19. G. I. Maikapar and A. I. Pyatnova, "Flow of a supersonic stream past the external angle of the shell of an air intake," Uchen. Zap. TsAGI, 11, No. 3 (1980).
20. K. K. Kostyuk, N. A. Blagoveshchenskii, et al., "Experimental investigation of the flow of a stream with high supersonic velocity past a dihedral angle and past the simplest configuration of the 'triangular plate + conical body' type," Tr. TsAGI, Issue 224 (1984).
21. H. Kubota and J. L. Stollery, "An experimental study of the interaction between a glancing shock wave and a turbulent boundary layer," J. Fluid Mech., 116 (1982).
22. D. S. Dolling and S. M. Bogdonoff, "Upstream influence in sharp fin-induced shock wave turbulent boundary layer interaction," AIAA J., 21, No. 1 (1983).
23. V. I. Kornilov and A. M. Kharitonov, "Experimental investigation of a compressed boundary layer near the line of intersection of two plates forming a right angle," Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk, No. 8, Issue 2 (1974).
24. M. D. Brodetskii, A. I. Maksimov, and A. M. Kharitonov, "Investigation of interference and diffraction phenomena in supersonic flow past longitudinal steps," in: Aerodynamic Interference in Flow Past Three-Dimensional Bodies [in Russian], Inst. Teor. Prikl. Mekh. Sib. Otd. Akad. Nauk SSSR, Novosibirsk (1980).

FORMATION OF BOUNDARY DISTURBANCES DURING SHOCK-WAVE PROPAGATION IN TUBES MADE OF DIFFERENT MATERIALS

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The boundary disturbance of the plane front of a shock wave (SW) as it propagates in a tube containing an inert gas was first discussed by Shreffler and Christian [1]. Conducting experiments in which a copper wire was stretched along the axis of a tube, they observed a disturbance of the SW front along the wire. This region of boundary disturbance of the SW had considerable destructive force, propagating with a higher velocity than the main SW, but it radiated with a lower brightness. Such a phenomenon was also investigated in [2, 3]. Conducting experiments in thick-walled tubes, Tsikulin and Popov [2] showed that the presence of the wall, rather than its destruction, as well as the presence of high-energy quanta in the SW emission are important for the formation of boundary disturbances. The vaporization, in advance of the SW front, of material of the tube walls under the action of the SW emission was noted in [3]. The authors of these papers suggested several mechanisms for the formation of a boundary disturbance, but the question of which of them actually occurs remained unresolved. In the present paper this phenomenon is explained on the basis of experiments and the picture of the gasdynamic flow generated is discussed.

In the experiments, a diagram of which is presented in Fig. 1, the SW propagated in a tube 1 filled with xenon at standard density. Flat glass plates 2 with coatings of different materials were placed inside the tube. The SW was generated upon the emergence of a detonation wave at the end of a hexogen charge with a mass of 800 g. A lens of a special shape, made of a mixture of trotyl and hexogen, and used to obtain a plane SW front. The emission from the SW front was recorded by a pyroelectric receiver 3. The generation and propagation of the region of boundary disturbance was recorded with an SFR-2M streak camera in the regime of slit scanning through a violet filter (432 nm) and with a VFU-1 camera in the regime of movie spectrography with a diffraction grating. The SFR-2M camera was also aimed at the side glass window 4 using the system of mirrors 5. The velocity of the central undisturbed part of the SW was measured in a separate test, where the boundary disturbances running ahead of the wave were intercepted by special projections on the tube wall. The SW velocity varied from 7.5 km/sec at the start of the path with a length of 160 mm to 6.5 km/sec at the end. The emission flux density from the front of the undisturbed SW grew from 0 to 4.2 MW/cm^2 in 2.5 μsec, fell to 3.5 MW/cm^2 by 10 μsec, and remained constant up to 25 μsec. The flux density of the radiation acting on the wall varied from 0 to 1.8 MW/cm^2 according to the calculations, while the energy density of the radiation incident on the end of each plate was 8.0,

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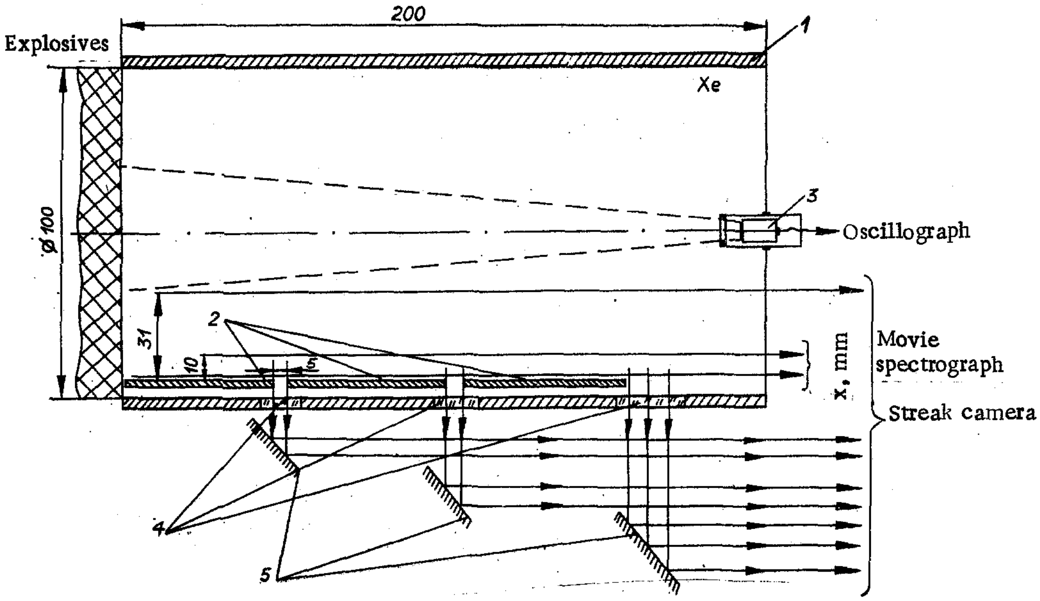

Fig. 1

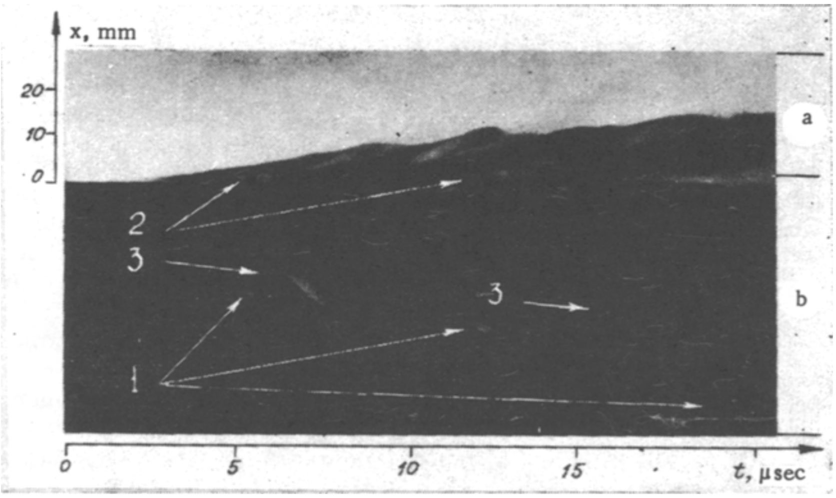

Fig. 2

10.3, and 12.5 J/cm^2, respectively.

Let us examine the results of the test in which sprayed bismuth was used as the coating on the glass plates. A streak picture of the test obtained with the SFR-2M camera is presented in Fig. 2. On part of it (a) one sees how, 2 µsec after the generation of the SW in xenon, a region of disturbance, having a lower brightness than the front of the main SW, starts to propagate from the bismuth-coated plates toward the tube axis. The velocity of expansion of the region of boundary disturbance from the wall toward the tube axis varied from 0.8 to 0.4 km/sec. Pulsations of the brightness and velocity of expansion of the region of disturbance developed as it passed through the gaps between the plates. The times of arrival of the boundary disturbance at the ends of the plates are seen in part b of Fig. 2; they are marked by the number 1. A brightness increase 2 was recorded at the same times in a narrow zone near the wall. "Burning through" of the bismuth layer occurred at the times 3. In this test the surface density of the bismuth layer deposited on the plates was 3.2 mg/cm^2. The velocity of propagation of the boundary disturbance along the plates exceeded the velocity of the main SW front and varied from 8.4 to 8.0 km/sec.

On a frame of the movie spectrograph (Fig. 3) the emission of the phenomenon is resolved in height x from the bismuth-coated plates and in the wavelength λ of the radiation. The exposure time of a frame was 2 µsec. The bismuth coated plates were located on the left. Four xenon absorption lines are seen over the entire width of the frame against the background of

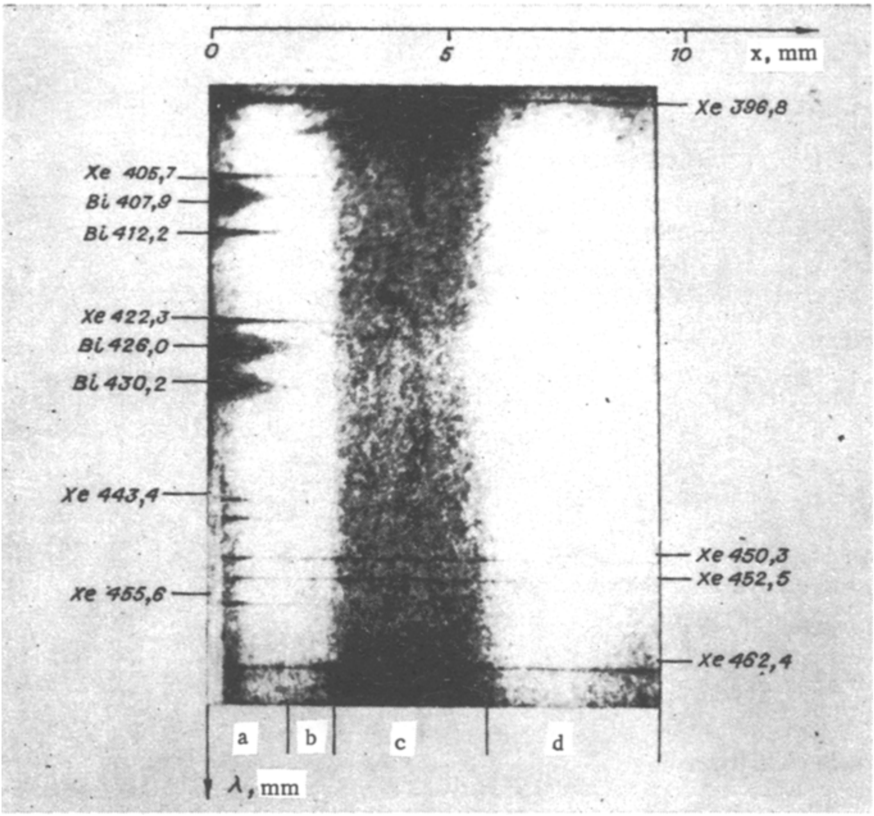

Fig. 3

the emission of the continuous spectrum. Region d corresponds to the emission of the undistorted SW front. Its temperature at this time is 30,000°K. The section of the boundary disturbance of the SW consists of regions *a*, b, and c. In region *a*, against the background of the continuous emission spectrum, broad bismuth absorption lines are seen, indicating the presence of a layer of bismuth vapor with a temperature of 15,000°K in it ahead of the plasma formation with a temperature of 19,000°K. The appearance of new xenon absorption lines is observed in regions *a* and b. Region c does not differ in the emission spectrum from the emission of the front of the undisturbed part of the SW, but it has a lower temperature of ∿15,000°K.

The streak pictures and the frames of the movie spectrograph show that the start of the formation of the boundary disturbance and the start of the vaporization of the material of the tube walls coincide in time. The bismuth vapor expanded toward the tube axis at a velocity of about 0.4 km/sec. But up to the time of arrival of the boundary disturbance it had risen above the surface of the plates by no more than 2.5 mm. The spectrogram of the boundary disturbance shows that region *a* in it is an SW moving through the bismuth vapor heated by the radiation of the main SW. Here the radiation of the SW moving through the vapor is screened by the heated layer ahead of its front. At the time of the emergence of this SW at the boundary between the vapor and the xenon, which occurs at the edge of the plates, the screening of the SW was removed and its temperature increased in about 0.5 μsec from 19,000 to 23,000°K. Region c is the SW moving through the xenon. Its lower brightness, in comparison with the brightness of the main SW, indicates a lower propagation velocity.

The propagation of an SW front through a gas in which there is a certain high-temperature layer near the wall can serve as a model of the boundary disturbance of an SW. According to the hypothesis of [4], the presence of such a "hot layer" leads to the development of a complicated gasdynamic flow which does not depend much on the thickness of this layer.

The shock-wave configuration explaining the structure of the boundary disturbance in our case is represented as follows. Vaporization of the material of the tube walls, leading to the appearance of a thin vapor layer 6 near the wall, occurs under the action of radiation from the front of the main SW 1 (Fig. 4). The vapor heated intensively by radiation (to 15,000°K in our test) and expands away from the wall, generating a weak SW 4 in the working

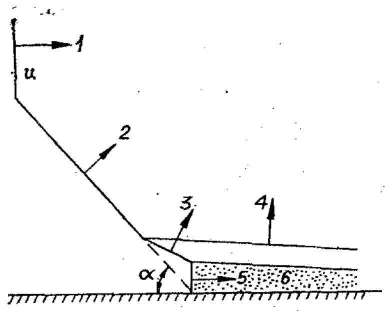

Fig. 4

gas, which was recorded in the test from the appearance of xenon absorption lines behind its front (region b in Fig. 3). Because of the considerable heating and expansion of the vapor in it, SW 1 starts to propagate with a higher velocity and forms SW 5. Discharging first into the layer of shock-compressed xenon ahead of the vapor and then into the undisturbed xenon, this SW 5 in advance of the main wave generates lateral SW 3 and 2. Despite the fact that the vapor layer occupies a region of only a few millimeters near the wall, the velocity of SW 5 in it is higher than the velocity of SW 1, and in time the associated SW 2 can cover the entire surface of the main SW 1. The velocity of the SW 2 is lower than the velocity of SW 1. Its value is determined by the velocity of the SW 5. If we neglect the sizes of the fronts of SW 5 and 3, then the connection between the velocities of SW 5 and 2 can be expressed by the relation $D_2 = D_5 \sin\alpha$. But $\tan\alpha = u/(D_5 - D_1)$, where u is the velocity of the point of junction of SW 2 with SW 1. Therefore, $D_2 = D_5/\sqrt{1 + (D_5 - D_1)^2/u^2}$. If we substitute into this function the experimentally measured values of D_5 = 8.5 km/sec, D_1 = 7 km/sec, and u = 0.6 km/sec, then $D_2 \approx$ 3.2 km/sec, and from the shock adiabat of xenon [2] it corresponds to a temperature of 16,000°K, close to the measured temperature of 15,000°K of SW 2, which confirms the correctness of the shock-wave configuration of a boundary disturbance proposed above.

SW 5 may have a more complicated shape than that shown in Fig. 4. This is connected with the fact that the vapor is usually heated intensively by radiation of the continuous spectrum in a thin layer, while near the vaporizing surface its temperature is considerably lower, and the presence of a significant amount of wall material in the form of finely dispersed drops is possible here.

The development of the phenomenon of a boundary disturbance is due to the transparency of the medium ahead of the main SW to the quanta capable of ionizing the vapor formed from the wall materials. The formation of free electrons promotes the development of "flashes" of absorption in the vapor and its intense heating at the rather low densities of the incident radiation flux occurring in these tests. For an SW in air or an inert gas containing an admixture of air, such a phenomenon is usually not observed owing to the opacity of these gases to the ionizing quanta.

We also made tests where glass, mercury salt, and aluminum were used as the material coating the pipe walls. In all the tests we recorded spectra of the vaporized and heated wall materials. The height of travel of the vapor from the wall did not exceed 4 mm and was small compared with the height of propagation of the disturbances along the surface of the main SW. The rates of development of the region of the boundary disturbance charged with a change in the material. Thus, in the case of a wall with an aluminum coating, the velocities u and $D_5 - D_1$ were about half those in the case of a bismuth coating. It is noted that the rates of development of the boundary disturbance depend on the surface density of the wall coating. When the surface density of the coating is lower, the disturbances develop earlier and their velocity increases considerably, which is evidently connected with the earlier onset of vaporization and heating to a higher temperature of the smaller mass of bismuth.

These experiments must be continued for a more detailed explanation of the influence of the wall properties on the development of a boundary disturbance of an intensely radiating SW. It is also interesting to investigate the radiative properties of SW 5, propagating through the developing vapor of a heavy metal. It is expected that a decrease in the effect of the screening of the emission of such an SW is possible at certain angles to its surface, which may lead to the emergence of strong ultraviolet radiation in these directions.

LITERATURE CITED

1. R. G. Shreffler and R. H. Christian, "Boundary disturbance in high-explosive shock tubes," J. Appl. Phys., 25, No. 3 (1954).
2. M. A. Tsikulin and E. G. Popov, Radiative Properties of Shock Waves in Gases [in Russian], Nauka, Moscow (1977).
3. S. D. Savrov and I. M. Ageev, "A laboratory explosive shock tube," Teplofiz. Vys. Temp., No. 6 (1980).
4. K. E. Gubkin, "Propagation of blast waves," in: Mechanics in the USSR over the Past 500 Years [in Russian], Vol. 2, Nauka, Moscow (1970).

APPROXIMATE CALCULATION OF STEADY-STATE SHOCK WAVE PARAMETERS IN POROUS COMPRESSIBLE MATERIALS

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Formulation of the Problem. Analysis of Calculation Model. Elastic polyurethane foams based on simple and complex polyethers [1] are among the class of materials characterized by high porosity (the total pore volume may reach 98% of the total specimen volume) and low skeleton elasticity values. The characteristic size of polyurethane foam pores depends on the brand and method of preparation, ranging from fractions to units of mm. We will consider a porous material with sufficiently large linear specimen dimensions (hundreds of mm and more) as a mixture of solid particles and a gas, which may be justified as follows. The skeleton elasticity of the majority of polyurethane foam brands is markedly less than the value of atmospheric pressure under normal conditions (thus, for the widely used type PPU-ÉM-1 with apparent density of 25-45 kg/m^3 the skeleton stress at 40% deformation comprises $(0.4-1.0)\cdot 10^4$ Pa [1]).

This indicates that it is possible to neglect the skeleton elasticity of such materials in comparison to the elasticity of the gas contained in the pores at an initial gas pressure $p^0 \sim 10^5$ Pa and model the real porous material by a liquid with gas bubbles or a homogeneous gaseous suspension of solid noninteracting microparticles.

The dynamics of propagation of acoustic or shock waves in such media were analyzed in [2-6] by representing the two-phase medium as a homogeneous mixture. As was noted in [6], the homogeneous mixture is the simplest possible model of a two-phase medium in which all effects related to the discrete nature of the structure are neglected, and only the volume fraction of the solid phase which effects the compressibility of the medium as a whole is considered. We will assume the solid phase to be incompressible while the gas within the pores is ideal. For complete thermodynamic description of a homogeneous mixture it is necessary to specify an exact or approximate law of interphase heat exchange for the concrete type of porous material. This is because within the small radius of the pores interphase thermal equilibrium in the two-phase porous medium can be established over a time less than the characteristic duration of propagating acoustical perturbations, so that it is permissible to consider the medium to be in thermodynamic equilibrium and even isothermal (in view of the considerable specific heat of the solid phase). Such an approximation was used in [2-6]; however, in [3] an approximate estimate was also made of the cooling time of an isolated gas bubble of radius r in a liquid initially adiabatically compressed from a pressure p_1 to p_2 (T_0 = 21°C):

$$t_1 \approx 43r^2(p_2/p_1)^{0.05},\ t_2 \approx 8600r^2(p_3/p_1)^{1/3}, \tag{1}$$

where t_1 and t_2 are the times required for cooling of the bubble by 10 and 90%, respectively; r is measured in m. Applying this estimate to elastic polyurethane and taking $r \sim 10^{-3}$ m (the characteristic value of the pore radius) we find in the acoustical approximation $t_1 \simeq 5\cdot 10^{-5}$ sec, $t_2 \simeq 10^{-2}$ sec. When the rate of propagation of hydrodynamic perturbations in the medium exceeds the value r/t_1, it is appropriate to assume heat exchange responsible and consider an "adiabatic" model of flow of the two-phase medium. At $r \sim 10^{-3}$ m and $t_1 \simeq 5\cdot 10^{-5}$ sec

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