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Bifurcation of the shock wave upon reflecting from the end wall of the shock tube

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THE PAPER contains the results of studies carried out in a rectangular shock tube in nitrogen and argon for Mach numbers of the shock wave varying between 2 and 7 and at initial pressures 10–30 mm of mercury column. In these studies the single Töpler photograph method or the method of streak records was employed. Pressures and heat fluxes were measured with miniature piezogauges and thin film gauges. The flow in a bifurcation zone is characterized by the complexity of the wave structure with distorted reflected wave and the oblique wave that give rise to flow separation. The measurements of pressure revealed that there exists a region on the wall in which the pressure exceeds the pressure behind the reflected wave. At the point of separation the pressure drop was measured and it was noticed that it agreed very closely with the calculation made in accordance with the Mark theory. A comparison was made between the pressure drop at the oblique wave and the pressure drop when a shock wave interacts with a non-stationary boundaty layer that brings about separation in starting up the supersonic nozzle.

Niniejsza praca zawiera wyniki badań przeprowadzonych na prostokątnej rurze uderzeniowej dla azotu i argonu przy liczbach Macha fali uderzeniowej wahających się między 2 i 7 i ciśnieniach początkowych od 10 do 30 mm słupa rtęci. W badaniach tych zastosowano pojedynczą metodę fotograficzną Toplera lub metodę rejestracji smugowej. Ciśnienie i strumień ciepła mierzono za pomocą miniaturowych czujników piezoelektrycznych i czujników foliowych. Przepływ w strefie bifurkacyjnej scharakteryzowany jest złożonością struktury fali z dystorsyjną falą odbitą i padającą skośnie falą, która inicjuje proces odrywania się strug. Pomiary ciśnienia wykazały, że istnieje obszar na ściance, w którym ciśnienie przewyższa ciśnienie istniejące za falą odbitą. W punkcie separacji strumienia był mierzony spadek ciśnienia i zaobserwowano, że jest on bardzo bliski wynikom numerycznym otrzymanym według teorii Marka. Przeprowadzono porównanie spadku ciśnienia na fali ukośnej ze spadkiem ciśnienia powodującym oderwanie się strug, gdy fala uderzeniowa oddziaływuje z niestacjonarną warstwą przyścienną tworząc naddźwiękową dyszę.

В работе содержатся результаты исследований, проведенных на прямоугольной ударной трубе в азоте и аргоне при числах Маха ударной волны от 2 до 7 и начальных давлениях 10–30 мм рт. ст. Исследования проводились методом покадровой съемки теплеровских картин, непрерывной фоторазвертки, измерений давления и тепловых потоков с помощью миниатюрных пьезодатчиков и термометров сопротивления. Течение в бифуркационной области характеризуется сложной волновой структурой с искривленными отраженной волной и косой волной, вызывающей отрыв потока. Измерения давления зарегистрировали, что есть область на стенке, давление в которой превышает давление за отраженной волной. Измерен перепад давления в точке отрыва и отмечено его хорошее совпадение с расчетом по теории Марка. Проведено сравнение перепада давления на косой волне с перепадом давления, вызывающем отрыв, при взаимодействии ударной волны с нестационарным пограничным слоем при запуске сверхзвукового сопла.

THE PRESENT paper contains the results of experimental studies on the reflection of shock waves from the end wall of a shock tube. The investigations were made in a shock tube of square cross-section (72×72) mm in nitrogen and argon for Mach numbers of the incident wave varying between 2 and 7 and at initial pressures 10–30 Torr. The Schlieren single photograph method or the streak records' method was employed; the surface temperature and pressure were measured with miniature piezoelectric gauges and thin film gauges.

Streak records of the time variant reflection process enabled to determine the trajectories and velocities of the incident and reflected shock waves and, for nitrogen, made it possible to determine the velocity and the trajectory of the separation point of the boundary layer. Bifurcation of a reflected wave takes place as a result of the interaction of the shock wave reflected from the end wall of the shock tube with the boundary layer that has formed behind the incident shock wave. For that case when in the boundary layer, even if it becomes immobile with respect to the reflected wave, the pressure will be lower than the pressure behind the reflected wave and the latter will bifurcate to form λ-configuration. The wave pattern of the bifurcation process has been studied experimentally and theoretically by a number of authors [1–6].

The model for a bifurcation process and the conditions of its appearance were determined by MARK [1]. Modified versions of the bifurcation process are given in the works of BYRON and ROTT [2], DAVIS and WILSON [3]. A review of the works on bifurcation given in the book written by BAZHENOVA and GVOZDEVA [9] has shown that almost all the models of bifurcation process are contradictory because of a large number of simplified assumptions.

The aim of our present studies was to define precisely the structure of the process. Apart from this, the measurements of pressure at the surface by means of large resolving gauges (the diameter of the sensitive surface was equal to 1 mm) enabled to determine the pressure drop at the oblique wave, which brings about the separation of flow, that is,

a

b

c

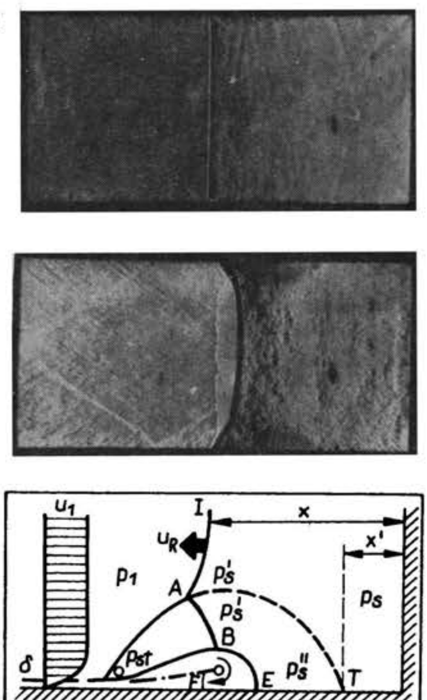

FIG. 1. Schlieren photographs of the reflected wave in argon (a — p_0/= 30 Torr, $M_0 = 2.7$) and in nitrogen (b — $p_0 = 30$ Torr, $M_0 = 4.6$). Bifurcation diagram (c).

it enabled to determine experimentally the criterion of flow separation for a nonstationary interaction of a shock wave with the boundary layer.

Typical Töpler photographs of a reflected wave in argon and nitrogen are shown in Fig. 1 (a, b). From these photographs it is evident that bifurcation does not take place in argon. This is in agreement with the prediction of Mark's theory [1]. In the case of nitrogen bifurcation of a complicated pattern was noticed. It may be mentioned that the reflected shock wave close to the triple point and the oblique shock, which brings about separation, bend, and this, apparently, explains large scatter in the values of its angle of inclination [2, 4]. The height h of the bifurcation zone and the distance a by which the point of separation moves from the front of the reflected waves was measured. The results of our measurements of the distance travelled by the triple point from the front of the reflected wave can be presented in the form of an approximated formula:

$$a = 0.11 \lg M_0 x^{0.8} p_0^{-0.1} \pm 2 \quad [\mathrm{mm}]. \tag{1}$$

Here x is the coordinate of the reflected wave (in mm), p_0 is the initial pressure (in Torr) and M_0, the Mach number of the primary wave.

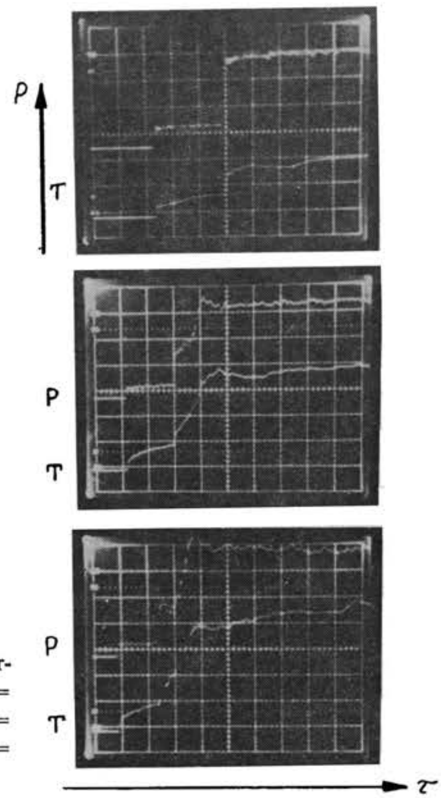

FIG. 2. Oscillograms of pressure and surface temperature when the shock wave reflects in argon (a — $p_0 = 30$ Torr, $M_0 = 2.6$) and in nitrogen (b — $p_0 = 30$ Torr, $M_0 = 4.63$; c — $p_0 = 10$ Torr, $M_0 = 5.9$). Time scale — 50 μ sec per division.

From this relationship, assuming that $h = a \operatorname{tg} \varphi$, it is not difficult to determine the height of the triple point; φ — angle of inclination of the oblique wave to the wall. Since the oblique shock is curvilinear, the value of the angle φ can be determined on the basis of the Mark theory, i.e. by assuming that the pressure in the range OAB is equal to the stagnation pressure of the stream filament in the range OBE (Fig. 1c).

Basing on the MIRELS theory [7], in the paper of DAVIS and WILSON [3] the height of a triple point was calculated depending upon the Mach number of the primary wave, initial pressure and the distance from the end wall. The results of our measurements of the height of the bifurcation zone are well in agreement both with the calculations made in [3] and with the experimental results of [4].

The oscillograms of pressure (upper ray) and temperature (lower ray) recorded at a distance of 46 mm from the end wall, when the shock wave reflects in argon (a) and in nitrogen (b, c), are presented in Fig. 2. Such oscillograms enabled to measure the pressure and temperature of the surface behind the primary and the reflected shock waves, but in nitrogen these oscillograms also enable to measure the pressure and temperature of the surface in the bifurcation zone.

The measurements of the temperature of the surface behind the primary wave showed that, depending upon the Mach number of the primary wave and the initial pressure p_0, the increase in temperature at the gauge surface when the reflected wave impacts was between 1 and 10°. The results of the measurements of the increase in temperature ΔT_w with time τ are approximated by the following formula

$$\Delta T_w = 2.2 p_0^{0.5}(M_0-1)^2 \tau^{0.3} \pm 0.5,$$

$$\tau^* = \frac{\mathrm{Re}^* \nu (u_0 - u_1)}{u_0 u_1^2} < \tau < 150.10^{-6}\mathrm{s}. \tag{2}$$

Here the units of measurements are p_0 —Torr, τ — sec, Re* — critical value of the Reynold number during transition, $\nu = \mu/\varrho$ — kinematic viscosity of the gas, u_0 and u_1 — velocity of the incident wave and the flow behind it, respectively.

A smooth change in temperature enables to affirm that at distances up to 150 mm from the end wall of the shock tube the change in the temperature of the surface behind the primary wave will not exceed 15°. This amounts to only 5% of the initial absolute temperature. This provides a support to the validity for the given conditions of the prediction of MARK [1] that near the wall there exists a layer of gas at a temperature close to the initial temperature. The analysis of measurements of the heat flux behind the primary wave showed that in the given shock tube a transition from the laminar boundary layer to a turbulent one takes place at $\mathrm{Re}^* = 10^6$. This is in accordance with the work of HARTUNIAN *et al* [8].

The pulsing nature of the variation of a heat flux in the bifurcation zone points to the fact that in the separation zone an intensive mixing of gas layers which are impact-heated up to different temperatures takes place due to the presence of shock waves and vortex flows.

The measurements of pressure by means of piezoelectric gauges enables to determine the ratio of pressures at the point of separation of the boundary layer and to compare the obtained results with the existing theories (Fig. 3). Here p_{st} represents the pressure behind the oblique wave, p_1 is the statical pressure of the incident flow. From the comparison it is evident that the model proposed by MARK [1] is in better agreement with the experiment.

As it is evident from Fig. 2 (b, c) the oscillograms of pressure corroborate the conclusion drawn in the paper of SANDERSON [6]. In conformity with this conclusion upon bifurcation there exists a pressure peak at which the pressure exceeds by 10–15% than the pressure behind the reflecetd wave.

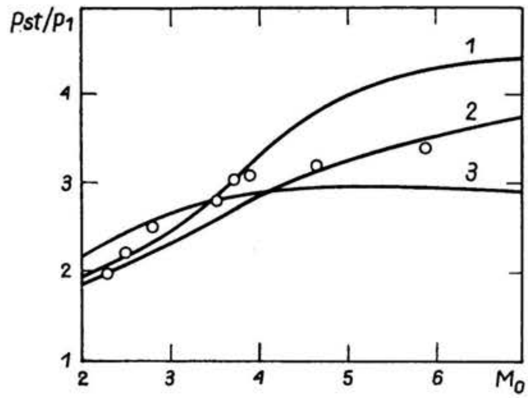

FIG. 3. Ratio of pressures at the separation point of the flow as a function of the Mach number M_0 of the incident wave. Dots — experimental data. Curves — calculated data; *1* — [2], *2* — [1], *3* — [3].

The measurements of pressure by means of piezoelectric gauges also enabled to notice an interesting feature of the bifurcation process. At relatively large initial pressures ($p_0 = 30$ Torr) a smooth increase in pressure is noticed throughout the separation zone from the stagnation pressure of the near-wall layer up to the stagnation pressure of the flow that has passed through two oblique shocks ($\sim 1.1\ p_5$). At small initial pressures ($p_0 = 10$ Torr) such a smooth increase is preceded by a more or less abrupt decrease. Upon comparing the oscillograms (Fig. 2b, c) one can clearly notice different modes of pressure variation in the separation zone. SANDERSON [6] observed a similar decrease in pressure and explained this decrease as a consequence of the expansion of the flow behind the wave OA (Fig. 1c). The observed decrease in pressure seems to be associated with the near-wall shock wave generated during the interaction of the vortex flow with the region of the stagnated gas in the separation zone. It is of interest to note that similar non-stationary near-wall shock waves were noticed for the shock starting of nozzles [10].

The following empirical model of the bifurcation process of a reflected wave was made on the basis of experimental investigations (Fig. 1c). In the near-wall area the oblique shock OA associated with the separation of the boundary layer is inclined at an angle close to that calculated by Marks' theory. In the near-wall area the pressure behind the oblique shock varies from p_1 to p_{st} — stagnation pressure of the boundary layer. To match the pressures and the directions of flow in the region of the triple point A, bending of the reflected wave and the oblique shock OA must take place. Because of the bending of the reflected wave the gas in the neighbourhood of the triple point does not move parallel to the wall but moves in the direction of the contact surface AT, that is, the flow moves slightly away from the wall and then turns towards it. The static pressure on both sides of the contact surface near the point A is equal to $p_5' < p_5$, but the flow that has passed through the reflected wave AI has a velocity smaller that of the flow that has passed through two oblique waves OA and AB. Further, the flow that has passed through AI moves with subsonic velocity through the expanding channel formed by the contact surfaces AT. In doing so it stagnates isentropically up to the pressure p_5. The flow that has passed through two oblique waves will stagnate in the region ET up to the pressure $p_5'' > p_5$. The dimensions of the whole bifurcation zone are proportional to the thickness of the boundary layer with which the reflected wave interacts. To calculate the thickness of the boundary layer it seems to be necessary to take into account the intense heat exchanges with the tube walls. The distance x' is most likely proportional to the dimenssions of the bifurcation zone but not to x, as it was thought to be in [4]. This conclusion was drawn on the basis of the analysis of the streak records. From these photographs it is evident that the point at which the pressure is equal to p_5 moves at a gradually decreasing rate, whereas the velocity of the reflected wave remains constant. Sometimes a near-wall shock wave (F in Fig. 1c) appears. Its apperance is the result of interaction of the supersonic non-stationary vortex flow with the stagnated gas in the separation region.

In the starting process of a supersonic nozzle, separation may take place inside the nozzle when the secondary wave interacts with the boundary layer behind the incident shock wave. The criterion of separation of a boundary layer when a shock wave interacts with the non-stationary boundary layer was compared with the criterion of separation for a stationary boundary layer [9, 10].

The data for the criterion of separation when a shock wave interacts with the non-stationary boundary layer in the nozzle with the criterion of separation during bifurcation are presented in Fig. 4. From this figure it is evident that the pressure that brings

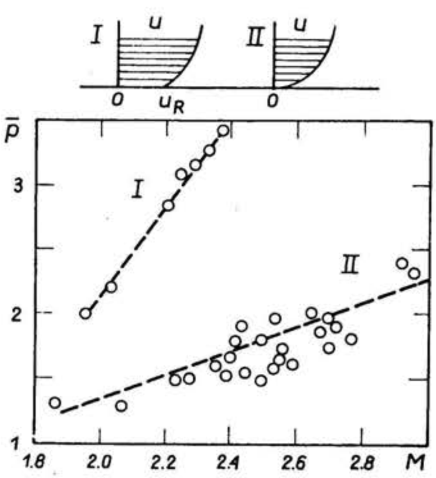

FIG. 4. Graph of the relation between the pressure drop at the oblique shock and the Mach number of the flow as related to the separation point. I — Bifurcation of the reflected wave. II — Quasi-stationary separation in nozzles [10].

about separation of the flow during bifurcation is much higher than the pressure in the nozzle. This is due to the fact that in the nozzle the secondary shock wave at the time of separation is immobile relative to the wall, but during reflection the shock wave moves with respect to the wall, i.e., separation takes place at the surface that moves in the direction towards the shock wave. This corresponds to the separation of a more inflated profile. For this reason separation during reflection is difficult. A similar effect was noticed at an immobile and mobile surfaces in a stationary cases during the separation of the boundary layer.

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