region and thus lowers their concentration in the latter. As was shown in [7], there is an abrupt increase in the concentration of reflected particles on the separatrix, which leads to the formation of a narrow zone in which the concentration of the disperse phase undergoes a significant increase. The concentration of this phase decreases as the end of the cylinder is approached but remains appreciably greater than in the incoming flow (see Fig. 3).

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INTERACTION OF A SHOCK WAVE WITH A BOUNDARY LAYER

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The propagation of a high-intensity shock wave in a gas along a solid surface is accompanied by distortion of the shock front – a wedge-shaped precursor which becomes larger over time is formed near the surface [1]. One possible reason for this phenomenon is the formation of a heated layer of gas or erosive vapor near the surface [2]. Analogous to this phenomenon is the thermal-layer effect discovered by G. I. Taganov [3, 4]. The restructuring that the flow undergoes when a thermal (low-density) layer precedes the shock front is of a global nature, since it occurs in a region much larger than the thickness of the perturbing layer. It was subsequently noted [5] that a precursor is formed when the surface of the wall vaporizes. Detailed spectral measurements made in [6, 7] showed that the given phenomenon does indeed begin to unfold in a thin vaporous boundary layer heated by radiation. At the same

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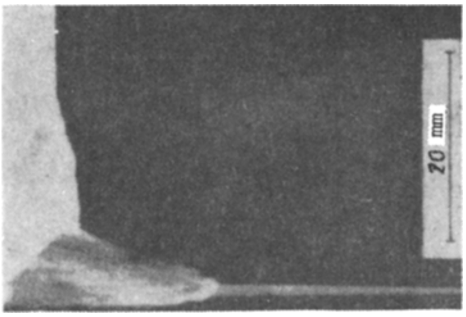

Fig. 1

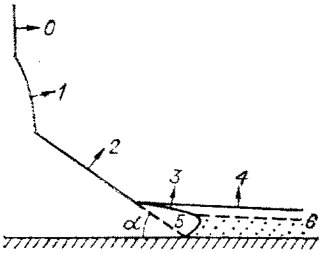

Fig. 2

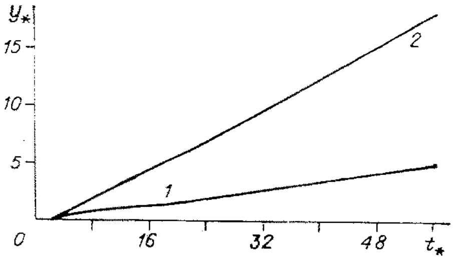

Fig. 3

time, as was noted in [8], serious difficulties are encountered when an attempt is made to interpret the empirical data from the viewpoint of the thermal layer theory. In accordance with Taganov's hypothesis, when a shock wave moving along a surface travels a distance x much greater than the thickness Δ of the heated (thermal) layer, the flow outside the wave ceases to depend on Δ and begins to exhibit asymptotic behavior. Theoretical studies of the problem of the interaction of a shock wave with a thermal layer [9-12] have supported this hypothesis and have shown that the motion is self-similar for long periods of time and constant shock-wave velocities. However, when the boundary layer is formed "spontaneously" — during the propagation of a radiative shock wave — the development of the precursor over time is often unpredictable. In similar tests [1, 2, 5-8], there were large differences in both the ratio $\xi = D_+/D_0$ (where D_+ is the velocity of the precursor and D_0 is the velocity of the main shock wave) and the angle α at the apex of the wedge-shaped precursor. It is necessary to determine the factors influencing these quantities and make a detailed study of the flow structure in the precursor itself. Figure 1 presents a photograph of a shock wave with a precursor obtained in an experiment similar to that described in [6, 7]. The photograph was obtained with a streak camera in which the slit was oriented parallel to the front of the main shock wave and was located a certain distance from the explosive charge generating the wave. The shock wave moved in xenon of normal density along a flat glass wall coated with a fresh layer of bismuth. The density of the bismuth layer (per unit of area of the surface) m = 0.44 mg/cm^2. The wall is at the bottom in the photograph. As was shown by spectral measurements made in [6, 7], the weakly luminous region near the wall is heated bismuth vapor. It is apparent the dimensions of the wedge-shaped precursor are already considerably greater than the thickness Δ of this vaporous boundary layer.

The choice of bismuth to coat the wall was based on the fact that the vapor of this element formed at the boiling point should be considerably denser than the surrounding xenon. In this case, no precursor should generally be formed. However, the photograph indicates that a precursor is formed. We should also note that, in contrast to the experiments [11, 12] and calculations [9, 10, 13], the apex of the precursor is located not on the surface itself, but a certain distance from it — near the vapor–xenon interface. The shock wave in the vapor is highly curved and approaches the wall at an acute angle. Clearly visible above the wedge-shaped part of the precursor in Fig. 1 is a zone in which the front of the main shock wave is extended outward somewhat in the direction of its propagation. The wave front is uneven in this region due to the accompanying pulsations, and its mean brightness temperature is 1-2 kK higher than the temperature of the undisturbed part of the front (about 35 kK).

Figure 2 schematically depicts the external configuration of the shock-wave system. Here, 0 represents the undisturbed main shock wave, 1 represents the slightly disturbed region on the front of the main shock wave, 2 indicates the oblique shock wave of the wedge-shaped precursor, and 3 indicates the section of the precursor which moves in the layer of gas compressed behind the shock front 4. This layer is formed by the expanding vapor from the wall. The shock wave 5 propagates through this vapor and is inclined oppositely to waves 1-4. Line 6 denotes the boundary between the vapor and the surrounding gas.

Figure 3 shows dimensionless time $t_* = tD_0/\Delta$ in relation to the relative height $y_* = y/\Delta$ of the points of intersection of shock waves 1 and 2 (curve 2) and shock waves 0 and 1 (curve 1) above the wall with m = 0.35 mg/cm^2. Here, the characteristic velocity D_0 = 7.5 km/sec, while the time $t_0 = \Delta/D_0$ = 0.2 μsec. The angle of inclination of the oblique shock wave 2 in the experiment remains constant and equal to approximately 25°. As is evident, both the wedge-shaped part of the precursor and the high-brightness region at the front of the main shock wave develop similarly at $t_* \gg 1$.

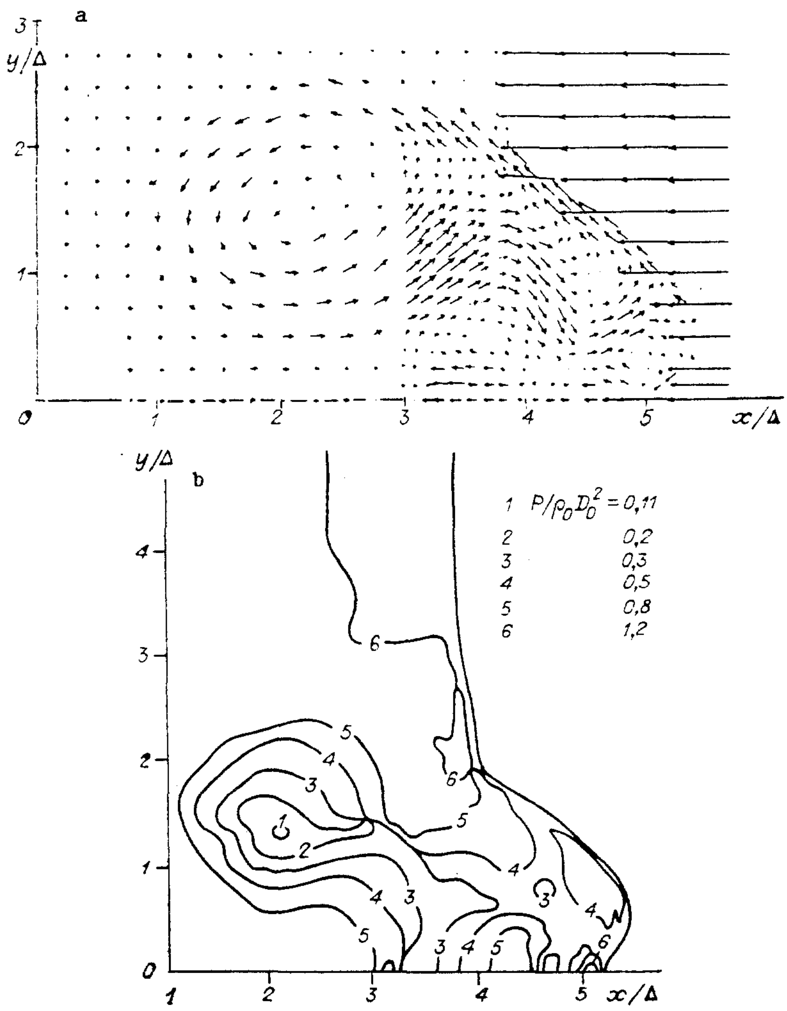

Fig. 4

To study the flow structure in detail, we numerically solved a gas-dynamic problem similar to that examined in [9-11]. However, we concerned ourselves with the case of an unevenly heated near-surface layer. The Mach number of the main shock wave was 32, while the adiabatic exponent $\gamma = 1.4$ was constant. The initial pressure was assumed to have been the same everywhere (in both the thermal layer and in the undisturbed region). We ignored the fact that the erosive vapors expanding outward from the wall generate (in the working gas) a relatively weak shock wave 4 behind which the pressure is greater than the initial value. This was done to facilitate comparison with the calculations in [9-11], where the same assumption was made. In fact, the presence of shock wave 4 and the associated pressure increase are insignificant, since all of the other shock waves are strong and since the pressure ahead of these waves is not the determining parameter. Since we did not determine the distribution of density in the vapors, we assumed in the calculations that density changed linearly through the thickness of the thermal layer. Here, density changed from a minimum ρ_* equal to 0.333 ρ_0 at the middle of the layer to the value ρ_0 at its boundaries. The computing mesh had a sufficiently large number of nodes — 200 in the horizontal direction and 100 in the vertical direction. The distances between these nodes was constant in each direction. The distances between these nodes was constant in each direction. There were 20 points over the cross section of the thermal layer.

The calculated velocity field (a) and pressure field (b) for one moment of time is shown in Fig. 4 in the coordinate system connected with the piston that generated shock wave 0. Figure 4b shows values of dimensionless pressure $P/(\rho_0 D_0^2)$ corresponding to the given isobars. It is also evident that, as in the case of the calculations performed in [9-11] for constant density in the thermal layer, the flow of gas compressed in oblique shock wave 2 into the region behind the front of shock wave 0 results in curvature of the front above the main wedge of the precursor (it results in the appearance of shock wave 1) and gives rise to intensive vortical flow in the precursor itself. However, there are also other vortices, associated with the reflection of shock wave 5 from the surface of the wall. These vortices

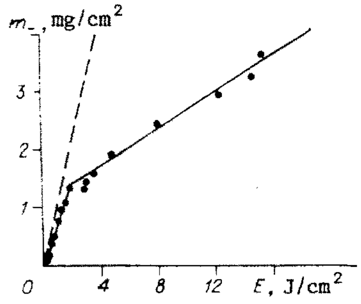

Fig. 5

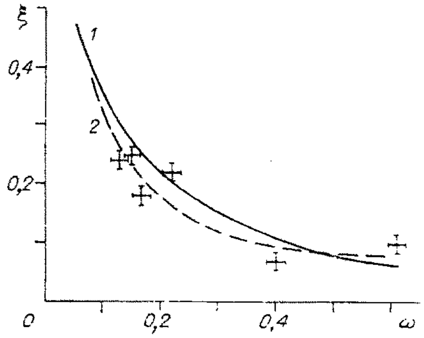

Fig. 6

propagate through the thermal layer below the point of minimum density. Such reflection produces a local region of relatively high pressure on the surface of the wall, pressure in this region being close to the pressure in the main shock wave 0. Flow outside the thermal layer develops in a self-similar manner as the precursor propagates further along the layer – the angle α of inclination of the oblique shock wave 2 on its nearly rectilinear section remains constant. The following relation was proposed in [10] to determine this angle for a uniformly heated layer:

$$\sin\alpha = \sqrt{\rho_-/\rho_0} \qquad (1)$$

(ρ_- is density in the thermal layer). This relation was obtained with the assumption that the pressure behind the normal shock moving in the thermal layer is equal to the pressure in the oblique shock. In the given case of an unevenly heated thermal layer, it turns out that α can still be determined from (1) even though the shock in the layer is highly curved. The quantity ρ_- in (1) represents ρ_*.

In the experiment (see Fig. 1), we used the brightness of the saturated lines of bismuth to determine the maximum temperature reached in the outer region of its vapor (15 ± 1 kK). The use of a piezoelectric transducer to directly measure pressure on the surface vaporizing under the influence of the radiation of shock wave 0 showed that it was close to the pressure determined behind the front of shock wave 4 on the basis of the measured velocity of this wave. Equality of the former pressure to the pressure behind shock 4 was confirmed by the low velocity of the latter compared to the speed of sound in the heated vapors. It follows from this that pressure in the vapors in the given test was equal to 10^6 Pa when the velocity of shock 4 was 0.35 km/sec. The equation of state of bismuth [14] can be used to find the minimum density of its vapors corresponding to this pressure and the measured maximum temperature. It is equal to 10^{-3} g/cm^3, which nearly coincides with the value $\rho_* = 1.1\cdot10^{-3}$ g/cm^3 found from Eq. (1) for the value $\alpha = 25°$ measured at this moment of time. Thus, Eq. (1) is satisfied with sufficient accuracy in the calculation and the experiment and can be used for estimates of minimum density in vapors.

Figure 5 shows the specific mass m_- of bismuth entrained from the vaporizing surface. This quantity, determined in special experiments, is shown in relation to the energy density E of radiation from the shock wave incident on the surface in xenon (the dashed line corresponds to the sublimation energy of bismuth ~1 kJ/g). The value of m_- was determined on the basis of recordings of the moments that bands of bismuth of different thickness deposited on the glass became luminous (the method of deposition is described in detail in [15]). At the beginning of vaporization, the energy consumed in entraining the substance was about 1.4 kJ/g, i.e., was close to the heat of sublimation of bismuth. Energy expenditure increased as the mass of the vapor layer increased – the phenomenon of self-shielding of the surface was seen [16-19]. Radiant energy equal to 10 J/cm^2 was supplied in the above-described experiment before the arrival of the precursor at the wall. According to Fig. 5, this amount of energy corresponds to ablation equal to $m_- = 2.6$ mg/cm^2. With a vapor layer 2 mm high, this value yields a mean density of $1.3\cdot10^{-2}$ g/cm^3. The latter is an order of magnitude greater than the value we determined from the maximum temperature and pressure in the vapor, as well as the value determined from the angle α. Since the indicated mean density is twice as great as the density of the surrounding xenon, a precursor will not form if the density of the vapor layer is uniform. This conclusion follows from theoretical representations.

It should be noted that the estimate of the mean density of the vapor is somewhat exaggerated because the vapor contains droplets. Some of these drops are carried off to regions outside the layer and even propagate ahead of shock front 4 generated by the vapor in the surrounding xenon. These drops are surrounded by nonoverlapping clouds of vapor heated by radiation. This is seen in the photographs (including the photograph in Fig. 1) as weak luminescence at individual points above a solid vapor layer. Another manifestation is the generation of wedge-shaped disturbances at the front of the precursor. These forward-directed disturbances are formed as the precursor approaches the above-indicated points.

The density of the vapor at a pressure of 10^6 Pa and the temperature corresponding to the phase transformation is also higher than the density of xenon. Thus, the mere occurrence of vaporization cannot by itself be responsible for the formation of the precursor (at least under our conditions, when the vapor had a high atomic weight and the pressure in the vapor was high).

The main factor governing the formation and the development of the precursor in our experiments was heating of the vapor by the radiation of the main shock wave 0 to temperatures much greater than the phase-transition temperature. This is due to the fact that a significant part of the radiation emitted by shock wave 0 (temperature behind the front of shock wave 0 ~ 3 eV) is within the region of quanta energies lower than the first ionization potential of xenon (12.1 eV) but above the ionization potential of bismuth (7.3 eV). The mass coefficient expressing the absorption of cold bismuth vapor for the ionizing ultraviolet radiation was on the order of $\chi \approx 10^4$ cm^2/g. Thus, with ultraviolet radiation having a specific energy of about 0.01 J/cm^2, the vapor should be heated enough so that absorption of the radiation begins to decrease due to the photoelectric effect. Although additional absorption takes place as a result of the Bremsstrahlung mechanism, absorption associated with highly excited states, and absorption in the corresponding lines, the mean absorption coefficient should decrease with a further supply of energy, while the mass of the heated and ionized layer should increase. Thus, the discontinuity on the relation $m_-(E)$ and the constant ratio $\Delta m_-/\Delta E \approx 6$ kJ/g at $E > 2$ kJ/cm^2 (see Fig. 5) can be interpreted as follows: given the indicated value of energy, an ionization wave begins to propagate through the vapor behind the vaporization wave and the vapor luminesces [20]. The energy expended on heating the substance for the incident radiation is about 6 kJ/g. According to the equation of state of bismuth [14], this corresponds to a vapor temperature of about 15 kK. The latter value is consistent with the measurements of maximum temperature. Under the conditions of our experiment, the ionization wave envelops a small region of the vapor. Here, the hottest vapor layer has a mass which is only of the order $\chi^{-1} \approx 10^{-4}$ g/cm^2 and is about 1 mm thick. These values agree with the data obtained from the photographs. In the case being discussed, most of the incident radiation passes through this layer and is expended on heating of the deeper layers of vapor and the deposited layer of bismuth, as well as on vaporization of the solid surface. Some of the energy of the hottest outer layer of vapor is reradiated in the opposite direction, which also serves to limit the maximum temperature and mass attained by the layer.

Estimation of the heating of the vapor becomes more complicated when shock wave 5 propagates through a substance with a higher atomic mass than the surrounding working gas. As a result, temperature behind shock front 5 becomes greater than behind the front of the main shock 0. In the case of vapors of bismuth, this temperature reaches 65 kK. Such a wave is supercritical and has a developed boundary layer in front of it [21]. The temperature in the heated layer of a supercritical wave reaches the temperature behind its front, while density is close to the density of the gas ahead of the heated layer. However, according to estimates, the thickness of the heated layer ahead of shock wave 5 is comparable to the thickness of the vapor layer. Thus, since the process is essentially two-dimensional, an increase in pressure in the boundary layer can cause additional motion of vapor in the direction of the surrounding working gas. This would in turn lead to a reduction in density in the outer vapor layer. However, considering that the velocities of such motion would be at least three times lower than the velocity of shock wave 5, the additional expansion in the heated layer could not reduce density by more than 30% compared to the density of the vapors ahead of the heated layer. Of course, these estimates should be refined further through detailed numerical calculations allowing for the intensive radiant flows in shock wave 5, the additional vaporization of the wall in the heated layer and behind the front of shock wave 5, the entrainment of a liquid fraction into the vapor, and turbulent mixing of the interface between the vapor and the working gas. Such a complete analysis of the problem is presently too complex to be undertaken. However, we can conclude from the analysis made thus far that ionizing ultraviolet radiation from the front of shock wave 0 plays the decisive role in the heating of the vapors and the formation of the precursor. This was confirmed by special experiments in which a small (about 2%) air impurity was placed in the xenon. The transmission limit of air in the ultraviolet region is below the first ionization potential of the vapor. Despite the fact that vapor was formed near the surface in these experiments, no precursor was seen since the vapor was not heated by ultraviolet radiation.

The authors of [6] found that the angle α and the velocity D_+ of the precursor are dependent on the surface mass m of the deposited bismuth. A decrease in m is accompanied by an increase in velocity D_+ and a decrease in the angle α. Curve 2 in Fig. 6 shows the measurement results in the form of the dependence of $\xi = D_+/D_0$ on $\omega_* = \rho_*/\rho_0$. The value of ω_* was determined from Eq. (1) on the basis of measurements of α. Figure 6 also shows the theoretical relation $\xi(\omega_*)$ (curve 1). The agreement between the curves in the figure is satisfactory, which allows us to assume that a decrease in m will be accompanied by a decrease in ρ_*. The existence of this relationship can probably be attributed to several factors: a decrease in heat removal to the interior of the substance for thin layers deposited on a low-heat-conducting substrate; an earlier beginning of vaporization and more intensive vaporization due to the greater energy concentration achieved in the vapor for the same given incident energy. Confirmation of this comes from the fact that the formation of a precursor was recorded no later than 0.3 μsec when $m = 0.3$ mg/cm^2, while the formation of a precursor was recorded only 1.5 μsec after the beginning of motion of shock wave 0 when $m = 3.2$ mg/cm^2.

In our experiments, shock waves propagated in a tube with an inside diameter of 100 mm. During the motion of the wave along the tube, there was sufficient time for shock waves 1 and 0 to intersect on the tube axis. As already noted, the brightness temperature of shock wave 1 was 1-2 kK higher than that of shock wave 0. After shock wave 1 moved off the axis, the region in which its brightness temperature was 3 kK greater than the temperature of shock wave 0 began to expand. This perturbed region continued to pulsate, alternately being reflected from the center and the line of intersection of shock wave 1 and shock wave 2. The attenuation of the central part of the shock front was compensated for by the fact that its brightness temperature remained constant for a long period of time.

Due to the limited diameter of the tube used in the experiments, self-similar development of the precursor occurred only over a period during which the main wave traveled a distance equal to 2-3 tube diameters. Growth of the precursor subsequently slowed and its velocity became the same as that of the main shock wave 0 after the traversal of 4-5 diameters. A similar effect was seen in [8]. Such steady propagation of the precursor can be attributed to a decrease in the radiant flux reaching the tube wall due to a decrease in the diameter of the intensively radiating shock wave 0. The diameter of this wave is reduced as a result of an increase in the height of the precursor and an increase in the distance from shock wave 0 to the section of the wall that is not enveloped by the precursor (which is in turn due to an increase in the length of this section). In this case, the maximum temperature in the vapor should decrease, while the minimum density should increase. In the tests described above, the brightness temperature of shock wave 2 was 15 kK and the radiant flux from its surface was no greater than 0.3 MW/cm^2. This value is an order of magnitude lower than the flux from the surface of shock wave 0. Self-similar development of a precursor up to the moment of its collapse on the tube axis was seen in the experiments in [22], where the velocity of the main shock wave 0 was higher ($D \geqslant 10$ km/sec) and the radiant flux from the surface of shock wave 2 was significantly greater (reaching 1 MW/cm^2). The self-similar motion was followed by the movement of a shock-wave configuration in the form of a conical funnel along the tube. This structure moved at a constant velocity.

It should be noted that, in contrast to the experiments in [1, 2, 5], we made it a point to use a fresher coating of a pure substance for the tube wall. The substance also had a higher atomic weight, which increased the density of the vapors. As our special experiments showed, the precursor forms at considerably lower radiant fluxes and develops more rapidly in the case of a wall composed of light elements. This finding is in agreement with the results of the experiments in [1], where a shock wave propagated in a Plexiglas tube 75 mm in diameter in argon at a velocity of 8 km/sec. Here, the velocity of the precursor $D_+ = 10\text{-}11$ km/sec, which corresponds to $\xi = 1.4$ and, in accordance with Fig. 6, the parameter $\omega_* = 0.1$. The temperature of the front of shock wave 0 (20 kK) is clearly insufficient for ionization of the vapor. Nevertheless, the precursor was highly elongated, which indicates that the vapor that was formed was of low density. This result was obtained despite the fact that the temperature of the vapor was not much greater than the temperature at which the material of the tube wall decomposes. The given result can be attributed to the low molecular weight of the vapor, the relatively low radiant flux, and the consequent low pressure in the expanding vapor. Such a situation naturally leads to a significant decrease in the density of the vapor relative to the surrounding argon. Thus, a precursor can also form when the vapor is not ionized.

The presence of impurities and adsorbed light gases facilitates the formation of a precursor. Thus, we observed the development of a precursor on the front of a shock wave moving a relatively low velocities (2.1-1.9 km/sec) in a xenon-filled (at a pressure of 1.3 kPa) shock tube (500 mm in diameter) with stainless-steel walls. With a temperature of about 9 kK behind the front of the main shock wave 0, the radiant flux from its surface was approximately 40 kW/cm^2. The latter figure is insufficient for vaporization of steel walls. However, a precursor was seen and for a period of 3 msec enveloped most of the surface of shock wave 0. Rather than forming about the entire perimeter of the tube (as usual), the precursor formed only near the lower part of the tube wall and propagated upward over the surface of the main shock wave. An analysis of these tests showed that dust settled in the gravitational field on the lower part of the tube wall when it was positioned horizontally. After several tests had been completed, the dust adsorbed the hydrogen used as the driving gas in the shock tube. Heating of this dust by radiation then resulted in the evolution of hydrogen and the formation of a low-density layer in the immediate vicinity of the lower part of the wall. The tests conducted in [11, 12] showed that a precursor can also form without the movement of vapor or gas from the wall. Here, the precursor develops as a result of the heating of the working gas by the hot walls through normal heat conduction. However, in tests with intensively radiating shock waves resulting in rapid vaporization of walls made of a material with an atomic weight greater than that of the working gas, only ionization of the vapor and its heating to temperatures much greater than the phase-transition temperature can lead to the formation of a precursor.

The author of [8] pointed to the possibility of the entry of explosion products into the low-density layer as one reason for the development of a wedge-shaped precursor. The motion of explosion products and the boundaries of the low-density layer were studied experimentally and numerically in [23], where it was found that some of the driving explosion products actually penetrate the low-density layer at the beginning of motion of the shock wave through the dense gas and the layer. However, with subsequent movement of the shock wave, the boundaries of the layer collapse and prevent the further entry of the products. This occurs at a distance from the contact boundary between the products and the gas in the layer equal to roughly 1.5 of the thickness of the layer. No entry of explosion products was seen in other regions of the precursor. Since the thermal layer of vapor in our tests was about 1 mm, the likelihood of penetration of the layer by explosion products was negligible. At the very least, their presence in the precursor had no effect on its external configuration or the radiative properties of its components.

We have yet to experimentally study how an increase in tube diameter would affect the parameters of a precursor. However, evaluation of this effect would be interesting, since the creation of explosive sources of radiation with a large radiating surface would be important for a whole range of scientific and technical applications. Other conditions being equal, an increase in tube radius R is accompanied by an increase in energy density E at a given point of the surface before arrival of the shock wave. At a first approximation, $E \sim R$. Thus, heating of the vapor is intensified and the precursor extends farther along the tube. However, maximum vapor temperature cannot exceed the temperature of the shock wave 0 itself due to reradiation effects (in our tests, this temperature nearly reaches half the temperature behind the shock wave 0). There is also an increase in the rate of expansion of the vapor layer and the pressure within it in the given case. It is therefore impossible to expect a dramatic decrease in density ρ_* or a significant increase in the velocity of the precursor. At the same time, it would be useful to make a more detailed study of the pattern of vaporization of substances under the influence of continuous-spectrum radiation generated in vapor and the formation of precursors in order to find new ways of controlling their parameters. Another purpose of such investigations would be to acquire a deeper understanding of the global restructuring undergone by a flow when the density ahead of a shock front is disturbed in thin regions. Also yet to be determined is the minimum thickness of low-density layer that can bring about this result.

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