MEASUREMENTS ON MASS TRANSFER IN A ROTATING DISK SYSTEM

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Results are given on the local mass transfer between rotating and fixed disks with and without a radial gas flow between them.

There has recently been much interest in the flow characteristics and heat and mass transfer in rotating systems of disk type on account of new designs of such systems (gas turbines, disk storage devices, condensers for desalinating seawater, and aircraft nose-cooling devices).

Several studies have been reported [1-3] of heat and mass transfer from a screened rotating disk; however, the methods gave only integral or average values for the heat- and mass-transfer coefficients. Therefore, it was not possible to distinguish some major features of the heat and mass transfer. Nothing has been published on the local characteristics of heat and mass transfer in relation to gap size, rotation speed, and gas-flow speed.

We examined mass transfer from the local and integral removal of a subliming material (naphthalene) deposited on the surface of a rotating disk. Before each experiment, the chemically pure naphthalene ($C_{10}H_8$) was deposited in the molten state on a disk preheated to t = 50°C, which provided a dense layer. The coated disk was turned on a lathe, and then polished manually. The surface roughness did not exceed 1-2 μm. Then the disk was mounted in an X-Y control, and a vertical optical system with a scale division of 0.001 mm was used to record profiles of the surface in four mutually perpendicular radial directions. The difference in the profiles before and after the run determines the local loss of naphthalene. The integral loss was determined by weighing the disk on an analytical balance to an accuracy of 0.1 mg. Corrections were applied for the loss during emplacement, startup, and stopping.

The local mass-transfer coefficient is defined by

$$\beta_m = \frac{m'}{\rho_0 - \rho_\infty}. \tag{1}$$

The mass loss from unit surface was found from the change Δy in the profile during the time $\Delta\tau$ of a run:

$$m' = \rho \frac{\Delta y}{\Delta \tau}. \tag{2}$$

As the density of the naphthalene vapor in the gas flow ρ_∞ was only (2-3%) ρ_0, one can assume with sufficient accuracy that $\rho_\infty = 0$; the naphthalene vapor density at the surface ρ_0 may be put in the following form if the vapor is represented as an ideal gas:

$$\rho_0 = P/RT. \tag{3}$$

The following semiempirical formula [4] gives the partial pressure of the saturated vapor of naphthalene:

$$\lg P = \frac{0.0533a}{T} + b; \quad a = 714010; \quad b = 13.575. \tag{4}$$

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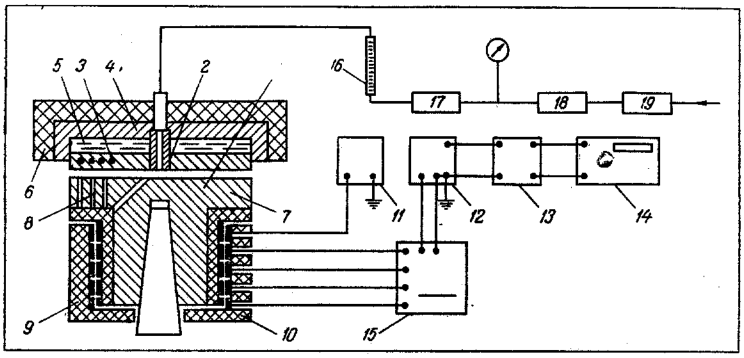

Fig. 1. The apparatus: 1) rotor; 2) stator; 3) thermistors; 4) jacket; 5) water; 6) insulating jacket; 7) naphthalene coating; 8) thermistor; 9) fixed current lead; 10) rotating system; 11) oscillator; 12) hf amplifier; 13) detector; 14) digital millivoltmeter; 15) switch; 16) flowmeter; 17) filter; 18) ballast vessel; 19) air pump.

Then the expression for the local mass-transfer coefficient becomes

$$\beta_m = \frac{RT}{P}\, m' = \frac{\rho RT}{P} \cdot \frac{\Delta y}{\Delta \tau}. \tag{5}$$

The mean mass-transfer coefficient is defined by the following formulas:

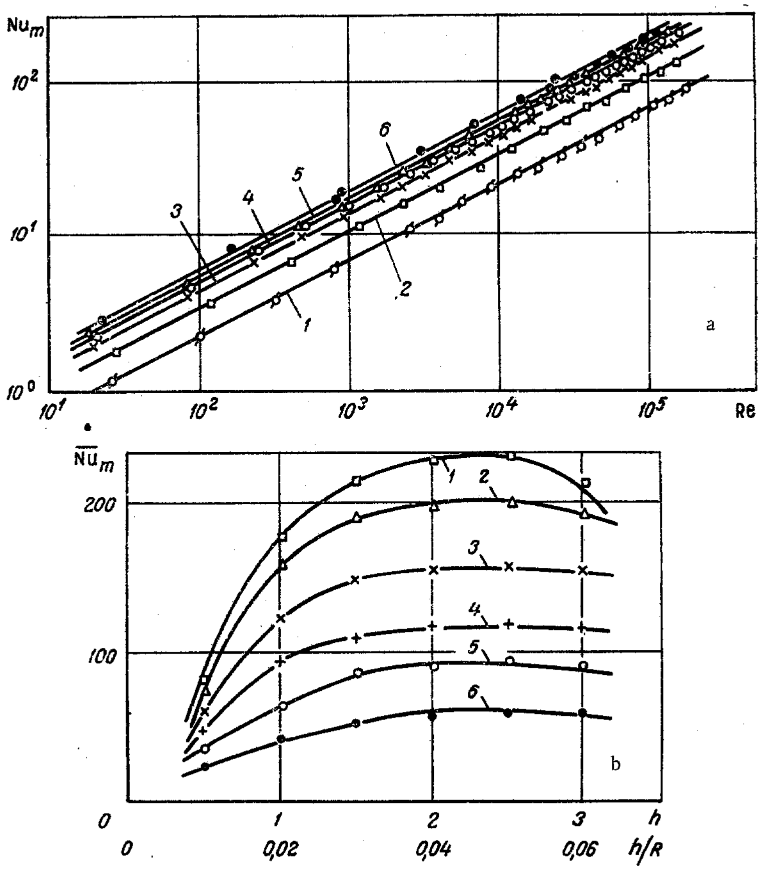

Fig. 2. Heat transfer from screened rotating disk: a) local $\mathrm{Nu_m}$ [1) h = 0.5 mm; 2) 1; 3) 1.5; 4) 2; 5) 3; 6) 2.5]; b) mean integral $\overline{\mathrm{Nu}}_\mathrm{m}$ [1) $\mathrm{Re_r} = 1.97 \cdot 10^5$; 2) $1.664 \cdot 10^5$; 3) $1.106 \cdot 10^5$; 4) $0.611 \cdot 10^5$; 5) $0.368 \cdot 10^5$; 6) $0.136 \cdot 10^5$].

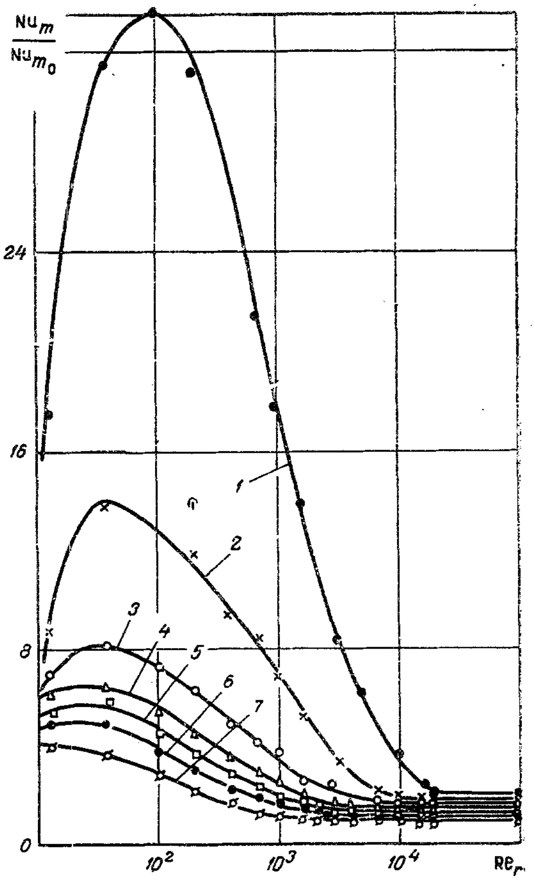

Fig. 3. Relation of Nu_m/Nu_{m0} to Re for various $Q/2\pi h\nu$ = 1) 1130; 2) 564; 3) 337; 4) 202; 5) 109; 6) 73; 7) 28.

$$\bar{\beta}_m = \frac{\bar{m}RT}{PA}, \tag{6}$$

$$\bar{\beta}_m = \frac{\int_s \beta_m dA}{\int_s dA}. \tag{6'}$$

The value given by (6') using the actual surface profile and the measured $\bar{\beta}_m$ from (6) agreed to within 2-2.5%.

The Nusselt diffusion number is

$$Nu_m = \frac{\beta_m r}{D} = \rho \frac{RT}{P} \cdot \frac{\Delta y}{\Delta\tau} \frac{r}{D}. \tag{7}$$

The following semiempirical relationship gives the diffusion coefficient for naphthalene vapor in air:

$$D = 1.185 \cdot 10^{-9} T^{3/2}. \tag{8}$$

The measurements were made with an apparatus whose working part (Fig. 1) consisted of two plane-parallel horizontal disks, one of which rotated at 10-25 • 10^3 rpm, while the other was immobile; the speed throughout the run was kept constant using an autotransformer controlled by a servo system. The speed was measured either by an induction transducer or by a stroboscope.

Formulas (4)-(8) show that a considerable effect on the error in the result comes from the error in measuring the surface temperature of the naphthelene layer. We cannot agree with the conclusions of [1-3] that the temperature rise caused by aerodynamic heating is essentially small and can be neglected. Preliminary tests showed that the dissipative heating raises the rotor temperature by 3-4°C. The temperature of the rotor under the naphthalene was measured at four points along the radius with MT-57 microthermistors, which were linked to a capacitive coupling system [7]. The error in this system did not

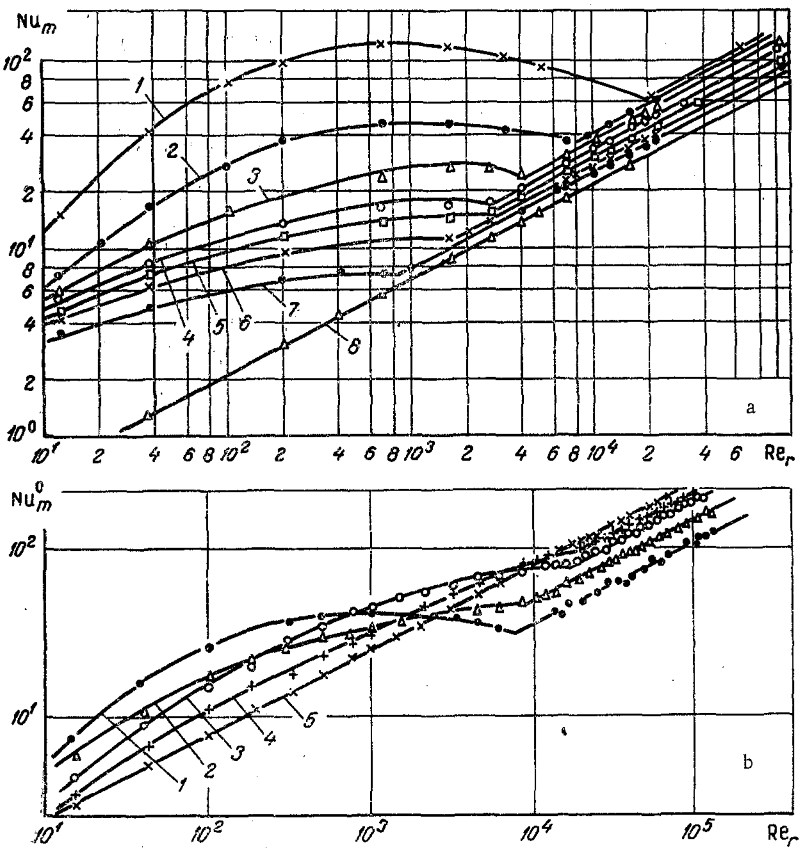

Fig. 4. Mass transfer in a rotating system with through flow: a) effects of flow rate: [1) $Q/2\pi h\nu = 1130$; 2) 564; 3) 337; 4) 202; 5) 109; 6) 73; 7) 28; 8) 0]; b) effects of disk separation [1) h = 0.5 mm; 2) 1.0; 3) 2.0); 4) 2.5; 5) 3.0].

exceed ±0.2°. The stator was fixed in a thermally insulating jacket, with a cavity containing water at a constant temperature maintained in circulation. The surface temperature of the stator was measured by KMT-14 thermistors to an accuracy of 0.1°.

In some of the runs, air was supplied from a pump via an air filter and reservoir to a central hole in the stator of diameter 1.2 mm. The air-flow rate was measured by a flowmeter to an accuracy of 0.25 liter/h. During the experiment the stator was held in a coordinate device to set the gap between the disks. This device also eliminated any taper in the gap.

It has been shown [6] that the flow pattern set up by rotation of the screened disk is complex and dependent on the geometry and size of the system, as well as on the speed. In the absence of the central gas flow, the motion on the immobile disk is directed towards the center, while that on the rotating disk is from the center outwards, on account of centrifugal and viscous forces.

The input air substantially alters the flow pattern in the gap; it has been observed [8] that the radial component of the flow is entirely dependent on the flow characteristics in the absence of air input, whereas an air input causes the flow to be determined in the main by the output from the source, and the difference between natural and forced flows is not important in examining the heat- and mass-transfer processes.

The flow pattern caused by a rotating disk is dependent on the stator size [9]; if a diameter of the fixed disk exceeds that of the rotor, the flow may become unstable, with periodic fluctuations in the flow to and from the center. Therefore, to avoid secondary flows and eliminate effects on the rotating center, we used disks of identical diameter in all experiments.

Figure 2 shows the results of mass transfer in the absence of air flow. The mass transfer increases with the gap up to h/R = 0.05 (h = 2.5 mm); further increase results in some reduction in the transfer rate, and at h/R = 0.06 (h = 3 mm) the type of transfer approaches that for an open disk.

The effects of the gap may be explained by supposing that the boundary layers on the stator link up

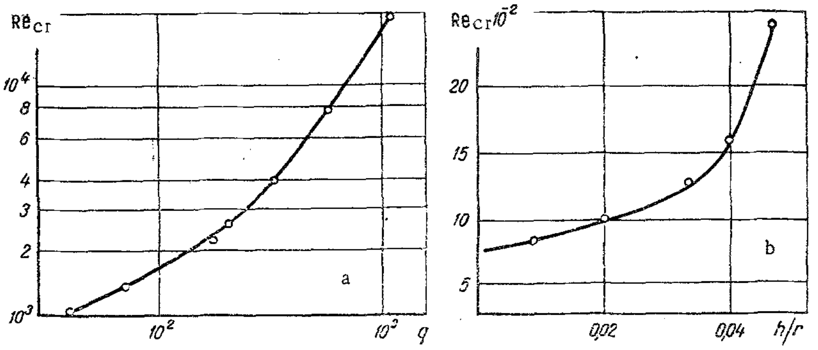

Fig. 5. Critical Reynolds number as a function of: a) gas-flow rate; b) disk separation.

for laminar flow in a narrow gap with $h/R = 0.006-0.02$; as the gap increases $(0.006 < h/R < 0.02)$, a secondary flow of the fluid is set up, which substantially increases the mass-transfer rate. Any further increase in the gap results in a core between the boundary layers on the rotating and fixed disks, which rotates with an angular velocity approximately equal to half that of the disk [10]. The thickness of this core increases with the gap, which results in the following nonlinear relationship:

$$\mathrm{Nu}_m = 4.33\,(h/R)^{0.65}\,\mathrm{Re}^{0.5}.$$

Figure 2b shows the mean value $\overline{\mathrm{Nu}}_m$ as a function of the gap between the disks for various Re.

In the second stage of the tests, we examined the local mass removal rate in the presence of the radial air flow. Figure 3a shows $\mathrm{Nu}_m/\mathrm{Nu}_{m_0} = f(\mathrm{Re})$ for various flow rates (Nu_m is the value for the air flow present, while Nu_{m0} is the same without the air flow). In the range $\mathrm{Re} = 10-10^4$, the air-flow rate, as represented by the dimensionless parameter $q = Q/2\pi h\nu$ causes a marked increase in the mass-transfer rate (by a factor of 10-16). Figure 4 shows $\mathrm{Nu}_m = f(\mathrm{Re})$ for the air flow present. It is clear that the mass transfer increases up to a certain critical value Re_{cr} in the central region, which is evidently due to onset of turbulence due to the incoming air.

Figure 4b shows the effects of gap width on the mass-transfer rate in the presence of the air flow. The latter has the most effect for small gaps in the range around $h/R = 0.05$.

It is clear that the flow towards the center on the fixed disk gradually becomes weaker as the gap is reduced, and the flow does not attain the central zone in the space between the disks. Therefore, reduction in the gap accentuates the effect of the incoming air, and the value of Re_{cr}, which characterizes the zone of influence of the incoming air, is dependent on the air-flow rate and the interdisk gap (Fig. 5). The $\mathrm{Re}_{cr} = f(q, h/R)$ relationship takes the form

$$\mathrm{Re}_{cr} = [(h/R)^2 + 0.01]\,(0.795q^2 + 562q + 6.15\cdot 10^4).$$

NOTATION

β_m	is the local mass-transfer coefficient;
m'	is the mass entrainment rate;
ρ_0	is the naphthalene vapor density of surface;
ρ_∞	is the naphthalene vapor density at infinity;
Δy	is the change in naphthalene-layer profile;
$\Delta\tau$	is the experiment duration;
ρ_s	is the density of solid naphthalene;
R	is the universal gas constant;
T	is the surface temperature;
P	is the partial vapor pressure of naphthalene;
a, b	are the dimensionless factors;
A	is the surface area of disks;
β_m	is the mean heat-transfer coefficient;
Re	is the Reynolds number;
Pr	is the Prandtl number;
Sc	is the Schmidt number;
Nu_m	is the diffusion Nusselt number for flow;

Nu_{m0}	is the diffusion Nusselt number without flow;
h	is the disk spacing;
r and R	are the disk radii;
q	is the dimensionless parameter for gas-flow rate, $q = Q/2\pi h\nu$;
Q	is the gas-flow rate;
ν	is the kinematic viscosity

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