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EXPERIMENTAL STUDY OF FLOW IN A CAVITY ON AN AXISYMMETRIC BODY

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The flow past a cylindrical cavity on an axisymmetric body in the range of Mach numbers from 0.6 *to* 1.18 *and the effect of the Mach number in the transition from subsonic to supersonic flow velocities are studied experimentally. In addition, a broad,* 5.3–11.3 *range of relative elongations of the cavity which permits one to determine the influence of the elongation on flow regimes including flows with closed and open separation zones is studied.*

The flow in open hollows (cavities) is observed past axisymmetric bodies, in wind tunnels, and in various units of technological installations. A number of theoretical and experimental studies devoted to the study of cavities in flow in a broad range of incoming-flow velocities from low subsonic to hypersonic ones have been published. Bogatyrev et al. [1] studied experimentally the flow of a viscous incompressible liquid in a cavity of square cross section. It was shown that a core with constant vorticity forms in the cavity and there are secondary vortices at the corners. Zhak et al. [2] measured the flow characteristics of a liquid in plane rectangular cavities for Reynolds numbers in the range $\mathrm{Re} = 500$–5000. The structure with secondary flows in the side regions and with Taylor–Görtler vortices developed along the cavity walls was found in a "plane" vortex flow in a cavity of square cross section. Bogatyrev and Mukhin [3, 4] investigated an incompressible liquid flow in shallow and deep cavities of rectangular cross section with a laser Doppler velocity meter. The experiments were performed in a laminar flow regime in front of the cavity. Two cavities were tested: a shallow cavity ($L = l/D = 2$) and a deep cavity $L = 0.5$ (l and D are the length and depth of the cavity, respectively). It was found that in the deep cavity, there are two (upper and lower) elliptic vortices rotating in the opposite directions. The problem of a viscous incompressible fluid flow in a three-dimensional cavity that is driven by a moving lid was considered by Belolipetskii and Kostyuk in [5]. The Navier–Stokes equations in vector potential–vortex variables were solved numerically. The new structures characteristic of three-dimensional flows were obtained. In [1–5], publications dealing with the study of incompressible fluid flows in cavities are also reviewed.

For a supersonic external flow, Zaougul'nikov et al. [6] calculated numerically the nonstationary flows in rectangular cavities with the use of the model of an ideal compressible gas. The Euler equations were integrated by means of Godunov's finite-difference method. A formula for determination of the flow-rate oscillation frequencies in a cavity depending on the Mach number of an incoming flow and the geometry of a cavity was proposed on the basis of an analysis of calculation results. In the joint solution of the Navier–Stokes equations and the equations of the dynamics of solids, the data were obtained for the description of flow near an open rectangular cavity simulating the exit of a rocket from the bomb hatch of an airplane ($\mathrm{M} = 1.2$) [7]. Bormusov et al. [8] showed experimentally that turbulization of an external flow leads to a significant increase in the velocity of recirculation motion and the intensity of turbulent fluctuations in a rectangular cavity. The propagation of a plane shock wave for $\mathrm{M} = 1.2$–5.0 above a shallow rectangular cavity located in the direction

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transverse to that of wave propagation was studied by Gvozdeva and Lagutov on the basis of an analysis of shadow and interference patterns and pressure measurements by piezoelectric transducers [9]. It is shown that the oscillations are self-excited inside the cavity owing to the mass transfer between the cavity and the external flow. Wilcox [10] proposed to use passive methods of control to obtain a favorable pressure distribution in a closed cavity, which allows one to decrease the strength of the cavity by a factor of approximately 3.

At the same time, there are only sketchy data on subsonic and low supersonic flow past cavities. In particular, the pressure fluctuations were measured in [11], and numerical results obtained in the range $\mathrm{M} = 1.05$–1.2 are given in [12]. Kim and Chokani [13] studied supersonic turbulent flows past rectangular cavities of relative lengths $L = 6$ (open cavity) and $L = 17.5$ (closed cavity) and width 1 and 2.5 cm, respectively. The two-dimensional Navier–Stokes equations were solved according to the MacCormack scheme. It was shown that the passive supply of gas to the cavity changes the flow geometry and transforms a closed cavity to an open one. Baysal and Srinivasan [14] studied theoretically and experimentally a supersonic turbulent flow past a two-dimensional rectangular cavity whose relative lengths are $L = 6$ (open cavity) and $L = 12$ (closed cavity) under conditions of a thick boundary layer. The flow in a cavity was simulated by means of the two-dimensional Navier–Stokes equation. The flow and pressure-fluctuation characteristics in the cavity were considered depending on the Mach number and the relative length L and thickness of the boundary layer. In [14], the calculated values of the pressure do not agree with experimental values. The discrepancy is caused mainly by the three-dimensional character of flow in experiments (the cavity width is $W/D = 5.5$). The effect of a three-dimensional flow on the pressure distribution in the cavity was also observed in a transient flow regime ($10 < L < 13$) for cavities of different width [13]. It was found that this influence is more significant for a closed cavity. This explains, in particular, why the calculations for closed cavities coincide with experiment only qualitatively.

It is noteworthy that in the studies considered, attention was mainly focused on the range of moderate supersonic velocities. At the same time, the studies concerning the averaged-flow structure in the range of subsonic and low supersonic velocities are lacking.

Experimental Technique. In the experiments, the axisymmetric body of diameter 68 mm with a conic head was used as a model (the semiangle of the cone opening is 9°). A cavity of depth $D = 10$ mm, in which a pressure gauge was placed at a distance of 280 mm from the conic part. The cavity length l was changed from 10 to 140 mm with a 10-mm step by displacing automatically the rare cylindrical part of the model. The cavity length was first set in the experiments and then the internal cylindrical part of the model with a pressure gauge was displaced automatically.

A supersonic wind tunnel of variable density with a punched working part that operates in the range of transonic velocities with a continuous passage through the velocity of sound was used in the experiments. The tunnel was equipped with pressure-head and suction ejectors, which allowed us to perform tests in a broad range of Mach ($\mathrm{M} = 0.4$–4.0) and Reynolds ($\mathrm{Re} = 10^5$–$2.5 \cdot 10^7\ \mathrm{m}^{-1}$) numbers. The flow structure was visualized by a Töpler device.

The pressure at the model surface and the Mach number of the incoming flow were measured by IKD-27 pressure gauges. The pressure at the cavity bottom was measured by a DMI 10-2 gauge, and the relative rms error of pressure measurement was equal to 0.03. The measurement data were processed on a computer.

Pressure Distribution. Two flow regimes are observed for a supersonic gas flow past cavities. If the ratio of the length of a cavity to its depth $L = l/D$ is smaller than a definite value, the entire cavity is occupied by the separation zone (open cavity). Another flow regime (closed cavity) occurs when the ratio l/L exceeds a certain critical value and the second separation zone appears near the rare wall. In the case of supersonic velocities and a turbulent boundary layer, the boundary of the transition from the flow regime in an open cavity to that in a closed cavity corresponds to $L = 10$–13.

To study the flow in a cavity, it is necessary to know the flow parameters near its front wall, which differ from the undisturbed-flow parameters. This difference is especially considerable at subsonic and low supersonic flow velocities. The incoming-flow and boundary-layer parameters were measured by a total-pressure tube at a distance of 20 mm from the front wall of the cavity. The Mach number near the cavity was determined with the use of the Rayleigh formula relative to the flow parameters at a distance of 10 thicknesses of the

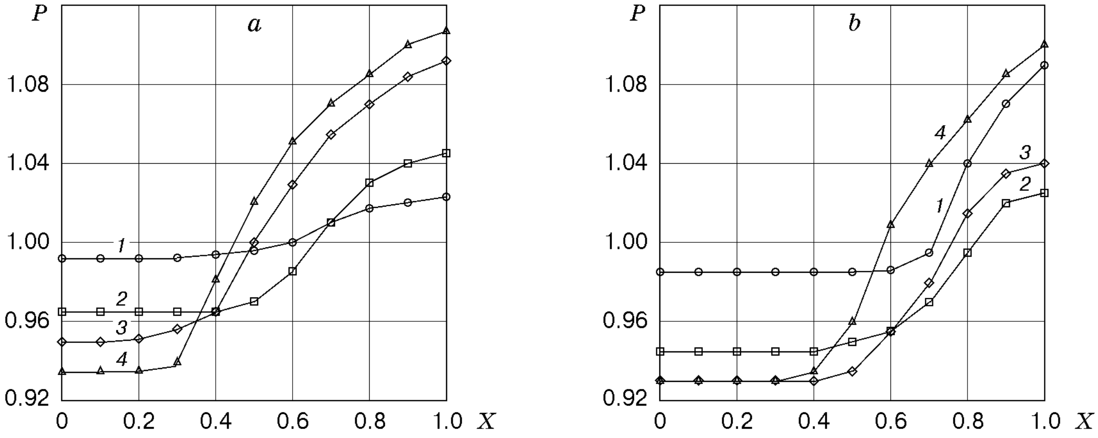

Fig. 1

boundary layer from the cylindrical surface. The Reynolds numbers calculated with the use of the incoming-flow parameters were $\mathrm{Re} = 0.6 \cdot 10^7$ and $0.75 \cdot 10^7$ m^{-1} for $\mathrm{M} = 0.6$ and 0.8, respectively. The measurements of the boundary-layer structure have shown that the boundary layer in front of the cavity is turbulent in the entire velocity range considered, the thicknesses of the boundary layer are $\delta = 7$–8 mm for $\mathrm{M} = 0.6$ and 0.8 and 6 mm for $\mathrm{M} = 1.18$; note that, for $\mathrm{M} = 1.18$, the external flow directly in front of the cavity is more nonhomogeneous than for $\mathrm{M} = 0.6$ and 0.8.

Figure 1a and b shows the pressure distribution at the bottom of an axisymmetric cavity for $\mathrm{M} = 0.6$ and 0.8, respectively. Curves 1–4 refer to $L = 5.3$, 7.3, 9.4, and 11.3 [$P = p/p_\infty$ (p_∞ is the pressure in an undisturbed flow) and $X = x/l$ (X is the relative distance from the front wall of the cavity to the point to be measured)]. One can distinguish two zones on the curves: a zone with $P = \mathrm{const}$ behind the front wall of the cavity and an increased-pressure zone in front of the rear wall. The pressure remains constant up to the distance $X = 0.6$ (Fig. 1a) for $\mathrm{M} = 0.6$ at the bottom of relatively short cavities ($L = 5.3$). As L increases, the constant-pressure zone decreases and it equals $X = 0.2$ for $L = 11.3$. For all the values of L, the pressure rises as the rear wall is approached; note that with increase in L, the pressure P near the wall increases from 1.02 to 1.11.

For any relative length, the pressure in the cavity behind the front wall remains almost unchanged up to $X = 0.3$–0.6. With increase in the distance, the pressure increases monotonically and reaches the maximum for $X = 1$; however, this occurs only at a large relative length ($L = 7.3$–11.3). It follows from Fig. 1a that, as the cavity elongates, the extent of the front section decreases and its length changes significantly with L varied from 7.3 to 9.4.

A decrease in the front separation zone and an increase in the rear zone are observed for $\mathrm{M} = 0.8$ as well (Fig. 1b). However, in this case, the pressure in the front separation zone for $L = 9.4$ and $L = 11.3$ is the same. A more intense pressure rise in front of the rear wall (for $L = 5.3$) is also noted. As the cavity length increases, the constant-pressure zone decreases from $X = 0.6$ (for $L = 5.3$) to $X = 0.35$ (for $L = 11.3$). In contrast to Fig. 1a, Fig. 1b shows that the pressure near the rear wall increases nonmonotonically: it first decreases from $P = 1.09$ (for $L = 5.3$) to $P = 1.02$ (for $L = 7.3$) and, then, the increase in the cavity length leads to a pressure rise to $P = 1.1$. One can assume that the relative pressure rise for $L = 5.3$ is connected with the formation of a local supersonic zone and a closing shock. The increase in pressure at the trailing edge as L increases is characteristic of both low subsonic and supersonic velocities.

For a closed cavity ($L = 11.3$), the minimum pressure is observed in the front part owing to flow expansion at the leading edge and behind the section where the viscous layer attaches to the cavity bottom, and the pressure increases beginning from the point where the layer separates again in front of the rear wall. In contrast to a supersonic flow past closed cavities where the pressure between the isolated separation zones changes insignificantly, in the case of a subsonic flow, a mutual influence of the separation zones and a smooth increase in pressure between the front and rear separation zones are observed.

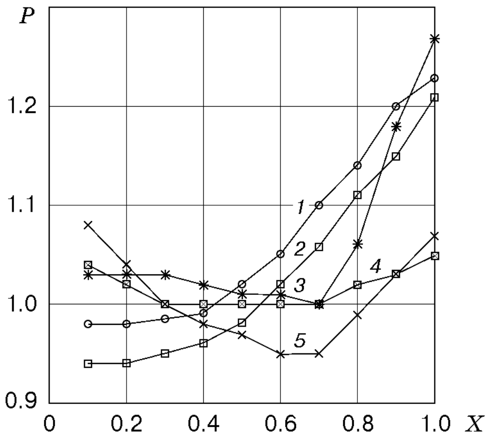

Fig. 2

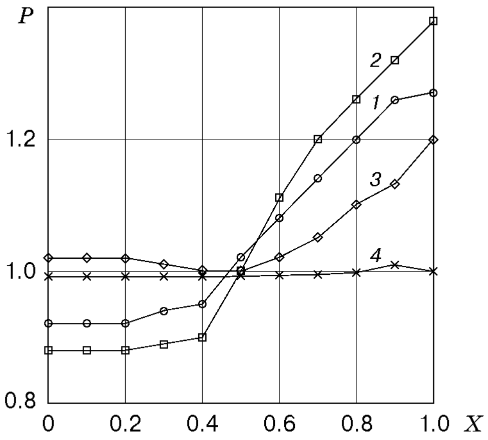

Fig. 3

In the range of Mach numbers considered (for open and closed cavities), the pressure behind the front wall is smaller than the value of p_∞ and larger in front of the rear wall. For subsonic flow velocities, an increase in the Mach number from 0.6 to 0.8 results in a decrease of the front separation zone and an increase of the rear zone for $L = 11.3$ and in a pressure rise in front of the rear wall $L = 5.3$.

At subsonic velocities, the flow structure for a closed cavity differs from the case $\mathrm{M} > 1$, because shock waves do not appear in the cavity and the perturbations from the rear separation zone propagate upward. At the same time, flows with one and two separation zones arise. There is a range of L values in which a transition from a closed-cavity to an open-cavity regime is observed. The values of L in this range are determined by the boundary-layer parameters for different lengths of the cavity.

For $L = 5.3$ and 7.3 and $\mathrm{M} = 1.18$, the pressure distribution at the cavity bottom is shown in Fig. 2 (curves 1 and 2, respectively). In this case, the pressure distribution near the front wall remains constant up to $X = 0.2$, and then it increases monotonically as the rear wall is approached. The pressure in the model with $L = 5.3$ exceeds that in the model with $L = 7.3$ throughout the cavity. The results of these tests were compared with results of a number of studies obtained at a close value of the Mach number. Figure 2 shows calculation results [13] obtained for $L = 6$, $\mathrm{M} = 1.5$, and $\mathrm{Re} = 6.56 \cdot 10^6 \mathrm{m}^{-1}$ (curve 3) and calculation results [14] obtained for $L = 6$, $\mathrm{M} = 1.5$, and $\mathrm{Re} = 6.5 \cdot 10^6\ \mathrm{m}^{-1}$ (point 4 refer to experiment, and curve 5 to calculation).

Figure 3 shows the pressure distribution at the bottom of long cavities for $\mathrm{M} = 1.18$ and $L = 9.4$ and 1.3 (points 1 and 2, respectively). The minimum-pressure region is near the front wall of the cavity owing to the propagation of a rarefaction wave from the front wall. The pressure increases behind the zone where the viscous layer attaches to the cavity bottom. It follows from a comparison of the results presented in Figs. 2 and 3 that, for open cavities, at the distance $X = 0.4$ the pressure exceeds that for closed cavities, the pressure decreasing with increase in the relative length of the cavity. At the same time, an inverse dependence is observed as the rear wall is approached: the pressure increases with L. The exception is a cavity with the relative length $L = 5.3$, for which the pressure is higher than that for a cavity with $L = 7.3$. In contrast to the case of subsonic velocities, for $\mathrm{M} = 1.18$, a more intense pressure rise is observed in front of the rear wall, which reaches the values of $P = 1.2$–1.4.

Figure 3 also shows experimental results [15] obtained for $L = 9$ and $\mathrm{M} = 1.5$ (curve 3), in which the flow in a rectangular two-dimensional cavity was studied under conditions of a thick boundary layer for $\mathrm{M} = 1.5$ and 2.5. In [15], the pressure and fluctuation distribution in the cavity was considered depending on the Mach number and the relative length and thickness of the boundary layer. Two mechanisms of fluctuations were revealed, which are caused by

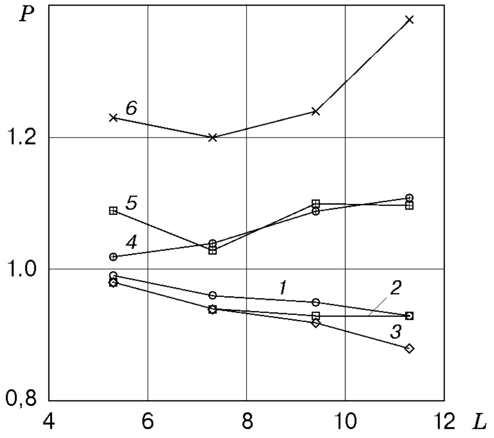

Fig. 4

— interaction of a vortex descending from the front wall with a vortex descending from the rear wall;

— transverse oscillations of a single vortex in a cavity. In addition, Fig. 3 shows calculation data [12] obtained for $L = 20$, $\mathrm{M} = 1.05$, and $\mathrm{Re} = 10^3$ (curve 4) in the numerical modeling of a supersonic flow of a viscous compressible heat-conducting gas past the cavities.

It is of interest to study the dependences of the pressure variation behind the front wall and in front of the rear wall on the Mach number. It is necessary to note that in contrast to the case of supersonic flow with a closed cavity (where the front separation zone is separated from the rear supersonic flow zone), a significant mutual influence of these zones is observed in the case of a subsonic flow. For $\mathrm{M} = 0.6$, 0.8, and 1.18 (curves 1–3, respectively), the pressure distribution behind the front wall ($X = 0$) is plotted in Fig. 4. In the range of cavity lengths considered, the decrease in the subsonic flow velocity results in a pressure drop. At the point $X = 0$, as the Mach number is increased from $\mathrm{M} = 0.8$ to $\mathrm{M} = 1.18$, the following specific features are observed. In the case of an open cavity ($L = 5.3$), the pressure does not vary and it decreases for $L = 7.3$ and 9.4 with increase in L. For a closed cavity ($L = 11.3$), the pressure decreases abruptly, which corresponds to the character of the change in the bottom pressure behind the return step in the indicated range of Mach numbers.

Figure 4 also shows the pressure distribution near the rear wall ($X = 1$) for $\mathrm{M} = 0.6$, 0.8 and 1.18 (curves 4–6, respectively). In contrast to the flow behind the front wall, near the rear wall, as L increases, the pressure also increases (except for the case $L = 7.3$). In addition, in a transition from $\mathrm{M} = 0.6$ to $\mathrm{M} = 1.18$, the pressure does not decrease and grows as in the case of flows in front of the steps.

Optical Study of Flow. In the experiments, the photographing and streak recording of the flow with large and small exposure times were performed. For the exposure time $t = 10$ msec, which considerably exceeded the duration of the oscillation cycle, the time-averaged flow pattern was recorded. In the case $t = 1$ μsec, there was the possibility of observing flow oscillations and the motion of eddy formations. Because of the small density gradient for small flow velocities, the flow pattern was not distinct. In this case, a small amount of the visualizing substance was introduced into the flow. Injection was performed at several points on the radial plane from one side of the model: in the boundary layer before the cavity and in the flow at the lower points near the front and rear walls of the cavity.

In the experiments, photographs of the cavities subjected to subsonic ($\mathrm{M} = 0.6$ and 0.8) and low supersonic ($\mathrm{M} = 1.18$) flows were obtained. Figure 5 shows the scheme of the flow past a cavity which was constructed with the use of schlieren photographs of the flow and photographs of the visualizing substance. In the case of an open cavity ($L = 5.3$ and $\mathrm{M} = 0.6$), boundary layer 1 transforms to free viscous layer 4 and, separating from the leading edge, it moves away and then approaches the cavity; the layer thickens in front of the trailing edge. Almost the entire cavity is occupied by large vortex 3. The photographs of the visualizing

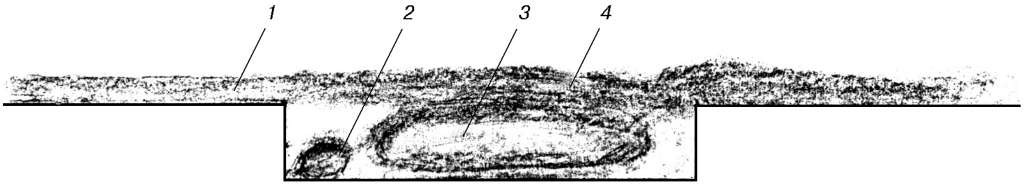

Fig. 5

substance make it possible to assume that one more small vortex 2 rotating in the opposite direction forms in the vicinity of the lower corner of the front wall.

In the case of a closed cavity, separating from the front wall, the boundary layer approaches the cavity bottom and then comes away from it and passes above the rear wall. For this regime, the presence of separate closed circulation-flow zones at the front and rear walls of the cavity is characteristic; note that the extent of the leading vortex exceeds considerably the extent of the trailing vortex in this regime.

At a low supersonic velocity, in the case of an open cavity, the incoming flow separates near the front wall of the cavity and also attaches to the rear wall. A portion of gas is involved in circulation flow and returns to the front wall of the cavity. As the rear wall is approached, the free viscous layer is displaced in the external flow. Open cavities can be shallow and deep. The boundary of the transition from the flow regime in shallow cavities to that in deep cavities corresponds to $L = 1$. If $L < 1$, the shock and expansion flow are absent (deep cavity). Deep cavities are characterized by a smooth free viscous layer and "act" as resonators.

In the case of a closed cavity, the boundary layer separates in the vicinity of the front wall and approaches the lower surface of the cavity; after that, the flow is parallel to the cavity bottom. A circulation-flow zone forms near the front wall. In this case, the rear wall of the cavity looks like a ledge and the flow past this ledge is accompanied by a secondary separation. The second separation zone appears in front of the ledge. As the gas propagates toward the rear wall, the flow decelerates gradually with the formation of a shock wave in its external part. A certain portion of gas enters the circulation flow and returns to the front wall; then, a repeated flow expansion in the rarefaction wave occurs.

One can see on the small-exposure photographs and the high-speed streak records that the flow rate in the cavity is not high, its increase is observed only near the rear wall. For $L > 5$, several vortices are observed in the free viscous layer of the upper part of the cavity. These vortices form near the front wall, then move downward and they are almost equidistant. The displacement velocity of vortices at a subsonic velocity of the external flow is approximately equal to half the displacement velocity of the free viscous layer above the cavity. One can see on the photographs that the free layer oscillates upward and downward near the rear wall of the cavity. Moving upward, the free layer closes the rear wall from the external layer. When the layer displaces downward, a material supply from the external layer to the cavity is observed and an increased-pressure zone forms near the rear wall. The increased pressure in a cavity propagates in the forward direction, the free layer is lifted, and the process is repeated.

It follows from the experimental results obtained for a cylindrical cavity on an axisymmetric body that an increase in the subsonic flow velocity in the range $\mathrm{M} = 0.6$–0.8 results in a decrease of the leading separation zone and an increase of the trailing zone. In contrast to the case $\mathrm{M} = 0.6$, for $\mathrm{M} = 0.8$, the pressure near the rear wall increases nonmonotonically: it first decreases for $L = 5.3$–7.3 and, then, the increased length of the cavity causes a pressure rise. For $\mathrm{M} = 1.18$, a more intense growth of pressure in front of the rear wall is observed.

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