FLOW OF AIR THROUGH A CAPILLARY UNDER THE ACTION OF ULTRASOUND

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The results of an experimental investigation of the motion of air in capillary tubes under the action of ultrasound are presented. A qualitative description of the mechanism responsible for the phenomenon is proposed.

It is well known [1] that under the action of ultrasound a liquid in a capillary rises more rapidly and to a greater height than the usual capillary rise. It is shown below that under certain conditions ultrasonic oscillations cause a flow of air in a capillary tube.

We used a UZDN-1 U4.2 generator as the ultrasonic source, and the pressure in the capillary was measured with a manometer connected to it by a rubber tube.

The capillary with a ground end was placed vertically above a concentrator and, using a micrometer screw, the required gap was set. The value of a gap was read off from the upper position of the oscillating concentrator to the end of the capillary. All the measurements were made with the end of the capillary strictly parallel to the area of the concentrator above its central point. At the beginning of the readings (zero gap) the readings of the micrometer were taken corresponding to the instant when the capillary was displaced downward, when it began to vibrate. The amplitude of the displacement was measured optically with an accuracy of $\pm 1.0 \cdot 10^{-6}$ m.

Figure 1 shows the measured excess air pressure as a function of the gap δ for a constant displacement amplitude A for a capillary with an internal diameter d = 0.4 mm and a wall thickness Δ = 2.9 mm, and also as a function of the displacement amplitude for a constant gap for a capillary with d = 1 mm and Δ = 5 mm at a frequency of 21.7 kHz. The instant when the radiator touches the capillary for A = 38 μm corresponds to an excess pressure of P = 2.4 m H_2O, and when the capillary is clamped, P = 6 m H_2O.

The results obtained on capillaries of different internal diameters and wall thicknesses show that the action of the ultrasonic oscillations at a frequency of 21.7 kHz on the air in the capillary leads to its flow from the radiator and to the appearance of an excess pressure in the capillary. It is seen from Fig. 2, for example, that an increase in the wall thickness Δ for d = const leads to an increase in the pressure in the capillary. The pressure also increases as the internal diameter of the capillary d is reduced.

Similar experiments were carried out at a frequency of 41.9 kHz. For capillaries with $\Delta < 3$ mm the action of the ultrasound always led to the appearance of an excess pressure in the capillaries, which increased as δ and d were reduced for a constant wall thickness Δ (Fig. 3). However, when $\Delta > 3$ mm the dependence of the pressure on the gap for certain values of the internal diameter (depending on the wall thickness) acquires a different character. As δ is reduced, the pressure first increases, reaches a maximum, and then falls, changing into a rarefaction when the capillary touches the radiator and with further clamping.

If when touching occurs, i.e., when $\delta = 0$, the amplitude is increased, the dependence on it of the degree of rarefaction also has a maximum in a number of cases (Fig. 4). Experiments carried out with several capillaries showed that the existence and the position of the maxima of excess pressure and rarefaction depend on the wall thickness and the value of the internal diameter of the capillary.

Hence, besides the effect of ultrasound on the flow of liquid in the capillary, a phenomenon of similar form is observed when a gas is present in the channel.

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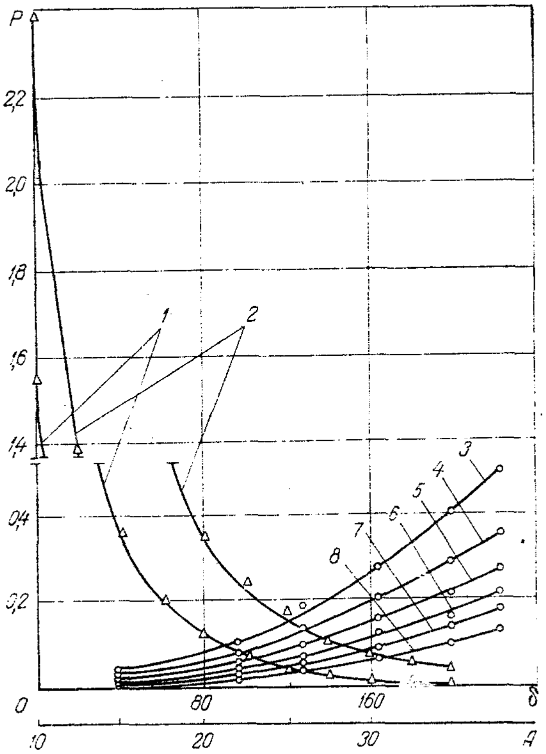

Fig. 1. Dependence of the pressure on the amplitude A (curves 3-8) and the gap δ (1, 2) for f = 21 kHz; 1, 2) d = 0.4 mm, Δ = 2.9 mm, A = 25 μm (1) and 38 μm (2); 3-8) d = 1 mm, Δ = 5 mm, δ = 500 μm (3), 600 μm (4), 700 μm (5), 800 μm (6), 900 μm (7), and 1000 μm (8). P, m H_2O.

Experimental investigations carried out in recent years [2-4] have shown that cavitation plays an important part in the flow of liquid along a capillary when ultrasonic oscillations act on it. Since there is no cavitation in air, this motion around the capillary under the action of the ultrasound is governed by other processes. We investigated the role of the following proposed reasons for the observed phenomenon:

1) flows of air in the gap between the surfaces of the radiator and the end of the capillary;

2) oscillations propagating in the capillary wall;

3) oscillations of air in the capillary channel interacting with its walls.

To clarify the part played by oscillations of the capillary wall we compared the results of experiments carried out with a capillary using the previously described method, and also with a section of capillary of length 1 cm, connected to the rubber tube, the other end of which went to the manometer. Since the acoustic characteristics of the rubber tube and the glass capillary differ considerably from one another, we should obtain different manometer readings in these experiments if wall oscillations have any influence. Since the readings obtained in both cases were approximately the same, it follows that wall oscilaltions play no appreciable part. Note that this result says nothing about the role of the material at the end of the system through which the air flows, since the ends were the same in both experiments.

We then placed a diaphragm transparent to ultrasound in air in the place where the section of capillary was connected to the rubber tube. Its transparency was verified after measuring the attenuation in air of the amplitude of the ultrasonic oscillation with a piezoelectric probe placed behind the diaphragm, the readings of which were taken with a millivoltmeter. At the other end of the tube a section of capillary, in which a column of water had been previously introduced, was connected. If oscillations of air in the channel have any effect, the column should be set in motion and should stop when the force due to the action of the ultrasound and the pressure difference due to rarefaction in the region between the

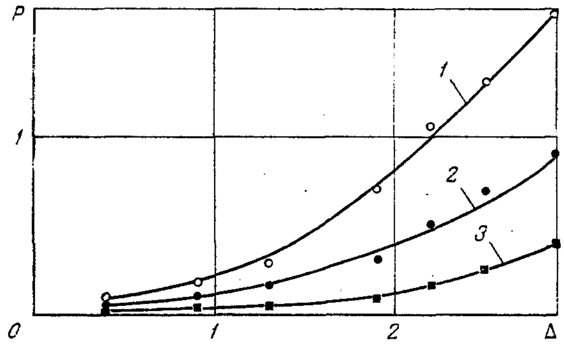

Fig. 2. Dependence of the pressure on the wall thickness Δ for d = 0.4 mm, f = 21.7 kHz, and A = 30 μm: 1) δ = 0 μm; 2) 20μm; 3) 50 μm.

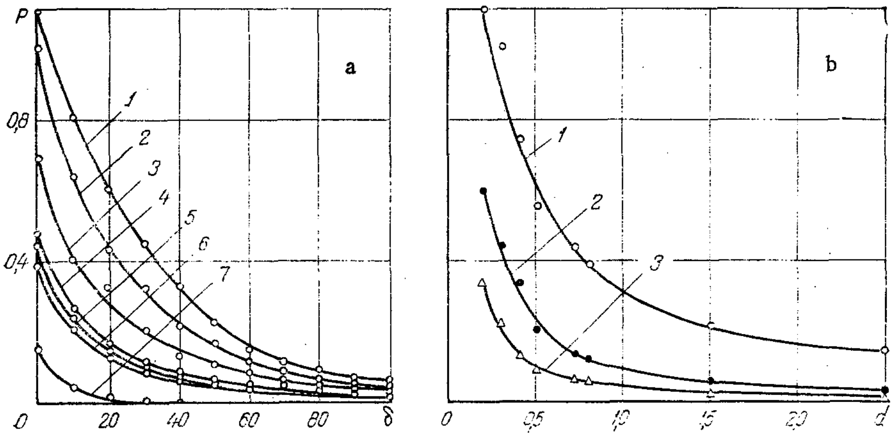

Fig. 3. Dependence of the pressure on the gap δ (a) and the internal diameter d (b) for f = 41.9 kHz, A = 11 μm, and Δ = 16 mm: a) d = 0.2 mm (1), 0.3 mm (2), 0.4 mm (3), 0.5 mm (4), 0.72 mm (5), 0.8 mm (6), 2.5 mm (7); b) δ = 0 μm (1), 20 μm (2), and 40 μm (3).

diaphragm and the lower meniscus of the column of water are equal. No such motion was observed.

Hence, the main reason for the flow of air through the capillary is the flow which arises between the radiator and the end of the capillary.

In [5] the effect of oscillations excited at a sonic frequency (f = 1 kHz, I = 10^{-3} W/cm^2) by a pneumatic siren on the air pressure in a capillary was investigated. It was shown that under these conditions the pressure in the capillary increases by 0.008-0.009 atm. It was suggested that the observed phenomenon is due to the asymmetry of the resistance when the air flows into and out of the capillary. This has been confirmed by a series of experiments carried out with capillaries in which the entrance is narrowing or widening. For the case of a plane end of the capillary and a plane surface of the radiator, no explanation is given for the asymmetry of the resistances, and it is merely suggested that "a plane end is an asymmetric system." The effect of the position of the end of the capillary both as regards the height and the area of the radiator is important but not systematic.

However, the experimental data we have obtained indicate that the position of the capillary as regards the height over the radiator is quite definite. The value of the resistance of the gap between the end of the capillary and the radiator determined by the thickness of the wall Δ, the value of the effective gap $\delta^* = \delta + 2A$, and the frequency f, and also the size of the internal diameter of the capillary d, play a definite role in the experiments.

The pressure in the capillary channel depends, first of all, on the velocity of motion of the air in the channel itself and, secondly, on the velocity of flow through the side surface of the gap. At frequencies of 21.7 kHz and 41.9 kHz, as an analysis of the experimental data shows, these flows have a different character.

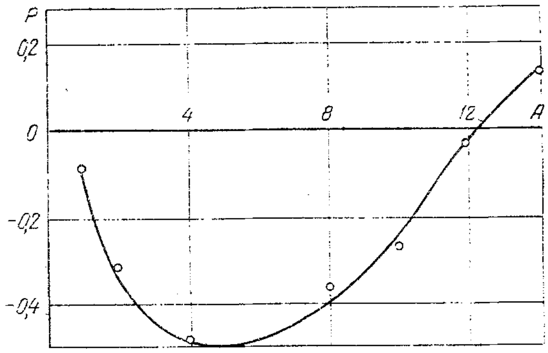

Fig. 4. Dependence of the pressure on the amplitude A for δ = 0 μm and f = 41.9 kHz for a capillary with d = 1.0 mm and Δ = 4.5 mm.

At a frequency of 21.7 kHz, when the concentrator is moved upward the air in the gap is compressed — part of it flowing upward and part flowing into the channel. Hence, a certain additional pressure δP_1 is produced in the channel. When the concentrator is shifted downward δP_1 decreases somewhat, but until the next movement upward remains positive, since the air, due to its inertia, moves upward while the gap is filled through the side surface. This leads to the appearance of a new $\delta P_2 > \delta P_1$. As a result, a certain excess pressure ΔP_n is established, which we also measured in the experiments. As the amplitude A and the wall thickness Δ are increased, and also as the internal diameter d and the value of the gap δ are decreased, the degree of compression of the air in the volume between the planes of the radiator and the end of the capillary increases, which leads to an increase in the established pressure in the channel (see Figs. 1 and 2).

At a frequency of 41.9 kHz the value of the effective gap $\delta^* = \delta + 2A$ is less than that at a frequency of 21.7 kHz for the same δ. This leads to an increase in the resistance of the gap, to the side surface of which the air flows from the outside. In addition, the time taken to displace the concentrator from one limiting position to the other is reduced by a factor of 2. These two facts cause the appearance at a frequency of 41.9 kHz of a flow of air directed from the capillary. When $\Delta < 3$ mm the resistance of the gap is such that the air succeeds in flowing into it externally from the side surface and the pressure in the capillary, as at a frequency of 21.7 kHz, increases. As the thickness of the wall increases, the resistance of the gap increases also, and when δ is less than a certain critical value δ_{cr}, it reaches a value for which the air easily enters the gap mainly from the capillary channel, and not from outside, which causes a rarefaction in the channel.

The presence of a maximum of the rarefaction as a function of the amplitude when the capillary touches the radiator is obviously due to the following. An increase in the amplitude up to a certain value leads to an increase in the degree of rarefaction in the channel, since as the concentrator is moved away from the capillary the rarefaction produced in the gap ΔP_k increases, while the resistance of the gap is still fairly high, in order to ensure that air flows into it mainly from the capillary channel. A further increase in the amplitude leads to an increase in the effective gap, for which its resistance decreases so much that the air more easily enters the gap again through the side surface. It should be noted that when δ = 0 due to mechanical action on the capillary, its natural oscillations may also affect the value of the effective gap.

It would seem that a mechanism similar to that described above for the case of ultrasonic oscillations in the flow of air through a capillary tube makes its own contribution also to the ultrasonic capillary effect in a liquid.

NOTATION

P, pressure; d, internal diameter of the capillary; Δ, thickness of the capillary wall; δ, distance between the upper position of the oscillating concentrator and the end of the capillary; δ*, effective gap; I, intensity of the ultrasound; f, frequency; A, amplitude of the displacement.

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CALCULATION OF THE THERMAL CONDUCTIVITY OF DENSE REAL GASES AND THEIR MIXTURES

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A procedure is proposed for calculating the thermal-conductivity coefficients of compressed gases and their mixtures; the real first density correction is introduced into the Enskog equation with allowance for the contribution of the internal degrees of freedom of the molecules.

In the calculation of the thermal conductivities of compressed real gases serious difficulties have been incurred to date by the lack of a rigorous and reliable transport theory for dense systems.

The only theoretically justified mathematical expression is the well-known Enskog equation [1]

$$\lambda/\lambda_0 = \frac{1}{\varkappa} + 1.2\, b\rho + 0.7554\, (b\rho)^2\varkappa, \tag{1}$$

which is exceedingly difficult to apply to real gases. The reason for this difficulty lies in certain specifics of the rigid-spheres model on which the Enskog theory is based (only pairwise collisions are taken into account, and forces of mutual attraction are disregarded), as well as in the restrictions and assumptions inherent in that model (the molecular-chaos hypothesis, approximate allowance for "screening" of molecules, etc.).

In addition, Eq. (1) describes only the translational part of the thermal conductivity, i.e., the part associated with translational motion of the molecules. In principle, therefore, it cannot be applied to polyatomic gases, whose thermal conductivity is largely determined by the presence of molecular internal degrees of freedom.

In the present study we attempt to modify the Enskog equation so that it can be used to calculate reliable values of the thermal conductivity of dense real gases and their mixtures. It is reasonable to speculate that to treat the attractive forces ignored by the original model as a perturbation in the system of rigid spherical molecules will result in a substantially more realistic version of the Enskog equation. We note that the attractive forces are felt primarily at moderate densities and to a lesser extent at high densities.

The latter consideration justifies the inclusion of mutual attraction only insofar as it influences the linear term of the expansion of the thermal conductivity in powers of the density:

$$\lambda/\lambda_0 = 1 + \beta\rho + \ldots,$$

where β is the so-called first density correction, which takes into account the contribution of ternary collisions [2].

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