HEAT AND MASS TRANSFER NEAR ROTATING SURFACES

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Extensive research concerning the heat and mass transfer near axially symmetrical surfaces which rotate in a viscous Newtonian fluid has, especially during the recent years, been correlated with the solution of various technical and scientific problems: development of cooling systems for the rotors of turbo and electrical machines, use of the rotating motion for increasing the heat transfer rate in chemical and other engineering processes, especially in the partition of gaseous and liquid mixtures, and it has also been correlated with the study of circulation in oceans and in the atmosphere, etc.

These problems appear rather complex, owing to the complexity of the hydrodynamic phenomena underlying these processes, especially owing to the three-dimensionality of flows and to the diversity of geometrical, hydrodynamic, and thermal parameters.

During the last few years there have been published several monographs and surveys on the subject of heat and mass transfer near rotating surfaces and in rotating systems [1-4]. Because of the fast growing amount of research work, however, these few references do not completely cover the state of the art and the aim of this here survey is to fill, to some extent, that gap.

Since the basic elements of axially symmetrical rotating surfaces include flat (disks) and cylindrical ones but also conical and spherical ones, hence the most significant research effort has been directed, above all, toward determining the heat- and mass-transfer characteristics of such surfaces. We will here also consider these first.

Disk in an Infinite Space (Laminar flow). Among the first problems solved theoretically was the one concerning a flow of fluid near an infinitely large disk rotating in a stationary medium. The solution obtained by Karman in 1921 [5] has become the basis of subsequent studies concerning the hydrodynamics and then also the heat and mass transfer in the case of a rotating disk. The exact solution to the system of ordinary differential equations, which had been obtained by Karman, was then checked by Cochran [6]. Tests have confirmed the validity of this solution for a laminar flow.

A solution to the problem of heat transfer near a rotating disk was first given by Kibel' [7]. The calculations were later refined on a computer [8, 9]. The first experiment was performed by Young [10], whose values for the heat-transfer coefficient were higher than the theoretically predicted ones, probably because of natural convection especially effective at low Reynolds numbers $\mathrm{Re} = r^2\omega/\nu$ and with the disk in a horizontal position. More precise experiments [11] yielded a close agreement with calculations: for air ($\mathrm{Pr} = 0.7$) near an isothermal disk the results fitted the formula

$$\mathrm{Nu} = \mathrm{Nu}_{\mathrm{mean}} = 0.36\mathrm{Re}^{0.5} \tag{1}$$

($\mathrm{Nu} = qr/(\lambda\Delta T)$, $\mathrm{Nu}_{\mathrm{mean}} = q_{\mathrm{mean}}r/(\lambda\Delta T)$). Further refined measurements [12] were made taking into account convection and the flow pattern at the disk boundary.

The heat transfer at a rotating disk is affected by the dissipation of mechanical energy, which is characterized by the following temperature parameter:

$$\vartheta = r^2\omega^2 : (c_p\Delta T) \tag{2}$$

(this quantity is sometimes called the Eckert number). A strong effect here have the radial gradient of temperature drop $\Delta T = T_D - T_\infty$ between disk and ambient medium as well as the Prandtl number. The effect of ϑ was studied in [13, 14, etc.], the effect of the Prandtl number was studied in [8, 13-16], and the

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effect of the radial temperature-drop gradient was studied in [14, 16-18]. The results obtained so far concerning the effects of these parameters under actual conditions are yet to be verified experimentally. Mass-transfer measurements were made with naphthalene sublimating on a rotating disk (Pr = 2.4) [19-20]. Also heat-transfer measurements were made at large temperature drops ΔT and with the viscosity of the fluid varying over a wide range [21].

The laminar mode of heat transfer under transient conditions was analyzed by the numerical method for the case of an isothermal disk with ΔT varying in time (at ω = const or $\omega = \omega(t)$) [22-28].

Temperature fields around a thermally insulated disk have been calculated as a function of the Prandtl number [29]. The values of $\tau_1(0)$ and $\tau_2(0)$ were obtained there necessary for determining ΔT due to viscous dissipation:

$$\Delta T = T_d - T_\infty = T_\infty \Pr \frac{r^2\omega^2}{c_p T_\infty}\left[\frac{\tau_1(0)}{\mathrm{Re}} + \tau_2(0)\right]. \tag{3}$$

The effect of compressibility of a viscous fluid on the heat transfer at a rotating disk was studied in [30, 31], and calculations for a rarefied gas were made in [32, 33].

Among the first ones to study the mass transfer near a rotating disk was Levich, who based the measurement of diffusion currents in solutions on the theory of an electrode with a rotating disk [34]. A survey of studies on this subject is given in [35], along with new experimental data obtained by that author. New data are also presented in [36-38].

The effect which a uniform blast on a rotating disk perpendicularly to its surface has on the heat transfer has been determined first numerically [39] by the integral ratios method. Exact solutions for the heat transfer under a blast and with a square-law temperature head variation along the disk radius, with heat dissipation and the Prandtl number taken into account, are given in [40, 41]. The effect of a blast on the sublimation of naphthalene off a rotating surface was studied experimentally in [42, 43].

The effects of blowing or suction at the surface of a rotating disk on laminar heat and mass transfer have been calculated in [9, 44]. The effect of simultaneous blowing and suction (or injection) has been analyzed theoretically in [45]. The effect of blowing on the heat transfer under a power-law temperature variation along the disk radius has been calculated in [46].

The heat transfer during a waveless spreading of a fluid film over the surface of a rotating disk has been analyzed in [47] by the method of finite differences. The heat transfer in a jet of coolant striking a rotating disk at right angles at the center has been calculated in [48]. The results for all these cases are yet to be verified experimentally.

Condensation and evaporation at the surface of a rotating disk have been analyzed theoretically and experimentally in [49-53]. The dissolution of a rotating tantalum disk in liquid tin was also studied [54].

The heat transfer near a horizontal isothermal disk rotating together with the surrounding medium, at the same velocity, when convection occurs as a result of a density gradient and a centrifugal force has been analyzed in [55]. This problem has some practical applications in geophysics.

Disk in an Infinite Space (Turbulent flow). As the local Reynolds number $\mathrm{Re} = r^2\omega\nu^{-1}$ reaches the value $3 \cdot 10^5$, the flow becomes turbulent. For calculating the heat transfer under turbulent flow conditions, one uses the Reynolds analogy in conjunction with appropriate data [5, 56, 57] pertaining to the velocity boundary layer. The Reynolds analogy is based on the similarity between velocity and temperature distributions. As Dorfman has noted in [58], a temperature profile resembles that of circulation velocities when Pr = 1 and the temperature drop ΔT is distributed along the disk radius according to a square law: $\Delta T \sim r^2$. In this case

$$\mathrm{Nu} = \mathrm{Re}\,\tau_\varphi : \rho\,(r\omega)^2, \tag{4}$$

where τ_φ is the circular component of frictional stress at the disk surface. The Nusselt number can be determined for any $\Delta T(r)$ distribution on the basis of the integral energy equation, assuming the dependence of the Stetson number on $R_T^{**} = \delta_T^{**} r\omega\nu^{-1}$ to be universal (δ_T^{**} denoting the thermal capacity thickness [58, 59]). Specifically, for a power-law distribution $\Delta T \sim r^m$

$$\mathrm{Nu} = (\mathrm{Nu})_{m=2}\left(\frac{3+2n}{m+1+2n}\right)^{n-1}, \tag{5}$$

where n is the exponent in the $(\mathrm{Nu})_{m=2} \sim \mathrm{Re}^n$ relation obtained from (4) on the basis of the $\tau_\varphi : \rho (r\omega)^2$ values. We note that for a laminar flow n = 0.5 and formula (5) too yields almost exact results. For a turbulent flow n = 0.8 in the Re = 10^6 range.

The effect of the Prandtl number has been analyzed on the basis of the three-layer model of the boundary layer according to Karman [59] for the circulation component of the velocity vector (at m = 2). These calculations yield subsequently for the isothermal case (m = 0):

$$\mathrm{Nu} = a\,\mathrm{Re}^{0.8}\mathrm{Pr}^{0.6}, \tag{6}$$

where a = 0.0196 for a Reynolds number in the $7 \cdot 10^5$ range and a = 0.0257 for a Reynolds number in the 10^6 range. This result agrees closely with the test data in [11, 60] for air (Pr = 0.72). As for other values of the Prandtl number, only test data on the sublimation of naphthalene (Pr = 2.4) are available [19] and they yield values higher than those based on formula (6). A predominance of mass transfer over heat transfer has been found also in other studies of naphthalene sublimation [20].

A different method of calculating the turbulent heat transfer at a rotating disk, with the radial ΔT distribution and with the Prandtl number taken into account, was proposed by Davies in [61]. An analysis of all theoretical and experimental data in [62], where also a modification of the Davies method is used, has shown that the available test data fit best the modified Dorfman formula [58]:

$$\mathrm{Nu} = 0.0212\,(m + 2.6)^{0.2}\,\mathrm{Re}^{0.8}\mathrm{Pr}. \tag{7}$$

Thus, it is suggested here that Nu is a linear function of Pr rather than of $\mathrm{Pr}^{0.6}$. On the other hand, on the basis of their own experimental data and on the basis of certain theoretical concepts, the authors of [63] have suggested $\mathrm{Pr}^{0.47}$ for large values of the Prandtl number. A different result was obtained in [64-65]. Consequently, there is a need for further experimental and mathematical studies in this area.

The effect of disk anisothermy on the heat transfer between disk and air has been analyzed on the basis of experimental data by solving the reverse temperature problem [66]. The heat transfer at a disk with a constant thermal flux along the radius was studied experimentally in [67, 68]. Not surprisingly [69], the result here shows that this is close to the isothermal case.

Studies were also made concerning the effect of surface roughness [70] and of perforations in the disk [71] on the increase in the heat-transfer rate.

Rotating Cone in an Infinite Space. We note that for large aperture angles (half-angle $\alpha \geq 45°$) the same Nu = f(Re, Pr) relations apply as for a disk, if the following notation is used:

$$\mathrm{Nu} = qx : \lambda (T_{\mathrm{wall}} - T_\infty), \quad \mathrm{Re} = xr\omega\nu^{-1}, \tag{8}$$

with x representing the length of the conical generatrix ($x = r : \sin\alpha$) [72, 73]. For small apertures, when the thickness of the boundary layer is comparable to the distance r from the axis, these relations become different – especially near the apex [74 et al.]. The effect of an anisothermal cone surface was studied in [16, 75], while simultaneous forced and natural convection from a hot cone rotating about its vertical axis and having a linear temperature distribution along its generatrix have been analyzed in [76] (see also [77]). The additional effect of suction was considered in [78]. Theoretical and experimental studies of heat and mass transfer at a cone under a uniform blast in the axial direction were made in [79-81]. Condensation on a rotating cone surface was studied in [82].

The mass transfer from a rotating cone frustrum (and cylinder) was studied experimentally in [83]. We note that, just as in the case of a disk, there is a need to further study turbulent heat and mass transfer, the effects of blast, injection, and suction, and other phenomena associated with turbulent flow.

Disk in a Bounded Space. Disk surfaces in various engineering devices and systems most often rotate inside a bounded space. Particularly important is the case of a surface rotating near a stationary plane surface. Of interest here is the Bödewadt problem [84] of a fluid rotating near a stationary plane. The laminar heat transfer in this case was been calculated in [85, 86]. The effect of finite disk dimensions on the Bödewadt flow has been analyzed in [87], but the heat transfer has not yet been calculated for this special case. We note that the rate of dissolution of a solid disk in a rotating mass of fluid was measured in [88].

Automorphic problems of an infinite plane rotating near a flat stationary wall were considered in [89-94], and with simultaneous injection in [93, 94]. The heat transfer in this case has been analyzed theoretically in [95], and experimental data (without injection) are given in [96].

When radial discharge flow occurs between disks, the problem becomes nonautomorphic and it is solved by small-parameter series expansion [97-99] or the partial differential equations are solved by the method of finite differences. In the latter case the solutions are rather easily obtained, provided that the axial gap is small and there is no backflow, i.e., when the system of Navier–Stokes equations reduces to a system of parabolic equations [100].

Such a method was used for analyzing the heat transfer in the case of two disks, one stationary and one rotating, with a discharge flow of fluid from the center to the periphery [100, 101] or from the periphery to the center [102], with a jet blowing against a flat surface [101], and also in the case of two disks rotating or with a curvilinear flow between two stationary disks [103] (see also [104]).

The first theoretical and experimental study of the flow hydrodynamics near a rotating disk inside a cylindrical shell was made by Schultz-Grunow [105]. Later on, other solutions were proposed [106 et al.] and measurements were made over a wide range of parameter values [107, 108]. The heat transfer under these conditions has been analyzed in [1, 109, et al.] by approximate methods. More precise methods for solving this problem have been developed in [91, 110]. The exact equations of hydrodynamics and heat transfer have been solved by the methods of finite differences [111-113] (with laminar flow under consideration).

The effect of discharge flow on a turbulent stream between a stationary and a rotating disk as well as between two rotating disks has been calculated approximately in [114, 115]. More refined calculations (including heat transfer) have been made in [116-119]. The heat transfer was calculated there by the method developed in [58, 59] for a free disk.

Sedach was among the first to study the hydrodynamics of a stream used for cooling the wheel of a gas turbine [120], while Kapinos [121] made an experimental study of the heat transfer under these conditions. A number of subsequent experimental studies deal with the heat transfer during the cooling of gas-turbine wheels: shielded cooling [122], radial cooling [117-119, 123, 124], jet cooling [125-128], centripetal and film cooling [129-131] (see also [132]). The mass transfer during the rotation of a disk near a stationary plane or inside a shell was studied experimentally in [133-135]. According to [136], the mass-transfer rate is here approximately 1.35 times higher than the heat-transfer rate.

Problems of transient flow and transient heat transfer between a rotating and a stationary disk have been analyzed theoretically in [137-139].

The problem of laminar convection in a cavity between two rotating disks at different temperatures, i.e., under an axial density gradient, has been solved in [140]. Transient modes in this configuration were considered in [141]. Approximate solutions have been obtained for convection inside a rotating bounded cavity [142-144]. Viscous heating of a fluid inside a narrow gap between a rotating and a stationary disk was studied in [145].

The hydrodynamic characteristics peculiar to a flow between rotating disks are used for separating liquids and gases. Calculations pertaining to these processes are shown in [146-150].

Rotation of a Spherical Surface. A laminar boundary layer at a rotating sphere was first calculated by Howarth [151] and then more precisely by others [152], whereupon the laminar heat transfer here was calculated in [153]. The characteristics of a laminar boundary layer were measured first by Kobeshi [154]. More extensive measurements, also of turbulent flow, were made in [155].

It is to be noted that the solutions for a rotating sphere which have been obtained through a series of Navier–Stokes equations [156-157] are valid for small Reynolds numbers.

The laminar heat transfer at a spherical surface at $Pr \to \infty$ has also been calculated by the Davies method [158].

Concerning the laminar heat transfer at a rotating sphere, experimental data have been obtained for air [159] which yield too high values for the Nusselt number and this can be explained by a radial current flowing away from the equator. The heat transfer has also been analyzed by the Schlieren method [160]. Sublimation of naphthalene off a rotating sphere was studied in [161]. The mass transfer to a spherical rotating electrode was measured in [162].

For a turbulent flow there are no test data available on the heat transfer, but theoretical calculations have been made by the approximate method of integral ratios with the aid of the generalized Reynolds analogy [163].

Laminar heat transfer at a spherical surface under a blast in the axial direction has been calculated in [164] on the basis of the corresponding solution to the problem of a velocity boundary layer [165]. The heat transfer between two rotating spheres at small Reynolds numbers (creeping flow) has been calculated in [166].

Heat Transfer at the Surface of a Rotating Cylinder. Laminar heat transfer during the rotation of a cylinder has been treated thoroughly in the monograph by Targ [167] (see also [1]). Further studies on this subject were made in [168]. The effect of compressibility was considered in [169].

Turbulent heat transfer during the rotation of a cylinder in free space was studied experimentally in [170-172]. The results agree closely with the three-layer Karman model [1]. We note that the velocity profile in a turbulent stream about a freely rotating cylinder was measured in [173]. More recently, temperature and velocity profiles along with the heat transfer near a cylinder were measured over a wide range of Reynolds numbers [174]. According to [175], fins on a rotating cylinder surface increase the mass-transfer rate appreciably.

Transition from laminar to turbulent flow in the gap between rotating cylinders was first studied by Taylor [176], who also studied the development of turbulence and the temperature fields between cylinders [177]. Numerous heat-transfer measurements were made in a fully developed turbulent flow in the gap between a rotating inner and a stationary outer cylinder [178-186], and the accompanying hydrodynamic phenomena were also examined [187, 188] (see also [177, 191, et al.]). A semiempirical method of calculating the hydrodynamics and the heat transfer under these conditions was proposed in [1]. A theoretical generalization of experimental results was then proposed in [183, 187, 189]. Test data have also been generalized in [190]. The effect of an axial stream in a narrow gap has been calculated in [191] and was studied experimentally in [178, 184, et al.]. An axial stream exerts a stabilizing influence on the laminar flow in that it inhibits the transition to turbulence.

An approximate method of calculating, on the basis of test data, the heat transfer during the transition stage with Taylor vortices generated in the gap was proposed in [192] (see also [193]). The heat transfer during rotation of the outer cylinder and during rotation of both cylinders was measured in [194] and [195], respectively (see also [196]). Several studies have been published on cooling systems for rotating cylindrical and other components of electrical machines [198-200 et al.].

Heat Transfer near an Arbitrary Axially Symmetrical Surface. The conditions have been established under which automorphic solutions to the equations of a laminar boundary layer exist for surfaces rotating in an infinite stationary viscous medium [201], these conditions being reducible to a power-law relation between distance from the rotation axis r and generatrix length x: $r \sim (x + x_0)^m$. The existence conditions for automorphic solutions to the energy equation are also expressed in terms of a power-law relation between temperature drop $T_{wall} - T_\infty$ and generatrix length x: $T_{wall} - T_\infty \sim (x + x_0)^n$ [85]. Numerical solutions to this problem have been obtained in [202, 203]. On the basis of automorphic solutions, an approximate method of calculating the thermal and the velocity boundary layer has been developed in [202] for arbitrary surfaces.

Another method of solution for surfaces with an arbitrary contour r(x) is by series expansion of the unknown quantities in terms of small parameters $\varepsilon_1 = dr/dx - 1$ and $\varepsilon_k = r^{k-1}(d^{k-1}\varepsilon_1/dx^{k-1})$, which leads to a system of ordinary differential equations [204]. Compressibility is taken into account by applying the Dorodnitsyn transform [204]. The solution to recurrent differential equations are given in [205], where a typical application of the results to a rotating sphere is also shown.

The boundary layer at an arbitrary rotating body under an axial blast was first calculated by Schlichting [206]. The results of his method have made it possible to calculate the heat transfer [207] (see also [208]). The compressible case was considered in [209]. We note that the basic principles of calculating the flow of a compressible fluid around a rotating surface are explained in [210-211].

For a turbulent flow, an approximate method of calculating a thermal and a velocity boundary layer was proposed in [212], with the results shown for a sphere and for half a solid of revolution. Calculations of the turbulent heat transfer are based on the similarity between the temperature distribution and the profile of circulation velocities at $T_{wall} - T_\infty \sim r^2$ and Pr = 1, which follows directly from the similarity between the respective equations and between the respective boundary conditions. The same method which has been developed for a disk [58] applies to an arbitrary $T_{wall} - T_\infty$ distribution along the generatrix. Appropriate experiments are required for refining the theory and for obtaining necessary data. Except for calculations pertaining to velocity boundary layers [213-215], neither calculations nor test data are available for surfaces under a blast other than the special surfaces mentioned here.

Heat Transfer at Rotating Tubes (and other objects). Some of the first experiments to determine the characteristics of heat transfer at a rotating surface were performed by Mikheev [216], who studied a tube revolving about a parallel axis. This was also the subject of more recent studies [217-219]. The effect of a tube rotating about its own axis was considered in [220, 221].

Other studies were concerned with the heat transfer in a short rotating tube [222] and in the entrance segment of a long rotating tube [223]. Also a tube rotating about a perpendicular axis was considered: in terms of the heat transfer [224] as well as diffusion [225] (see also [200, 226]).

Contiguous to these problems are those of the heat transfer in blind rotating tubes [227, 228] (a brief survey of the essential results is given in [229]).

Several studies were made in the area of geophysics and astrophysics, in regard to the heat convection around rotating bodies due to nonuniform heating [230-235 et al.].

Studies were also made to determine the effect of a magnetic field and of electric fields in rotating systems with an electrically conductive liquid. A survey of these studies must be presented separately.

CONCLUSIONS

During the last decade there has been done a huge amount of experimental and mathematical research into the characteristics of heat and mass transfer near rotating surfaces. Particularly successful has been the solution to the problem of laminar heat transfer, which is due to the development of computers and appropriate numerical methods increasingly indispensable for these studies. The situation is less satisfactory in the case of turbulent flow, because a theoretical model has not been perfected yet and empirical data are incomplete. Thus, for example, the effect of the Prandtl number in a turbulent flow remains indeterminate: the data obtained so far are insufficient and yield contradictory answers.

The calculation of turbulent heat and mass transfer are too approximate for the case of a radial flow between two disks when rotation occurs, although apparently the available data in the first approximation seem to satisfy practical requirements. An analysis of the more complicated case of rotating disks with jet and face cooling still rests on a rather weak theoretical foundation as far as turbulent flow is concerned.

Entirely untouched has been the problem of heat transfer during the rotation of an arbitrary body either under a blast, with injection, with suction, or with a surface jet. Calculations are incomplete even for the laminar case.

There is much activity underway in solving flow field equations (Navier–Stokes), energy equations, and continuity equations for streams near various rotating bounded solids, in determining the structure of currents flowing out of equatorial regions, and in evaluating their effects on the heat and mass transfer. Both numerical and analytical computer oriented methods are applicable here.

As a basis for solving problems of turbulent flow, one may use methods analogous to those proposed by Glushko [236] and Spaulding [237], which reduce the problem to a computer solution of the differential equations of turbulent flow and heat transfer in appropriately closed forms. The principles of such an approach were recently incorporated into the calculation of turbulent discharge flow between rotating and stationary disks [238] with a subsequent determination of the heat transfer [239].

There is an urgent need to study the loss of stability in a laminar flow and the transition to turbulence, to study the separation or detachment zone at sudden changes in the surface curvature, etc.

Still unsolved problems include relating problems of heat transfer, i.e., a combined determination is yet to be made of the temperature distribution inside a rotating body and the temperature field in a surrounding viscous fluid. This problem has been solved so far only for a thick and infinitely large rotating disk with different (differently heated) fluids on both sides [240].

We note that the subject of this survey, as has been pointed out earlier, covers only Newtonian fluids and includes neither problems of heat and mass transfer near surfaces rotating in rheologically complex fluids nor the anomalous (non-Newtonian) behavior of gases. And yet, the rheological characteristics of fluids become manifest particularly during rotation. These problems have been covered by Reiner in his monograph [241] as well as by Lykov and his students (see, e.g., [242] and appendix, also many other references). They merit a separate survey.

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