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DEFORMATION MECHANISM OF A SHOCK RADIATING FRONT DURING ITS MOTION IN A CHANNEL

S. D. Savrov

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Shock front deformation by a powerful shockwave at the walls of a channel filled with inert gas was detected by Shreffler and Christian [1]. A quantitative description of this phenomenon and, even more, a prediction of the conditions for its origination are barely accessible even now. For instance, the detection of such a shock front deformation in a laboratory shock tube turned out to be unexpected [2].

The first attempt at a satisfactory explanation of the front deformation phenomenon was by Taganov [3] on the basis of an analogy between the near-wall curvature of the front and the phenomenon of viscous boundary layer separation. The starting point in this model was the assumption about the presence of a "thermal layer" in front of the shock near the wall heated by radiation. Such a model is in good agreement with experiments in which the "thermal layer" is produced artificially, by heat transmission from a hot burner or a discharge of a metallic wall [4-7]. Under these conditions, the origination of the "thermal layer" is clearly distinct from the conditions of its origination in shock tubes or in a powerful explosion under the surface of the earth. Evaporation of the channel wall is detected ahead of the shock front in a shock tube [2] at quite moderate brightness temperatures (~15 kK). The presence of vapors complicates the problem.

A detailed investigation showed [8] that the vapor layer is thin relative to the channel diameter, and at first glance this permits a bifurcation model that is the development of the scheme presented in [3] to be applied to describe the front deformation.

The flow diagram for such a model is displayed in Fig. 1, where 1 is the tangential surface, 2 is the unperturbed shock front, 3 is the secondary shock front, 4 is the oblique shock, 5 is the boundary of stream collapse, and 6 is the near-wall vapor layer.

The characteristic pattern of bifurcation development in a laboratory shock tube is represented in Fig. 2. The tube diameter is 150 mm, the length of the xenon-filled channel is 1000 mm. The wall material is stainless steel. The initial pressure in the xenon is 13.3 kPa, the shock Mach number is M = 17. At the end of the channel the shock collides with a glass plate which permits determination of its front during observations of the process on a slit photoscanner from the shock endface (Fig. 2, where 1 is the time of shock entrance into the xenon through the separating diaphragm from Lavsan, 2 is the image of the trajectory of the line of intersection of the shock front flanks with the channel walls on the photoscan, 3 is the impact of the front on the glass plate). Despite the clear pattern of the shock front deformation phenomenon, a quantitative analysis of the parameters by the scheme of Fig. 1 is fraught with difficulties.

It is seen from additional experiments that under the same initial conditions in a long channel (3 m) propagation of the front deformation to the channel axis ceases after shock traversal of a distance of 6-8 calibers of the tube channel. The deformed shock front surface emerges into the stationary mode. Such a mode had not been assumed earlier in the scheme in Fig. 1. The shock front deformation in [1, 4-10] was nonstationary.

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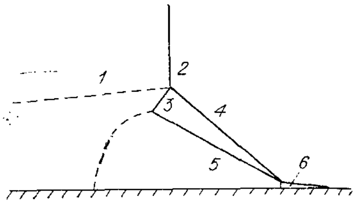

Fig. 1

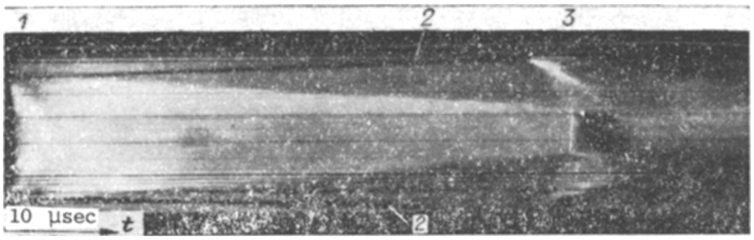

Fig. 2

Experiments with a copper foil covered channel wall showed that the size of the deformed shock front flanks diminished several times, however, their slope remained the very same (~45°). The difference between the atomic weight of iron and copper vapors and in their boiling points is not great enough to give a large difference in the front deformation rates. A strong influence of a wave brightness increase on the front deformation is also observed. For M = 23 the bifurcations overlap the whole channel section at a distance of three calibers from the separating diaphragm. Since more powerful irradiation of nonionized vapors cannot increase the sound speed therein substantially, this fact is also unexplainable.

The explanation of the strong influence of an increase in the channel section on the deformation [8] also encounters analogous difficulties. All this merits a more detailed analysis of the correctness of applying the bifurcation model [3, 8] to describe the shock front deformation. Observation of the fact [2, 8] that the "thermal layer" consists of channel wall vapors substantially alters the condition for application of this model with respect to the heating, proposed earlier, of a thin working gas layer at the wall by heat conduction. The principal condition for the development of bifurcation is the lower gas density at the wall, which permits the shock front flanks to overtake the central part. Satisfaction of this condition for hot vapors at the wall is not self-evident. The relationship between the atomic weights of the working gas and the vapor, the boiling point of the wall material, and most importantly, the intensity of wall evaporation turn out to be essential. Under quite powerful irradiation intense evaporation is capable of producing an independent oblique shock. The density of the vapors propelling it can exceed the density of the unperturbed working gas, and the condition for bifurcation development is not satisfied. Upon utilization of nonmetallic materials (glass, plastic, cardboard [1], etc.) in which the coefficient of light absorption in the ultraviolet band of the spectrum is relatively small, for channel wall fabrication, the boiling point can be reached almost simultaneously in a comparatively thick layer (~10 µm) and the evaporation process will be explosive in nature even at moderate brightness temperatures. The presence of an oxide film, heat conduction, and also contamination of the channel surface by micron layers of organic substances, inevitable in the exploitation of high-enthalpy tubes with large dimensions, play an important role for metallic materials.

The shielding of the high-brightness light flux originating because of their photoionization [10] must be taken into account also in the dynamics of vapor layer development. Shielding fresh layers of condensed substance from irradiation and additional heating of the vapors accelerating their expansion contribute to the achievement of a low density for the development of bifurcation behind the oblique shock produced by the expanding vapors. It is difficult to determine the nature of the near-wall perturbations in experiments with powerful shocks (T_b ~ 30 kK) even by direct observations and the accompanying computation since the absorptivity of channel walls is not known in a broad spectrum range. Consequently, as before, the treatment of the mechanism of near-wall curvatures of the front remains unclear [1].

Another circumstance appears primary in the question of diagreement between the results of experiments performed in laboratory shock tubes by the scheme of Fig. 1. Conditions for the development of bifurcation are satisfied relatively easily for a moderate rate of channel wall evaporation therein (T_b ~ 15 kK). A certain time after the shock entrance into a channel with an inert gas, its front meets the wall with the thin low-density vapor layer just formed, resulting in the beginning of bifurcation development. The phase of the beginning of wall evaporation moves ahead of the shock front at a velocity exceeding the front velocity since the wall was heated a longer time by radiation at large distances from the diaphragm than in the initial section. This phase velocity under the poor light transmission conditions over the channel in the ultraviolet range of the spectrum does not exceed the shock velocity by much. Consequently, in the majority of cases the initial bifurcation section at the wall succeeds in following the initial domain of vapor origination at the wall. The velocity of near-wall perturbation motion turns out to be the phase velocity. This phase velocity should drop during gradual contraction of the surface of the bright undeformed shock front and become equal after a certain time to the velocity of the unperturbed shock front. The deformed wave should emerge into the stationary mode, as is indeed observed in the above-mentioned experiment. The distance of the wall evaporation phase from the unperturbed shock front depends on the absorptivity of the wall and its heat conductivity. It will be closer to the front for a copper wall than for a steel wall; therefore, less front deformation will occur at copper walls.

As the wave brightness or channel section increases, the initial evaporation phase moves away from the front, which also explains the large front deformation noted above for these cases. Consequently, the excess of the near-wall perturbation velocity over the unperturbed shock front velocity is notable only in the initial stage of wave motion and is a secondary fact for the theory of phenomena in shock tubes. At the same time, the experiments in all the preceding research studies were performed with short channels (less than ten calibers) and a great deal of attention was spent on the measurement of this excess of the velocity.

Another interesting question in the mechanism of bifurcation formation is the role of the propelling gas (explosion products [1, 9], buffer gas [2, 8]). Deformation of the wave flanks starts with the shock entrance into the channel with the inert gas with a several microseconds delay when the layer of shock-compressed xenon or argon is still small. Under these conditions the propelling gas can evidently penetrate into the domain behind the stream collapse boundaries (see Fig. 1) and fill it during further shock motion in the channel. In such cases the effect of "pinching" of the working gas holds near the channel axis and the idealized scheme (Fig. 1) turns out to be barely suitable.

The reasoning elucidated above and the doubts of the correctness of the interpretation of previous experiments are also applicable in full measure to [10] in which the bifurcation scheme [3, 8] is utilized in simplified form to investigate front deformation in a channel destroyed by an explosion that is faced with glass with a deposited metal layer.

In conclusion, let us note that the phenomenon under discussion became a serious obstacle on the road to further development of the technique of high-enthalpy shock tubes and merits further study and discussion.

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HYDRODYNAMIC PHENOMENA DURING INTERACTION OF OPTICAL RADIATION WITH STRONGLY ABSORPTIVE DIELECTRIC FLUIDS

V. V. Zosimov, M. Yu. Kukushkin, K. A. Naugol'nykh,
and O. V. Puchenkov

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At this time various aspects of intense optical radiation interaction with strongly absorptive fluids are considered in numerous experimental and theoretical research studies [1-7]. The traditional experimental method of investigating this interaction is to record the acoustic perturbations occurring under the action of the optical radiation in the fluid and the gas adjoining it. Such recording is performed by pressure sensors of different constructions [3, 6] as well as by using optical shadow methods [1, 2, 5]. However, because there is no generally recognized theoretical model of the process of intensive optical radiation interaction with strongly absorptive fluids, experiments associated with acoustic measurements do not receive a single interpretation in the research articles of different authors [4, 6, 7]. Consequently, there is the need to obtain new additional data about the physics of the occurring phenomena.

The hydrodynamic perturbations of the interfacial liquid—gas boundary accompanying the interaction process are investigated in this paper. The time scale for development of these perturbations considerably exceeds the characteristic time of acoustic perturbation formation and evolution. This ("hydrodynamic") stage of the interaction process has not been studied in detail (the experiments [8] are of qualitative, demonstrative nature). However, there are papers devoted to a study of similar hydrodynamic phenomena in a fluid caused by by an explosion on its surface [9, 10]. The investigation we performed permitted setting up a linear relation between the total recoil pressure pulse of the pair escaping from the surface and acting on the fluid surface and the energy density of the incident laser radiation in a certain range of laser radiation intensity. The proportionality factor within the limits of measurement accuracy is identical for the three liquids under consideration (water, ethanol, heated glycerine).

1. FORMULATION OF THE PROBLEM

Absorption of sufficiently high laser radiation energy in a fluid is accompanied by intensive vapor-formation processes in its near-surface layer [6]. A certain pressure acts on the surface because of the recoil pulse of the vapor escaping from the surface, resulting in the generation of sound and causing a residual flow in the liquid half-space. Neglecting viscosity effects as well as the entropy change, an integral relationship

$$\varphi(\tau) = -\frac{1}{\rho_0}\int_0^\tau p'\,dt + \frac{1}{\rho_0}\int_0^\tau \frac{p'^2}{\rho_0 c^2}\,dt - \int_0^\tau \frac{v^2}{2}\,dt, \qquad (1.1)$$

can be written for the potential of this flow, where ρ_0 and c are the density and sound speed, p' is the excess pressure occurring under the action of the recoil pulse, v is the motion velocity, and τ is the duration of the recoil pulse. Considering the case of moder-

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