicated

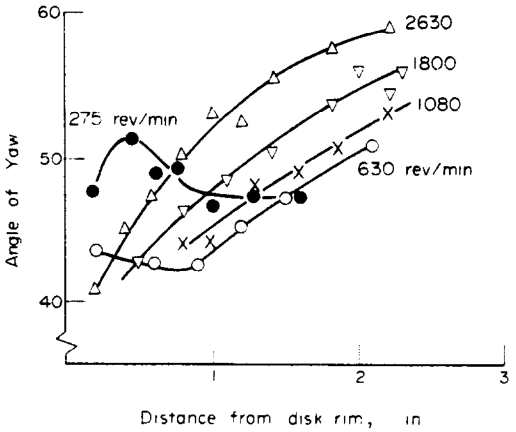

FIG. 3. Angle of yaw measured in center plane of disk jet as a function of distance from the disk rim at various disk speeds. Disk of radius 10.7 cm and 0.35 mm thickness rotating in still air.

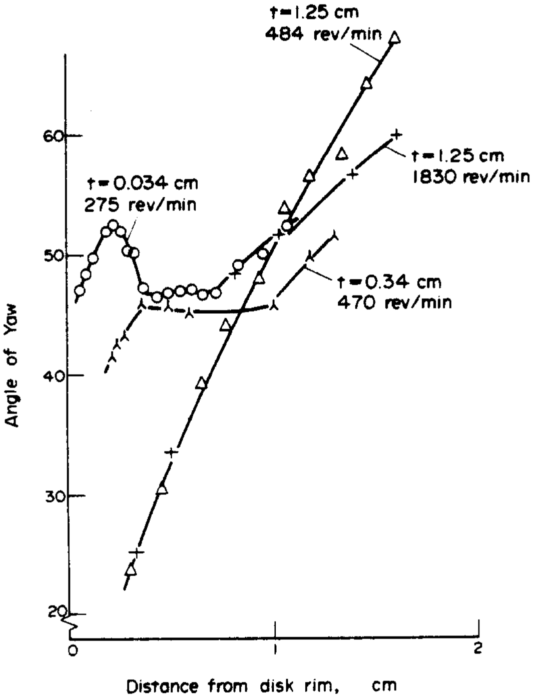

FIG. 4. Angle of yaw measured in center plane of disk jet as a function of distance from the disk rim. Disks of radius 10.7 cm and various thicknesses rotating in still air.

that the rim flow was similar to that produced by thick disks of the same thickness as the width of the rim. Such experiments were performed with thin rims (about 0.13 mm).

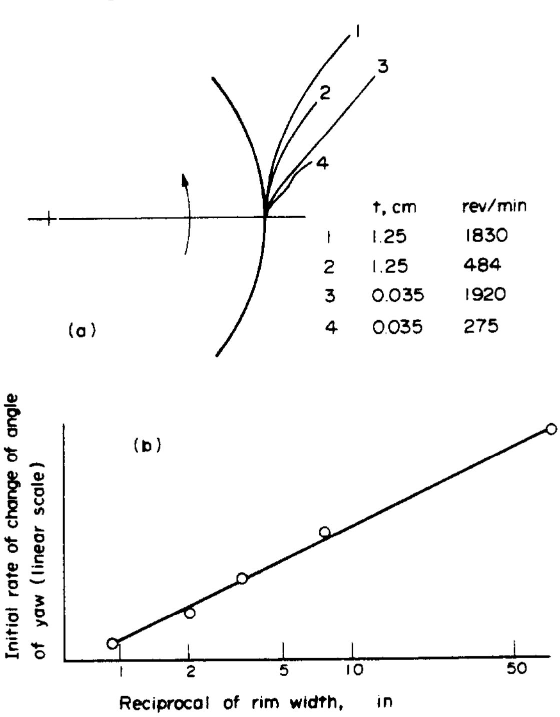

FIG. 5. (a) Mean flow lines in center plane of disk jet. Close to the rim the lines are curved; at larger radii they become straight. (b) Rate of change of angle of yaw with respect to radius close to the rim: effect of disk thickness. Disk radius 10.7 cm, speed ~400 rev/min.

Transverses of yaw angle across the disk jet were made. The angle of yaw in planes parallel to the disk center plane was relatively constant over most of the width of the jet, the angle perhaps increasing at the edge of the jet. The latter result is tentative because the angle of yaw in the plane through the axis of rotation was not insignificant near the edge of the jet in the near-rim region, and this handicapped measurement. Chanaud observed a marked loss of sensitivity of his yawmeter in the same region which he attributed to the same cause.

In general the mean angle of yaw appeared to be steady throughout the traverses made. Variations were observed, however, with thicker disks, e.g. with a disk of 28 mm thickness irregular variations of the order of a few degrees and with a period of the order of 30 s were seen.

Measurements of total velocity were also made. The variation with distance from the disk rim of the product, total velocity x radius, is shown in Fig. 6 for the jet center plane. The product tends to a constant value, from above, at large radii. The effect of disk

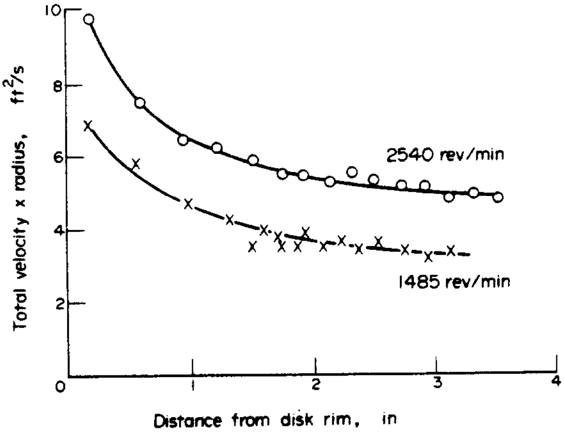

FIG. 6. Variation of the product, total velocity times radius, with distance from the disk rim in the center plane of a jet from a disk 10.7 cm radius and 0.35 mm thick.

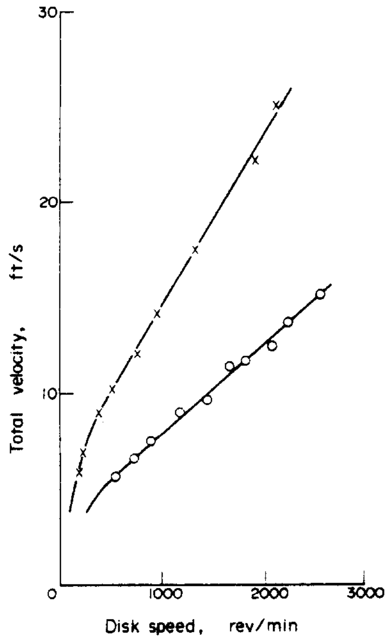

FIG. 7. Effect of disk speed on total velocity at fixed positions in jet center plane. Disk 10.7 cm radius and 0.35 mm thick.

speed on the total velocity at fixed positions in the center plane, for the same disk, is illustrated in Fig. 7. Following an initially rapid rise of total velocity with speed, further rise occurs at a lower, uniform rate; the transition between rates of rise coincides with the downward shift of the angle of yaw close to the disk rim with increase in speed and presumably reflects changes in detail of the flow pattern. Traverses across the disk jet were made parallel to the axial direction; symmetric, bell-shaped profiles were obtained, mostly corresponding to transitional profiles as illustrated by Chanaud, and are not illustrated here.

Observations of heat transfer from the rim of a rotating disk 25.1 cm radius and 2.86 cm thick were obtained in connection with another investigation. This disk was fitted with a separately-powered rim guard heater which yielded data on heat transfer from the isothermal disk rim. The heat-transfer coefficients were above those for a long cylinder at comparable Reynolds numbers. They also rose rapidly with increase in *Re* when the face boundary layer was laminar, and even more rapidly when the boundary layer had undergone transition on the disk face.

DISCUSSION

The flow due to an isolated rotating disk radially beyond its rim has the appearance of a radial jet with swirl, especially at large radii. Close to the rim the flow has some likeness to the wake of a bluff body. At intermediate radii the flow would appear to settle into a roughly self-similar pattern in which specific details of flow associated with the disk edge become progressively indistinguishable. This is like the behavior of familiar two-dimensional jets and wakes: these can be divided into near-jet (e.g. potential core) or near-wake (e.g. Kármán vortex formation) regions, and far-jet or far-wake regions.

Turbulent nature of the flow

Jets and wakes, even when two-dimensional, have an intrinsically low stability and undergo transition from laminar to turbulent flow at quite small Reynolds numbers. A theory for laminar radial jets without swirl was developed several years ago by Squire [8]; he found that the center-plane radial velocity decreases inversely with increase in radius. A similar variation would be expected in a turbulent radial jet when the usual self-similar jet profile is assumed, with mixing-length proportional to local jet width. When rotation is added to such a jet another cause for instability is added. There is a negative radial gradient of tangential (swirl) velocity, a flow configuration whose instability was so well demonstrated by Taylor with concentric cylinders. All the experiments described here were apparently at conditions sufficient to cause turbulence in the jet flow.

Flow close to the rim: vortices

The flow radially just beyond the rim was observed to involve a fairly regular array of vortices. The flow at the rear of bluff-tailed bodies transverse to a stream involves vortices in the near-wake region over a wide range of Reynolds numbers, and the associated flow patterns are known to possess manifold subtleties while preserving the gross vortex structure. If the flow over the disk faces is somewhat analogous to the attached flow over a bluff-tailed body, examination of the laminar solution [1, 2] or turbulent boundary-layer approximation [9, 10] shows that the average flow approaches the edge at a finite angle of yaw, and not radially. Consequently, if one is to look for some analogy in wake flows it should be for a body with a yawed tail. Very little seems to have been reported for such configurations: the study of the flow behind yawed cylinders by Surry [11] would appear to offer the greatest prospect of comparison. He observed the formation of vortices persisted in position for some time rather than being continuously formed and shed into a Kármán street.

Two differences from bluff-tailed body wakes may be significant with the rotating disk. One is that the radial momentum of the disk face boundary layers is modest enough to allow the mean flow to expand rapidly in the axial direction, as can be seen in Fig. 2 (also in Fig. 5 of [12], where an axial growth to the right is seen above the disk rim even though the radial disk jet is deflected strongly to the left). The second is that the vortices may sometimes have their vortex lines in skewed hairpin form, with the tips on the disk rim and the bend radially outward from the rim; then, in the presence of a negative radial gradient of mean angular velocity about the disk axis, the vortex lines could be stretched, leading to intensification of the corticity.

A rim Reynolds number can be defined as $Re_R = \omega R t/\nu$. While the incidence of flows with inflections in the angle of yaw as measured in the center plane is greater at smaller Re_R for a given disk, it is not a sufficient variable to correlate the set of angle of yaw measurements for different disk thicknesses and speeds. Moreover, while the inflections disappeared at larger Re_R here (where the face boundary layer was laminar), an inflection was found by Chanaud [7] when Re_R was much larger (but the face boundary layer was turbulent).

Considering further the structure of the flow at the disk rim, it is seen that the pressure in the region at and just beyond the rim is below that of the surrounding fluid: a pressure drop is needed to accelerate fluid axially entrained from the surroundings. The surface pressure on the rim should fluctuate because of the movement of the vortices. This pressure and its fluctuations should have no direct effect on the disk drag, in contrast to effects of separated flow regions on drag of bluff-tailed bodies.

An adequate set of measurements is not available to detail the changes that occur in the rim region flow when the boundary layer on the disk faces passes from laminar to turbulent as the disk Reynolds number is increased. Measurements of heat transfer from the rim indicate a shift in the rim-Nusselt number vs Reynolds number relation at the transition Reynolds number for the disk face boundary layer, a shift that probably reflects some changes in flow pattern.

Tangential shear at the disk rim

The large radial gradient of tangential velocity immediately above the disk rim, and the associated entrainment of fresh fluid in that region, explain qualitatively the observations of the effects of disk rims on overall disk friction and overall heat transfer. The total torque—associated with drag on both disk faces and the disk rim—must manifest itself as the angular momentum flux of the disk jet. It was this very principle that was used by Davies in his studies of disk drag, in which he suspended the disks and their driving motor on a torsion wire and measured the net torque exerted on the atmosphere.

The shape of the rim used in the experiments reported here corresponded to that of a very short cylinder. The turbulent flow associated with a long rotating cylinder was investigated theoretically by Kays and Bjorklund [13] and the friction coefficient measured, e.g. by Theodorsen and Regier [14]. However, Davies found that the friction coefficient on the rim of a disk was considerably greater than that on a corresponding cylinder. He also found that the ratio of friction coefficients of the disk rim and the long cylinder was a function of the rim width. The friction of the disk rim became nearer to that on the long cylinder as the rim became wider. This suggests on the one hand that the friction on the disk rim is a function of the axial direction, and on the other hand it also corresponds to the effect of disk thickness suggested by the present experiments. On a long rotating cylinder it would be expected that the mean flow lines would be circles concentric with the cylinder, at least in regions near the cylinder; in that region the rate of change of angle of yaw with respect to radius would be zero. Values of the initial rate of change of the angle of yaw were taken for low disk speeds and plotted as a function of the reciprocal of thickness, Fig. 5(b). Extrapolation to zero rate of change of angle of yaw gave a corresponding value of $1/t$ of the order of 0.2, that is, a thickness of about 5 cm for a disk of 10.7 cm radius. This is a very rough estimate, but it does indicate the order of size at which flow near the center of a wide rim begins to become like that on a long cylinder. By the same token, it gives some idea of the distance along a rotating cylinder over which end effects may be found. The distance would probably be reduced with reduction of cylinder radius. Chanaud [7], in making a momentum integral analysis of the disk jet, considered the radial and swirl components of the turbulent boundary layer passing from the disk faces at the disk edge, and estimated the local ratio of swirl and radial momentum as 2.02. (He pointed out that experiments [3] did not compare well with the profiles assumed by von Kármán [9] from whose analysis the estimate of 2.02 was made; also Cobb and Saunders [6] noted that Kármán's profiles led to underestimation of heat transfer to the turbulent boundary layer.) Thus he did not explicitly include effects of the rim shear on the whirl momentum. However, in discussing the Kármán [9] and Goldstein [10] approximations for the turbulent boundary layer on the face of a rotating disk, Davies [5] noted that the constants were adjusted to agree with experimental measurements of drag—which included corresponding edge effects anyway. The far-jet flow lines, Fig. 5(a), indicate that the ratio of swirl and radial momentum varies with disk thickness and speed.

Outer regions of the jet

At large radii the disk jet has seemingly lost structural details that reflect details of the disk rim geometry; the transverse velocity profiles develop a self-similar form, and grow linearly in the axial direction with increase in distance from the axis of disk rotation, as illustrated by Chanaud [7] (Figs. 3 and 4). The local product of total velocity times radius tends to a constant value at large radii. These are characteristics expected in a simple radial jet. The meanflow streamlines, as determined from yaw measurements in the center plane, are straight. This is not surprising: in the outer jet there are no significant radial or tangential pressure gradients to cause deflection from straight lines. As the radius increases, the streamlines come progressively closer to being radial. From this region, the straight streamlines can be extrapolated back to touch tangentially a circle around the axis of rotation; this circle is smaller than the disk itself. The ratio of the radius of this circle to that of the disk is a measure of the relative swirl in the far-jet; the smaller the ratio the smaller the relative swirl is changed by disk thickness and disk speed. It is noteworthy that the relative swirls in jets, even from relatively thick disks but with laminar face boundary layers, are smaller than that measured by Chanaud in the far-jet from his thin disk with turbulent face boundary layers.

Riley [15] and Chanaud [16] presented solutions of the boundary-layer equations for a laminar radial jet with weak swirl. Riley observes explicitly, and illustrates in his Fig. 1, that the projections of streamlines on to a plane normal to the axis for a radial jet with swirl are asymptotic to a circle of finite radius. Schwarz [17], apparently unaware of Squire's earlier solution, tackled the problem of the laminar radial free jet again but added to it a solution for the turbulent radial free jet, introducing the assumption of self-similar velocity profiles and so on, making use of some data of Heskestad [18]. Chanaud [7] pointed out the existence of a solution to Schwarz first problem with weak swirl added. Schwarz and O'Nan [19] sought solutions for turbulent radial jets with swirl. The solutions with swirl pertain to weak swirl, in which centrifugal effects are neglected. Such solutions are therefore fitted to asymptotic comparison with experimental results, those found in the far-jet. It is possible to seek higher-order corrections appropriate to intermediate radii; such corrections were discussed by Riley for the laminar radial jet with swirl, for example. The problem in comparing such analyses with disk-jet experiments is that the inner portions of disk jets bear structural details which arise from flow near the rim, and these details are not incorporated in the models: significant comparisons are difficult in these circumstances.

Effects on heat transfer

If a disk rotating about a horizontal axis is heated, the heat will be convected away by the flow induced by rotation. The heated fluid will move into the wake. In the disk wake the fluid will experience buoyancy forces and these should be able to overcome the relatively weak radial momentum in the disk wake, in those regions of the wake where these forces oppose each other. These regions are underneath the disk. Much of the warmed fluid from this region must be expected to rise and become trapped either by the wake entrainment or the flow towards the disk faces themselves. This will introduce a measure of recirculation in the flow on the surface and near the rim of the disk, with some consequent reduction in heat transfer. This may vary depending on the disk thickness. Under these circumstances the attached boundary layers on the disk surfaces may also show some influence of buoyancy, leading to an increase in heat transfer. Thus we find with a rotating disk that, particularly at lower Reynolds numbers, there are multifaceted natural convection effects. This is reminiscent of the situation described by Ede [20] for flow in a straight, horizontal pipe even when temperature differences are quite small. No analytic solution is known for the present problem.

CONCLUSIONS

1. Flow in the boundary layers on the faces or rotating disks is unaffected by the presence of the edge of the disk to within a boundary-layer thickness of the edge.

2. Flow in the near-rim region, radially just beyond the disk edge, involves rapid entrainment of surrounding fluid, reduction of mean fluid velocity, development of turbulence, and formation of a flow pattern reminiscent of flow behind a bluff-tailed body. This flow pattern includes the formation of discrete vortices with their axes approximately in the azimuthal direction: the vortices are more easily seen on thick disks than thin. The flow pattern appears to undergo changes with increase in disk speed; a change at rim Reynolds numbers $\omega Rt/\nu \sim 100$ has been identified from yaw and velocity measurements, and another change when the face boundary layer passes from laminar to turbulent is indicated by rim heat transfer measurements.

3. As disk thickness is increased, the flow in the center plane progressively approaches that of a long rotating cylinder. The relative strength of edge effects diminishes as the disk thickness increases.

4. Further from the disk rim the flow becomes a jet with straight (but non-radial) mean streamlines. The relative degree of swirl in the far-jet varies with disk thickness and speed. The far-jet has properties expected of a radial jet with mild swirl.

Acknowledgements—The author is grateful to the late Professor H. B. Squire and to Professor Sir Owen Saunders for discussions.

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ECOULEMENT AUTOUR D'UN DISQUE TOURNANT ISOLE

Résumé—Une visualisation et des mesures d'écoulement ont été réalisées dans le sens radial dans le champ d'écoulement autour de disques circulaires plats isolés en rotation dans leur plan. L'étude tient compte des effets de l'épaisseur du disque et de sa vitesse de rotation. L'écoulement dans la région située près des bords est semblable à celui dans le proche sillage d'obstacles à terminaison épaisse avec présence de tourbillons. Dans cette même région on trouve un important gradient radial négatif de vitesse de rotation. Au delà des bords du disque l'écoulement devient un jet avec lignes de courant moyennes rectilignes. Le degré relatif de rotation dans le jet lointain varie avec l'épaisseur du disque et sa vitesse de rotation.

DIE STRÖMUNG HINTER EINER ISOLIERTEN ROTIERENDEN SCHEIBE

Zusammenfassung—Es wurde das Strömungsfeld radial außerhalb der Ränder isolierter, flacher, kreisförmiger Scheiben, die in ihren eigenen Ebenen rotieren, sichtbar gemacht und vermessen. Dabei wurde der Scheibendicke und der Rotationsgeschwindigkeit mit untersucht. In der Nähe des Scheibenrandes weist die Strömung mit Wirbeln eine Ähnlichkeit mit der Totwasserströmung hinter einem Körper mit stumpfem Abströmprofil auf. In diesem Bereich tritt ein großer negativer Radialgradient der Wirbelgeschwindigkeit auf. Weiter entfernt vom Scheibenrand verändert sich die Strömung zu einem Strahl mit geradlinigen mittleren Stromlinien. Der relative Drallgrad in diesem entfernteren Strahl verändert sich mit der Scheibendicke und der Rotationsgeschwindigkeit.

ОБТЕКАНИЕ ИЗОЛИРОВАННОГО ВРАЩАЮЩЕГОСЯ ДИСКА

Аннотация — Проведены визуализация и измерение радиального поля течения за пределами изолированных плоских круглых дисков, вращающихся в собственных плоскостях. Исследовалось влияние толщины диска и скорости вращения. Течение в прилегающей к краям диска области сходно с течением в области вблизи ближнего следа за телами плохо обтекаемой фомы. В этой же области имеет место большой отрицательный радиальный градиент окружной скорости. Дальше от края диска течение переходит в струйное с прямолинейными линиями тока. С изменением толщины и скорости вращения диска изменяется относительная степень завихрения в данной области следа.