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CONVECTION NEAR A COOLED DISK ROTATING WITH ITS ENVIRONMENT

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Abstract—Numerical calculations have been carried out for the axisymmetric velocity and temperature profiles near a cooled infinite disk rotating at the same angular velocity as its infinite environment. It is assumed that the flow is laminar and steady. Fluid motion relative to solid body rotation is produced by the centrifugal force acting on the density gradients in the axial direction. The heat transfer to the disk is found for conditions under which the product of the Prandtl number coefficient of thermal expansion and temperature difference is order one or larger.

NOMENCLATURE

C_M, torque coefficient;
f, dimensionless radial velocity, $= u/r\Omega\beta\,\Delta T$;
g, dimensionless tangential velocity, $= v/r\Omega\beta\,\Delta T$;
Gr, Grashof number, $= g\beta\,\Delta T/\nu^{\frac{1}{2}}\Omega^{\frac{3}{2}}$;
h, dimensionless axial velocity, $= w/(\nu\Omega)^{\frac{1}{2}}\beta\,\Delta T$;
H, heat-transfer coefficient;
k, thermal conductivity;
$\mathbf{k}$, unit vector along axis of rotation;
Nu, Nusselt number;
p, pressure;
P, dimensionless pressure;
Pr, Prandtl number;
r, radial position;
T, temperature;
ΔT, $\bar{T} - T_0$;
$\mathbf{u}$, velocity;
u, radial component of velocity;
v, tangential component of velocity;
w, axial component of velocity;
z, axial position.

Greek symbols

α, thermal diffusivity;
β, coefficient of thermal expansion;
θ, tangential position;
μ, viscosity;
ν, kinematic viscosity;
ρ, density;
Φ, dimensionless temperature, $= (\bar{T} - T)/\Delta T$;
ξ, dimensionless axial position, $= (\Omega/\nu)^{\frac{1}{2}}z$;
ξ_{max}, value of ξ to which the numerical integration was carried out;
Ω, angular velocity of the disk.

Superscript

$-$, conditions at $z = \infty$.

Subscript

0, conditions at the disk surface.

INTRODUCTION

IF A DENSITY gradient is imposed normal to the centrifugal force in a rotating fluid, motion relative to solid body rotation is ordinarily produced. The effect of the centrifugal force in rotating systems is thus analogous to the effect of gravity in non-rotating systems. Significant convective heat transfer can be produced in this manner in rapidly rotating turbine blades [1]. Analyses of non-isothermal rotating flows are more complicated than analyses of non-rotating natural convection because of the Coriolis force and the position dependency of the centrifugal force. The Coriolis force often dominates the flow and therefore the fluid motion and heat transfer cannot ordinarily be predicted from experience with non-rotating systems.

Fluid between two parallel disks rotating at the same angular velocity has been considered by Ostrach and Braun [2]. A temperature difference is imposed between the disks so that a laminar axially symmetric flow is produced. In such a geometry the Coriolis force coupled with the centrifugal force tends to produce a tangential velocity (relative to the velocity of the disks); radial flow and convective heat transport are therefore inhibited. Ostrach and Braun present analytical expressions for the velocity field under the conditions that the heat transfer between the disks is governed solely by conduction so that the temperature profile is linear with position between the disks. This problem has also been treated by the author [3]. It was shown that the conduction dominated solution is a limiting case and that large rates of convective heat transfer can occur at high rotational rates. A criterion is given in [3] as to under what conditions convection is important relative to conduction. The above analyses consider small thermal expansion and a Prandtl number of order one.

Consideration is given in this paper to a disk of infinite radius rotating at the same angular velocity as its infinite environment. The disk is cooled and the rotational body forces cause flow of the variable density fluid. The disk is horizontal with the fluid being above; in this case gravity may be neglected since the resulting temperature in the fluid is independent of radial position as seen below. The resulting motion relative to solid body rotation is radially outward near the disk. The flow is assumed to be laminar, axially symmetric, and at steady state. Consideration is given to fluids having a large Prandtl number or a moderately large coefficient of thermal expansion; under these conditions the relative importance of convection to conduction becomes greater.

It may be noted that no steady-state solution exists for transport near a heated disk rotating with its infinite environment. In this case the net radial flow would be inward. Because of conservation of mass, the axial flow would be away from the disk as in the Bödewadt problem [4]. Conduction and convection would both transport heat away from the disk. A steady-state solution would therefore not be attainable; this is analogous to the fact that a steady-state solution does not exist for heat transfer in a semi-infinite wire which has its ends held at different temperatures.

Transport in a laminar axisymmetric rotating flow near a plate in an infinite environment has been previously treated; the acceleration varied along the plate [5]. An experimental study of axisymmetric flow in an annulus having a rotating plate and outer cylinder but with a heated stationary inner cylinder has also been made [6]. The study is interesting in that natural convection due to gravity opposes the forced convection due to the moving bottom.

Non-axisymmetric flows have also received some attention. Davies and Morris have experimentally studied the closed loop rotating thermosyphon [7]. Morris has also carried out an analytical investigation of heat transfer to fully developed flow in a tube rotating around a parallel axis [8]. The results are valid for low rates of heating as a series expansion in rotational Rayleigh number was used.

There has also been a considerable number of studies on non-isothermal flows driven by gravity and strongly influenced by the Coriolis forces of rotation; e.g. [9–13]. A radial temperature gradient (normal to gravity) is imposed on a rotating system non-isothermal surface temperature of a horizontal disk. Depending on the horizontal temperature gradient and the rotational rate the flow pattern is made up of a large cell, waves, or turbulent eddies. These regimes could also exist in the type of flows studied in this paper in which gravity is not important but the fluid is driven by centrifugal and Coriolis forces. Such motions could have the effect of significantly increasing the heat transfer.

FORMULATION AND SOLUTION OF THE EQUATIONS

Consider a viscous fluid near an infinite disk. The disk and the fluid infinitely far from the disk rotate at a constant angular velocity Ω. A cylindrical coordinate system (r, θ, z) rotates with the disk. The disk is cooled producing motion in the fluid with components (u, v, w). The flow is assumed to be steady, axially symmetric, and laminar.

The equations of motion, continuity and energy in the rotating coordinate system are

$$\rho\left[\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} + 2\Omega\mathbf{k}\times\mathbf{u} - \nabla\left(\frac{\Omega^2 r^2}{2}\right)\right] = -\nabla p + \mu\nabla^2\mathbf{u} + \rho\mathbf{g} \quad (1)$$

$$\nabla\cdot\mathbf{u} = 0 \quad (2)$$

$$\frac{\mathrm{D}T}{\mathrm{D}t} = \alpha\nabla^2 T \quad (3)$$

where $\mathbf{k}$ is the unit vector along the axis of rotation. The boundary conditions are

$$\left.\begin{array}{ll} z = 0 & \begin{cases} u = v = w = 0 \\ T = T_0 \end{cases} \\ z = \infty & \begin{cases} u = v = 0 \\ T = \bar{T}. \end{cases} \end{array}\right\} \quad (4)$$

It is assumed that all fluid properties are constant except density in the centrifugal and Coriolis terms of the momentum equations. Gravity has no influence since the disk is taken to be horizontal with the fluid above and the fluid temperature is independent of radial position as is seen below. The density is approximated by

$$\rho = \bar{\rho} - \bar{\rho}\beta(T - \bar{T})$$

in the centrifugal and Coriolis terms, where the overbars denote conditions far from the disk.

It has been shown by previous studies with rotating disks of infinite radius that the axial velocity w is a function only of axial position z and the radial and tangential velocities u and v are linearly dependent on radial position r; these dependencies of the velocities on position are verified by the fact that an exact solution to the governing equations and boundary conditions can be found in this manner [14]. The same dependencies of the fluid velocities on position arise in the present problem. In a like fashion it can be seen that the temperature and the deviation of the pressure from that of solid body rotation depend only on axial position z. In order to determine the length and velocity scales to use in defining dimensionless variables, it is assumed that a balance will arise between the centrifugal driving force of the motion and the Coriolis acceleration. Therefore,

$$\bar{\rho} r\Omega^2\beta\,\Delta T \sim \bar{\rho} V\Omega$$

where V is a characteristic tangential velocity. Replacing $\sim$ by an equality results in

$$V = r\Omega\beta\,\Delta T.$$

A balance between the viscous and Coriolis forces shows that $U = V$ and

$$\delta = (\nu/\Omega)^{\frac{1}{2}}$$

where U is the characteristic radial velocity and δ is the characteristic axial length, i.e. the thickness of the Ekman layer on the disk. Finally the continuity equation yields

$$W = U\frac{\delta}{r} = (\nu\Omega)^{\frac{1}{2}}\beta\,\Delta T$$

where W is the characteristic axial velocity.

The following dimensionless variables are therefore introduced into the equations governing the system.

$$\left.\begin{aligned} \xi &= \left(\frac{\Omega}{\nu}\right)^{\frac{1}{2}} z \\ \Phi(\xi) &= \frac{\bar{T} - T}{\bar{T} - T_0} = \frac{\bar{T} - T}{\Delta T} \\ u &= r\Omega\beta\,\Delta T\, f(\xi) \\ v &= r\Omega\beta\,\Delta T\, g(\xi) \\ w &= (\nu\Omega)^{\frac{1}{2}}\beta\,\Delta T\, h(\xi) \\ p &= p_0 + \bar{\rho}\nu\Omega P(\xi) \\ &\quad - \bar{\rho}gz + \tfrac{1}{2}\bar{\rho}\Omega^2 r^2 \end{aligned}\right\} \quad (5)$$

where p_0 is the pressure at $r = z = 0$. The equations then become approximately

$$f'' = -2g - \Phi + \beta\,\Delta T[f^2 + hf' - g^2 - 2g\Phi] \quad (6a)$$

$$g'' = 2f + \beta\,\Delta T[2fg + hg' + 2\Phi f] \quad (6b)$$

$$h' = -2f \quad (6c)$$

$$\Phi'' = Pr\beta\,\Delta T\, h\Phi'. \quad (6d)$$

In addition there is the z component of the equation of motion from which the pressure could be found

$$P' = -Gr\Phi + \beta\,\Delta T\, h''. \quad (7)$$

The prime denotes differentiation with respect to ξ. Gr is a Grashof number based on the characteristic length $(\nu/\omega)^{\frac{1}{2}}$, or

$$Gr = g\beta\,\Delta T/\nu^{\frac{1}{2}}\Omega^{\frac{3}{2}}.$$

The boundary conditions for (6) are

$$\left.\begin{aligned} f(0) = g(0) = h(0) = 0 \\ \Phi(0) = 1 \\ f(\infty) = g(\infty) = \Phi(\infty) = 0. \end{aligned}\right\} \quad (8)$$

In the above equations the velocities and temperature have been scaled to be order one in the Ekman layer. The quantity $\beta\,\Delta T$ is ordinarily small. If the Prandtl number is order one it can be seen from (6d) that conduction dominates over convection in the Ekman layer. Some numerical solutions are presented here for large Prandtl numbers and small $\beta\,\Delta T$ such as might arise in the heating of heavy oils. The results of calculations for carbon dioxide near its critical point are also presented although these results must be considered approximate since there is significant variation in the physical properties which violates an assumption of the equation formulation. For each of these two cases convection is of equal importance as conduction in the Ekman layer. It should not be inferred from (6d) that when the product $Pr\beta\,\Delta T$ is small that convection is not important in transporting heat to the cooled disk. Outside the Ekman layer the characteristic length scale is larger than $(\nu/\Omega)^{\frac{1}{2}}$ and convection becomes important. It is shown in [3] that for the related case of a fluid between two coaxial rotating disks that large heat-transfer rates can be produced at high rotational rates with $Pr = O(1)$ and $\beta\,\Delta T$ is small.

Equations (6) were solved numerically by means of Nordsieck integration on an IBM 7094. The derivatives $f'(0)$, $g'(0)$, and $\Phi'(0)$ were estimated, the integration carried out to $\xi = \xi_{max}$, and the initial slopes then corrected by an extension of Newton's method [15]. The solution was very sensitive to the estimates of the slopes for large ξ_{max}. Therefore the integration was first done for small ξ_{max} and iterations made until convergence was found. ξ_{max} was then incremented and $f'(0)$, $g'(0)$, and $\Phi'(0)$ estimated to be those which had resulted in $f = g = \Phi = 0$ using the previous ξ_{max}. The final results were obtained at $\xi_{max} = 11{\cdot}0$ which gave four figure accuracy up to $\xi = 6$ to $\xi = 8$ depending on $\beta\,\Delta T$ and the Prandtl number. Four figures were obtained in all cases up to a value of ξ outside the boundary layer and all comments in the discussion are based on this degree of accuracy.

RESULTS

Calculations were carried out for fluids having large Prandtl number while the product $\beta\,\Delta T$

was held small. For example, Glycerin at 68°F has a Prandtl number of $12{\cdot}5 \times 10^3$ and a coefficient of expansion of $0{\cdot}28 \times 10^{-3}\,°\mathrm{R}^{-1}$. For $\Delta T = 0{\cdot}858\,°\mathrm{R}$, $\beta\,\Delta T = 0{\cdot}24 \times 10^{-3}$ and $Pr\beta\,\Delta T = 3{\cdot}0$. Temperature and velocity profiles for this case are presented in Fig. 1. When $\beta\,\Delta T$ is small as in the case being considered, the terms multiplied by $\beta\,\Delta T$ in (6a) and (6b) are negligible and from (6d) it is seen that the dimensionless profiles depend only on the parameter $Pr\beta\,\Delta T$. Thus Fig. 1 is valid for $Pr\beta\,\Delta T = 3{\cdot}0$ with $\beta\,\Delta T$ small. This was checked numerically by solving (6) for $Pr = 1000$ and $\beta\,\Delta T = 0{\cdot}003$. The results were identical to the above discussed case. The cool fluid near the disk moves radially outward with an axial flow being produced toward the disk. The centrifugal force is balanced by the viscous and Coriolis forces in the Ekman layer. The Coriolis force tends to inhibit radial flow. The centrifugal force decreases with increasing axial position since the temperature approaches its value at $\xi = \infty$; the Coriolis force produces an inward radial flow. For the case under consideration this occurs for ξ greater than 2·3.

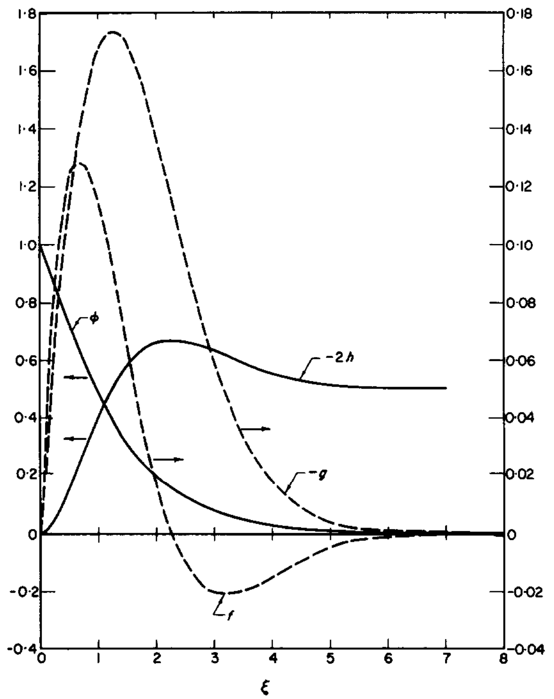

FIG. 1. Velocity and temperature profiles, $Pr\beta\,\Delta T = 3{\cdot}0$.

Profiles for $Pr\beta\,\Delta T = 50$ are shown in Fig. 2. As expected, the temperature approaches its value at infinity at a smaller value of ξ. As is the case in natural convection of high Prandtl number fluids driven by gravity, the velocities are significant outside the thermal boundary layer. It can be seen from equation (6) that outside the thermal boundary layer [but still in the Ekman layer so that $\xi = O(1)$] the equations of motion reduce approximately to

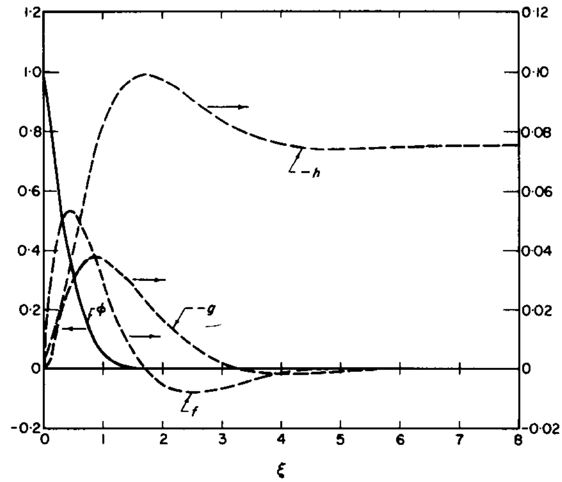

FIG. 2. Velocity and temperature profiles, $Pr\beta\,\Delta T = 50$.

$$f'' = -2g, \quad g'' = 2f. \tag{9}$$

These equations are the same as those governing an isothermal infinite rotating fluid near a disk rotating at a slightly different angular velocity [16]. The velocities of the isothermal flow exhibit decayed oscillations of period 2π in increasing axial position, with g and f $\pi/2$ out of phase. It is possible that the non-isothermal problem considered in this work also would exhibit damped oscillations with increasing ξ since it is governed approximately by (9) with

$f = g = 0$ at $\xi = \infty$ and non-zero conditions at some small ξ (outside the thermal boundary layer). The velocities shown in Fig. 2 do have maxima and minima. For example, g changes sign at $\xi = 3{\cdot}2$ and $\xi = 6{\cdot}5$, f at $\xi = 1{\cdot}7$, $4{\cdot}8$ and around $7{\cdot}8$, and h crosses its value at infinity at $\xi = 4{\cdot}0$. It is noted that the period is approximately 2π and that g and f are about $\pi/2$ out of phase. All of these maxima and minima are not discernible on the scale of Fig. 2. These maxima and minima are not caused by applying the boundary conditions $g(\infty)$, $f(\infty)$, $\Phi(\infty)$ at a finite ξ. Both the position and the values of the maxima and minima were independent of $\xi_{\max}$ (for $\xi_{\max}$ sufficiently greater than the maximum or minimum in question).

The heat transfer to the disk is given by

$$q = H(T_0 - T_w) = k\frac{\mathrm{d}T}{\mathrm{d}z}\bigg|_0$$

$$= -k(T_0 - T_w)\left(\frac{\Omega}{\nu}\right)^{\frac{1}{2}}\frac{\mathrm{d}\Phi}{\mathrm{d}\xi}\bigg|_0.$$

Defining a Nusselt number based on the characteristic length $(\nu/\Omega)^{\frac{1}{2}}$ results in

$$Nu = \frac{H(\nu/\Omega)^{\frac{1}{2}}}{k} = -\frac{\mathrm{d}\Phi}{\mathrm{d}\xi}\bigg|_0.$$

The moment on a disk of radius R is

$$M = \int_0^R \left(r\mu\frac{\partial v_\theta}{\partial z}\right)_{z=0} 2\pi r\,\mathrm{d}r.$$

Defining a torque coefficient by

$$C_M = \frac{2M}{\pi\rho\Omega^2R^4(\nu/\Omega)^{\frac{1}{2}}}$$

there results

$$C_M = \beta\,\Delta T\frac{\mathrm{d}g}{\mathrm{d}\xi}\bigg|_0.$$

The quantities $-\Phi'(0)$, $f'(0)$, and $-g'(0)$ are shown in Fig. 3 as functions of the product $Pr\beta\,\Delta T$. Primes denote differentiation with respect to ξ. The Nusselt number is not proportional to a constant power of $Pr\beta\,\Delta T$, but rather the slope of $-\Phi'(0)$ in Fig. 3 varies from 0·48 to 0·29 for increasing $Pr\beta\,\Delta T$. It is interesting to compare these results to those for convection from a stationary vertical flat plate. For high Prandtl number the average heat-transfer coefficient based on the plate length l can be approximated by

$$\frac{Hl}{k} = 0{\cdot}676\,Pr^{\frac{1}{4}}\left[\frac{gl^3\beta\,\Delta T}{\nu^2}\right]^{\frac{1}{4}}. \qquad (10)$$

To compare this result to those from the rotating disk, l is replaced by r and g by $\Omega^2 r$ where r is

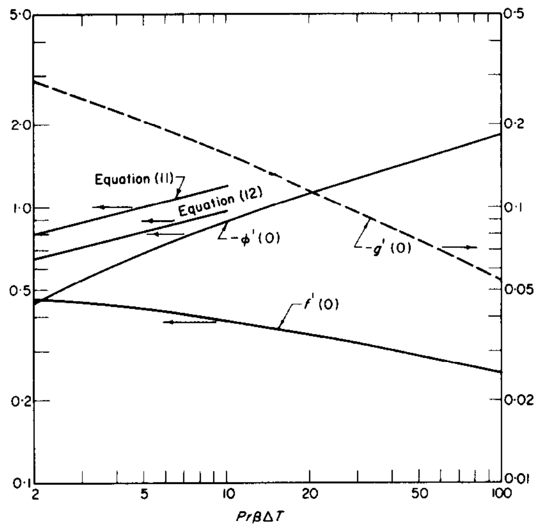

FIG. 3. Nusselt numbers and velocity gradients.

distance from the axis of rotation. With rearrangement this gives

$$Nu = H(\nu/\Omega)^{\frac{1}{2}}k = 0{\cdot}676[Pr\beta\,\Delta T]^{\frac{1}{4}}. \qquad (11)$$

This is also shown in Fig. 3. The Nusselt is also compared to that obtained for the rotating plate with the Coriolis acceleration neglected [17]. In the nomenclature of the present paper the Nusselt number predicted in [17] is

$$Nu = 0{\cdot}546[Pr\beta\,\Delta T]^{\frac{1}{4}} \qquad (12)$$

for large Pr. This is also shown in Fig. 3. It is seen that the results of this paper depend more strongly on $Pr\beta\,\Delta T$ than either (11) or (12).

Equations (11) and (12) are shown only for $Pr\beta\,\Delta T \leqslant 10$. Equations (11) and (12) have both been predicted by integral methods by employing a single thickness for the momentum and thermal boundary layers, an approximation which becomes worse as the Prandtl number increases. Equation (11) has been verified numerically for a Prandtl number up to 1000 [18]. Equation (12) has been verified numerically for $Pr \leqslant 10$ [5]. It is assumed that both (11) and (12) give reasonable accuracy for $Pr \leqslant 1000$. Since $\beta\,\Delta T$ has an order of magnitude of around 0·01, (11) and (12) are shown in Fig. 3 for $Pr\beta\,\Delta T \leqslant 10$. It can be seen from Fig. 3 that the Coriolis force inhibits heat transfer to the disk.

Calculations were also carried out for carbon dioxide at a pressure of 1071 lb/in^2 and a temperature of 83°F, which is near the critical temperature of 87·8°F. At these conditions $Pr = 36{\cdot}4$ and $\beta = 0{\cdot}02°\mathrm{F}^{-1}$ [19]. A temperature drop of up to 3 degF ($\beta\,\Delta T$ up to 0·06) was used. Temperature and velocity profiles for $Pr = 36{\cdot}4$ and $\beta\,\Delta T = 0{\cdot}06$ are shown in Fig. 4. They are quantitatively the same as those shown in Fig. 1. The quantities $\Phi'(0)$, $f'(0)$, and $g'(0)$ have values of $-0{\cdot}470$, $0{\cdot}464$, $-0{\cdot}280$ and $-0{\cdot}381$, $0{\cdot}477$, $-0{\cdot}317$ for $\beta\,\Delta T = 0{\cdot}06$ and $0{\cdot}04$ respectively and a Prandtl number of 36·4.

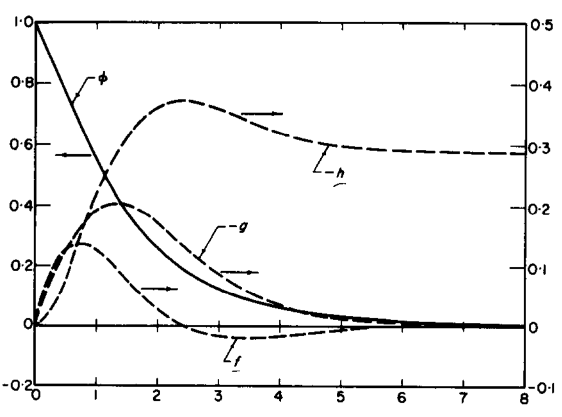

FIG. 4. Velocity and temperature profiles, $Pr = 36{\cdot}4$, $\beta\,\Delta T = 0{\cdot}06$.

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Résumé—Des calculs numériques ont été conduits pour les profils de température et de vitesse à symétrie de révolution près d'un disque infini refroidi et tournant à la même vitesse angulaire que son environnement infini. On suppose que l'écoulement est laminaire et permanent. Le mouvement du fluide relatif à la rotation du corps solide est produit par la force centrifuge agissant sur les gradients de densité dans la direction axiale. Le transport de chaleur vers le disque est obtenu dans des conditions telles que le produit du nombre de Prandtl, du coefficient de dilatation thermique et de la différence de température soit d'ordre de l'unité ou supérieur.

Zusammenfassung—Numerische Berechnungen wurden durchgeführt für achssymmetrische Geschwindigkeits- und Temperaturprofile nahe einer gekühlten unendlichen Scheibe, die mit der gleichen Winkelgeschwindigkeit rotiert als ihre unendliche Umgebung. Es wird angenommen, dass die Strömung laminar und stationär ist. Eine Flüssigkeitsbewegung relativ zur Festkörperrotation wird von der Zentrifugalkraft hervorgerufen, die auf die Dichtegradienten in Achsialrichtung wirkt. Der Wärmeübergang an die Scheibe wurde für Zustände gefunden, bei welchen das Produkt aus Prandtl-Zahl, thermischem Ausdehnungskoeffizient und Temperaturdifferenz von der Grössenordnung eins oder grösser ist.

Аннотация—Проведены численные расчеты осесимметричных профилей скорости и температуры вблизи охлаждаемого бесконечного диска, вращающегося с той же угловой скоростью, что и бесконечная окружающая среда. Движение жидкости относительно вращения твердого тела возникает под действием центробежной силы, действующей на градиенты плотности в осевом направлении. Определен перенос тепла к диску для условий, при которых произведение коэффициента теплового расширения на число Прандтля и температурную разность будет порядка единицы или больше.