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GENERALIZED SHOCK ADIABATS OF THE ELEMENTS

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UDC 532.593:536.711

Shock adiabats are needed for the analysis of any kind of explosion processes. They are the main source of information on the equations of state of substances at high pressures and temperatures. This also explains the great interest in their experimental determination. At the present time, approximately 1000 shock adiabats are known, including about 200 shock adiabats of many of the elements of the D. I. Mendeleev periodic table, determined by various authors. This large number of data makes it possible to analyze them statistically and to bring out definite regularities.

Generalized forms of the shock adiabats of substances have been proposed repeatedly, for example, in [1-3]. Here the shock adiabats were assumed to be approximately linear in the coordinates mass velocity–velocity of shock wave. Below we discuss generalized shock adiabats of the elements which are free from this assumption.

§1. In the coordinates mass velocity–velocity of shock wave, experimental shock adiabats are usually approximated by simple analytical dependences, most frequently segments of straight lines:

$$D = a + \lambda u. \tag{1.1}$$

The quantity λ in (1.1) can be regarded as the derivative $\lambda = dD/du$ at some intermediate point of the shock adiabat. The value of λ varies, generally speaking, along the shock adiabat with an increase of the compression in the shock wave.

The distribution of the values of λ or of the derivatives with respect to the shock adiabat (shown in Fig. 1) was plotted on the basis of approximately 150 experimental shock adiabats, approximated by segments of straight lines, mainly taken from [4, 5] (but, in the case of hydrogen, from [6]). On the vertical axis with an

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Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 117-121, May-June, 1978. Original article submitted May 19, 1977.

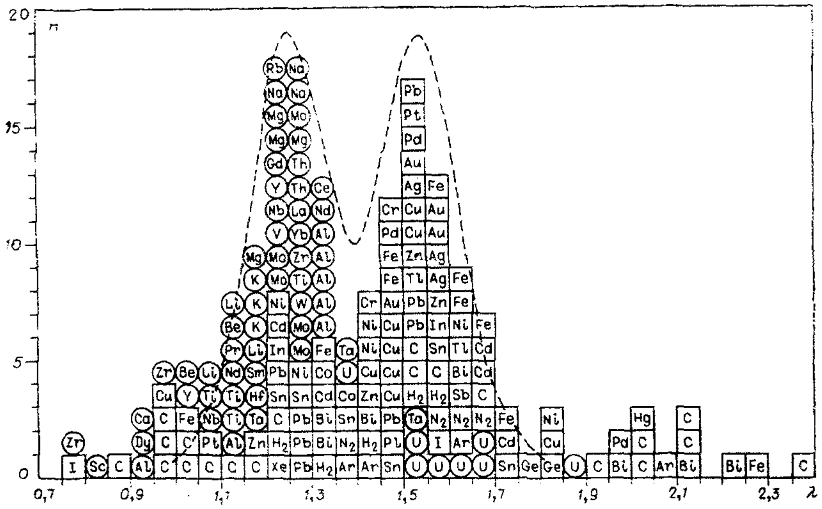

Fig. 1

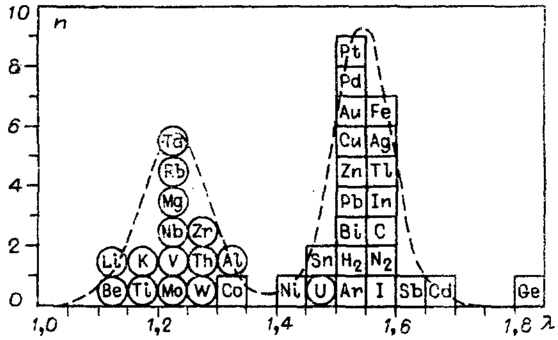

Fig. 2

accuracy to 0.05, the number of shock adiabats having equal values of the derivatives is plotted. As a result of this rounding-off of the values of λ, the discrete distribution is obtained:

$$n = n(\lambda).$$

It can be seen that the coefficients λ are close to the isolated values ~ 1.2 and 1.5 for a majority of the shock adiabats.

The appearance of two isolated values of λ could be the result of an increased attention on the part of investigators to substances having values of λ close to 1.2 and 1.5. Such a possibility is ruled out below by averaging the data of different authors.

In Fig. 1 the dashed line represents the sum of two Gaussian distributions, showing what the distribution should be if the deviations of λ from the two equally probable values above are random. The agreement is rather good, except for the boundaries. At the boundaries, the distributions mainly represent substances which undergo sharply expressed phase transitions, specifically, carbon. But phase transitions with shock compression bring about points of inflection on the shock adiabats and, consequently, sharp changes in the value of λ.

Another reason for random deviations of λ from the two isolated values may be experimental errors in finding the shock adiabat, which, in individual cases, can reach 10% or more of the value of λ.

In addition, the derivative with respect to a shock adiabat is not constant, varying with the degree of compression of the substance in the shock wave. Such a nonlinearity of the shock adiabats has been observed for many substances [4].

To partially eliminate these reasons for deviations of λ from the two isolated values, the distribution shown in Fig. 2 was constructed in the following manner: Regions of obvious phase transitions were not considered; if several shock adiabats of the form (1.1) were known for exactly the same substance, the data of the

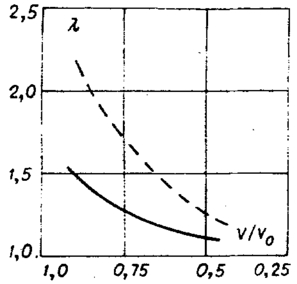

Fig. 3

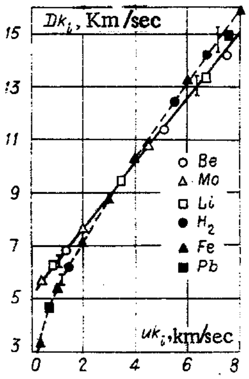

Fig. 4

different authors were averaged; values of λ were taken only with identical degrees of compression of the substance $V/V_0 = 0.675$ at the shock front.

The reason for the deviations of the value of λ from the two isolated points can be both the errors of the experiment as well as lack of agreement of the derivatives with respect to the shock adiabat as functions of the relative volume V/V_0; however, it is important to note that the value of these deviations, on the average, does not exceed the possible experimental errors in determination of the shock adiabats.

Distributions analogous to that given in Fig. 2 can be constructed also for other relative degrees of compression of substances in a shock wave. The positions of the maxima of such distributions were used to obtain the curves shown in Fig. 3 for the change in the derivatives with respect to the shock adiabats for the first (solid line) and second (dashed line) groups of elements.

In support of the existence of two groups of elements having shock adiabats with identically varying derivatives, there is also the place which they occupy in the D. I. Mendeleev table. Elements making up the first group are located mainly at the start of each period of the system of elements (in Figs. 1 and 2 they are marked with small circles); the second group is made up of the remaining elements of the period (shown by squares). This is in agreement with the postulation that the character of the compressibility of a substance is mainly determined by the degree of filling of the outer electron shells of their atoms.

§ 2. From what has been said above, it follows that, within the limits of the error of the experiments, the derivatives with respect to the shock adiabats may be assumed to be identical functions of the relative volume for each of the separate groups of elements. For each of the groups, the derivatives with respect to the shock adiabats are found to be equal for identical values of V/V_0, i.e., at straight lines departing from the origin of coordinates in the plane u, D. For a parametric representation of a shock adiabat,

$$u = u(V/V_0),\ D = D(V/V_0),$$

this means that

$$\frac{dD_i(V/V_0)}{du_i(V/V_0)} = \frac{dD_j(V/V_0)}{du_j(V/V_0)}. \tag{2.1}$$

If the shock adiabats are continuous dependences of the velocity of the shock wave on the mass velocity, then, integrating (2.1), we obtain

$$k_i u_i(V/V_0) = k_j u_j(V/V_0),\ k_i D_i(V/V_0) = k_j D_j(V/V_0), \tag{2.2}$$

where k_i and k_j are certain constants.

Relationship (2.2) means that the shock adiabats of one group can be obtained from one another by extension an identical number of times along the coordinate axes in the plane u, D; i.e., they are geometrically similar. In the plane p, V/V_0, the shock adiabats can also be superimposed by extending a corresponding number of times along the axis of pressures. Since

$$p = \rho_0 D u,$$

then, in accordance with (2.2), we obtain

$$\frac{p_i(V/V_0)}{p_j(V/V_0)} = \frac{\rho_{0i}}{\rho_{0j}} \frac{k_j^2}{k_i^2}. \tag{2.3}$$

Figure 4 shows both types of generalized shock adiabats, together with some experimental shock adiabats transformed using formulas (2.2). The same figure shows the mean experimental errors. It can be seen that the shock adiabats of different elements are superimposed.

§3. The geometric similarity of the shock adiabats of one group makes it possible, in accordance with (2.2) and (2.3), to reconstruct a shock adiabat from one experimental point, excluding regions of two-phase states. The statistical results set forth above also make it possible to select, out of several known experimental shock adiabats, the most reliable one, which should be geometrically similar to the shock adiabats of the same group.

The elements of each of the two above separate groups have different shock compressibilities. The most easily compressed elements are lithium, sodium, and potassium in the first group, and hydrogen and its isotopes in the second. Potassium was compressed 3.5 times in a single shock wave [4] and deuterium, 3 times [6]. The geometric similarity, satisfied with a good degree of exactness, makes it possible to construct the shock adiabats of difficultly compressible elements up to the same large relative densities. In an experiment, to compress, for example, iron by 3 times, a pressure of around 60 Mbar in the shock wave was required, and, to compress molybdenum by 3.5 times, a pressure of around 80 Mbar was needed.

With shock compression, as has been found, only elements of one group behave in a similar manner. It follows from this that shock-wave processes can be modelled only using substances of one group.

In conclusion, it must be noted that, due to the lack of literature data, all the elements of the periodic system have not been investigated above. In addition, the results have a statistical character. Therefore, deviations from the observed regularities exceeding the mean error of the experiment are possible.

The author wishes to express his thanks to V. M. Titov and Yu. I. Fadeenko for their useful observations.

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