SHOCK COMPRESSION OF TWO-COMPONENT PARAFFIN – TUNGSTEN MIXTURES

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Up to pressures of 2 mbar, curves have been recorded experimentally for the shock compression of paraffin and for two paraffin–tungsten mixtures, containing 66.2 and 84.0 wt.% tungsten. It is shown that over the whole range of pressures investigated experimentally, the mixture shock adiabatic curves satisfy the principle of additivity. Attention is called to the great potential of the method of weighting additives for the investigation of light media at high shock pressures. The criteria for the applicability of the principle of additivity have been analyzed.

The introduction of disperse weighting additives into light media increases their mean density and, consequently, also the pressure in the shock wave arising with the slowing down of the shock agents. This simple method for increasing the pressures, permitting a considerable broadening of the experimental possibilities in the investigation of the compressibility of light compounds, was developed and put into practice at the beginning of the nineteen fifties by the present authors. The mixture method was developed independently by A. N. Dremin and I. A. Karpukhin [1]. Some of its theoretical aspects have been discussed recently by V. N. Nikolaevskii [2].

The basis of mixture methods is the assumption of a sufficiently exact satisfaction of the rule of additivity. In the additive approximation, the volume of the shock-compressed mixture is assumed equal to the sum of the volumes of its components, obtained at the same pressures by separate shock compression, in the form of homogeneous monolithic samples. This condition is expressed by the relationship

$$V_{12}(p) = \alpha_1 V_1(p) + \alpha_2 V_2(p) \tag{1}$$

Here p is the pressure; V_{12} is the specific volume of the mixture; V_1 and V_2 are the specific volumes of the light and heavy components with the shock compression of each of them independently; α_1 and α_2 are their weight concentrations ($\alpha_1 + \alpha_2 = 1$); the double subscript 12 denotes the mixture. Equation (1) permits finding the adiabatic curve of the light component from the adiabatic curves of the mixture and the heavy component.

We turn to the conditions which determine the accuracy of the additive approximation. The results of dynamic experiments establish a dependence of the specific volume of the mixture on the pressure and, for each $p-V_{12}$-state, determine the specific energy of the shock compression

$$\varepsilon_{12} = {}^1/_2\, p\, (V_{120} - V_{12})$$

The last equation may also be written in the form

$$\alpha_1\varepsilon_1^* + \alpha_2\varepsilon_2^* = {}^1/_2 p\,[\alpha_1 (V_{10} - V_1^*) + \alpha_2 (V_{20} - V_2^*)] \tag{2}$$

Here ε_1^* and ε_2^* are the specific compression energies of the components, acquired with compression of the mixture; V_1^* and V_2^* are their specific volumes under the same conditions; V_{10} and V_{20} are their initial volumes.

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TABLE 1

ρ, g/cm³	Shock agent	w, km/sec	D, km/sec	U, km/sec	p, mbar	σ	V, cm³/g
	Al	2.20	5.51	1.68	0.083	1.44	0.772
Paraffin	Al	3.14	6.56	2.34	0.138	1.555	0.714
	Al	3.08	6.44	2.30	0.133	1.556	0.714
$\rho_0 = 0.9$	Al	3.17	6.80	2.34	0.143	1.525	0.728
	Al	3.44	6.66	2.57	0.154	1.628	0.682
	Fe	4.56	8.40	3.82	0.289	1.834	0.606
	Al	5.30	8.86	3.78	0.302	1.745	0.637
	Fe	8.50	12.57	6.94	0.780	2.232	0.498
	Fe	14.40	17.79	11.45	1.835	2.805	0.396
	Fe	14.66	17.82	11.67	1.886	2.900	0.383
Light mixture	Al	3.14	4.97	1.91	0.231	1.626	0.252
$\rho_0 = 2.44$	Al	3.17	5.13	1.90	0.244	1.589	0.258
	Al	5.30	6.65	3.08	0.500	1.854	0.221
	Fe	4.56	7.06	3.32	0.574	1.888	0.217
	Fe	8.50	10.13	6.05	1.495	2.482	0.165
Heavy mixture	Al	3.14	4.33	1.59	0.310	1.584	0.140
	Al	3.17	4.26	1.62	0.311	1.612	0.138
	Al	5.30	5.62	2.59	0.656	1.856	0.119
$\rho_0 = 4.51$	Fe	4.56	6.12	2.95	0.816	1.931	0.115
	Fe	8.50	9.04	5.37	2.200	2.462	0.09

TABLE 2

U, km/sec	D, km/sec	p, mbar	σ	V, cm³/g	U, km/sec	D, km/sec	p, mbar	σ	V, cm³/g
		0	1	1.111					
1.5	5.35	0.072	1.390	0.800	7.0	12.65	0.797	2.239	0.496
2.0	6.05	0.109	1.494	0.744	8.0	13.84	0.996	2.370	0.469
3.0	7.43	0.201	1.677	0.662	9.0	15.00	1.215	2.500	0.444
4.0	8.83	0.318	1.828	0.608	10.0	16.10	1.449	2.639	0.421
5.0	10.15	0.468	1.971	0.564	11.0	17.18	1.701	2.780	0.400
6.0	11.42	0.617	2.107	0.527	12.0	18.25	1.971	2.920	0.380

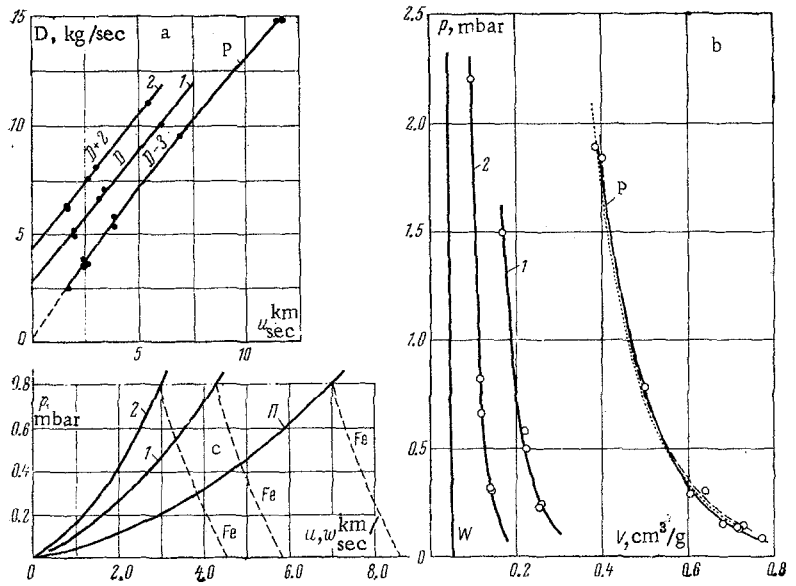

Fig. 1

In addition to Eq. (2), the condition of additivity demands the satisfaction of the term-by-term equalities

$$\varepsilon_1^* = {}^1/_2 p\,(V_{10} - V_1^*), \quad \varepsilon_2^* = {}^1/_2 p\,(V_{20} - V_2^*) \tag{3}$$

coinciding with the Hugoniot equations for the individual components. In this case, as follows from the system (2), (3), the validity of one of the equations of (3), with compression of the mixture, is also evidence of the satisfaction of the Hugoniot equation for the other component.

Equations (3), and consequently also Eq. (1), are approximate, since they assume the complete identity, which does not exist in reality, of the compression processes of particles in heterogeneous mixtures, with the shock compression of the homogeneous components. They are completely exact only for an idealized situation, when the particles of one of the components (for example, the heavy one) are incompressible and non-heat-conducting. For this component, Eq. (3) is satisfied since both the compression energies and the differences between the initial and final volumes revert to zero. Equations (3) hold also for hypothetical materials with null Gruneisen coefficients, in which no thermal pressures arise with compression. For all thermodynamic processes, in both mixed and monolithic states, the specific volumes in this case are single-valued functions of the pressures.

For real substances, the errors in determination of the shock adiabatic curve for one of the components (for example, the light component) from the shock adiabatic curve for the mixture are less, the less the relative volume occupied by the other fraction, and the smaller of the fraction of the energy entering it with shock compression. It is therefore advisable to use additives which are as heavy as possible and as incompressible as possible. In addition, for any given pair of components, the additive approximation is more rigorous at lower shock pressures and less accurate with large amplitudes of the shock waves, under conditions when the course of the compression curves depends considerably on the entropy.

The results of [2], expressed by the following relationships, are not in agreement with these simple concepts

$$\varepsilon_1^* = {}^1/_2\, p\,(V_{10} - V_1) + \alpha_2\, {}^1/_2\, p\,(V_{20} - V_{10} + V_2 - V_1)$$
$$\varepsilon_2^* = {}^1/_2\, p\,(V_{20} - V_2) + \alpha_1\, {}^1/_2\, p\,(V_{10} - V_{20} + V_1 - V_2)$$

As follows from these equations, with the shock compression of mixtures, there is always an increase in the internal energy of the component with the smallest initial specific volume (even in the case when the component is incompressible and non-heat-conducting). With regard to the light component, in accordance with [2], its internal energy rises with pressure less than for the Hugoniot adiabatic curve of the continuous substance and, as the formulas show, at sufficiently high concentrations of the heavy component, can become negative. These paradoxical conclusions are explained by the fact that, with a limiting transition to an infinitely small thickness of the front, the forces of interaction between the particles were not taken into account correctly in [2].

For the experimental investigations the present authors chose mixtures of paraffin and tungsten, i.e., substances which differ very strongly in their densities and compressibilities (in their densities by 21 times and in their compressibilities by approximately 4 times). Measurements over a wide pressure range were made in pure paraffin (mean density 0.9 g/cm^3) and in two mixed compositions with the following values of the mean densities, ρ, g/cm^3, and of the weight, q, and volumetric, Q, concentrations of tungsten:

	ρ	q%	Q%
Light mixture	2.44	66.2	8.4
Heavy mixture	4.51	84.0	19.8

Table 1 gives the results of shock experiments carried out using the standard method [3, 4]; the results are illustrated in Fig. 1a, by curves 1 and 2 for light and heavy mixtures and P for paraffin. Table 1 shows the material of the sample and its density ρ, g/cm^3; the material and velocity of the shock agents ω creating the pressure; the wave D and mass U velocities; the pressure p; and the relative densities $\sigma = \rho/\rho_0$, i.e., all the parameters characterizing the shock states in the samples. The values of the wave velocities were obtained by averaging the results of several experiments. The mass velocities were found using graphic plots on pressure–velocity diagrams, and the pressures and the densities from the equations of the laws of conservation $p = \rho_0 UD$ and $\rho = \rho_0 D(D-U)^{-1}$.

In DU-coordinates, the shock adiabatic curves obtained for mixed compositions (and for tungsten in accordance with [4, 5]) are described by the following linear relationships:

$$D = 2.80 + 1.225\ U \quad \text{(for light mixture)} \tag{4}$$
$$D = 2.32 + 1.26\ U \quad \text{(for heavy mixture)} \tag{5}$$
$$D = 4.0 + 1.285\ U \quad \text{(for tungsten)} \tag{6}$$

Figure 1b gives pV diagrams for the mixed compositions and for tungsten, plotted using Eqs. (4)-(6). Three dependences are given here for tungsten. One of them (the solid line) is the Hugoniot adiabatic curve, approximating the results of direct measurements of the shock compressibility of paraffin. Its parameters are given in Table 2. The other two curves were found by the mixture method, by substituting into Eq. (1)

the specific volumes of tungsten and the light phase (dashed curve), and of tungsten and the heavy mixture (dotted curve).

As follows from the course of the curves, over the whole experimentally investigated region of pressures up to 2 mbar, the adiabatic curve for paraffin obtained by the usual method practically coincides with the adiabatic curves found from experiments with mixed compositions. This important result is evidence of the validity of the principle of additivity over a wide range of thermodynamic parameters, and of the great promise of the method of weighted additives for the investigation of light media at high pressures.

The experimental advantages gained with the introduction of weighted admixtures are very considerable. This can be seen from the data of Table 1 and from the pressure–velocity diagram (Fig. 1b). This diagram gives plots of the adiabatic curves for paraffin and paraffin–tungsten mixtures, and curves for the slowing down of iron shock agents. To obtain data on the compressibility of pure paraffin at a pressure of 800 kbar, there is required a velocity of a steel shock agent equal to 8.6 km/sec, using a mixture with 66% W, a velocity of 5.85 km/sec, and with the introduction of 84% tungsten (volumetric content Q = 20%), a velocity of only 4.5 km/sec. Similar velocities are easily obtained in launching devices of the simplest type, described in [3, 4].

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