

The dependences of the maximum temperature nonuniformity on the surfaces of shells on the Re number are presented in Fig. 5 for different values of  $D_0/D_C$ . The results obtained can be generalized by the expression

$$(t^{\max} - t^{\min}) \lambda_m / (\bar{q}_{in} R_e) = 25.8 (\lambda_m / \lambda_t)^{0.66} [1 - 2.34 D_0 / D_C + 1.52 (D_0 / D_C)^2] Re^{-0.59}$$

with a maximum error of 15%. Here  $\bar{q}_{in}$  is the average density of the thermal flux on the inner shell surface in  $W/m^2$ ,  $R_e$  is the external radius of the shell in m, and  $\lambda_t$  is the thermal conductivity of the gas in  $W/(m \cdot ^\circ K)$ .

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#### INFLUENCE OF THE TYPE OF THERMODYNAMIC APPROXIMATION ON THE DESCRIPTION OF THE DYNAMIC COMPRESSIBILITY OF MULTICOMPONENT MEDIA

S. V. Bobrovskii,\* V. M. Gogolev,  
and V. P. Lozhkina

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A large class of soils can be treated as multicomponent mixtures. Accordingly, in the analysis of strong dynamic effects acting on them it is necessary to inquire into the nature of the thermodynamic interaction of the components. Considerable difficulties are met in the attempt to solve this problem insofar as one must work with nonequilibrium thermodynamic models. In the solution of many practical problems this fact can inject unwarranted complexities into the description of the state of the medium. The simplest approximations in the solution of this problem are the equilibrium and completely nonequilibrium approximations. They can be regarded as limiting approximations. The actual interaction of the components will produce parameters occupying an intermediate domain of thermodynamic states. In the present study we consider the degree of disparity between the limiting approximations in shock compressions and isentropic stress relief and we investigate the conditions under which they yield either close or sharply different mechanical parameters of the state of the medium. The solution of these problems will provide a basis for considering the application of a particular thermodynamic approximation to various practical problems involving multicomponent soils.

#### 1. Equations of State and Fundamental Assumptions

The equations of state proposed in [1-4] for granite, water, salt, and air can be used to describe the thermodynamic properties of water-impregnated porous soils with a silicate and salt base. We consider the equilibrium and completely nonequilibrium approximations for these classes of multicomponent media. It is well known that the equilibrium approximation postulates equality of the pressures and temperatures in all components of the medium. In the nonequilibrium approximation only equality of the pressures is postulated. In the comparative analysis of these approximations, therefore, it is meaningful to compare only the "mechanical parameters" of the mixture, i.e., the pressure and specific volume or the

\*Deceased.

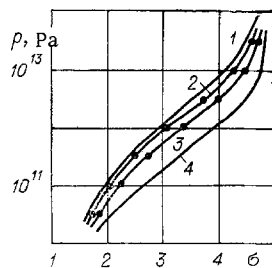


Fig. 1

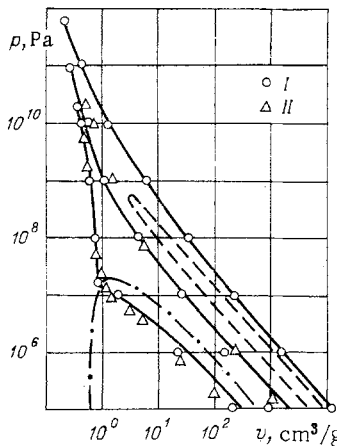


Fig. 2

particle velocity and shock velocity, etc. We use the following assumptions in our comparative analysis:

1. The thermodynamic states of granite, water, salt and air are described by the equations of state given in [1-4].

2. The state of the multicomponent media is described by the mixture form of the equation of state

$$E = \alpha_1 E_1 + \alpha_2 E_2 + \alpha_3 E_3; \quad (1.1)$$

$$p = p_1 = p_2 = p_3; \quad (1.2)$$

$$v = \alpha_1 v_1 + \alpha_2 v_2 + \alpha_3 v_3; \quad (1.3)$$

$$\alpha_1 + \alpha_2 + \alpha_3 = 1, \quad (1.4)$$

where  $E$ ,  $p$ , and  $v$  are the specific energy, pressure, and specific volume of the mixture, the indices 1-3 refer to the solid component, water, and air respectively, and  $\alpha_i$  is the fraction by weight of the  $i$ -th component in the mixture.

Because of the smallness of  $\alpha_3$  and the finiteness of  $E_3$ , we can use the approximate equations

$$E \approx \alpha_1 E_1 + \alpha_2 E_2; \quad (1.5)$$

$$\alpha_1 + \alpha_2 \approx 1. \quad (1.6)$$

In the description of porous soils the parameter  $\alpha_3$  can sometimes be replaced by the porosity  $\Pi = \alpha_3 v_{30}/v_0$ , where the index 0 refers to the initial state of the medium, or by the porosity parameter  $m = v_0/v_{10}$ . The following relation is valid for dry soil ( $\alpha_2 = 0$ ):  $\Pi = (m - 1)/m$ .

3. In the equilibrium approximation the system (1.1)-(1.4) is augmented with the condition of equal temperatures of the components of the medium  $T_1 = t$ . It can be shown on the basis of the equation of state for air [4] that its compression ratio in this approximation at pressures  $\sim 10^9$  Pa or higher is much greater than the quantity  $\sigma_3 = v_{30}/v_3 = 30$ . Consequently, the air can be neglected in plotting the shock adiabats for porous media in the equilibrium approximation, and the air pores can be regarded as vacuum voids, simplifying

TABLE 1

$\alpha_1$	1,0	0,9	0,8	0,7	0
$\sigma_{\max}$	4,78	4,80	4,81	4,81	4,83
$\sigma_1$	4,78	4,25	3,85	3,53	—
$\sigma_2$	—	8,69	7,83	7,17	4,83
$p \cdot 10^8, \text{ Pa}$	2,30	1,63	1,48	1,35	0,49

the calculations. The energy equation in this case takes the form (1.5), and the equation for the specific volume is  $v = \alpha_1 v_1 + \alpha_2 v_2$ .

4. In the nonequilibrium approximation it is assumed that shock loading and isentropic relief take place in accordance with the individual shock adiabats and isentropes of each component. The specific volume of the mixture for a given pressure is determined according to (1.3). In this approximation the compressibility of air is finite and cannot be neglected.

## 2. Shock Adiabats and Isentropes of Completely Water-Saturated Soils

On the basis of the above-stated assumptions we have calculated the shock adiabats and isentropes for completely water-saturated ( $\alpha_3 = 0$ ) silicate soils in the equilibrium and nonequilibrium approximations. Figure 1 shows the shock adiabats in the  $(p, \sigma)$  plane. The solid curves represent the adiabats for the equilibrium approximation: 1)  $\alpha_1 = 1$ ; 2)  $\alpha_1 = 0.9$ ; 3)  $\alpha_1 = 0.7$ ; 4)  $\alpha_1 = 0$ ; the dots correspond to the results of the calculations in the nonequilibrium approximation. It is evident from an analysis of the data that the equilibrium and nonequilibrium approximations are quantitatively close to one another. The maximum discrepancy of 1-2% with respect to the compression ratio is observed in the zone of maximum compressions.

It is evident from Fig. 1 that the adiabats for water-saturated soils are situated between the adiabats for granite (curve 1) and water (curve 4). As the degree of saturation increases, the adiabats shift monotonically from the granite curve to the water curve. The maximum compression of the mixture increases in this case.

Another peculiarity is noted. The results of the calculations of the adiabats show that whereas the maximum compression ratio is equal to 4.83 for water and 4.78 for granite in the shock loading of pure water or pure granite, in the case of their mixture, within the framework of the equilibrium approximation, there is a considerable redistribution of the compression ratios of the individual components. This situation is illustrated by the data in Table 1, which, along with the maximum compression ratios  $\sigma$  in the last column, also shows the pressures corresponding to these compressions. This peculiarity is a consequence of heat transfer in the process of equalization of the temperatures between the water and granite components. As a result, the temperature and specific energy of the granite component increase, while for water they decrease, thereby increasing the ability of granite to resist compression and decreasing it for water.

Figure 2 shows the results of calculations of the isentropes for  $\alpha_1 = 0.7$  in the equilibrium (solid curves) and nonequilibrium (points I) approximations. The isentropes shown in Fig. 2 emanate from the points of the shock adiabats corresponding to pressures of  $(0.2, 0.92, 6.2) \cdot 10^{11}$  Pa (curves 1-3). Also shown in the figure are the boundaries of the domain of two-phase states of granite (dashed curve) and water (dot-dash curve).

It follows from an analysis of the data that the equilibrium and nonequilibrium approximations for the domain of complete evaporation of granite yield practically identical isentropes. In the domain of the condensed state of granite and complete evaporation of water (curve 2) they begin to diverge. But in the domain below the critical point of water the difference becomes appreciable. For curve 2 the difference in the specific volumes approaches a factor of two. A similar disparity in the approximations occurs in the domain of the two-phase states of water.

In Fig. 2, for comparison, the points II indicate the results of calculations of the isentropes in [5] according to a nonequilibrium approximation scheme for pressures at the

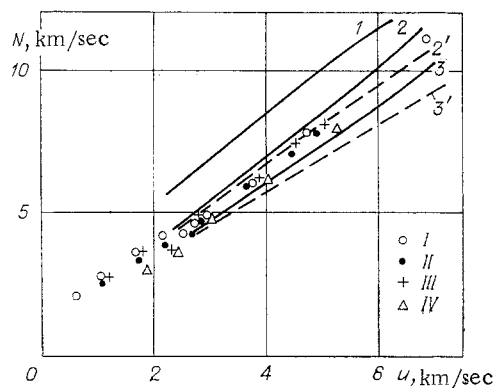


Fig. 3

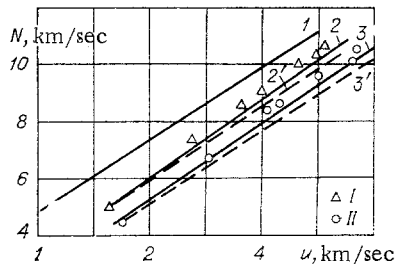


Fig. 4

shock front equal to  $0.2 \cdot 10^{11}$  and  $1 \cdot 10^{11}$  with  $\alpha_1 = 0.724$ . Figure 2 exhibits fully satisfactory agreement between the data of [5] and the present study.

The foregoing analysis therefore shows that if the water and granite exist in identical states of aggregation, the mechanical parameters on the shock adiabats and isentropes will practically coincide in the equilibrium and nonequilibrium approximations, i.e., will be equivalent from the gasdynamic point of view. But if the states of aggregation of these components differ, the two approximations will yield a difference in the state parameters. The difference is particularly great in the domain below the critical point for the state of water.

### 3. Dry Porous Soils

We now consider the influence of the type of approximation on the calculated state parameters for nonwater-impregnated ( $\alpha_2 = 0$ ) porous soils. We carry out the investigation in application to porous quartz and porous salt. This choice is dictated by the availability of experimental data on their shock compressibility [6, 7], which provide a means for estimating how realistic either approximation is. We also note that the state of quartz can be described by the equation of state for granite [1].

The results of calculations of the shock adiabats and experimental data for porous quartz and salt are plotted in the plane of the shock velocity  $N$  versus the particle velocity  $u$  in Figs. 3 and 4. Curves 1 represent the shock adiabats of the nonporous material, the results of the calculations according to the nonequilibrium approximation are represented by the solid curves, and those according to the equilibrium approximation by the dashed curves. Curves 2, 2' and 3, 3' in Fig. 3 are calculated for  $\Pi = 0.32$  ( $\rho_0 = 1.75 \text{ g/cm}^3$ ) and  $\Pi = 0.56$  ( $\rho_0 = 1.15 \text{ g/cm}^3$ ). Also shown in Fig. 3 are the experimental data of [6]: I)  $\rho_0 = 1.75$ ; II) 1.55; III) 1.35; IV)  $1.15 \text{ g/cm}^3$ .

It is evident from these data that the shock adiabats in the equilibrium and nonequilibrium approximations are quite far apart. Clearly, in the  $(p, v)$  plane this discrepancy will be even greater. The difference in the approximations increases with the shock intensity and with the porosity. This trend is clearly attributable to the increasing role of the thermal component in the state of the porous medium. It is the controlling factor for air and therefore plays the dominant role in the state of the mixture. We consider the unit-porosity limit, which has purely theoretical significance. In this case, clearly, the shock adiabats of the mixture will tend to the limiting shock adiabat of air. Beginning

with certain values of the porosity, the shock adiabats in the nonequilibrium and equilibrium approximations will approach one another, because the contribution of the solid component to the shock compressibility of the mixture will diminish. However, the calculations show that with a variation of the porosity in the typical range for real soils the difference between the approximations increases with the porosity.

An analysis of the experimental data shows that they have a certain scatter, within the limits of which a monotonic shifting of the shock adiabats with increasing porosity is not observed. For example, the points for  $\rho_0 = 1.35$  are situated above the points for  $\rho_0 = 1.55$ , but below the points for  $\rho_0 = 1.75$ . Only the points for  $\rho_0 = 1.15$  are regularly situated below the points for  $\rho_0 = 1.75$ . This fact makes it impossible to infer the validity of either approximation on the basis of a comparison of the calculated and experimental data. It is noted, however, that the experimental data for  $\rho_0 = 1.75$  lean toward the adiabat of the equilibrium approximation, and the data for  $\rho_0 = 1.15$  favor the adiabat of the nonequilibrium approximation. This is possibly a consequence of physical factors. Thus, in the first case the fraction of air in the pores is comparatively small, so that its thermal contribution to the state is small and heat transfer between the components does not exert any appreciable influence on the shock compression. In the second case the situation is reversed, and the role of nonequilibrium is significant.

We now examine the data shown in Fig. 4 for the cases  $\Pi = 0.34$  and  $0.54$  (experimental [7]: points I and II respectively). In the given case the difference between the approximations is somewhat less than for quartz. This fact can be attributed to the greater compressibility of salt in comparison with granite. Consequently, for the same shock intensity the relative contribution of the thermal component to the state of the mixture is greater for salt than for granite, i.e., the relative influence of the air component is diminished.

An analysis of the experimental data and a comparison with the calculated results show that the theoretical adiabats for both approximations are situated in the zone of scatter of the experimental results. This fact prevents us from estimating the degree of correspondence of either approximation to the true state.

So far we have discussed only the shock adiabats. Judging from the results of an analysis of the isentropes for the water-saturated mixture (Fig. 2), it is expected that the presence of a gaseous component in it will create a difference between the isentropes in the equilibrium and nonequilibrium approximations. We therefore refrain from carrying out a special analysis of the problem in the given situation.

It can also be anticipated on the basis of the results obtained above that the presence of a gaseous component in water-saturated porous soils will create a difference between the shock adiabats and isentropes of both approximations, with characteristic features similar to those of the disparity between the approximations for dry porous media (see Figs. 3 and 4).

Thus, the foregoing analysis leads to the following preliminary conclusions. For mixtures of condensed media the mechanical parameters on the shock adiabats and isentropes, calculated in the equilibrium and nonequilibrium approximations, are close to one another in the domain of identical states of aggregation. The presence of a gaseous component (air or the vapor of some component of the mixture) induces a disparity between the indicated parameters calculated in the equilibrium and nonequilibrium approximations because of the abrupt variation of the compressibility of the mixture and the role of the thermal component in its state.

The currently available experimental data are not sufficient for obtaining reliable estimates of the degree of correspondence of the data of either type of thermodynamic approximation of the true states. The results presented here are more of a qualitative than a quantitative nature, owing to the approximate character of the present-day equations of state.

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