SOME RHEOLOGICAL EFFECTS IN GAS MIXTURES

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The results are discussed of an experimental investigation of the effect of the centripetal injection of air into rotary systems of the type of two plane-parallel disks, one of which is rotating whilst the other is stationary.

It is well known that in the case of shear flow of a resilient highly elastic liquid in a rotary device, the rotating drum in the stationary receptacle or, on the contrary, a stationary shaft immersed in the rotating medium, the liquid is moving from the periphery to the center and is lifted upward in directions contrary to the centrifugal and gravitational forces. The combination of these effects has been called the Weissenberg effect [1].

It has been found that all fluid systems exhibiting the Weissenberg effect display elasticity of shape under the action of loads.

It has been established successfully in experiments on the mechanical behavior of consistent lubricants in ball- and roller-bearings that, because of the growth of the air film on the rotating surfaces, contact between the lubricant and the moving surface is prevented [2].

The work of Popper and Reiner has been devoted to the experimental investigation of this phenomenon [2]. Schematically, their equipment is represented by two very closely positioned coaxial plane-parallel disks. One of these (the stator) is stationary and the other (the rotor) is moving. When the gap is increased to about $20\,\mu$ and the number of revolutions of the rotor is 10^4 rpm, air is sucked inwards to the center at $p_0 = 1.013 \cdot 10^5$ N/m^2 [3].

However, in Reiner's experiments certain extremely important problems remain unexplained:

a) the pressure distribution along the radius of the interdisk gap with atmospheric pressure and rarefaction of the medium;

b) the effect of the pressure and temperature of the surrounding medium on the centripetal effect and the radial pressure distribution.

Because of this, there has arisen the necessity of setting up additional experiments in order to improve the procedure. The experimental device shown in Fig. 1 has been designed and built. The speed of rotation of the rotor was controlled smoothly within the limits $(3-25) \cdot 10^3$ rpm.

The device is provided with a measurement system and automatic control of the rotor at a specified temperature.

The rotor was made of instrument alloy-steel, tempered to a hardness of 58-60 NRS units. Various materials were tried for the stator: steel, fluoroplastic-4 (on a metal backing), and plastic. The working surfaces of the stator and rotor were machined on a high-precision grinding lathe and carefully lapped manually. As a result of this, the maximum unevenness of the surface of the disks amounted to $0.8-1\,\mu$ at diameters of 100 mm.

The low positioning of the rotor permitted measurements to be made of the radial pressure profile at any point of the interdisk space. In addition, by means of a special reference system, the stator could
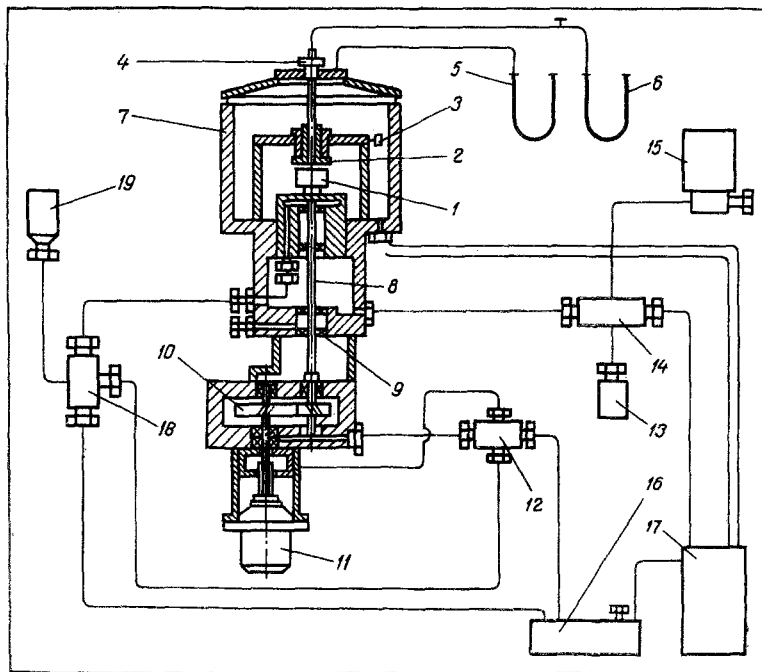
Fig. 1. Diagram of experimental equipment: 1) rotor; 2) stator; 3, 4) micrometer screws; 5, 6) U-shaped mercury manometers; 7) working chamber; 8) driving shaft; 9) vacuum bearing; 10) reduction gear; 11) electric motor; 12, 14) distribution boxes; 13) vacuum relay; 15) air valve; 16) lubricant pump; 17) vacuum pump; 18) throttle; 19) pressure relay.

be moved relative to the rotor in the radial direction. A hole with diameter 2 mm at the center of the stator was connected with the U-shaped manometer.

I. Experiments at Atmospheric Pressure

With a relatively large gap between the rotor and the stator (of order 600 μ), i.e., under the conditions of action of the normal centrifugal effect, and with a rotational speed of n = 15,000 rpm the manometer indicated a vacuum of 980 N/m^2 (100 mm water column) which agrees well with Stewardson's calculation [4]. According to Stewardson, the vacuum at the center of the disk is equal to $0.15 \rho \omega^2 R^2$ (R is the radius of the disks).

With further reduction of the gap, the pressure at the center increased gradually up to complete equalization with atmospheric pressure. The stator was then released from the retainers. The stator, together with the additional load imposed on it, was now maintained in the floating state by the normal forces originating in the interdisk space. The vacuum at the center of the disk converts to a positive excess pressure which reaches 2840 N/m^2 (290 mm water column) with a gap of order 20 μ and a stator weight of 19.4 N (1.98 kg).

We note that the magnitude of the excess pressure depends, other conditions being equal – i.e., with a fixed number of revolutions of the rotor and with unchanged geometry of the system – on the weight of the stator.

The pressure distribution along the radius of the interdisk space was measured on the apparatus (see Fig. 1), for which a system of pneumometric holes with diameter 1 mm was constructed in the stator along 3 radii with an angle of 120° between them. According to Taylor and Saffman [5], in the case of misalignment of both disks there are regions of increased and reduced pressure in the gap. Inequality of one or other pressures at three points of the disk, equidistant from the center, confirms a misalignment in the equipment. The experiments were carried out only after the pressures at the points of takeoff located at the circumference had reached equalization.

It can be seen from the profilograms of the working surfaces of the disks, plotted before and after the experiments, that the average height of microirregularities amounted to 0.4 to 0.6 μ. Unevenness of
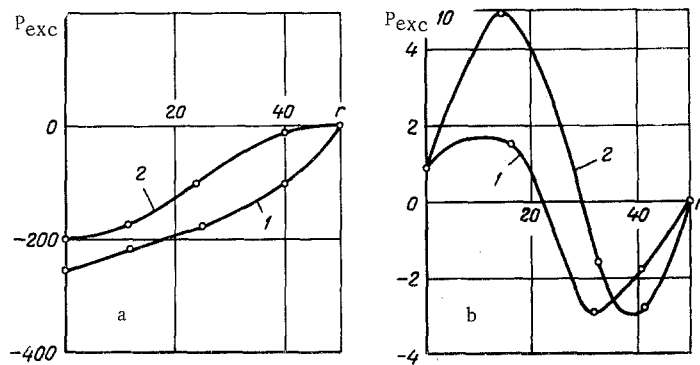
Fig. 2. Pressure distribution along the radius of the interdisk space at normal atmospheric pressure. a) n = 15,900 rpm: 1) h = 150 μ; 2) h = 100 μ. b) n = 8000 rpm: 1) Q = 0; 2) Q = 9.8 N; $P_{exc} \cdot 10^{-3}$.
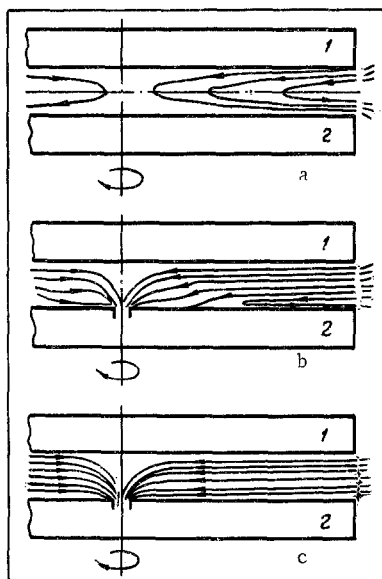

Fig. 3. Flow patterns: a) without flow; b) small flow; c) large flow.

the working surfaces of the disks has a considerable effect on the velocity and pressure fields in the interdisk gap. Therefore, special attention should be paid to control of the geometry of the working surfaces of the disks which, before the experiments, were carefully lapped one to the other. The curves of the measured pressures shown in Fig. 2 have an extremely monotonic nature. As a result of this, the maximum P_{exc} is located not at the center of the disk but at a distance of (0.25-0.3)r. Obviously, such a curve shape is governed by the asymmetry of the radial components of the velocity field in the interdisk gap. In order to explain the data obtained, we use the results of [6], in which the flow structure of water was studied between a rotating disk and a stationary container enclosing the disk in the presence of and in the absence of a radial straight-through forced flow. It was determined that the peripheral velocity component at high Q-values remains just the same as in the absence of a forced feed Q = 0. However, at low Q-values maxima appear on the radial velocity distribution. Consequently, in certain sections of the bed (in the boundary region) the liquid has a peripheral velocity greater than that near the disk. This is because the liquid at the periphery acquires an enhanced velocity in proportion to its motion through the gap to the center.

Figure 3 shows profiles of the radial and axial velocity components in the meridinal plane, taken from [6], for the following cases: a) without flow; b) with a small flow; c) with a large flow.

In order to explain the nature of the curve obtained in our experiments (see Fig. 2) it can be supposed that the flow in the gap is divided into two regions, as was observed in [6] (Fig. 3b). In the vicinity of the stationary disk the liquid is moving toward the center and toward the wall, whereas in the regions adjoining the rotating disk the flow is directed toward the periphery. The flow in the latter region is similar to that which is formed at the entrance to the gap for the model [6] of Fig. 3a) with Q = 0. In the near-axial region, the liquid is moving inward, i.e., toward the center. Thus, there must be a section r = r_0 where the flow velocity toward the center and away from it are equal to one another and which, obviously, corresponds to the condition Q = 0. For all values of r greater than r_0 the flow is directed toward the periphery of the disk. In the case of values of r less than r_0 there is no flow from the center to the periphery. The Weissenberg effect can be observed also in gases when the Trusdell number is comparable with unity (Tr $\approx$ 1).

II. Investigation of the Centripetal Effect at Reduced Pressure

In the foregoing part of our experiments, the Weissenberg effect was achieved because of the strong increase of the shear strength. The test stand and measurement circuits were modified in conformity with the characteristics of rarefied gases. The apparatus shown in Fig. 4 was also designed and manufactured.
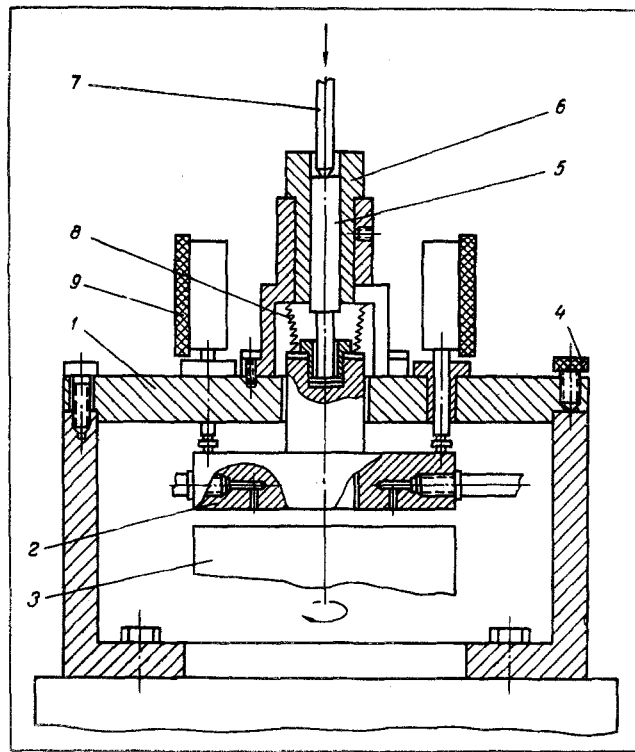
Fig. 4. Layout of equipment: 1) cover plate; 2) stator;
3) rotor; 4) microscrews; 5, 6) piston couple; 7) micro-
screw; 8) return spring; 9) indicator.

In order to regulate the parallelism of the stator and rotor surfaces, four holes were drilled through two diametrically opposite directions at an identical distance from the center.

The stator was set parallel to the rotor before pressure equalization was attained in these holes. In order to measure the pressure distribution the measuring holes were drilled on a separate radius.

First of all, the effect of evacuation on the change of pressure in the central opening was investigated. The results of the experiment are given in Table 1. It follows from Table 1 that at the initial instant under normal atmospheric conditions the pressure at the center of the disk is negative, i.e., the normal centrifugal effect is observed. When the pressure of the surrounding medium is reduced, $P_0 = 5.33 \cdot 10^3$ N/m^2, despite the considerable gap, the pressure at the center becomes positive relative to the chamber, i.e., the Weissenberg effect begins to appear.

The excess pressure profiles along the radius of the interdisk gap with different underpressures of the medium are shown in Fig. 5a. In the case of normal atmospheric pressure $P_0 = 1.013 \cdot 10^5$ N/m^2 and gaps of h = 100 and 150 μ, the normal centrifugal effect occurs. With further reduction of pressure of the medium, the excess pressure profile flattens out and at $P_0 = 5.33 \cdot 10^3$ N/m^2 (40 mm Hg) or less the centripetal effect appears. The maximum P_{exc} is then located at a distance of $(0.5-0.6)r$ from the axis of the disk.

The excess pressure distribution is shown in Fig. 5b for various gaps h. It can be seen from Fig. 5b that when $P_0 = 5.33 \cdot 10^3$ N/m^2 (40 mm Hg) the centripetal effect develops markedly at h = 80 μ.

TABLE 1. Change of Pressure at Center of Stator with Different
Underpressures of the Medium

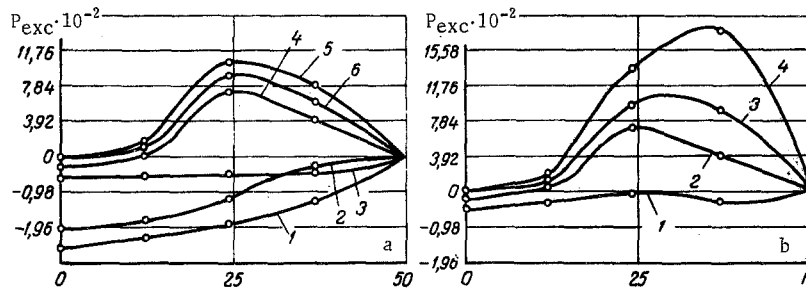| P_{ch}, mm Hg	n, rpm	$P_{exc} = P_{ef} - P_{ch}$ (mm H$_2$O)	P_{ch}, mm Hg	n, rpm	$P_{exc} = P_{ef} - P_{ch}$ (mm H$_2$O)
760	16500	—90	33	16500	+30
760	8600	—26	33	10000	+10
135	16500	0	33	9000	+7

Fig. 5. a) Excess pressure distribution along the radius of the interdisk gap with different underpressures of the medium: 1) P_{ch} = $1.013 \cdot 10^5$ N/cm^2 (760 mm Hg), h = 150 μ, n = 15,900 rpm; 2) respectively, $1.013 \cdot 10^5$, 100, 9000; 3) $1.066 \cdot 10^4$ (80 mm Hg), 100, 18,000; 4) $5.33 \cdot 10^3$ (40 mm Hg), 100, 19,600; 5) $2.665 \cdot 10^3$, 100, 18,500; 6) $5.33 \cdot 10^3$, 80, 19,000. b) Effect of gap size on the pressure distribution along the radius of the interdisk space. P_{ch} = $5.33 \cdot 10^3$ N/m^2 (40 mm Hg), n = 19,000 rpm; 1) h = 500 μ; 2) 100; 3) 80; 4) 70.

III. Eccentripetal Effect in Gases

As mentioned above, in contrast from the Reiner and the Taylor–Saffman experiments [5], the stator in our experiments could be moved relative to the rotor in a radial direction. It was found that in the presence of eccentricity between the rotor and stator, with other conditions equal, the effect of centripetal injection increases with increase of displacement (Fig. 6a).

We note that, right up to a value of e/R = 0.2, the radial displacement of the axes of the disks does not affect the centripetal effect. Beyond this threshold the pressure at the center increases progressively almost according to a linear law.

When e/R = 0.7, the centripetal effect intensifies by a factor of 4. It should be noted that the magnitude of the eccentripetal effect, other conditions being equal, depends linearly on the weight of the stator (together with the additional load) (Fig. 6b).
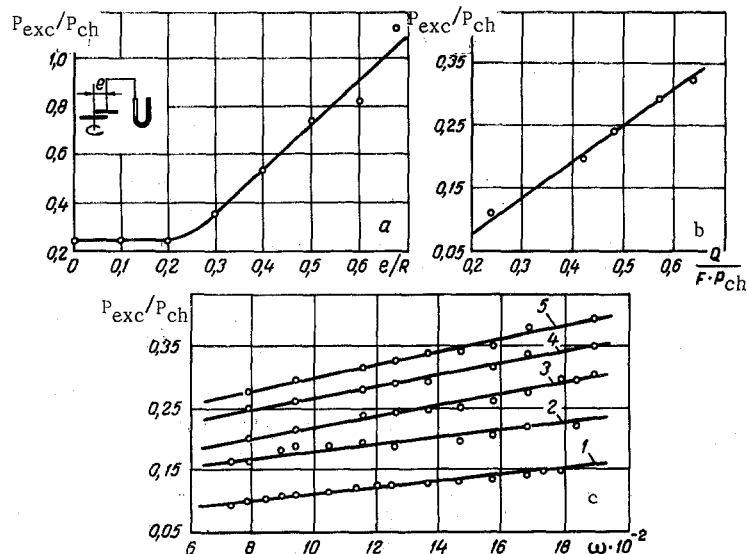

Fig. 6. Dependence of: a) magnitude of centripetal effect on the eccentricity between the disk axes: n = 15,000 rpm; P_{ch} = $1.013 \cdot 10^5$ N/m^2; b) magnitude of eccentripetal effect on the stator weight: n = 12,000 rpm; e/R = 0.56; P_{ch} = $1.013 \cdot 10^5$ N/m^2 (760 mm Hg); c) magnitude of eccentripetal effect on speed of rotation of rotor: e/R = 0.56; 1) Q = 19.8 N; 2) 33.1 N; 3) 47.43 N; 4) 53.31 N.

Figure 6c shows the experimentally obtained dependence of the magnitude of the eccentripetal effect on the speed of rotation of the rotor.

Thus, a new rheodynamic effect appears in the form of an additional injection. It has been ascertained that the centripetal effect is intensified considerably with increase of the speed of rotation and the eccentricity between the rotor and stator.

Analysis of the results obtained and certain supplementary data will be given in a subsequent paper.

NOTATION

P_{exc} is the excess pressure at the center of the stator;
P_{ch} is the air pressure in the chamber;
n is the speed of rotation of the rotor;
ω is the angular velocity of the rotor;
r is the instantaneous radius;
ρ is the air density;
Q is the weight of the stator, together with the additional load;
h is the gap;
e is the eccentricity between the disk axes;
R is the radius of the disks.

LITERATURE CITED

1. K. Weissenberg, Nature (London), 159, 310 (1947).
2. B. Popper and M. Reiner, Brit. J. Appl. Phys., 8, 493 (1957).
3. M. Reiner, Proc. Roy. Soc., A240, 173 (1957).
4. K. Stewardson, Proc. Cambr. Phil. Soc., 49, 333-342 (1952).
5. G. Taylor and Saffman, J. Aero. Sci., 24, 533 (1957).
6. R. Konover, Theoretical Foundations of Engineering Calculations [in Russian], Vol. 90, Series D, No. 3 (1968).
7. A. Srivastava, Quart. J. Mech. Appl. Math., 14, 353 (1961).
8. A. V. Luikov, "Some rheological effects in gas mixtures," Int. Sem. Heat and Mass Transfer in Rheologically Complex Fluids, Herceg Novi, Yugoslavia (1970).