# INVESTIGATION OF CONVECTIVE HEAT- AND MASS-TRANSFER ON SUBLIMATION OF A ROTATING SPHERE IN RAREFIED AIR

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The process of heat and mass transfer for a substance on sublimation of a rotating sphere in rarefied air is examined experimentally in this paper. We have determined the average values for the coefficients of convective heat transfer at pressures of $10 < P < 10^5$ N/m$^2$ for the medium at rotation velocities for the sphere up to 60 rad/sec.

Many researchers have recently devoted their time to studying the process of heat transfer and the hydrodynamics of flow in the rotation of disks, cones, and spheres in air, without considering the transverse flow of mass. Here the author makes an attempt experimentally to study the process of heat transfer from a rotating sphere in rarefied air when phase conversion of the first kind takes place on the surface of that sphere.

The transfer of heat and mass from a rotating sphere in rarefied air is of considerable interest to astrophysicists, aerodynamicists, and thermophysicists.

When a sublimating sphere rotates in a gas medium in the viscous regime, the flow of the vapor-air mixture about the sphere—generated by centrifugal and Coriolis forces—is additionally complicated by a transverse flow of matter. The nonuniformity in the density gradients of the medium at various points on the sphere in this case complicates the convective heat- and mass-transfer. Considering the complexity of the convective heat transfer in the rotation of a sphere, the author undertook an experimental study in order to determine only the average values for the heat-transfer coefficient. The experiments were carried out on a test installation described in [1]. Several changes had been introduced into this installation, and namely: the circular heat shield was replaced with a spherical shield of the same diameter, and instead of the balance beam, on the shaft of the electric motor we mounted the spherical body being studied. The sphere was made of textolite whose surface was coated with a thin layer of highly sublimated material—naphthalene. A number of microthermocouples were introduced to the surface of the sublimating material through the hollow shaft; these thermocouples were used to measure the average temperature of the sphere surface.

In addition, during the course of the experiment we measured the surface temperature of both the shield and the ambient medium, the loss of mass on the part of the sublimating material, and the velocity of sphere rotation. To avoid vibration during the rotation, the experiments were carried out with a sphere of small dimensions and low weight, and the hollow shaft was short and quite rigid. The results from these experimental studies are shown in Figs. 1, 2, 3, and 4.

Figure 1 shows $J_m$ (kg/m$^2\cdot$sec) as a function of $\omega$ (rad/sec) for various pressures of the ambient medium, i.e., $(10 < P < 10^5)$ N/m$^2$. The experimental data show that with an increase in the angular velocity of the sphere there is an increase in the rate of sublimation. This quantitative relationship appears over a wide range of pressures. However, with a drop in the over-all pressure ($P < 1.33\cdot10^4$ N/m$^2$), the velocity of sphere rotation begins to exert only slight influence on the sublimation process, and when $P \approx \approx 10$ N/m$^2$, we find that $J_m$ is independent of $\omega$.

Proceeding from the function $J_m = f(\omega)$, on the basis of the thermal and material balance we determined the convective heat transfer

$$\alpha_{\text{con}} = \frac{j_m r - C_{\text{pr}}\left[\left(\frac{T_{\text{st}}}{100}\right)^4 - \left(\frac{T_{\text{p.m}}}{100}\right)^4\right]}{T_{\text{av}} - T_{\text{p.m}}}. \qquad (1)$$

Here it was assumed that the heat which is supplied to the surface of the sphere is completely expended on the phase conversion. Figure 2 shows $\alpha_{\text{con}}$ as a function of $\omega$. We see from the figure that with an increase in $\omega$ for a pressure of $P > 10$ N/m$^2$, $\alpha_{\text{con}}$ increases. The function $\alpha_{\text{con}} = f(\omega)$ appears most markedly at ambient-medium pressures of $P > 1.33\cdot10^4$ N/m$^2$ (curves 1 and 2).

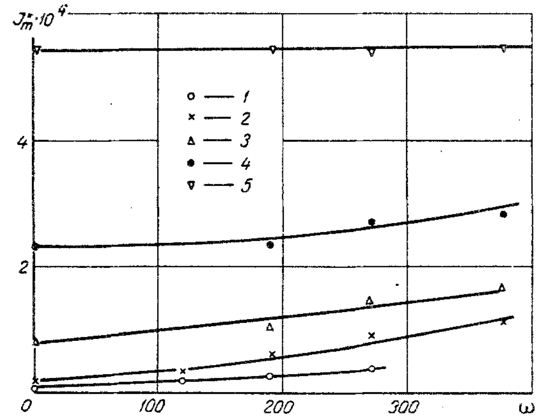

Fig. 1. Sublimation rate $J_m$ (kg/m$^2\cdot$sec) versus angular velocity of sphere rotation $\omega$ (rad/sec) at pressures: 1) $1\cdot10^5$; 2) $1.33\cdot10^4$; 3) $1.33\cdot10^3$; 4) $1.33\cdot10^2$; 5) $1.33\cdot10^1$ N/m$^2$.

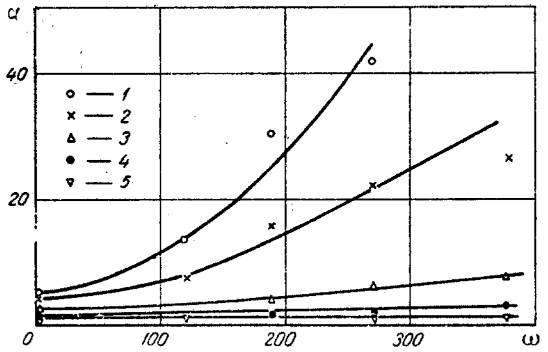

Fig. 2. Convective heat transfer coefficient $\alpha_{cr}$ (W/m$^2$ · ·deg) versus conditions of sphere rotation velocity $\omega$ (rad/sec) at the following ambient pressures: 1) $1 \cdot 10^5$; 2) $1.33 \cdot 10^4$; 3) $1.33 \cdot 10^3$; 4) $1.33 \cdot 10^2$; 5) $1.33 \cdot 10^1$ N/m$^2$.

To verify the experimental results, we carried out tests on the heat transfer of a rotating sphere at normal atmospheric pressure, for which the rate of sublimation is very low. These results were compared with the data of other authors.

Figure 3 shows the comparative data for convective heat transfer as functions of the velocity of sphere rotation in dimensionless form. We see from the figure that the reduced results of our investigations lie on a single common straight line plotted from the results—obtained by other authors [2–4]—on heat transfer not encumbered by mass transfer. These data can be expressed by a criterial equation of the following form:

$$\mathrm{Nu} = 0.3\,\mathrm{Re}^{0.52}. \qquad (2)$$

The results shown in Fig. 3 are in satisfactory agreement with the theoretical data derived in [6].

For free convection when $\omega = 0$, the results of the study at atmospheric pressure are described by the equation

$$\mathrm{Nu} = 2 + 0{,}34\,(\mathrm{Gr})^{0{,}27}, \qquad (3)$$

where when Gr = 0 we obtain Nu = 2, which coincides with the theoretically found value for the transfer of heat by means of pure heat conduction.

In [5, 6] the authors—investigating the transfer of heat in the rotation of spheres and cylinders—took into consideration the influence of free convection. The coefficient of convective heat transfer or, correspondingly, the dimensionless Nu number, in this case, is a function of the viscosity, inertia, and lift forces. The influences of these forces on convective heat transfer is expressed in dimensionless form as the ratio of the inertial and lift forces to the forces of friction. The results of the studies are generalized in the form of the equation

$$\mathrm{Nu} = 2\,(\mathrm{Re}^2 + \mathrm{Gr})^{0.164}, \qquad (4)$$

where the Re number varies in the range $1 \cdot 10^4 < \mathrm{Re} < 1.8 \cdot 10^5$, and the ratio $\mathrm{Gr}/\mathrm{Re}^2 > 0.1$. When $\mathrm{Gr}/\mathrm{Re}^2 < 0.1$, the influence of free convection can be neglected, and the Nu number is then determined from Eq. (2).

In the rotation of a sublimating sphere in a rarefied gas, the mass forces generated on sublimation may be more substantial than the lift or inertia forces. As demonstrated by the results of our experiments, at low pressures ($P < 1.33 \cdot 10^4$ N/m$^2$), the rate of sublimation for $\omega = 0$ is of the same order of magnitude as for the rotating sphere. Consideration of the quantitative effect of these forces on the process of convective heat transfer is not always possible. We therefore attempted indirectly to evaluate the effect of the inertial forces on the rate of convective heat transfer in a rarefied gas where, because of the over-all intensity of heat transfer resulting from the lift and mass forces when $\omega = 0$. The results of the experimental study in the pressure range $10 < P < 10^4$ N/m$^2$, processed in dimensionless form are generalized in the following equation:

$$\mathrm{Nu} - \mathrm{Nu}_0 = 1.83\,\mathrm{Re}^{0.022}. \qquad (5)$$

The correlation of the experimental data is shown in Fig. 4. The Nusselt number and, correspondingly, the Reynolds number were calculated on the basis of the experimental data. The physical parameters of the gas were determined from the arithmetic mean of the temperature between the surface of the sphere and the ambient medium.

Having analyzed the experimental data in the pressure range $10 < P < 10^5$ N/m$^2$, we see that the rotational motion of the sublimating sphere leads to a pronounced increase in the rate of sublimation. The

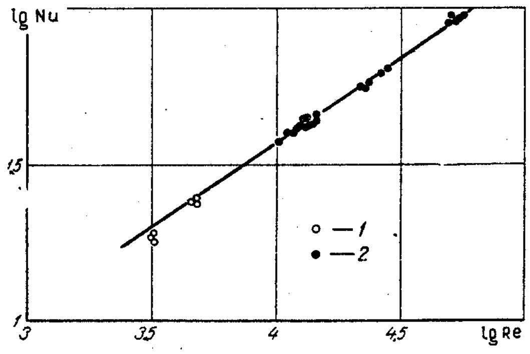

Fig. 3. Convective heat transfer versus sphere rotation velocity in dimensionless form at normal atmospheric pressure: 1) authors' data; 2) other data.

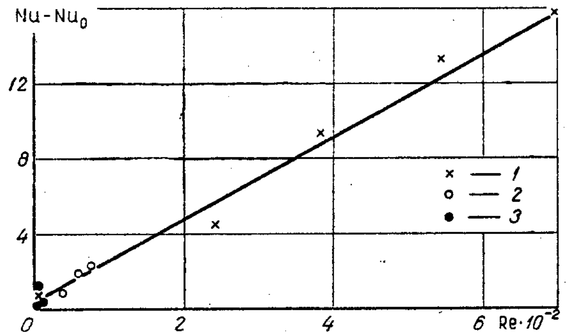

Fig. 4. Correlation of experimental data on heat transfer on sublimation of rotating sphere at various pressures of surrounding medium: 1) $1.33 \cdot 10^4$; 2) $1.33 \cdot 10^3$; 3) $1.33 \cdot 10^2$ N/m$^2$.

intensification of the process of convective heat- and mass-transfer is due in this case to the hydrodynamic action on the layer of gas adjacent to the sphere.

When the sphere is rotating in an unbounded volume and the gas-flow regime is viscous, the molecules of the vapor-air mixture—because of the viscosity—are drawn into the circular motion. The increase in the velocity of rotational motion in this case leads to a rise in the velocity of sphere streamlining, which governs the increase in the intensity of convective heat transfer. On the other hand, when we find phase conversion at the surface of the sphere the rotational motion enhances the increase in the speed with which the vapor is removed from the sublimation surface, i.e., it increases the intensity of the convective mass transfer.

Because of the nonuniform distribution of the gas-flow velocities about the rotating sphere, as well as because of the appearance of a transverse flow of vapor from the sublimating material, the flow of the vapor-air mixture becomes complex. The nature of such a flow is experimentally not easy to determine. On the basis of experimental results, we can state that only a transverse flow of substantial density can exert perceptible influence on the nature of the gas flow and, consequently, on the process of heat- and mass-transfer. As is shown by the experimental data, for a low-intensity process of sublimation which, in our case, takes place at atmospheric pressure, we find complete analogy between the processes of heat- and mass-transfer. In this case, the intensity of heat transfer in the presence of mass transfer virtually coincides with the intensity of pure heat transfer. With a drop in P, the relative density of the transverse mass flow increases, while the role of the convective heat-flow component diminishes. This results in a phenomenon such that—even in the range of pressures corresponding to the viscosity regime—the velocity of sphere rotation has but slight effect on the sublimation process. The nature of sphere streamlining by a flow of a rarefied gas depends on the relationship between the mean molecular free path $l$ and the sphere dimension d, i.e., $l/d$. Investigations have shown that with a value of $l/d > 0.01$, we cannot neglect the discrete nature of the medium, since we note the effects of slippage and a temperature discontinuity about the surface of the sphere in the process of heat- and mass-transfer, and these introduce an effective thermal resistance into the convective heat transfer. In our case, when $P \approx 10$ N/m$^2$, $l/d \approx 0.03$, and neither the rate of sublimation nor the velocity of convective heat- and mass-transfer are functions of the velocity of sphere rotation.

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