EXPERIMENTAL INVESTIGATION OF FLOW IN A CONVERGENT AIR-INTAKE WITH PLANE WALLS

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In addition to the traditional two-dimensional air-intake configurations (plane and axisymmetric with central spike, divergent configurations), greater attention is being devoted in recent times to studies on three-dimensional configurations in spite of considerable difficulties in obtaining experimental and computational fluid dynamic data. Three-dimensional configurations offer the possibility of a reduction in area of the duct walls [1-3] and also an improvement in the air-intake characteristics at off-design conditions [4-6]. Of these, convergent air-intake configurations (KVZ) [2-4, 6, 7] give compact transverse sections of the ducts and in view of this, specifically, a reduction in their wall area. The present study considers flow in the KVZ model whose configuration is made up of sections along the streamlines from the flow in air-intakes described in [7] (Fig. 1). The flow in such KVZ has a significantly three-dimensional nature, though at design conditions the inviscid flow parameters in the external compression region are determined from simple relations for plane shocks. These relations themselves can also be used for an approximate estimate of flow parameters at off-design conditions. The characteristic feature of the flow in the external compression region of KVZ of this type is the three-dimensional oblique shock—boundary layer interaction. It could be extremely complex (separation may occur and modify the external flow field) and depends on many parameters: Mach and Reynolds numbers, the state of the boundary layer, flow detection angles through shocks, heat transfer, etc. A large number of studies (e.g., [8-10]) is devoted to various external flows with this feature. Computation of such flows does not appear to be possible at present. Hence it is necessary to conduct experimental studies on flows in KVZ models. The objective of the present paper is to verify the realization of the design conditions for the ideal fluid, explanation of the features of shock—boundary layer interactions, determination of the flow structure in the external compression region of KVZ in the range of free stream Mach numbers M_e and angle of attack α.

The KVZ model (Fig. 1) had a design Mach number $M_e = 4$; the initial wedge angle $\vartheta_1 = 9.4°$; the second wedge angle $\vartheta_2 = 13.3°$; half angle between the side walls $\varphi_2/2 = 55.3°$; total compression at the design condition $F_e/F_t = 3.02$, where F_t is the cross-sectional area at the throat and F_e is the frontal projected area of the leading edges of the air-intake at zero-angle of attack.

The initial compression surface of KVZ is the wedge 1. The plane shock generated by it at design conditions ($M_e = 4$, $\alpha = 0$) lies at the leading edges of the air-intake. There are two side walls 2 in the initial segment of the wedges which prevent lateral flow and hence, the flow past the initial segment of the wedge to a large extent should be two-dimensional or nearly planar over a wide range of M_e and angles of attack. Further compression is carried out with the help of two secondary side wedges 3 which result in shocks 4 interacting with boundary layer on the first wedge. Experiments were conducted in the wind-tunnel T-313 at the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Academy of Sciences of the USSR (ITPM SO AN SSSR) at $M_e = 4.0$ and 3.0, Re_e [1/M] = 51×10^6 and 35×10^6 respectively in the angle of attack range $\alpha = -3$-15° (in [11] results are for $M_e = 1.79$-4.76). The boundary layer on the wedge in the shock interaction region is either turbulent or transitional according to the estimates made. The inclinations of the compression surfaces of the model ϑ_1 and ϑ_2 were adjusted (reduced) when compared to the design values obtained for ideal fluid (ratio of specific heats $\kappa = 1.4$) taking into consideration the boundary-layer displacement thickness under these conditions.

The following experimental techniques were used: Topler's shadowgraph method, static pressure measurements on the compression surface of the air-intake at 20 points (see Fig. 1),

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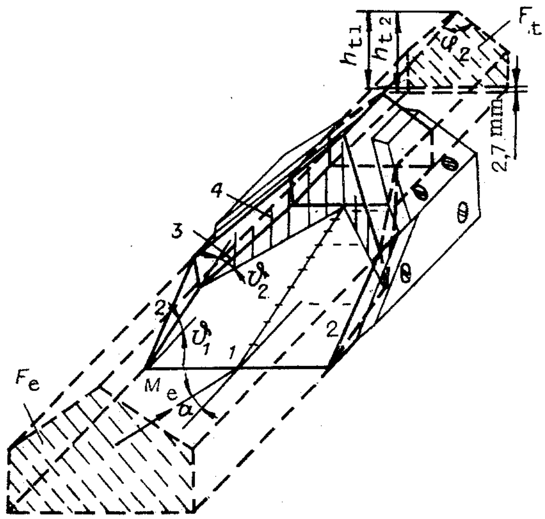

Fig. 1

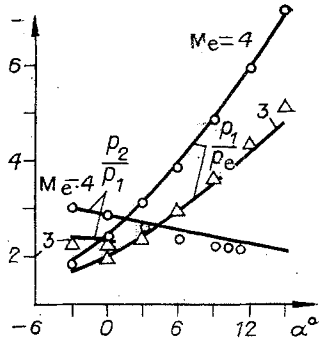

Fig. 2

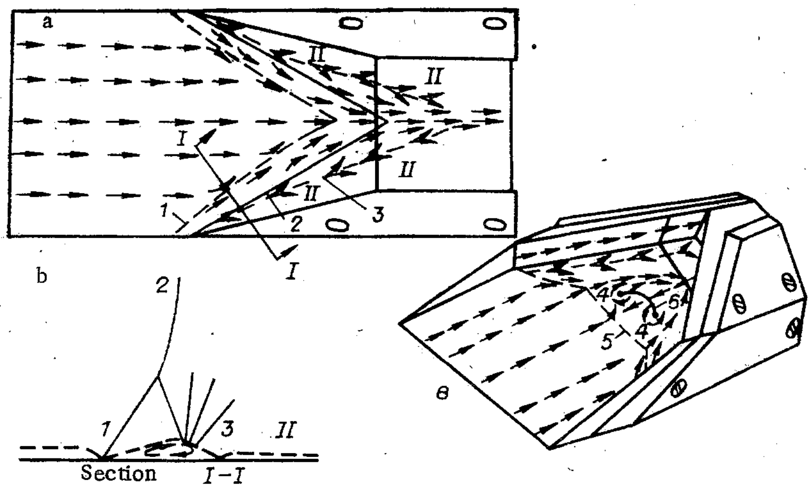

Fig. 3

and oil flow technique for surface flow visualization.

A comparison of pressure ratios across the first shock p_1/p_e (Fig. 2) obtained from computations and the experiment for the model of Fig. 1 (the pressure p_1 was measured at a point 20 mm from the leading edge of the wedge), shows good agreement. Satisfactory agreement is also observed in the case of the pressure ratio p_2/p_1 across the second shock 4 (Fig. 2).

Under design conditions experiments showed that the supersonic flow in external compression region is close to the design conditions except in a small region of the second shock-boundary layer interaction: the second shock causes three-dimensional skewed boundary layer separation which was also redicted by preliminary estimates. Oil flow visualization on the model surface clearly delineate (Fig. 3a) the separation line 1 and the reattachment line 3 behind the separation region. Consequently, the separation region is local. Computed wake of the side shock 2 passes between lines 1 and 3. Oil flow traces show that the streamline ahead of the separation line 1 at the surface turns along the line 1 (Fig. 3). As a result, the boundary layer which grows on the primary compression surface (the first wedge) converges to the center of this surface, i.e., the the plane of symmetry of the air-intake. It means that the boundary-layer thickness grows here. At the same time the convergence of the boundary layer that has grown in the initial segment of the surface ahead of the skewed separation lines should lead to a reduction in the thickness of the boundary layer in the regions II-II (Fig. 3a, b) behind the lines 3 connecting the skewed separation which should improve the ability of the boundary layer to effectively overcome subsequent shocks or pressure gradients in these regions.

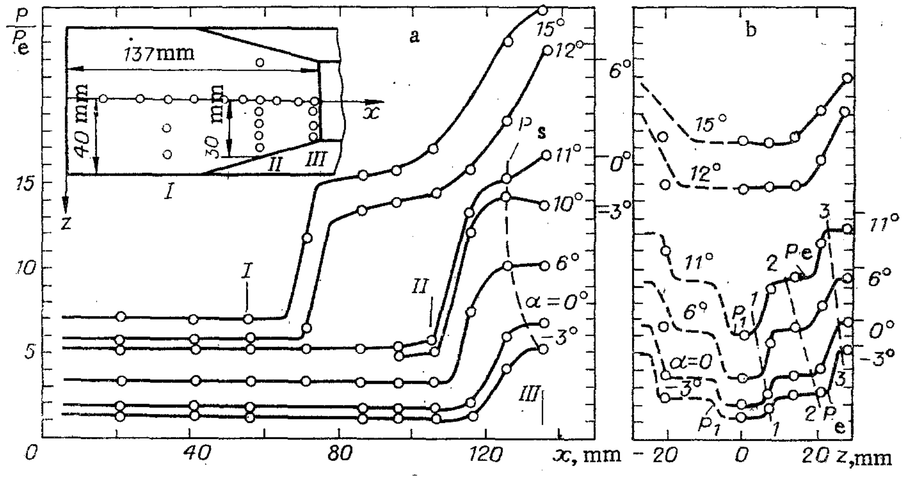

Fig. 4

At the design condition the pressure on the wedge along the central line $p(x)/p_e$ (Fig. 4a) is a constant all the way up to the point of convergence of the right and the left skewed separation lines. Subsequently it increases sharply and then gradually. In the transverse section I the value of pressures p/p_e are constant along z. In the section II during the transition through the skewed shock (Fig. 4b) the pressure distribution has a plateau which is a characteristic feature of local separation of turbulent boundary layer. The location of the separation line 1 for the section II, the reattachment line 3 determined from oil flow visualization, and also the design shock 2 obtained from preliminary computations are shown in Fig. 4b. It is seen that their location agrees satisfactorily with the characteristic pressure distribution along z. In the section II the pressure at the point near the corner (the right extreme point) is close to the design value (the sketch on the right in Fig. 4b). In the section III located in the immediate neighborhood of the inlet to the duct, the pressure distribution is quite nonuniform. The flow region through which this section passes is the interaction region of intersecting secondary shocks, boundary layer, and separated vortex flows produced upstream in local skewed separations and hence the flow structure at the location of their intersection along the model center line is complex. The value of p/p_e determined from approximate computations for the section III (sketch on the right in Fig. 4a) are higher than experimental values. This difference is probably also explained by the strong influence of the boundary layer.

There is no qualitative change in the shadowgraph with a change in the angle of attack in the range (α = −3-11°). The surface of the initial shock in the external compression region is close to the leading edges of the air-intake. However, with further increase in α there is a sudden appearance of a bow shock at a certain distance ahead of the inlet to the duct which is clearly seen in the shadowgraph. It is also seen in Fig. 4a that in the range α = −3-11° the pressure distribution does not qualitatively change and is similar to the design condition, but when α = 12° the pressure rise location is considerably closer to the leading edge (x = 65 mm) than when α = 11° (x = 100 mm). There is also a sharp change in the pressure distribution in oil flow visualization which was also qualitatively unchanged at α = −3-11° and when α = 12° it indicated the appearance of transverse separation 5 with the formation of a pair of vortices (see Fig. 3c). The three-dimensional vortex has the shape of half a ring and its curves axis of rotation 6 rests with its ends on the surface (two points 4 in Fig. 3c). The transverse separation results in the formation of the above mentioned bow shock.

When M_e = 3, α = −3-15° the experimental data are similar to the above described at M_e = 4: the bow shock in front of the inlet to the duct formed, according to the shadowgraph pictures, at α = 3° and a sharp change in the pressure distribution at M_e = 3 occurred when $0 < \alpha \leq 3°$. Thus, with an increase in α the transverse separation on the given KVZ-model occurs when α = 11-12° for M_e = 4 and α = 0-3° for M_e = 3.

Similar experiments were conducted on a KVZ-model with a 9% increase in throat area at the expense of duct depth (F_e/F_t = 2.77 and h_{t2} = 32.9 mm) (see Fig. 1). This small increase in the throat led to appreciable improvement in flow: the transverse and streamwise dimensions of the separated flow was reduced by orders of magnitude, which occurred,

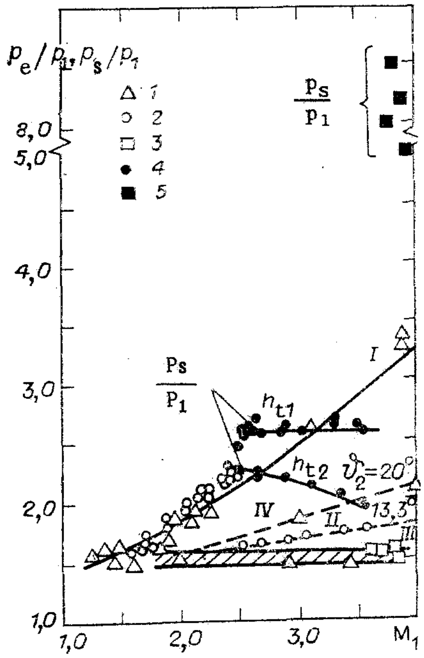

Fig. 5

incidentally, at $\alpha \approx 15°$. Changes in pressure distribution at $M_e = 3$ and 4 accompanying its formation became appreciably weaker.

Thus, the results of experiments show that, in the region of external compression of the air-intake being investigated, very complex shock–boundary layer interaction including three-dimensional boundary-layer separation is observed. The important feature in the present case is the presence of shocks whose lines of intersection with the compression surface are at a sharp angle to the streamlines whereas in other types of air-intakes, viz., in the traditional plane and divergent air-intakes, and also in convergent air-intakes made up of axisymmetric sections [2, 3], the shock lines, at least on the first compression surface, pass across streamlines. Consequently, the boundary-layer separation on the compression surface of the present air-intake occurs at the sharp pressure rises that are significantly less than those in the above mentioned air-intakes.

Boundary-layer separation characteristics for these two cases of interaction are shown in Fig. 5 where the experimental data on pressure ratio p_e/p_1 with turbulent separation (p_1 is the static pressure at the wall ahead of the separation point, p_e is the static pressure at the wall in the "plateau" behind the separation point, and M_1 is the Mach number upstream of the separation point). The line I is derived from the empirical formula [12] $p_e/p_1 = 1 + 0.2\,\kappa M_1^2/(M_1^2 - 1)^{1/4}$ and very well describes the experimental data of [12] (points 1) and those obtained on the model in Fig. 1 with transverse separation (points 2). The situation corresponding to the curve I (usual transverse separation) is characteristic for above-mentioned air-intakes of the traditional types and for convergent air-intakes with axisymmetric flow.

Experimental results resulting in the line II were obtained in the present tests and relate to skewed separation caused by secondary shocks. The quantities p_e and p_1 have been taken from the pressure distribution along the line of orifices II-II (see Fig. 4b). It is seen that the values of p_e/p_1 at separation are less for the present air-intake (line II) than for other air-intakes (line I). The line IV above the line II is formed when $\vartheta_2 = 20°$ by the points 1 from [9].

Skewed separation as a phenomenon, significantly differing from transverse separation, is described in [10], where, in particular, it has been noted and reinforced by experimental data that the pressure jump in the presence of skewed separation p_e/p_1 is approximately equal to 1.5-1.6 and remains constant with an increase in M_1. Experimental points 1 [10] form the line III (Fig. 5) on which also falls the point 3 from [13] where the skewed separation was found in the nozzle under conditions of overexpansion and resulted there in a significantly favorable effect on the flow. It is seen that the line III lies below the line II. As shown in [10] the line III indicates the appearance of skewed shock.

It was mentioned above that on the basis of oil flow visualization the skewed separations carry the boundary layer to the center of the primary wedge surface, to that location where the right and the left skewed shocks converge, and as a result the boundary-layer thickness at this location increases. It might appear that this should have unfavorable effect on the ability of the boundary layer to overcome the pressure gradient at this point. In order to explain this question consider the pressure distribution along the center line of the primary wedge $p(x)/p_e$ (see Fig. 4a) at the same conditions (angles of attack and M_e) when there is no transverse separation. Graphs show that the pressure along the center line on this segment in front of the inlet to the duct experiences a shocklike jump in the ratio p_e/p_1.

The values of p_s/p_1 are given in Fig. 5 for the tests in which there was no transverse separation. It is seen that p_s/p_1 in these tests (points 4) do not agree with p_t/p_1 characterizing the usual phenomenon of normal boundary-layer separation (curve I). It is thus clear that under the present conditions the interaction of the boundary layer in the neighborhood of the center line with the pressure jump is not the case of separation. It is interesting to note that number of values of p_s/p_1 without transverse separation (point 4) appreciably exceed p_t/p_1 with transverse separation (line I). This means that the boundary layer in the neighborhood of the center line, inspite of the above described increase in the thickness due to the convergence along the skewed separation, overcomes the pressure rise p_s/p_1 that is higher than the jump p_t/p_1 which is characteristic of turbulent boundary layer with transverse separation. The fact that lines of p_s/p_1 for two model configurations (with the first throat h_{t1} and increased h_{t2}, see Fig. 1) are different confirms that the pressure jumps at the center line obtained for the given tests configurations (air-intake model), inspite of their large values, did not cause boundary-layer separation, i.e., did not lead to the separation of the flow from the surface of the body in the region of the center line.

The cause for this improvement in the separation characteristics of the boundary layer in the pressure jump region along the center line, i.e., an improvement in the fullness of the boundary-layer velocity profiles is due to the clash of two flows against each other (from the right and the left sides of the air-intake, see Fig. 3a, b). Similar phenomenon was observed in [13] based on which are shown points 5 in Fig. 5 indicating pressure jumps without boundary-layer separation p_s/p_1 that exceed the jump with separation p_t/p_1 (curve I) by an order of magnitude.

The side wedges of the air-intake 3–3 in Fig. 1 (that lead to secondary, lateral shocks 4–4 in Fig. 1 and 2–2 in Figs. 3 and 4) lead to the formation of unseparated flow near them in all cases not only without transverse separation but also in its presence. This flow is seen in Figs. 3a and c, its unseparated flow assists in the lateral convergence of the boundary layer described above (along local skewed separation from the right and the left) partially remaining even in the presence of transverse separation, as seen in Fig. 3c. Unseparated lateral flow, moving at an angle to the right and left towards the center of the air-intake, in the case of transverse separation (see Fig. 3c) merge subsequently with each other at the inlet to the duct and, consequently, also localize the region of transverse separation, giving it the form of a triangle on the surface of the splitter plate of the air-intake with the base formed by the transverse separation line and the vertex behind at the center of the splitter plate near the inlet to the air-intake duct. This separated region, as seen from the top within the flow, is also localized by the fluid boundary similar to that shown in Fig. 3b for the skewed local separation.

Thus, for the convergent air-intakes with the laterally moving skewed shocks the above experimental investigation showed that the flow mechanism in them, including effects associated with the boundary layer is, inspite of initial fears, favorable for the effective operation of the air-intake. Furthermore, this relates not only to flow conditions without bow shock in front of the inlet but also to conditions with such a bow shock. It is known that it inescapably occurs in any air-intake (whether it is the traditional type or convergent) at appropriate conditions, viz., at sufficiently low Mach numbers M_e, large angles of attack, and choking of the air-intake, etc.

In the 1940s, while working on the principles of arrow wings at the Aero-Hydrodynamic Institute (TsAGI), V. V. Struminskii and his colleagues [14] developed the theory of the effect of yaw with cross flows in the boundary layer and showed their strong influence on the flow past the wing and all its characteristics.

The present work is similar to these results on the boundary layer: there is a lateral displacement of the boundary layer on such wings because the pressure gradients on their surfaces are at an angle to the free stream; in flows of the type considered in the present work the lateral movement of the boundary layer is caused by the laterally moving pressure jumps along the surface and also results in a strong influence on the flow which is very favorable in KVZ.

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