Journal of Engineering Physics and Thermophysics, Vol. 64, No. 5, 1993

SIMILARITY FLOW IN INTERACTION OF A SHOCK WAVE WITH AN INCLINED HEATED CHANNEL

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UDC 533.6.011

A study is made of gasdynamic flow that initiates when a shock wave propagates along a thin heated channel. Analytical conditions of the onset of an unsteady flow precursor are obtained. The flow similarity is proved experimentally; precursor characteristics vs shock wave and heated channel parameters are analyzed.

A local density decrease in a thin long layer or channel ahead of a shock wave (SW) can completely change the behavior of SW propagation, i.e., a large-scale growing precursor can appear. In calculations and experiments [1-3], the fundamental specific features of this effect have been revealed: if the motion of an undisturbed SW is similarity, then when it interacts with a heated layer or an infinitesimal thickness channel ("heated layer" (HL) or a "heated channel" (HC)) unsteady flow originates which is a result of generalizing the initial similarity problem to a higher dimensionality. The channel gas (ρ_T)-to-main flow (ρ_0) density ratio $\omega = \rho_T/\rho_0$ is the parameter determining the similarity flow configuration. The structure of precursor-containing flow under different modes of initiating HL has also been studied experimentally [4].

In the previous calculations and experiments the interaction of SW with HL and HC oriented normal to the SW front surface was examined. When HL interacted with an oblique shock wave an additional dimensionless parameter appeared, namely, the angle φ between the SW front plane and the HL (HC). Both the general flow pattern and the conditions for the onset of the unsteady HL effect must depend on the value of φ. The flow similarity must be retained but it will become three-dimensional for inclined HC.

Conditions of the Precursor Onset. A quantitative criterion for the onset of an unsteady precursor for an arbitrary angle φ can be obtained on the same basis as Taganov's criterion [5]: steady interaction between SW and HL is impossible if the pressure of a completely stopped gas jet from HL is smaller than the one behind undisturbed SW. Let us consider steady flow in the coordinate system where SW is stationary and is at an angle φ to the incoming flow. M_0 is the Mach number normal to the shock wave plane. The flow contains HL with a density ρ_T which is smaller than the undisturbed gas one: $\rho_T = \omega\rho_0$, $\omega < 1$. ρ_0 is the density equalized in the entire incoming flow. The pressure behind undisturbed SW is

$$p_1 = p_0 \left(\frac{2\gamma}{\gamma+1} M_0^2 - \frac{\gamma-1}{\gamma+1} \right). \tag{1}$$

For $M_0\omega^{1/2} > 1$, in HL there is an oblique shock wave, whose inclination angle φ_1 is unknown beforehand. We shall consider that the shock wave position in HL provides that the rotation angles θ and θ_1 of the undisturbed gas and HL gas are equal. Then the quantity φ_1 can be determined from the condition

$$\operatorname{tg}\theta = \operatorname{tg}\theta_1 = \frac{\sin^2\varphi - 1/M_1^2}{\frac{\gamma+1}{2} - \sin^2\varphi + 1/M_1^2} \operatorname{ctg}\varphi = \frac{\sin^2\varphi_1 - 1/\omega M_1^2}{\frac{\gamma+1}{2} - \sin^2\varphi_1 + 1/\omega M_1^2} \operatorname{ctg}\varphi_1, \tag{2}$$

Institute of Geosphere Dynamics, Russian Academy of Sciences, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 54, No. 5, pp. 543-547, May, 1993. Original article submitted June 16, 1992.

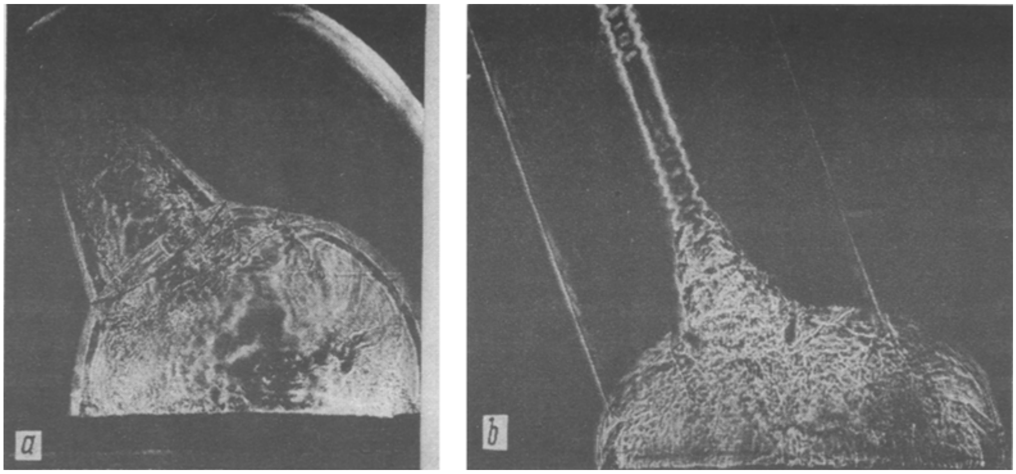


Fig. 1. Thermograms of the interaction between laser breakdown-generated SWs and HC forming under electric explosion of a tungsten wire (density ratio $\omega \approx 0.1$): a) spherical explosion HC is normal to the SW plane; b) plane explosion, HC is at an angle $\varphi = 62^\circ$ to the SW plane.

where $M_1 = M_0/\sin\varphi$.

The solution to equation (2) is chosen so that the shock wave in HL and principal SW belong to one (strong or weak) family. At some values of the parameters no solution to (2) can exist. In this case, we shall assume that the shock wave in HL provides the flow rotation angle θ_1 maximum allowable at given values of γ and $\omega M^2{}_1$.

We shall consider that upon passing the shock wave the HL gas moves adiabatically. Then for the stagnation pressure we have

$$p_* = \left(\frac{2\gamma}{\gamma+1} M_1^2 \omega \sin^2\varphi_1 - \frac{\gamma-1}{\gamma+1}\right)\left(1 + \frac{\gamma-1}{2} M_2^2\right)^{\gamma/(\gamma-1)}, \tag{3a}$$

where

$$M_2^2 = \frac{2 + (\gamma-1) M_1^2\omega}{2\gamma M_1^2 \omega \sin^2\varphi_1 - (\gamma-1)} + \frac{2M_1^2\omega\cos^2\varphi_1}{2 + (\gamma-1) M_1^2\omega\sin^2\varphi_1}.$$

With subsonic motion in HL ($M_0\omega^{1/2} < 1$) the stagnation pressure is equal to

$$p_* = p_0\left(1 + \frac{\gamma-1}{2} M_1^2\omega\right)^{\gamma/(\gamma-1)}. \tag{3b}$$

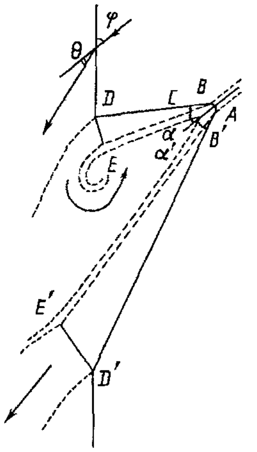
For $p_1 > p_*$, where p_1 is determined by formula (1) and p_* by formulas (2) and (3), even in the case of complete stagnation the HL gas cannot penetrate into the region behind SW. This means that the proposed steady flow cannot occur. Let us introduce the critical value of the density ratio $\omega^* = \omega(p_1 = p_*, \gamma, \varphi, M_0)$. This quantity is implicitly assigned by expressions (1)-(3) and by the condition $p_1 = p_*$. For an unsteady precursor to appear under given values of the parameters γ, φ, M_0 it is sufficient to satisfy the condition $\omega < \omega_*$.

The onset of a precursor is possible at any values of the angle φ between HL or HC and the SW front surface. But with decreasing φ the domain of the values of the parameter ω where a precursor must appear is reduced. For shock waves of a very large amplitude we have

$$\omega^*(\varphi) = \omega^*(\pi/2)(\sin\varphi)^{2\gamma/(\gamma-1)}. \tag{4}$$

From formula (4) it follows that at $M_0\omega^{1/2} \gg 1$ for angles noticeably smaller than 90° an unsteady precursor can appear only at small values of the parameter ω.

Experiments. In the performed experimental study of the heated channels interacting with SW two modes of SW generation and HC initiation were used. In a diaphragmed shock tube 35×35 mm in channel cross section



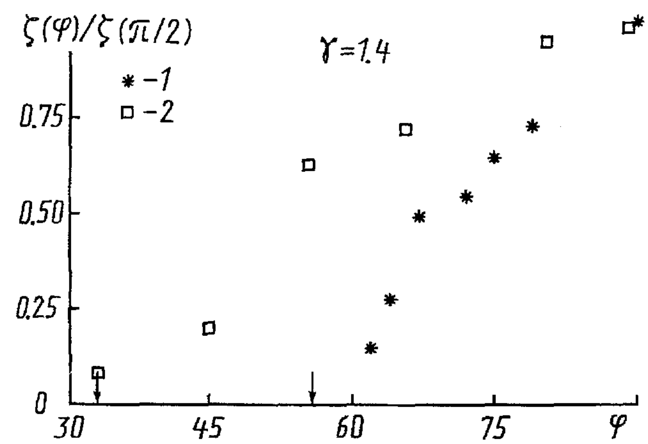


Fig. 2. Similarity flow pattern at SW interaction with HC.

Fig. 3. Relative size of the precursor ζ vs φ between SW and HC: 1) Mach number $M_0 = 1.7$ and density ratio $\omega = 0.44$; 2) $M_0 \approx 5$, $\omega = 0.1$. φ, deg.

moderate-intensity SWs were generated. Experiments were carried out for SW in air ($\gamma = 1.4$) at the Mach number $M_0 = 3.0$ and in acetone vapors ($\gamma = 1.08$) at $M_0 = 1.85$. HC was formed near the surface of a thin metal wire heated by a short electric pulse. The characteristic channel thickness usually did not exceed 0.5 mm, and the maximum temperature attained 1700 K.

Strong plane SWs with $R \sim t^{2/3}$ corresponding to Sedov's strong similarity explosion appeared in air when the laser pulse acted upon a wall. The pulse time was 100 nsec; energy, 100 J; radiated spot diameter, 2.5 cm. The shock wave front was plane at distances up to 1-1.5 cm from the wall surface. HC with a temperature up to 4000-5000 K and a thickness of 2-3 mm was initiated under electric explosion of a 13-m-thick tungsten wire. In all experiments, instantaneous interferometric or schlieren photography of the flow pattern carried out.

The angle φ between SW and the heated channel is 90 to 45°. Both the steady interaction between SW and HC and the onset of the unsteady precursor are observed. The boundary between the two regimes of the SW propagation approximately corresponds to the criterion (1)-(3). The rate of growth of the precursor that appears at $\omega < \omega^*$ is constant, and the general flow configuration is retained as SW moves along the channel, i.e., three-dimensional similarity flow occurs. Figure 1 shows thermograms of the interaction between laser-breakdown-generated SWs and HC forming under electric explosion of a wire.

The general pattern of similarity flow at interaction of SW with inclined HC is shown in Fig. 2. The precursor vertex (point A) moves with a constant velocity along HC. Together with the condition for pressure equalization in the separated flow region, this must result in precursor symmetry relative to the axis passing through HC. Inclination angles α and α' of conic shock waves BD and B′D′ measured from the flow photos are equal. This supports the above symmetry. In this case, the motion of the heated channel gas that has passed through SW (or the continuous compression region for subsonic flow in HC) at point A and adiabatically has stopped at point C does not depend on the angle φ. Therefore, the dependence of the precursor inclination angle α at an arbitrary value of φ must be determined by the analytical relations obtained in [3] for the normal HL orientation relative to the SW front.

A three-shock configuration is formed at a point where the conic precursor intersects principal SW (points D and D′). The third shock wave which turns the flow that has passed through the precursor parallel to the flow that has passed through principal SW has a complex spatial shape. The flow behind the shock wave DE proves to be closer to separation point C than the flow behind the shock wave D′E′. The gas enters the return flow region CEE′ mainly from the upper part of the flow that has passed through the precursor. The lower part of this flow (obviously, together with some part of the HC gas) escapes from the precursor region. The loss of some part of the gas must decrease the precursor size with decreasing angle φ. This assumption is supported by the experimental results in Fig. 3: at fixed SW and HC parameters the relative precursor size $\zeta(\varphi) = L_T/L_1$ (L_T is the precursor length, L_1 is the distance travelled by SW in AC) greatly decreases with φ. The arrows in Fig. 3 denote the values $\varphi^* = 54^{\circ}$ and 33° calculated by formulas (1)-(3) which are critical for the onset of the precursor at given M_0, γ, ω. The disappearence of the precursor at

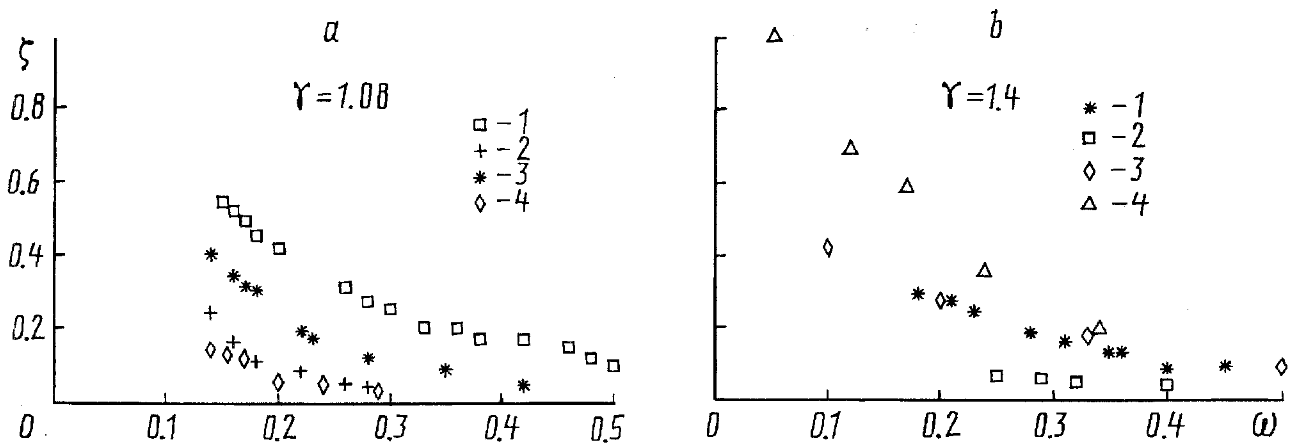


Fig. 4. Relative size of the precursor ζ vs density ratio ω: a) experiments for SW in acetone: 1) $\varphi = 90^{\circ}$; 2) 70; 3) 55; 4) 45°; b) experiments and calculations for SW in air: 1) $\varphi = 90^{\circ}$; 2) 69; experiment at $M_0 = 3$; 3) $\varphi = 90^{\circ}$, caclulation [3]; 4) $\varphi = 90^{\circ}$, plane explosion.

$\varphi \to \varphi^*$ is experimental support of the obtained criterion.

Figure 4 plots the experimental relative size of the precursor ζ vs density ratio ω at different values of φ. The precursor size grows with decreasing parameters ω and γ. Note the important feature: the size of the precursor ζ at $\varphi = 90^{\circ}$ for plane SW generated by a strong explosion is twice as large as for a shock wave moving with a constant velocity at small ω. The same result is obtained for a strong spherical explosion in [6].

The performed analytical and experimental results have shown that the effect of the onset of a large-scale precursor when SW interacts with thin long layers and channels filled with a decreased-density gas is stable to the inclination of HL and HC relative to the SW front surface. This offers additional possibilities of controlling gasdynamic flows containing shock waves by means of artificially formed HL and HC [7, 8].

NOTATION

γ, gas adiabatic exponent; M_0, Mach number normal to a shock wave plane; ω, ratio of heated layer gas density ρ_T to main flow gas density; φ, angle between the shock wave front and the heated channel; ζ, relative size of a precursor. Quantities γ, M_0, ω, φ, ζ are dimensionless.

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