Journal of Applied Mechanics and Technical Physics, Vol. 38, No. 4, 1997

WAVE PROCESSES AND STRUCTURE DYNAMICS IN INHOMOGENOUS MEDIA UNDER PULSED LOADING

V. K. Kedrinskii

UDC 534.222+532.528+622.235.5

The present review deals with the results of the experimental, theoretical, and numerical studies of the behavior of media under dynamic loading performed at a number of institutes of the Siberian Division of the Russian Academy of Sciences over the last decade. Both new formulations and continuations of the fundamental studies considered in [1] are discussed. These studies are primarily concerned with wave processes and flows that occur upon explosive loading of complex multiphase media, including the inversion of the two-phase state and the rheology of cavitating liquids behind the front of intense rarefaction waves, waves in bubble media with a chemically active gas phase, waves in dense powder media and slug systems, and also explosion processes in grounds, cumulation, etc.

WAVES IN MULTIPHASE GAS–LIQUID SYSTEMS

Bubble Detonation. In the early 1980s, the formation of quasi-stationary waves in bubble systems such as inert liquid–chemically active gas and fuel (liquid)–oxidizer (gas) was discovered, and flow regimes were determined in which the energy lost by the wave during interaction with a bubble medium is compensated by the heat release due to the reaction in the gas mixture. Experimental studies in this field have been continued, in particular, to elucidate the fine structure of a bubble-detonation wave and to analyze the effect of bubble size on the wave propagation and parameters.

Pinaev and Sychev [2] studied experimentally the existence conditions for detonation waves in gas–liquid systems of various structures with a uniform distribution of bubbles 2–4 mm in diameter in a vertical shock tube 4 m long and 35 mm in diameter over a wide range of volume concentrations of the gas phase ($0.25 \leqslant k_0 \leqslant 8\%$) and dynamic viscosity of the liquid phase ($1.01 \cdot 10^{-3} \leqslant \nu \leqslant 1.89$ Pa·sec).

It was established that the critical amplitude of the initiating shock wave necessary for mixture ignition increases with increase in k_0 and in the induction period τ of the chemical reaction as a result of leaning or enrichment of the mixture and with decrease in the liquid viscosity. It turned out that the viscosity of the carrier liquid phase plays an important part in the formation of a detonation wave: in almost all the systems studied, the process enters a steady regime at $\nu \approx 10^{-2}$ Pa·sec and higher. The authors associate this effect with the increasing stability of the shape of the bubble surface during collapse.

Sychev [3–6] studied detonation waves in multicomponent bubble media such as a mixture of bubbles of a chemically active gas with concentration $k_{\rm ch}$ and an inert gas with concentration $k_{\rm in}$, a mixture of bubbles with an oxidizing gas and a chemically active gas in a liquid fuel, and combinations of these systems. It was found that the presence of inert-gas bubbles has no effect on the structure but decreases the velocity of detonation waves and limits the region of existence of the waves to $k_{\rm in} \leqslant 0.5k_{\rm ch}$. It turned out that the properties of inert gases affect the detonation parameters only when these gases dilute the chemically active mixture in bubbles. Experimental studies of the effect of bubble size on the process have shown that, in monodisperse systems, the length of detonation waves varies in proportion to bubble diameter [7]. It was

Lavrent'ev Institute of Hydrodynamics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 38, No. 4, pp. 111–139, July–August, 1997. Original article submitted January 13, 1997.

0021-8944/97/3804-0598 $18.00

found that detonation is absent in systems with bubbles when $d \geqslant 5$–6 mm for $k_0 \geqslant 2\%$ and when $d \leqslant 1.8$–2 mm for $k_0 \geqslant 4\%$.

Analyzing models of bubble media with equilibrium and nonequilibrium pressure, Liapidevskii [8] evaluated theoretically the velocity limits for the propagation of self-sustained waves in active bubble media. Thus, the minimum wave velocity for the first case can be determined from the formula

$$D^{\mathrm{e}}_{\min} \simeq c_{\mathrm{e}}(\bar{\varphi} y_{\mathrm{e}}^{-\gamma-1})^{1/2},$$

where $y = \tau_{\mathrm{g}}/\tau_{\mathrm{g}0}$, $\bar{\varphi} = \gamma\varphi/\gamma_0$, $c_{\mathrm{e}} = \sqrt{\gamma_0\ p_0\ \tau_0/k_0}$, γ is the polytropic exponent of the gas, $\bar{\varphi}$ is the jump in pressure as a result of adiabatic explosion with a constant volume, τ_{g} is the specific volume of the gas phase, c_{e} is the equilibrium speed of sound, and τ_0 is the specific volume of the mixture. In the second case, the wave velocity $D_{\min}$ is shown to determine the upper limit. It is assumed that, with decrease in liquid viscosity, bubbles can break, and the wave velocity becomes the equilibrium velocity $D^{\mathrm{e}}_{\min}$.

Liapidevskii solved the problem of the structure of one-dimensional flow of a chemically active bubble medium in a channel with elastic walls. He obtained a stationary solution to the equations of joint motion of the medium and the membrane that relates two different states of equilibrium and contains shock transition with energy release at the wave front. It is suggested that this solution could be used to describe qualitatively the cavitation mechanism that sustains low-velocity detonation in liquid explosive films on an elastic substrate [9].

Trotsyuk and Fomin [10] proposed a model of bubble detonation that takes into account the compressibility and viscosity of the liquid phase, the induction period of the chemical reaction, and the shift of chemical equilibrium but ignores heat and mass transfer. To calculate the specific internal energy of the gas U and to describe the state of chemical equilibrium, they used the equations

$$U = \left[\frac{3}{4}\left(\frac{\mu}{\mu_{\mathrm{a}}} + 1\right) + \frac{3}{2}\left(\frac{\mu}{\mu_{\mathrm{a}}} - 1\right)\frac{\Theta/T}{\exp(\Theta/T) - 1}\right]\frac{RT}{\mu} + E_D\left(\frac{1}{\mu} - \frac{1}{\mu_{\min}}\right),$$

$$\frac{\rho_{\mathrm{g}}}{\mu}\,\frac{(1-\mu/\mu_{\max})^2}{\mu/\mu_{\min} - 1}\exp\left(E_D/RT\right) \doteq \frac{AT^{3/4}(1-\exp(-\Theta/T))^{3/2}}{4K_+},$$

where μ is the molecular mass of the gas in the atomic (the subscript a), ultimately dissociated (the subscript min), and ultimately recombined (the subscript max) states, Θ is the effective temperature of excitation of the vibrational degrees of freedom, E_D is the average dissociation energy for the reaction products, and A and K_+ are the rate constants for the dissociation and recombination of the overall reaction products. The temperature of the chemical-reaction zone was calculated using the isentrope

$$\frac{dT}{d\rho_{\mathrm{g}}} = -\frac{U_\mu \mu_{\rho_{\mathrm{g}}} - RT/\rho_{\mathrm{g}}\mu}{U_T + U_\mu \mu_T},$$

for which the values of μ and U were found from the two equations given above. It has been shown that, at high initial pressures, a supersonic (with respect to the frozen speed of sound) wave regime is established in the bubble medium, i.e., the detonation-wave velocity does not exceed 2500 m/sec at a gas-phase concentration $k_0 = 0.01$.

One of the first numerical analyses of the formation of a bubble-detonation wave was performed by Kedrinskii and Mader [11]. They studied the interaction of a strong plane shock wave with a single spherical bubble with radius 2 mm and wave propagation in a two-component bubble medium with a chemically active gas component and an incompressible liquid component.

In the calculation for the first case, Mader [12] used the HOM equations of state for water and detonation products of a mixture (mole per mole) of acetylene and oxygen and the Arrhenius law for reaction rates. The result was surprising. When a shock wave with an amplitude of 50 MPa interacted with a bubble, the intensity of the wave refracted into the bubble was sufficient to initiate detonation in the vicinity of the bubble wall on the side of incidence of the shock wave. Thus, the detonation process was initiated without adiabatic compression of the bubble. In the detonation-initiation zone arose an intense pressure peak with an amplitude of the order of 0.12 GPa, which was much higher than the amplitude of the incident wave. The temperature was distributed nonuniformly over the bubble volume, and, at 10 μsec, it far exceeded the

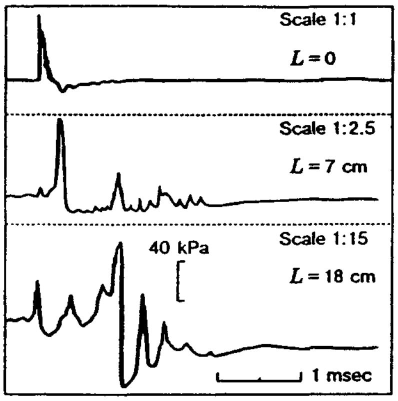

Fig. 1

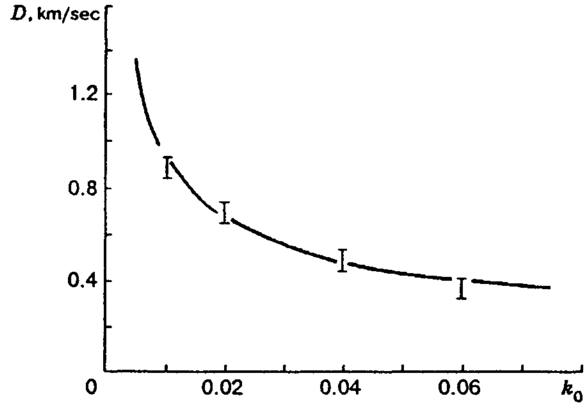

Fig. 2

temperature of initiation of the reaction and varied from 3000 to 1200 K along the bubble diameter.

The second approach was based on a two-phase model assuming incompressibility of the liquid component (Kedrinskii [13]):

$$\Delta p = -\rho_0 k_0 \frac{\partial^2 k}{\partial t^2}, \qquad \frac{\partial^2 k}{\partial t^2} = \frac{3k^{1/3}}{\rho_0 R_0^2}(\beta p_0 k^{-\gamma} - p) + \frac{1}{6k}\left(\frac{\partial k}{\partial t}\right)^2.$$

Here k_0 and R_0 are the initial volume concentration of the gas and the bubble radius, respectively, $k = (R/R_0)^3$, and γ is the adiabatic exponent.

The formulation of the problem of calculation of wave processes in a chemically active medium was supplemented by a special physical condition, according to which, with the attainment of the ignition temperature, the mixture in bubbles explodes instantaneously, and the total heat due to the reaction Q is converted to the internal energy of detonation products. In this case, the pressure in the bubbles increases instantaneously to the quantity $p_* = (\gamma_* - 1)\rho_* Q$, where ρ_* is the density of the mixture at the moment of explosion; the asterisk refers to the reaction products.

In the given system, the above-mentioned physical condition is modeled by the cofactor β in the equation for the concentration k. The absence of any kinetics for chemical reactions makes this model of bubble detonation ultimately simple. Before explosion, $\beta = 1$. After explosion, the adiabatic exponent of the gas mixture in the bubble changes instantaneously, and β is determined from the value of p_* (in the example considered, it was equal to 6.5) [11].

Calculations showed that the parameters of a bubble-detonation wave do not depend on the intensity of the incident wave. The incident wave is required only to initiate the reaction in the bubbles. In contrast, the time during which a quasi-steady regime is attained is sensitive to the parameters of the initiating wave. For example, as the wave duration decreases from 60 to 20 μsec (for an amplitude of 3 MPa), the time increases from 66 to 420 μsec. The wave profile and velocity calculated within the framework of this model are comparable with experimental data over a wide range of volume concentrations of bubbles.

The velocity of a bubble-detonation wave is a process parameter that is most easily determined in experiments and often used to evaluate the adequacy of various approaches to the description of the process, including the classical approach, which is used in the case of real explosives [8]. One approach (Kedrinskii and Mader [14]) is based on two experimentally observed features of transformation of shock waves in passive bubble media [13].

The first feature is that, with the propagation and dissipation of a shock wave in a bubble media, a certain zone L forms in which bubbles collapse synchronously. The dimension of this zone is apparently proportional to the characteristic distance $\delta = R_0/\sqrt{3k_0}$, at which the incident wave decays [13]. This statement is confirmed by the time history of the wave profile structure during the wave propagation over bubble layers of different thicknesses (Fig. 1, the amplitude of the incident wave is 1MPa, and the precursors and wave trains are obtained for $L = 7$ and 18 cm and $k_0 \simeq 0.06$). Naturally, a similar effect also occurs in a chemically active bubble system, as judged by the dimension of the detonation-initiation zone at the same volume concentration (Sychev and Pinaev [15]).

The second feature is associated with the estimated time of collapse of a "collective" bubble layer to the degree $\bar{R}_* = R_0/R_*$, which corresponds to the ignition temperature

$$t_{\rm ign} \simeq 0.14 R_{\rm max}\sqrt{\rho_0/p_0}\,\exp\,(L/2\delta), \qquad 4\pi p_0 R^3_{\rm max}/3 = Q\ m_{\rm g}.$$

Taking into account these features, Kedrinskii and Mader [14] proposed the following semiempirical dependence of the bubble-detonation wave velocity on the volume concentration of bubbles:

$$D \simeq \lambda[\rho_*(\gamma_* - 1)Q/\rho_0 k_0]^{1/2}.$$

It is shown in Fig. 2 (the solid curve shows the calculated data). The value of λ was chosen for one experimental point. Comparison with the experimental data (vertical lines) shows that the proposed estimate is quite acceptable.

Shagapov and Vakhitova [16] studied stationary solutions of the type of a solitary wave for a chemically active bubble medium with an incompressible liquid component. They concluded that the detonation-wave Mach number $\mathrm{M} = D/c_{\rm w}$ does not depend on the volume concentration of the gas phase ($c_{\rm w}$ is the shock-wave velocity in the bubble medium). According to [16], $\mathrm{M} \simeq 8$. In essence, this means that $D \propto k_0^{-1/2}$.

Bimolecular kinetics (O. Todes, 1933) for determining the number of molecules n formed in a unit volume during the reaction was used in the form of the equation

$$\frac{dn}{dt} = A\sqrt{T}\,e^{-E_{\rm act}/BT}(a - n)^2$$

in the first numerical studies based on the assumption of an adiabatic explosion of a gas mixture at a constant volume (Kedrinskii, Zamaraev, and Mader [17, 18]. Here $E_{\rm act}$ is the activation energy, B is the gas constant, and a is the initial concentration of the starting component. It was found that, with preservation of spherical symmetry during bubble collapse, the heat exchange is insufficient to form a truly solitary wave: behind the detonation-wave front occurs a zone of intense radiation, which is associated with the preservation of the heat due to the reaction in the bubbles. The mechanism of possible losses, which can be caused by both additional heat exchange (due to the instability of the bubble shape and increase in the interfacial area) and mass exchange, requires further investigation.

Recent studies have shown that the bubble-detonation phenomenon can be used to explain the mechanisms of well-known physical phenomena and the role of cavitation effects in large-scale explosion processes. Indeed, real liquid media contain microinhomogeneities: microbubbles of free gas, solid microparticles, and their combinations, called cavitation nuclei (Besov, Kedrinskii, and Pal'chikov [19] and Matsumoto and Ohashi [20]). According to the modern concepts based on numerical experimental studies, the density of free-gas microbubbles, for example, in a pure liquid is of the order of 10^3–10^4 cm^{-3} for $R_0 \simeq 1.5\ \mu$m. This leads to the conclusion that it is necessary to take into account the two-phase character of real liquids. Naturally, with the occurrence of tensile stresses, gas–vapor bubbles begin to develop on nuclei, and a so-called cavitation cluster forms. The shape and dynamics of the cluster are determined by the initial sizes of the nuclei, the characteristics of the applied stresses, and the boundary conditions. This phenomenon is called bubble cavitation.

Experiments show that the heterogeneity of media and cavitation physics are intimately related to phenomena such as the detonation of liquid explosives and explosion processes in volatile and flammable liquids contained under pressure in vessels when the latter are suddenly depressurized, for example, upon impact (Kedrinskii, Vshivkov, and Dudnikova [21]). In this case, the observed catastrophic failures of containers were explained by two mechanisms (Barbone et al. [22]):

(1) possible discharge of compressed liquids in the form of two-phase cavitating bubbles with subsequent spraying; as a result, a gas–droplet cloud is formed and a so-called volume-detonation charge occurs;

(2) partial depressurization of the container leads to generation of rarefaction waves, which, propagating in the liquid fuel, cause fast processes such as boiling (the pressure in the vessel suddenly increases).

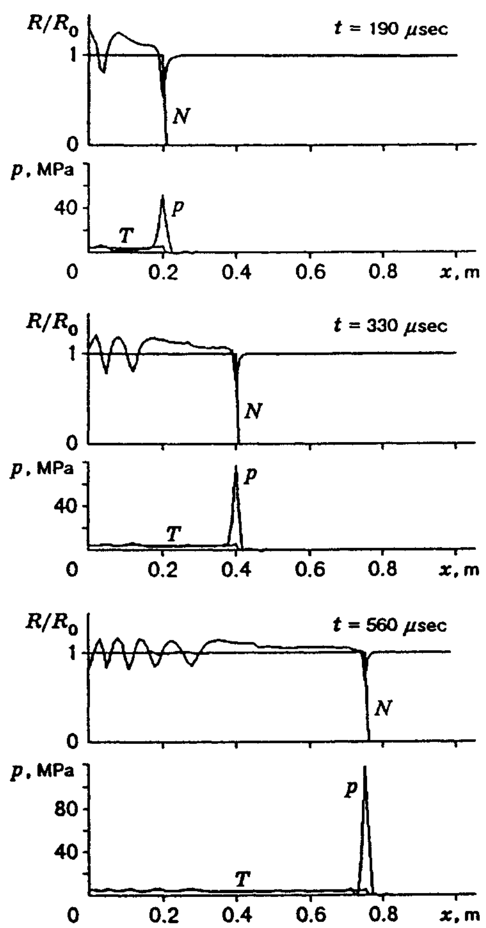

Fig. 3

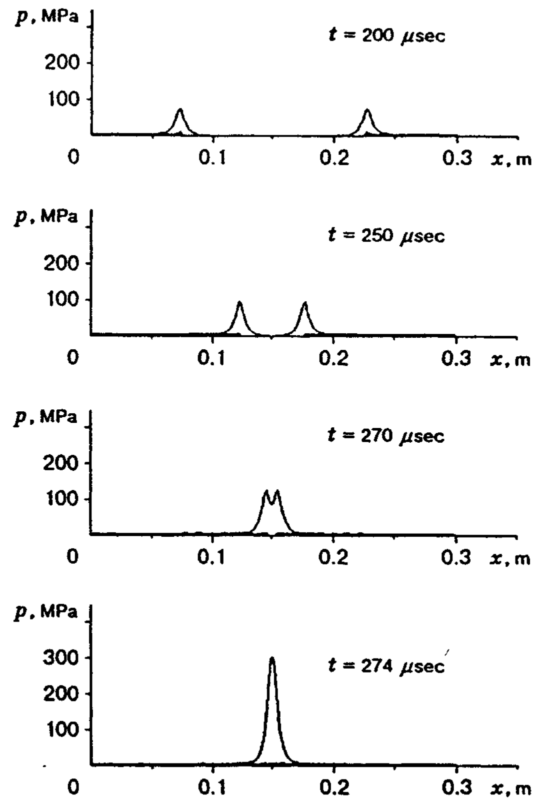

Fig. 4

However, a third mechanism is also possible, which can produce higher (by several orders) pulse loads. It is probable that filling a container with a liquid leads to the formation of a large number of bubbles that contain a mixture of air with fuel vapors capable of igniting under adiabatic compression. A similar mixture can also form as a result of expansion of bubbles that initially contained only air, because of the mass exchange in rarefaction waves. Upon impact and depressurization of the container, rarefaction waves and shock waves capable of initiating a bubble detonation wave will arise, propagate, and interact in the liquid. The result of such interactions is evident in Figs. 3 and 4, which demonstrate the formation and collision of detonation waves, respectively. Figure 3 shows the distributions of the average radius R/R_0, the relative content of the mixture components that have reacted $N = n/a$, and the average pressure in the medium p: $k_0 = 5 \cdot 10^{-3}$ and $R_0 = 0.2$ cm for three moments of time (190, 330, and 560 μsec). The pressure at the boundary of the medium ($x = 0$) was specified as a step with an amplitude $p_l = 5$ MPa. Upon collisions of such waves, the resulting pressure can reach 300 MPa (Fig. 4).

An interesting effect was discovered by Kedrinskii, Vshivkov, Dudnikova, and Shokin [21, 23], who studied numerically the collision of rarefaction waves in a medium with microbubbles of an active gas, which modeled the loading of a liquid explosive with a free boundary. It turned out that initiation of bubble detonation at the center of the specimen is possible in this case, too (the pressure in the plane of collision reaches 300 MPa). This effect is associated with features of the transformation of a rarefaction wave during its propagation in a cavitating liquid. Pulsation with an intense positive phase occurs behind the wave front. Collision of such waves ultimately leads to heating of the gas mixture to the ignition temperature and to the occurrence of a bubble-detonation wave. A sudden increase in pressure behind the front of this wave could be responsible for the above-mentioned effects.

Passive Multiphase Media. Wave processes in complex passive gas–liquid systems have also aroused considerable steady interest [24–47]. Thus, for example, the experimental studies of Dontsov, Nakoryakov, and Kuznetsov [24, 25] on the dynamics of the structure of pulsed perturbations in porous media saturated with a liquid, a gas, or a liquid with gas bubbles confirmed the existence of two types of longitudinal waves: "fast" and "slow" waves. It is shown that the formation of these waves depends on the conditions of perturbation generation at the interface and also on the compressibility of the porous bed and of the liquid (gas or gas–liquid mixture) that saturates it.

It is assumed that the interfacial friction at the liquid–solid interface determines the mechanism of dissipation losses, in particular, because of the elastoplastic forces due to the squeezing of the viscous liquid from the thin gap near the points of grain contacts in the porous bed. The experimental data on the structure, velocity, and damping characteristics of pressure waves in porous media saturated with a liquid are generalized in [24–27] based on calculations using the Frenkel–Biot linear model.

Dontsov, Maslov, Nakoryakov, and Pokusaev [28–31] derived evolutionary equations for the propagation of weakly nonlinear pressure perturbations of a two-wave structure, taking into account nonlinear bubble oscillations and viscous decay of these oscillations in the porous bed, and also the nonlinearity at grain contacts in the solid structure upon deformation. It is shown that the main nonlinearity of the evolution of pressure waves is due to the dependence of the compressibility of the porous bed on the wave amplitude.

Nakoryakov, Dontsov, and Pokusaev [32–35] obtained experimental data on the velocity, structure, and decay of waves of moderate intensity in a liquid suspension with solid particles and gas bubbles. The effect of the liquid added-mass coefficient on the wave-propagation velocity has been studied, and a model describing weakly nonlinear waves in three-phase suspensions has been proposed. It has been shown that the main mechanism governing the wave attenuation is the heat exchange between the gas in the bubbles and the ambient liquid. The formation mechanism of oscillating solitary waves — multisolitons — in a liquid with bubbles of various sizes was discovered and explained by Gasenko, Dontsov, Nakoryakov, Kuznetsov, and Markov [36–40]. The effect of bubble fragmentation on the wave evolution, bubble breakup mechanisms, and collisions of solitary waves of moderate intensity have been studied experimentally [41–45].

Studies of the passage of waves through the interfaces in the systems "a liquid–a porous medium saturated with a liquid with gas bubbles" and "a liquid–a liquid suspension with solid particles and gas bubbles" showed that the parameters of the reflected waves due to the presence of the solid phase are significantly affected by inertial effects. The available experimental data for the reflection coefficient were generalized within the framework of the Biot model [46, 47].

Phase Transition. Slug Structures. Lezhnin, Pribaturin, Nakoryakov, Pokusaev, Aktershev, Zhakupov, and Vasserman [48–60] performed extensive experimental and theoretical studies on the propagation of wave pressures in gas- and vapor–liquid media with various internal structures and intense phase transitions. Thus, Lezhnin and Aktershev [54], analyzing the dynamics of a vapor void (slug) in a channel for the case of external shock action, determined the following main similarity criteria: the nonlinearity parameter $M = (\gamma+1)\Delta p/2\gamma p_0$ and the phase-transformation criterion $W = 3Ja\sqrt{at_0}/2R_0$ (the Jacob integral criterion, where t_0 is the characteristic time of the initial perturbation). The latter criterion determines the ratio of the enthalpy of underheating of the liquid involved in the heat exchange to the amount of heat that must be removed for vapor condensation in the slug. The time of "penetration" of the thermal layer through the wall was estimated. A chart of collapse regimes of a slug under external shock loading was proposed. The boundary of the transition from the hydraulic shock regime of collapse to the oscillatory thermal regime was determined numerically [54, 55, 58, 59]. The analytical solutions obtained show that the greatest difference in dynamics between a vapor slug and a bubble is observed in the stage of their growth. At large values of W, the inertial stage of growth for a vapor slug continues for an arbitrarily long time.

Lezhnin and Zhakupov [57] and Pokusaev et al. [58] studied the collapse dynamics of a vapor slug in a channel with allowance for its damage and proposed a qualitative model for the development of a cumulative jet under the action of a stepped load on the system "a vapor slug–a liquid plug" for phase transitions of various intensity. Collapse of a slug in which a two-phase vapor–liquid droplet mixture resulting from slug failure is present has been studied. A numerical value of $\simeq$0.5 was determined for the critical number W, which characterizes the intensity of the phase transition. It was shown that the manifold increase in pressure in a vapor–liquid medium is explained by collapse of the equilibrium vapor–liquid clusters that occurred as a result of destruction of vapor formations.

The waves in the slug structure of a gas- and vapor–liquid medium have been studied within the framework of the mechanical analogy [48–52, 55, 56, 60], with allowance for the "aperiodicity" of this structure [50, 52] and the presence of a liquid film on the interface [49, 52]. A quasi-continua [48–52, 56, 60] model and a discrete model [52, 55, 56] for the wave evolution were developed, and analytical solutions describing the wave dynamics were obtained [52, 56]. The wave evolution in intense phase transitions was modeled under the assumption of elastic and absolutely inelastic interactions of liquid plugs [55, 56]. It was shown that the breaking of a slug under dynamic loading radically changes the wave regime, and that the "elastic" model describes qualitatively the shock-wave evolution, and the "inelastic" model gives a correct asymptotic value for the wave velocity of complete condensation. It was proved experimentally [55, 58] that the "combs" of pulses are superpositions of local hydraulic shocks.

The evolution of weakly nonlinear waves in a periodic bubble medium in which liquid plugs alternate with gas–liquid clusters [51, 52, 60], in a stratified bubble medium with a liquid layer containing gas bubbles [53, 60], in a slug–cluster structure (gas slugs alternate with gas–liquid clusters [60]), in a comb structure (a slug structure in horizontal and inclined channels [60]), etc. were analyzed by reducing complex structures to superpositions of canonical systems (bubble, stratified, and slug systems).

The analysis of Pokusaev et al. [60] of the acoustics of slug structures showed that, in the presence of gas bubbles in liquid plugs, the wave evolution is affected by the ratio between the volume gas content in the slugs and bubbles. In periodic bubble media and stratified bubble media, "slug" and "stratified" wave dispersions dominate, as a rule, over "bubble" dispersion [51, 53].

Experiments showed that in a bubble vapor–liquid medium, with increase in shock-wave intensity, the shock waves become short pulses with a duration of 300–500 μsec, whose amplitude far exceeds the initial amplitude and whose wave-front steepness increases with distance (Nakoryakov, Pokusaev, Shreiber, Pribaturin, et al. [51, 61–65]). Vapor bubbles in such a pulse almost completely collapse and can arise again after passage of the pulse. The condensation front in the shock pulse becomes steep and coincides in time with the leading edge of the pulse.

Experimental studies of the behavior of a system of vapor bubbles of various sizes in shock waves using a stroboscope with a high time resolution showed that bubble collapse is accompanied by radiation of high-amplitude spherical shock waves into the ambient liquid. In this case, collapse of large and small bubbles in the second oscillation stage occurs simultaneously, indicating the tendency to "collective" pulsation and radiation of a high-amplitude secondary pressure wave.

In experiments on the dynamics of individual gas slugs and their systems in shock waves, Pokusaev et al. [62] and Nakoryakov et al. [66, 67] varied the gas content of the mixture ($0.08 < k_0 < 0.8$), the initial pressure-wave amplitude ($0.05 < \Delta p < 3$) and duration ($10 < \Delta t < 500$ msec), the gas (air, nitrogen, helium, hydrogen, and Freon-11) density, the surface-tension coefficient of the liquid (isopropyl alcohol and water), viscosity (water and glycerin), and the channel diameter (D = 8, 15, 25, and 55 mm). It was found that a slug, in contrast to a bubble, is extremely unstable under the action of pressure perturbations, and, beginning from a wave amplitude of 0.5–0.18, it breaks up into small bubbles. Changes in gas density (by a factor of 10) and in tube diameter did not affect the threshold value, which was constant for the given slug and liquid–plug lengths.

Pokusaev and Pribaturin [68] showed experimentally that the mechanism of breakup of a chain of slugs in a pressure wave is determined to a large extent by the gas content, whose increase does not lead to an increase in the drift velocity behind the shock-wave front. With a small gas content ($k_0 < 0.5$), breakup begins, as in the case of a solitary slug, with the formation of a cumulative jet. For $k_0 > 0.5$, the structure of the medium behind the shock-wave front changes qualitatively: because of the high drift velocity, the head part of the slug breaks up into small gas bubbles, which rapidly fill liquid plugs. When the gas content in the plugs reaches a critical value, the small gas bubbles merge into a continuous gas nucleus. The probable boundaries of structural transformations behind the pressure-wave front in slug, periodic bubble (cluster), and ring systems were determined.

Experimental studies of the dynamics of a vapor slug showed that the slug collapse (condensation) in a weak wave is accompanied by decaying pulsations with a monotonic decrease in volume up to complete disappearance (Nakoryakov, Pribaturin, Pokusaev, Lezhnin, et al. [55, 69, 79]). With increase in the intensity of the initial perturbation, a "shock" condensation regime occurs in which complete condensation of the slug proceeds at the leading edge of the pressure wave. The intensity of the heat exchange between the vapor and the liquid is large so that the vapor pressure practically does not increase during the slug collapse. The collapse proceeds with a constant acceleration, and the liquid velocity in the final stage reaches tens of meters per second. In this case, a powerful pressure pulse, whose amplitude is an order of magnitude higher than the amplitude of the initial loading [71–73], is generated in the channel.

Experiments showed that the propagation patterns of shock waves of relatively weak intensity in vapor–liquid media of slug and bubble structures are similar: the initial oscillations are smoothed as the wave propagates, and the wave degenerates into a wave with a flat front, behind which the slug length decreases monotonically up to the complete disappearance of the slugs. In contrast to gas–liquid systems, an increase in vapor content even to a value of 0.8 does not change the structure of the medium.

With increase in the amplitude of the initial shock wave, the wave shape changes q 'alitatively: vapor slugs break up and intensely collapse to radiate a high-amplitude pressure pulse. This leads to the formation of a typical "comb" shape, each pulse of which corresponds to the collapse of the next slug in the motion path. The first shock pulse of this shape corresponds to the complete condensation front, and its velocity agrees well with the shock-wave velocity with complete vapor condensation behind the wave front [69, 70]. The front velocity and amplitude of the main shock wave exceed the corresponding shock-wave characteristics in a medium without phase transition. In this case, the amplitude is approximately equal to the pressure during collapse of a solitary vapor slug.

BUBBLE CAVITATION AND WAVE PROCESSES

Failure of Liquids under Pulsed Loading. In the last decade, significant advances have been made in the problem of liquid failure under dynamic loading because of new experimental formulations and procedures and also because of the development of new physical models that describe the complex behavior of cavitating liquids and changes in their properties.

Stebnovskii and Chernobaev [74] studied experimentally failure of liquid cylindrical shells at various times of loading (explosion of a wire along the shell axis) and showed that, for the threshold value of the specific energy of pulsed loading, the failure characteristics depend on the parameter τ, which is the ratio of the time of loading of the liquid volume T to the time t_* during which the rarefaction wave travels the distance from the free surface of the shell to the cavity with explosion products. For $\tau = T/t_* > 9$, failure results from development of initial perturbations on the internal and external boundaries. For $9 > \tau > 3$, cavitation begins to play a part in the failure process, and, for $\tau < 3$, failure results only from the development of cavitation.

The experimental methods of recording the onset of cavitation damage of liquids under pulsed loading were based on the electrokinetic effect (Stebnovskii [75]), the retardation effect of a cavitating liquid flow (Chernobaev [76]), and pulsed radiography (Berngardt, Kedrinskii, and Pal'chikov [77–80]).

The first method involves measuring the potential difference $\psi(t)$, which changes sign with transformation of a bubble system (signal 1) into a gas–droplet system (signal 2 in Fig. 5a). In the second case, a pressure gauge was located at various distances from the shell and recorded the flow-retardation pressure. It turned out that the signal $p(\delta, t)$ has a two-pulse structure (waves 1 and 2 in Fig. 5b). The first pulse is the cavitating-flow pressure, which decreases with distance and practically disappears at approximately 200 μsec ($\delta = 2$ cm): the medium enters a foam-type state. According to the data obtained using the first procedure, a gas–droplet system arises within the next 100 μsec.

Pulsed radiography and a two-diaphragm shock tube were used to study an optically opaque, actively developing cavitation zone in the late stage of destruction. The setup is shown schematically in Fig. 6a, where X-R1, X-R2, and X-R3 are pulsed x-ray devices, A is the working section with the liquid to be tested, and

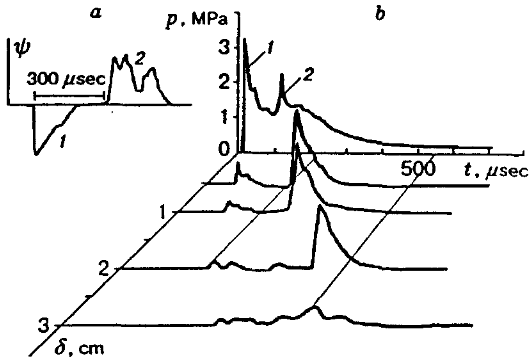

Fig. 5

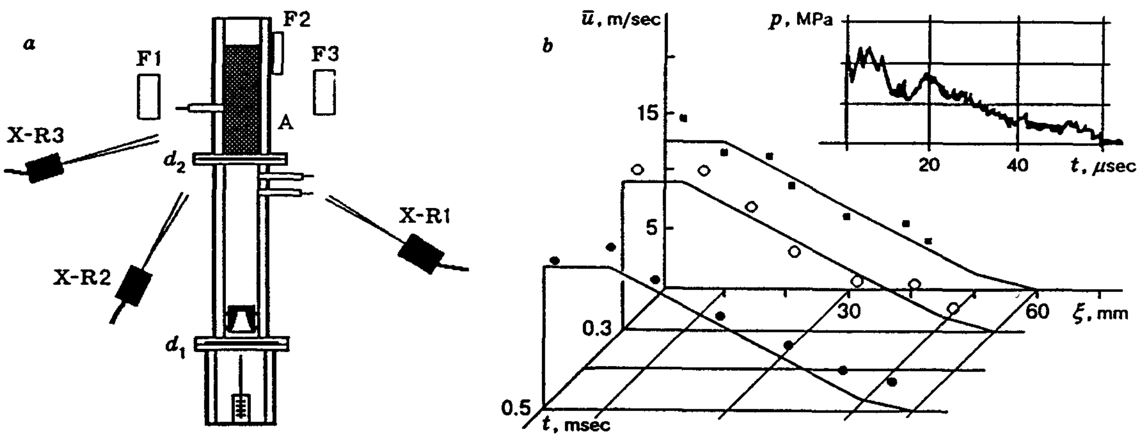

Fig. 6

d_1 and d_2 are diaphragms. Scanning and computer processing of negatives F1–F3 of the x-ray image of the cavitation zone behind the edge of the shock wave reflected from the free surface made it possible to study the dynamics of the average density $\bar{\rho}$ of the cavitation zone and the time t_* during which the cavitating medium attained the state of bubble bulk density as a function of the strain rate of the medium $\dot{\varepsilon}$ (Berngardt, Kedrinskii, and Pal'chikov [80]):

$$\bar{\rho} = \rho_0(1 + \dot{\varepsilon}t)^{-1}, \qquad \text{from which} \qquad t_* \simeq (\dot{\varepsilon})^{-1}.$$

According to the experimental data, for $\dot{\varepsilon} \simeq 1330$ sec^{-1}, the time of relaxation of the medium to a foam-type state is about 700 μsec, and, for $\dot{\varepsilon} \simeq 500$ sec^{-1}, it is about 2000 μsec, which fits the above dependence. Using the same procedure, Kedrinskii et al. [76] measured the mass-velocity distributions in the cavitation zone $\bar{u}(\xi, t)$ at various times, studied their dynamics, and discovered the "freezing" effect of the velocity profile (Fig. 6b). Here $p(t)$ is the profile of the incident wave, and the symbols are experimental data.

It was noted [75] that if the rate of the radial extension of a liquid shell is of the order of 50 m/sec or higher, fractures similar to cracks in a solid arise in the cavitating medium. Stebnovskii [81] showed that increasing bubble concentration in the liquid leads to an increase in the relaxation time of shear stresses (acquiring viscoelastic properties, the medium enters a new rheological state). Furthermore, he proposed that the fragmentation process is a consequence of the accumulation of elastic energy, during which the bubble system enters an energetically unstable state [82] with the formation of ruptures in the zone of spontaneous increase in bubble concentration.

Cavitation damage of liquids under pulsed loading can be defined as the inversion effect of the two-phase state of the medium involving transformation of the cavitating liquid into a gas–droplet system. In studies of

Fig. 7

this effect, it is necessary to combine numerical analysis and experiments to obtain the most adequate physical model of the inversion. In this regard, the results of computer processing of x-ray negatives, which revealed the existence of sudden pulsations of local intensity in bubble clusters (Berngardt et al. [80]), numerical analysis of the cavitation development under explosive loading of a liquid spherical shell (Kedrinskii and Chernobaev [83]), and studies of the role of cavitation in the breaking mechanisms, including focusing of shock waves in lythotropic systems (Kedrinskii [84–86]), allowed one to make significant headway in determining the structure of the medium in the stage preceding failure.

The idea of studying the dynamics of the state of a solitary liquid droplet under the action of an ultrashort pulse (Kedrinskii, Besov, and Gutnik [87]) turned out to be most fruitful. It has been found that the activation zone that occurs in the droplet is a system of bubble microclusters, whose inertial development leads to the formation of a cellular structure of the type of a liquid lattice, which differs greatly from the well-known spherical and polyhedral models of foams with a Plateau triangle. Breakup of the liquid-lattice cells into individual bubbles and then into droplets (Fig. 7) is the basis of the inversion mechanism of the two-phase state of the liquid under dynamic failure.

Fragmentation of non-Newtonian liquids (emulsions, suspensions, and pastes) in the zone of tensile stresses under explosive loading were studied by Stebnovskii [88], who established experimentally the cavitation breakup of emulsions. He showed that if the solid particles of this two-phase system are wetted with the liquid matrix, the structure of this system is unstable; otherwise, nonwettable particles are displaced from the liquid fragments, and individual flows of pure liquid droplets and solid particles are formed. The thermodynamic stability condition for the structure of a deformed suspension volume is obtained as a function of the solid-particle concentration, the angle of wetting of the particle material with the liquid, and the surface-tension coefficient.

To describe the cavitation process when the concentration is close to the bubble bulk density, Stebnovskii proposed a macrorheological approach [75, 89, 90], which includes three stages: experimental investigation of the evolution of the structure of dispersed liquids, development of rheological models of volume extension [89] and shear deformation [90], and, finally, construction of the corresponding rheological equations of state of the relaxation type.

Explosive Formation of Gas–Droplet Systems. Pulsed breakup of finite liquid volumes terminates by the stage of dispersion of the gas–droplet cloud, whose characteristics are also of interest from a practical viewpoint.

Extensive research in this direction was performed by Stebnovskii [91–93]. He developed an experimental analysis method for the structure of a gas–liquid medium in the stage of pulsed fragmentation, developed a measuring procedure, and studied high-velocity gas–droplet flows (the volume concentration of droplets in the flow, the droplet sizes, and mass flow velocity) over wide ranges of geometrical parameters of the system "an explosive–a liquid shell," physical characteristics of the dispersed liquid, and specific energies of explosive loading [91, 92]. Functional relations were obtained that allow one, using the initial data of this system, to calculate the period of formation of a dispersed gas–droplet cloud, the concentration dynamics, and the volume distribution of droplet sizes and to analyze the evolution of the volume average dispersivity [91, 93] during the formation of the cloud.

One real physical model for formation of a gas–liquid droplet cloud as a result of cavitation damage was constructed by Gets and Kedrinskii [94], who suggested that, upon reaching the bubble bulk density, a cavitating liquid transforms instantaneously into a dense layer of elastic unmerged liquid droplets (a "sand" model). This layer "is thrown" by detonation products to form a gas–droplet system. Numerical studies of wave processes occurring in the layer, comparison of the dynamics of the layer structure [94] with dispersion of sand shells, and also experimental analysis of the sand-particle distribution in space [78] confirmed the possibility of such modeling.

Dynamics of Interfaces During Reflection of Shock Waves. The interaction of shock waves with bubble media is characterized by complex processes of absorption and reradiation of the incident-wave energy by the bubble medium. These processes proceed in the most nonstandard manner during reflection and refraction of waves at the interface, which, in essence, is not a flat boundary surface. It is formed within a finite time interval as a result of collapse of the boundary bubble layer (Kedrinskii [95, 96] and becomes a flat boundary surface when the average mass velocity reaches a value that corresponds to the $\bar{\rho}c$ of the bubble layer.

Derzho and Malykh [97, 98] compared the results of experimental and numerical studies of the structure of strong pressure pulses reflected from the bubble layers in water for various sizes of bubbles and various spatial gradients of the gas volume concentration in the layer. Experiments showed that the reflection proceeds not on the physical boundary of the layer, but inside the layer and depends on the pressure-pulse parameters and local characteristics of the bubble layer. The formation of the reflected signal is a dynamic process, and it should be described with allowance for the nonlinear dynamics of bubble collapse under the action of an incident shock wave. It turned out, in particular, that the higher the gradient of the volume concentration in the layer and the lower the amplitude of the incident wave, the less marked the dispersion and nonlinear deflections of the reflected signal. In the presence of a rigid wall behind the layer, the process becomes more complex because of the superposition of the waves reradiated by the layer and the waves dispersed and reflected from the wall.

Malykh [99] discovered experimentally the so-called resonance solitons, i.e., solitary pressure waves that are stable against changes in shape under conditions of strong nonlinearity and dispersion.

Reflection of shock waves from the free boundary of a liquid with natural microinhomogeneities leads to the development of a cavitation zone near the boundary. This zone absorbs the energy of the rarefaction wave and determines its profile. In a cavitating medium, as in artificial bubble media, arise a precursor and a main perturbation with an oscillating front, or a wave train in the case of short waves. Figure 8 shows the pressure distribution $p(x)$ at $t = 13$ μsec after reflection; $x = 0$ corresponds to the free boundary [100]. Another feature of the reflection process is the unexpected behavior of the free surface, which practically retains the mass velocity over a period of time that far exceeds the duration of the incident wave [$u(x)$ is the mass-velocity distribution]. It was assumed (Kedrinskii and Plaksin, 1984, [1]) that this effect is associated with the development of a bubble cluster [$R(x)$ is the distribution of the bubble radius in the cavitation layer].

Besov and Kedrinskii [101] studied experimentally the shock-wave reflection and discovered that the development of a cavitation zone changes radically the dynamics of the free surface (Fig. 9, oscillograms s). Shock waves were generated by the motion of a membrane under the action of a pulsed magnetic field and the wave duration was of the order of several microseconds. The displacement of the free surface s was measured by a variable-capacitance transducer, and the intensity I of the laser beam scattered by bubbles in the cavitation zone near the free surface was measured by photoelectron multipliers. The development of a cavitation cluster depended on the intensity of the shock wave incident on the free surface. This intensity was chosen from the results of experimental studies of the cavitation threshold (Besov, Kedrinskii, and Pal'chikov [102, 103]), obtained by three procedures: light scattering by microinhomogeneities, dynamics of the free surface, and absorption of the rarefaction wave. The measurements showed that the free surface began to react in a stable

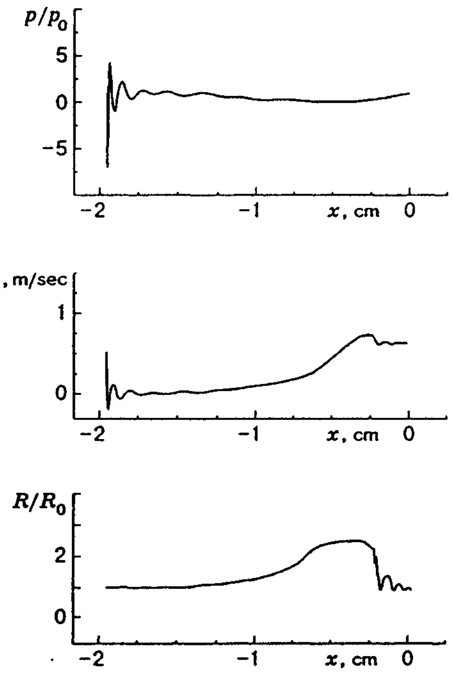

Fig. 8

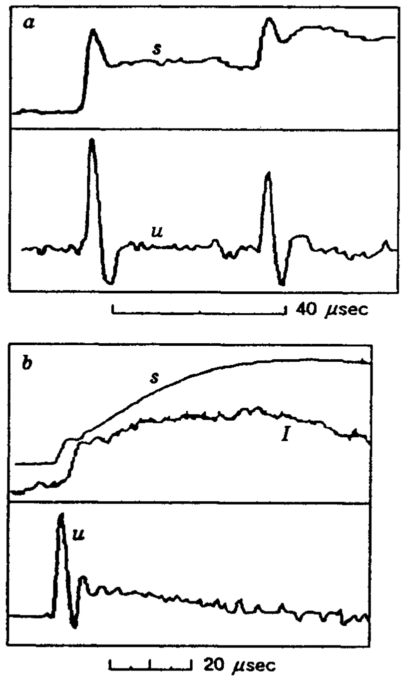

Fig. 9

manner to the development of a cavitation zone when the amplitude of the incident wave was 2 MPa or higher. The oscillograms in Fig. 9a correspond to the threshold value of the wave amplitude, and the oscillograms in Fig. 9b correspond to the cavitation regime for an amplitude of ~5 MPa. Comparison of oscillograms of the displacement of the surface s and oscillograms of the intensity of the scattered light I shows some features of the cavitation zone development. Thus, for example, the jump in intensity of the scattered light and the secondary peak of the mass velocity u occur in the rarefaction phase of the incident wave. The monotonic displacement of the surface, the decrease in its mass velocity, and the change in intensity of the photomultiplier signal correspond to the development dynamics of a cavitation cluster up to the maximum concentration and further.

It was shown that, using the well-known formula for determining the time of collapse of a cavity in the bubble layer and knowing the decrease in scattered-light intensity and the dynamics of the free surface, one can estimate the main parameters of the cavitation zone (the bubble density and radius) by the relation

$$\alpha^2 \exp(-\alpha) \simeq \frac{3l^2 \ln(I_0/I)}{8d\tau_* \sqrt{p_0/\rho_0}},$$

where $\alpha^2 = \pi n_0 R l^2$, I is the intensity of the light scattered by microbubbles of radius R, n_0 is the density of the bubbles, d is the diameter of the bubble cluster along the beam direction, I_0 is the beam intensity in the noncavitating liquid, and τ_* is the time of synchronous collapse of bubbles in a layer of thickness l and volume concentration k_0. The quantities entering the right side of this expression are easily determined from experiments, except for the thickness of the "collective" layer, which was estimated from the time interval between the beginning of the rarefaction phase of the incident wave and the second peak of the mass velocity (the oscillogram u in Fig. 9b), during which the parameter n_0 is presumably established.

Cavitation Erosion. The two-phase state of real liquids is essential to the solution of the problem of cavitation erosion, which means the damage to the solid surface as a result of pulsation of a cavitation cloud near it. According to the adopted concepts, the erosion mechanism is determined by the impacts of cumulative microjets formed upon collapse of bubbles. The dynamics of the bubbles, however, depends on their collective behavior in the cluster. Significant advances in the solution of this problem are associated with

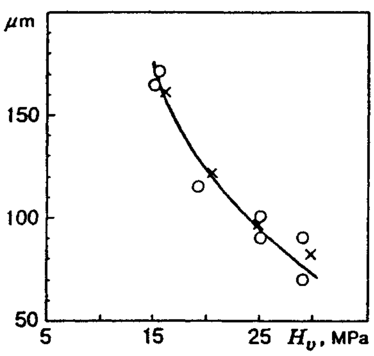

Fig. 10

the use of the two-phase model of a cavitating liquid and the results of the experiments of Takayama and his colleagues, who studied the local zone of damage and obtained the dependence of the cavity depth h_p on the amplitude p_{sh} of the shock wave that compresses the bubble near the specimen and on the microhardness of the specimen H_v (Kedrinskii and Stepanov [104–106]).

Experimental data for the fine structure of the local damage zone indicate the existence of a threshold energy barrier and monotonic dependence of the mass loss on the maximum diameter of the bubble $D_{\max}$, i.e., on the initial potential energy of the system $U_{\max}$. The latter is converted to the energy of the compression wave and the energy of the cumulative jet that occurs during bubble collapse. The use of the two-phase model is essential to the solution of this problem, because, despite the local character of erosion effects, their frequency and intensity are determined by hydrodynamic characteristics of the bubble cluster and the feature of the wave-field structure in it. The semiempirical dependence of the penetration depth of the microbubble h_p on the main parameters of the problem (the initial radius of the bubble R_0, the potential energy of the system, and the microhardness of the surface H_v) has the following form (crosses in Fig. 10) [106]:

$$h_p \simeq 11.6 R_0 \int\limits_{y_{\min}}^{y_*} p y^2 \, dy / H_v.$$

The quantities h_p and R_0 are measured in micrometers, and p and H_v are measured in megapascales. The coefficient 11.6 is determined from experimental data.

Relaxation of Tensile Stresses. The development of bubble cavitation in a real liquid with natural microinhomogeneities under dynamic loading is intimately related to relaxation of applied tensile stresses. In numerical studies of the two-phase model, Kedrinskii (1975) showed that the tensile stresses allowable by the medium are primarily related to the loading rate. Modeling breakup of the liquid layer, Kedrinskii [107, 108] was able to find an analytical solution of this problem.

Assuming that the liquid is incompressible and ignoring the gas pressure in bubbles during the cavitation cluster development, one can write the system of equations describing this process as

$$\Delta p = -\rho_0 k_0 \frac{\partial^2 k}{\partial t^2}, \qquad \frac{\partial^2 k}{\partial t^2} \simeq -3k^{1/3} \frac{p}{\rho_0 R_0^2}.$$

The solution of this system determines both the tensile-stress parameters in the liquid and the cavitation dynamics. Within the frameworks adopted, the spatial distribution of pressure is established instantaneously at each time, and, for the given values of k, it can be found in analytical form.

This model was used to analyze the cavitation process in a vertical tube with water which gained downward acceleration $a(t)$ upon impact. If z is the vertical coordinate reckoned from the tube bottom and $\alpha = \sqrt{3k_0/R_0^2}$, the liquid pressure is determined by the expression $p = -\rho_0 |a(t)| \exp(-\alpha k^{1/6} z)/\alpha k^{1/6}$. In this case, for $z = 0$, the full equation of the concentration dynamics

$$\frac{d}{dt}\left(k^{-1/6} \frac{dk}{dt}\right) = \frac{3a(t)}{\alpha R_0}$$

has an analytical solution, according to which, for example, in the case $a(t) = a_{\max} \exp(-t/t_*)$ (t_* is the characteristic time of change in acceleration), and the expression for the volume concentration $k(t)$ has the form

$$k^{5/6} = 1 + \frac{5t_* a_{\max}}{2\alpha R_0^2} [t - t_*(1 - \exp(-t/t_*))].$$

The expressions for p and k allows one to obtain all necessary estimates for stresses in the cavitating liquid. For example, for $a_{\max} = 5 \cdot 10^5$ m/sec^2, which corresponds to an amplitude of -30 MPa in the rarefaction wave, $k_0 = 10^{-10}$, $R_0 = 1$ μsec, and $t_* = 10$ μsec, the wave amplitude in the cavitating liquid decreases by a factor of 20 at time $t = t_*$, and in a one-phase medium, it decreases only by a factor of e. According to the expression for the limiting amplitudes, if the front steepness of the rarefaction wave is 1 μsec and the applied amplitude is -30 MPa, the cavitating liquid allows only -3 MPa for the following negligibly small parameters of the initial gas content: $k_0 = 10^{-11}$ and $R_0 = 0.5$ μm.

SHOCK-WAVE PROCESSES IN ELASTOPLASTIC, BRITTLE, AND COMPOSITE MATERIALS

Shock Waves in Porous Materials. Multiphase media include not only systems with liquid matrices. Much fundamental research has been devoted to wave process in porous media, which are an elastoplastic material with a large number of small spherical pores. The propagation of shock waves in such systems with stress concentration in the vicinity of pores and filling of the pores is a complex physicomechanical process. Averaging over the volume, which gives the average porosity, is most frequently used in constructing numerical models for this process. The averaged shear and bulk moduli are functions of porosity, and the averaged yield point of a porous material is a function of porosity and pressure. It is assumed that, in the elastic region, the behavior of a continuous material obeys Hooke's law, which relates the average stresses σ_{ij} and the average strains ε_{ij} via the average shear and bulk moduli, and in the plastic region, it is described by the Prandtl–Reis model.

The stress–strain state of materials is markedly affected by the presence of pores. At some pressure, plastic zones occur in the vicinity of pores, and the deformation becomes elastoplastic. The consideration of plastic deformations performed by Kiselev, Fomin, Ruev, and Trunev [109–113] showed that both the shear and bulk moduli depend not only on the porosity m_1, but also on the pressure p. At some critical pressure $p_* = (2/3)Y_s \ln(1/m_1)$, the shear modulus and the yield point Y vanish.

Using this model, Kiselev and Fomin [114–117] studied the propagation of elastoplastic shock waves in porous metals. It was established that, as in bubble media, the presence of pores leads to a considerable decrease in wave amplitude and velocity and, finally, to decay of shock waves. The calculation results agree satisfactorily with experiments for porosity lower than 0.4 for both strong ($p_{\text{sh}} \gg Y_s$) and weak ($p_{\text{sh}} \approx Y_s$) shock waves. A rarefaction shock wave in an inert porous material was predicted theoretically and studied in [118, 119]. It turned out that the formation of the rarefaction shock wave is associated with the occurrence of microstresses in the vicinity of pores. At the critical pressure, these microstresses transform the material to a plastic state, and the yield point vanishes. At pressures higher than the critical pressures, the mechanical properties of a porous body are similar to those of a liquid (the stress tensor is spherical), and at lower pressures, they are similar to those of a solid body. If tensile stresses are applied to a porous body, then, after intersection of the critical point, the speed of sound increases jumpwise, the characteristics of one family intersect, and a rarefaction shock wave arises. In the vicinity of the critical point, $\langle \partial^2 V / \partial \sigma_1^2 \rangle < 0$, and, therefore, the rarefaction shock wave is evolutionarily stable, and the entropy increases with intersection of the wave front by the material. Here V is the specific volume, and σ_1 is the main stress-tensor component directed along the wave propagation.

Explosive Compaction. The occurrence of a "cold" particle layer upon explosive compaction of a powder in the scheme with a central body, discovered by Wilkins, Nesterenko et al., was explained by Kiselev et al. [109, 110] using the method of shock adiabats. Kostyukov showed experimentally that this effect is associated with the presence of a "deformation nodule" on the central body, which produces a weak shock wave. The latter overtakes the strong wave resulting from detonation of the explosive. Using this shock-wave pattern and shock adiabats, Kiselev and Fomin [120] showed that, near the central body, compaction of the powder (filling of pores) occurs in the weak shock wave, and far from the central body, it occurs in the weak wave. In this case, the heat evolved is proportional to the pressure in the corresponding waves.

Panin, Kostyukov, Bondar', et al. [121] studied the behavior of powdered titanium mononickelide for various types of loading and showed that, in contrast to static compaction, the large number of lattice defects upon explosive compaction activates subsequent sintering. When pressings are sintered after static loading, they undergo the reverse transformation, and the shape-memory effect and loosening are observed. Kostyukov [122] was the first to perform, using pulsed x-rays, direct experimental observations of the flow structure under shock loading of two-component mixtures of light and heavy ("opaque," impurity) solid particles with a size of about 1 mm. Velocity nonequilibrium between the mixture components was found, which can be preserved over the total loading time if the interparticle forces are small. In powerful shock waves, when the loading energy exceeds a certain value $E_* = c(T_{\rm mel} - T_0) + H_{\rm mel}$, the material of the main component enters a liquid state, and the interparticle interaction is primarily determined by the viscous-friction force. Here c is the specific heat of the material, T_0 is the initial temperature, and $T_{\rm mel}$ and $H_{\rm mel}$ are the temperature and latent heat of melting at the shock-loading pressure.

Kostyukov [123], using a simplified description of the adiabats of double compression and a nontraditional approach to the problem of regular reflection, calculated approximate critical parameters of shock-wave reflection in condensed media. Kostyukov and Sagdiev [124] performed a comparison of the calculated and experimental critical parameters of shock-wave reflection in powder composite materials (a mixture of powders of titanium carbide and nickelide and Nichrome with boron nitride). It was noted that, in the case of stratified mixtures, the applicability of the calculation for the estimation of the critical parameters depends to a large extent on the inertial nature of stratification (which can be ignored at the branching point) and on the supersonic character of the flow behind the front of the reflected wave (perturbations do not affect the reflection regime).

Zagarin, Kuz'min, and Yakovlev [125] studied the loading of a porous material by a detonation wave incident normally on a flat surface adjacent to a powder or a fibrous material with randomly arranged fibers. They showed that surface melting of the material can lead to the formation of a strong bond between the matrix and the fibers. The thermocouple method was used in this work.

Nesterenko et al. [126] studied the magnetic properties of explosively compacted specimens of powdered Mn–Al–C alloy and showed that explosive compaction increases the coercive force by more than a factor of 3 (to $3.2 \cdot 10^5$ A/m) and decreases the residual induction. The anisotropy of the magnetic properties along the detonation direction and in the radial direction was noted.

Compaction of powder materials under two-dimensional explosive loading leads to the occurrence of zones of structural inhomogeneities located near the interfaces between the mixture and the deformable obstacle. The study of this effect requires the use of a complex approach that combines a structure analysis of the preserved specimen, direct experimental observations, and numerical calculations. Within the framework of this problem, Kostyukov [127] studied possible flow patterns occurring in powders upon inclined reflection of shock waves from the surface of a monolithic obstacle. It is noted that a "deformation nodule" can appear on the surface of the obstacle, and this leads to the pulsed action of the obstacle on the powder. It has been found that a shock wave can interact with the boundary pressed zone of the powder instead of the obstacle. Furthermore, the effect of the powder dispersity on the structural features of the compacts near the obstacle and the deformation regimes of spherical particles have been studied.

Kostyukov and Yakovlev [128] studied the structure of the local flow zone in powder materials behind the shock-wave front in the vicinity of impurity particles. It was found that stagnation zones arise at loading energies $E \geqslant 5 \cdot 10^2$ J/g and "deformation nodules" occur in the surface regions beneath the stagnation zones.

An analysis of the flow of powder materials in the region of shock-wave branching using the foil procedure and metallographic study showed the existence of a transient zone in the form of a viscous trace at the boundary between the high- and low-velocity flows (Kostyukov, Kuz'min, and Shatalin [129]). Comparison of the calculated and experimental data showed that the effective viscosity of a shock-compressed copper powder with a particle size ⩽60 μm is ≈0.01 $m^2 \cdot sec^{-1}$.

Collision Problem. Explosive Loading of Shells. Kiselev and Fomin [130] solved the problem of recoil of a porous cylinder from a rigid obstacle [130]. It was shown that filling of pores occurs in the region of contact of the impactor with the obstacle, and the remaining part of the impactor deforms elastically. In this case, the time of contact of porous and continuous impactors are close.

Gulidov, Kovenya, and Shabalin [131–135] developed a mathematical model and a numerical method of solution for problems of collision of solid bodies in two- and three-dimensional cases with allowance for failure and fragmentation. The numerical method is based on a difference scheme for equations of motion that include, along with the traditional notation, the reactive-force vector. This allows one to realize, in each time step, a two-stage homogeneous computation algorithm on regular difference grids both inside the calculation domain and at the boundaries. A symmetrical algorithm was developed to calculate contact boundaries [136], and the failed material was modeled by discrete elements [134, 135]. The proposed algorithm made it possible to solve the problem of penetration of a target in the form of an assembly of contacting plates by a tin impactor. It was shown that such an assembly surpasses the monolithic equivalent in ballistic strength, and they both surpass a packet of separated plates. In a similar problem of impact of a composite bullet with a steel core on a steel target of finite thickness, it was shown that monolithic targets show higher strength [134, 135].

In studies of oblique impact of elongated bodies on a target for a three-dimensional case, the vector of the instantaneous angular velocity relative to the center of mass of the impactor is an informative parameter (Gulidov, Sapozhnikov, and Fomin [137, 138]). In the problem of oblique impact of short rods, three stages are distinguished [137, 138]: the initial contact, recoil of the rod and flight with rotation, and subsequent contact of the rear end with the target. The behavior of long rods is shown to be of a more complex character: substantial bending of the rods is observed. In penetration of thin targets by a cylindrical impactor, the time dependence of the angular velocity allows one to reveal the tendency to normalization for the impactor in the case of initial deflection of its axis from the normal to the target [137, 138].

The studies of Deribas, Gulidov, Zlobin, et al. [139] on the effect of material strength on the formation of a cumulative jet by explosive welding showed that at a fixed angle of attack of the plate, the occurrence of a jet is possible only beginning with a certain impact velocity.

The problem of acceleration of a shell under explosive loading is studied in [121, 140] with allowance for shell failure and escape of detonation products. It was shown that, for a loading coefficient (the ratio of the mass of the explosive to the mass of the shell) of the order of unity, allowing for these effect leads to a 20–25% decrease in velocity.

Explosive Fracture of Brittle Media. Sher and Chernikov, using the zone approach in analysis of the deformation of materials near explosive charges, developed calculation schemes for describing the destructive effect of the explosion of concentrated [141–143] and cylindrical charges in brittle rocks [144] with allowance for the effect of dilatancy, dry friction in the grinding zone, and brittle development of the zone of radial cracks [141]. The latter is a new element in the theory developed. Quasi-static estimates of the average size of fragments as a function of the distance to the charge, properties of the rock and the explosive, and deformation dynamics were obtained [142, 143].

The calculations of explosive fracture performed by Martynyuk, Sher, and Basheev [145, 146] over a wide range of parameters of the medium and explosive made it possible to order the parameters by the degree of their effect on the fracture intensity. A calculation model for explosion of a cylindrical charge in a brittle medium was developed which takes into account the dynamics of the grinding zone, escape of detonation products from the bore, and external pressure. The effect of the biaxial field of rock pressure on the development of zones of radial cracks in explosion of cord charges in brittle media has been studied theoretically. The shape of fracture zones for various ratios of the main stresses of the external field of pressures was determined.

Efimov, Martynyuk, and Sher [147, 148] developed an experimental procedure of determining the crack strength of brittle media by wedging a compact specimen in dynamic tests. A computational procedure for crack paths in fracture of brittle media as a result of explosion, impact, and hydraulic rupture was developed.

Alekseeva, Martynyuk, and Sher solved a new class of problems of a hydraulic-rupture crack near a free surface [149, 150]. Paths of cracks emerging during wedging of a brittle medium near a wedge were calculated for the first time by Martynyuk, Sher, and Efimov [151]. These calculations are essential for the optimal design of percussion mechanisms of rock-blasting mining machines.

MIXED PROBLEMS

Ishutkin, Kuz'min, and Pai [152] studied the influence of nonstationary electromagnetic effects on the feasibility and reliability of temperature measurements by the thermocouple method under conditions of pulsed deformation. Shielding of the central region of a thermocouple by the edge zone was discovered, and the copper temperature at pressures from 15 to 39 GPa was measured.

Teslenko, Zhukov, and Mitrofanov [153] established experimentally the possibility of generation of multizone discharge in an electrolyte. Teslenko [154] studied experimentally the wave-field structure in the focus zone of an electromagnetic generator for the radiation intensity that allows one to separate in time the energy adsorption and the energy release processes. The occurrence of a cavitation zone at the radiator axis as a result of interaction of rarefaction waves was noted.

Gilev [155, 156] studied the electrical properties of porous materials under shock-wave loading. He showed that the conductivity of a finely dispersed aluminum powder is much lower than that of continuous aluminum and depends on the shock-wave pressure. This is explained by melting and partial evaporation. In experiments with a highly porous nickel sponge, the strength of the specimen changed by a factor of 20–30 under shock loading. The change was found to occur primarily at the end of the compression stage. Zhdan [157] performed a numerical analysis of shock-wave processes in gas–liquid foams using a closed one-velocity pressure-equilibrium mathematical model ignoring phase transitions: the problem of explosion of a spherical explosive charge in a relaxing foam was solved.

Cumulation problems have been investigated in a number of papers [158–160]. An approximate calculation procedure for the parameters of gas cumulative jets occurring in the explosion of tubular charges was proposed by Chistyakov [158]. The reverse procedure of "reconstructing" a cumulative jet from its penetration characteristics within the framework of the chosen models of motion of jet elements was proposed by Kinelovskii and Maevskii [159], who showed that the effective values of the dynamic strengths of targets are somewhat higher for the penetration of a cumulative jet than for a monolithic impactor. Kinelovskii [160], using the concept of elasto-inelastic interactions adapted to the collision of liquid bodies and jets, showed that the model of an ideal incompressible liquid corresponds to the limiting variant of inelastic interaction (which is characterized by the absence of heat losses). He obtained solutions for the problem of asymmetrical collisions of free jets of an ideal incompressible liquid and for the problem of collisions of jets moving along the wedge walls.

Pai, Kuz'min, and Yakovlev [161] proposed an approximate calculation scheme for loading parameters of powder materials for the case of strong shock waves where compaction reaches the monolith stage. Dependences of the loading pressure and kinematic parameters on the time of propagation of a shock wave in a material are obtained. The physical features of nonlinear phenomena occurring upon pulsed action on materials were considered with allowance for their internal structure in the monograph of Nesterenko [162].

Among the papers on the mechanics of multiphase media published in the last decade, the monograph of Nigmatullin [163] deserves attention. He proposed a wide spectrum of formulations and models, which were then developed at the Institute of Multiphase Systems (Tyumen') using new methods of theoretical analysis and experiments in the field of the dynamics of multiphase media and also in the mechanics and thermal physics of oil and gas beds (see the Results of the Research at the Institute of Multiphase Media of the Siberian Division of the Russian Academy of Sciences for 1989–1995).

Nigmatullin, Gubaidullin, Shagapov, Khabeev et al. [164–171] performed a series of studies on the wave dynamics of bubble liquids. They designed new complicated models for the dynamics of an individual bubble and a bubble medium as a whole that take into account the compressibility and viscosity of the carrier phase, the complex composition of the system, and loading conditions. Furthermore, the propagation and evolution of shock and detonation waves have been studied, and new physical effects have been discovered. Among the latter are the dynamics of a spherical bubble in a closed volume of an incompressible liquid with rigid walls, which can execute spherical symmetrical motions. The solution of this problem for a slightly compressible liquid, which was formulated as early as the 1940s, showed that periodic vibrations of the wall with time increase the amplitude of bubble oscillations. A method of ultrastrong compression of a gas bubble in a liquid by aperiodic action of a pressure field of moderate amplitude on the liquid was proposed.

Numerical simulations of nonstationary shock waves in Newtonian and non-Newtonian viscous liquids with gas bubbles showed that these liquids have fundamentally different wave structures at equal initial viscosity: the first is monotonic and the second is of an oscillation character,

The anomalous strengthening of shock waves in bentonite suspensions, polymer solutions, and viscous liquids observed in experiments on vertical shock tubes have been studied. This effect involves the occurrence of a jump in pressure at the leading edge of the pressure-jump wave, whose amplitude can manifoldly exceed the main perturbation. It is assumed that the strengthening mechanism is determined by the presence of "entrapped" gas bubbles that initially enter the suspension in the preparation stage. The number of these bubbles increases from shock to shock due to the gas penetrating from the high-pressure chamber when the diaphragm is open. A physical model for this phenomenon is proposed which assumes the existence of a gradient distribution of bubbles over the suspension depth. This idea was realized in a mathematical formulation using various simulation schemes for bubble-liquid dynamics. The determining parameters of this problem are the intensity of the incident wave, the initial pressure in the medium, the extent of the layer, the distribution of the volume concentration in the layer, and the bubble size.

Damping of explosion waves in liquids by bubble shields located ahead of obstacles has been studied. The dependence of the degree of wave damping on the number of factors has been investigated. It has been shown that controlling the parameters of the bubble shield (the properties of the gas, the bubble size, the gas distribution in the direction of wave propagation, and the shield thickness), one can attain manifold weakening of the action of underwater-explosion waves on obstacles.

Gumerov, Gubaidullin, and Ivandaev [173–175] studied systematically the main features of the propagation of monochromatic and pulsed waves in polydisperse vapor–gas–droplet mixtures with allowance for stationary and nonequilibrium effects of interphase interaction. Among the new physical results, the anomalously nonmonotonic dependence of sound dissipation on the droplet concentration should be mentioned. The paradoxical crisis of decay is due to the fact that, in certain ranges of drop concentrations and perturbation frequencies, the damping coefficient decreases with increase in the concentration of droplets, which are the main cause of wave dissipation.

Kutushev, Rodionov, Rudakov Ivandaev, et al. [176–184] developed a theory of shock-wave flows in rarefied inert and reacting dispersed systems. In particular, a mathematical model for motion of a reacting polydisperse collisional suspension of a monofuel in a gas with a continuous particle-size spectrum was designed. Shock initiation of spherical, cylindrical, and plane waves of heterogeneous detonation has been studied. Dependences of the lower concentration limits on the initial particle size for detonation of suspensions of a monofuel in gases were established. A nonmonotonic dependence of the minimum Mach number of the initiating shock wave on the fuel concentration in the mixture was obtained. Numerical analysis showed that a layer of inert particles can extinguish combustion and detonation in gas suspensions of a monofuel. Studies of the dynamics of wave discharge of a compressed burning gas mixture in a gas space has shown that the pressure behind the shock-wave front can exceed the diaphragm-rupture pressure in a shock tube.

Nigmatullin, Gubaidullin, and Kuchugurina [185–189] developed a theory for the propagation of linear and nonlinear waves in saturated porous media. The behavior of one-dimensional longitudinal and transverse waves with plane, cylindrical, and spherical symmetries has been studied. Passage of waves from a liquid or a gas to a saturated porous media and the dynamic action of air shock waves on a target covered with a porous layer has been investigated. Transient processes have been analyzed with variation in the wave shape and the determining parameters of the medium (porosity, grain material and size, intensity of interphase interaction, deformation characteristics of the structure, etc.). It has been established that in a medium with double porosity, one transverse and three longitudinal waves propagate. In this case, the occurrence of the third longitudinal wave is explained by the difference in velocity and pressure between the pore systems.

The author is grateful to N. A. Pribaturin, E. N. Sher, S. P. Kiselev, V. M. Fomin, A. A. Gubaidullin, and S. V. Stebnovskii for providing materials. The assistance of L. D. Vakulenko in the preparation of this paper is acknowledged.

This work was supported by the Russian Foundation for Fundamental Research (Grant Nos. 96-02-19369 and 96-01-01772).

REFERENCES

1. V. K. Kedrinskii, "Hydrodynamics of explosions," *Prikl. Mekh. Tekh. Fiz.*, **28**, No. 4, 23–48 (1987).
2. A. V. Pinaev and A. I. Sychev, "Effects of gas and liquid properties on detonation-wave parameters in liquid–bubble systems," *Fiz. Goreniya Vzryva*, **23**, No. 6, 76–83 (1987).
3. A. I. Sychev, "Detonation waves in multicomponent bubbly media," *Fiz. Goreniya Vzryva*, **29**, No. 1, 110–117 (1993).
4. A. I. Sychev, "Detonation waves in one- and multicomponent bubbly media," *Dokl. Ross. Akad. Nauk*, **334**, No. 65, 586–588 (1994).
5. A. I. Sychev, "Energy limits for the existence of detonation waves in bubbly media," *Fiz. Goreniya Vzryva*, **30**, No. 1, 86–91 (1994).
6. A. I. Sychev, "Structure of bubble-detonation waves," *Fiz. Goreniya Vzryva*, **30**, No. 4, 119–124 (1994).
7. A. I. Sychev, "The effect of bubble size on the detonation wave characteristics," *Fiz. Goreniya Vzryva*, **31**, No. 5, 83–91 (1995).
8. V. Yu. Liapidevskii, "On the velocity of bubble detonation," *Fiz. Goreniya Vzryva*, **26**, No. 4, 138–140 (1990).
9. V. Yu. Liapidevskii, "Bubble detonation in a channel with elastic walls," *Fiz. Goreniya Vzryva*, **31**, No. 3, 146–149 (1995).
10. A. V. Trotsyuk and P. A. Fomin, "Model of bubble detonation," *Fiz. Goreniya Vzryva*, **28**, No. 4, 129–136 (1992).
11. V. K. Kedrinskii and Ch. L. Mader, "Accidental detonation in bubble liquids," in: Proc. 16th Int. Symp. on Shock Tubes and Waves (Aachen, FRG, July 26–31, 1987), pp. 371–376.
12. Ch. L. Mader, "Numerical modeling of detonation," in: *Los Alamos Ser. in Basic and Applied Sci.*, Univ. of California Press (1979).
13. V. K. Kedrinskii, "Propagation of disturbances in liquid with gas bubbles," *Prikl. Mekh. Tekh. Fiz.*, **9**, No. 4, 29–34 (1968).
14. V. K. Kedrinskii and Ch. L. Mader, "On the velocity of bubble detonation," in: Proc. 13th Int. Symp. on Nonlinear Acoustics (Bergen, Norway, June 28–July 2, 1993), pp. 442–447.
15. A. I. Sychev and A. V. Pinaev, "Self-sustaining deformation in liquids with bubbles of explosive gas," *Prikl. Mekh. Tekh. Fiz.*, **27**, No. 1, 133–138 (1986).
16. V. Sh. Shagapov and N. K. Vakhitova, "Waves in a bubble liquid in the presence of chemical reactions in the gas phase," in: Proc. the 11th Int. Symp. on Nonlinear Acoustics (Novosibirsk, Aug. 24–28 1987), pp. 56–58.
17. V. Kedrinskii and F. Zamaraev, "Wave amplification in chemically active bubble media," in: Proc. 17th Int. Symp. on Shock Tubes and Waves (Bethlehem, USA, July 17–21, 1989), pp. 51–62.
18. F. N. Zamaraev, V. K. Kedrinskii, and Ch. Mader, "Waves in a chemically active bubbled medium," *Prikl. Mekh. Tekh. Fiz.*, **90**, No. 2, 20–26 (1990).
19. A. S. Besov, V. K. Kedrinskii, E. I. Pal'chikov, et al. "Microinhomogeneity structures and hysteresis effects in cavitating liquid," in: Proc. 14th Int. Congress on Acoustics (Beijing, China, Sept. 3–10, 1992).

20. A. S. Besov, V. K. Kedrinskii, I. Matsumoto, et al., "Structure of cavitating nuclei and anomalous properties of water," *Dynamics of Continuous Media* (Collected scientific papers) [in Russian], Institute of Hydrodynamics, Novosibirsk, **104** (1992), pp. 16–28.
21. V. K. Kedrinskii, V. A. Vshivkov, and G. I. Dudnikova, "Interaction of waves in chemically active bubble media," in: *IV Zababakhin Lectures, Proc. Int. Conf.*, Snezhinsk (1995), pp. 140–151.
22. R. Barbone et al., "Explosive boiling of a depressurized volatile liquid," *Proc. IUTAM Symp. on Waves in Liquid-Gas and Liquid-Vapor Two-Phase Systems* (Kyoto, May 9–13, 1994), Kluwer Acad. Publ., pp. 315–324.
23. V. K. Kedrinskii, V. A. Vshivkov, G. I. Dudnikova, and Yu. I. Shokin, "Interaction of waves in chemically active bubble media," *Dokl. Ross. Akad. Nauk*, **349**, No. 2, 185–188 (1996).
24. V. E. Dontsov, V. V. Kuznetsov, and V. E. Nakoryakov, "Propagation of compression waves in a porous fluid-saturated medium," *Prikl. Mekh. Tekh. Fiz.*, **29**, No. 1, 120–130 (1988).
25. V. E. Dontsov, V. V. Kuznetsov, and V. E. Nakoryakov, "Pressure waves in a porous media saturated with a liquid with gas bubbles," *Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza*, No. 4, 85–92 (1987).
26. V. E. Nakoryakov, V. V. Kuznetsov, and V. E. Dontsov, "Pressure waves in saturated porous media," *Int. J. Multiphase Flow*, **15**, No. 6, 857–875 (1989).
27. V. E. Nakoryakov, V. V. Kuznetsov, and V. E. Dontsov, "Pressure waves in porous media," in: Proc. 11th Int. Symp. on Nonlinear Acoustics, Novosibirsk (1987), pp. 108–112.
28. V. E. Dontsov, "Structure and dynamics of finite-amplitude pressure perturbations in a porous medium saturated with a liquid containing gas bubbles," *Izv. Ross. Akad. Nauk, Mekh. Zhidk. Gaza*, No. 1, 80–83 (1992).
29. V. E. Dontsov and V. A. Maslov, "Structure and dynamics of the slow pressure wave in a porous medium saturated with a liquid containing gas bubbles," *Prikl. Mekh. Tekh. Fiz.*, **35**, No. 1, 95–98 (1994).
30. V. E. Nakoryakov and V. E. Dontsov, "Finite amplitude pressure waves in nonlinear elastic porous media saturated with a liquid containing gas bubbles," *Dokl. Ross. Akad. Nauk*, **322**, No. 3, 481–483 (1992).
31. V. E. Dontsov, V. E Nakoryakov, and B. G. Pokusaev, "Propagation of pressure waves in a gas-saturated porous medium," *Akust. Zh.*, **40**, No. 4, 683–685 (1994).
32. V. E. Nakoryakov, V. E. Dontsov, and B. G. Pokusaev, "The propagation of pressure waves in liquid with solid particles and gas bubbles," *Russ. J. Eng. Thermophys.*, **4**, No. 2, 173–188 (1994).
33. V. E. Nakoryakov, V. E. Dontsov, and B. G. Pokusaev, "Pressure waves in liquid suspension with solid particles and gas bubbles," in: Proc. 2nd Int. Conf. Multiphase Flow, Kyoto, Japan (1995), pp. PH2-11–PH2-17.
34. V. E. Dontsov, V. E. Nakoryakov, and B. G. Pokusaev, "Pressure waves in liquid suspension with solid particles and gas bubbles," *Prikl. Mekh. Tekh. Fiz.*, **36**, No. 1, 32–40 (1995).
35. V. E. Nakoryakov, V. E. Dontsov, and B. G. Pokusaev, "Pressure waves in liquid suspension with solid particles and gas bubbles," *Int. J. Multiphase Flow*, **22**, No. 3, 417–429 (1996).
36. V. G. Gasenko, V. E. Dontsov, and V. V. Kuznetsov, and V. E. Nakoryakov, "Oscillating solitary waves in a liquid with gas bubbles," *Izv. Sib. Otdel. Akad. Nauk SSSR, Ser. Tekh. Nauk*, **6**, No. 21, 43–45 (1987).
37. V. E. Dontsov, V. V. Kuznetsov, P. G. Markov, and V. E. Nakoryakov, "Evolution of pressure waves of moderate intensity in a liquid with gas bubbles," *Akust. Zh.*, **33**, No. 6, 1041–1044 (1987).
38. V. E. Dontsov, V. V. Kuznetsov, P. G. Markov, and V. E. Nakoryakov, "Propagation of pressure waves in a liquid with gas bubbles of two different sizez," *Akust. Zh.*, **35**, No. 1, 157–159 (1989).
39. V. E. Nakoryakov, V. V. Kuznetsov, V. E. Dontsov, and P. G. Markov, "Pressure waves of moderate intensity in liquid with gas bubbles," *Int. J. Multiphase Flow.*, **16**, No. 5, 741–749 (1990).
40. V. E. Nakoryakov, V. E. Dontsov, and P. G. Markov, "Moderate pressure waves in a liquid with gas bubbles," *Russ. J. Eng. Thermophys.*, **1**, No. 1, 291–305 (1991).

41. V. E. Nakoryakov, V. E. Dontsov, and P. G. Markov, "Investigation of the behavior of gas bubbles in pressure waves of moderate intensity," *Dokl. Akad. Nauk SSSR*, **309**, No. 4, 818–820 (1989).
42. V. E. Dontsov and P. G. Markov, "Investigation of the breakup of gas bubbles and its effect on the structure of moderate-intensity solitary pressure waves in a liquid with gas bubbles," *Prikl. Mekh. Tekh. Fiz.*, **32**, No. 1, 45–49 (1991).
43. V. E. Nakoryakov and V. E. Dontsov, "Pressure waves interaction in a liquid with gas bubbles and bubble fragmentation," in: *Proc. Int. Symp. Two-Phase Flow Modeling and Experimentation*, Vol. 2, Rome, Italy (1995), pp. 951–958.
44. V. E. Nakoryakov, V. E. Dontsov, and P. G. Markov, "Interaction of moderate pressure waves in a liquid with gas bubbles," *Dokl. Akad. Nauk SSSR*, **313**, No. 5, 1074–1077 (1990).
45. V. E. Dontsov and P. G. Markov, "Experimental study of the interaction of pressure waves of moderate intensity in a liquid with gas bubbles," *Prikl. Mekh. Tekh. Fiz.*, **32**, No. 5, 83–87 (1991).
46. V. E. Dontsov and V. E. Nakoryakov, "Reflection of pressure waves at the interface between a liquid and a three-phase medium," *Russ. J. Eng. Thermophys.*, **5**, No. 3, 237–248 (1995).
47. V. E. Dontsov, V. E. Nakoryakov, and B. G. Pokusaev, "Reflection of pressure waves at the interface between a liquid and a three-phase medium," *Akust. Zh.*, No. 6, 783–789 (1996).
48. V. E. Nakoryakov, B. G. Pokusaev, S. I. Lezhnin, and N. A. Pribaturin, "Shock waves structure and their propagation in two-phase slug flow," in: *Proc. 16th Int. Symp. on Shock Tubes and Waves* (Aachen, FRG, July 26–31, 1987), Aachen (1987), pp. 305–309.
49. V. E. Nakoryakov, B. G. Pokusaev, S. I. Lezhnin, and N. A. Pribaturin, "Wave pressures in two-phase slug flow boiling media," in: *Proc. 11th Int. Symp. on Nonlinear Acoustics* (Novosibirsk, Aug. 24-28, 1987), Part 1, pp. 103–107.
50. S. I. Lezhnin, I. I. Mullyadzhanov, V. E. Nakoryakov, et al., "The evolution of weakly linear perturbations in a slug formed of an air-water mixture," *Prikl. Mekh. Tekh. Fiz.*, **30**, No. 6, 91–98 (1989).
51. V. E. Nakoryakov, B. G. Pokusaev, N. A. Pribaturin, et al., "Nonstationary wave processes in boiling media," in: *Adiabatic Waves in Liquid–Vapor Systems, Proc. IUTAM Symp.* (Gottingen, Germany, Aug. 28–Sept. 1, 1989), Springer-Verlag, Berlin (1990), pp. 381–391.
52. B. G. Pokusaev, S. I. Lezhnin, and N. A. Pribaturin, "Waves in gas–liquid medium of slug structure," *Russ. J. Eng. Thermophys.*, **1**, No 4, 259–290 (1991).
53. S. P. Aktershev and S. I. Lezhnin, "Waves in a nonuniform bubble medium with a low void fraction," *Russ. J. Eng. Thermophys.*, **2**, No. 3, 213–230 (1992).
54. S. I. Lezhnin and S. P. Aktershev, "Dynamics of a vapor slug in a channel," *Teplofiz. Aeromekh.*, **1**, No. 2, 97–110 (1994).
55. V. E. Nakoryakov, N. A. Pribaturin, S. I. Lezhnin, and B. G. Pokusaev, "Behavior of a vapor–liquid medium under nonstationary dynamic conditions," in: *Proc. 10th Int. Heat Transfer Conf.*, Vol. 3, Brighton (1994), pp. 389–393.
56. S. I. Lezhnin and B. S. Zhakupov, "Evolution of pressure waves in vapor–liquid media of slug structure during phase transitions," *Teplofiz. Aeromekh.*, **2**, No. 2, 133–144 (1995).
57. S. I. Lezhnin and B. S. Zhakupov, "Damage and collapse of a vapor slug under dynamic loading," *Teplofiz. Aeromekh.*, **2**, No. 3, 271–280 (1995).
58. B. G. Pokusaev, S. I. Lezhnin, N. A. Pribaturin, et al., "Modeling the dynamics of formation and development of a vapor void in channels under loading," in: *Thermophys. Aspects of Safety, Proc. Int Conf.* [in Russian], Vol. 2, Obninsk (1995), pp. 31–41.
59. S. I. Lezhnin, "Growth of vapor voids in channels under dynamic loading," *Teplofiz. Aeromekh.*, **3**, No. 2, 181–190 (1996).
60. B. G. Pokusaev, S. I. Lezhnin, and N. A. Pribaturin, "Wave pressures in vapor–liquid media with different internal structures," in: *Heat-and-Mass Exchange*: Abstracts 3rd Int. Conf. (Minsk, May 20–24, 1996), Vol. 4, Part 1 (1996), pp. 190–193.

61. V. E. Nakoryakov, B. G. Pokusaev, I. R. Shreiber, and N. A. Pribaturin, "The wave dynamics of a vapor–liquid medium," *Int. J. Multiphase Flow*, **14**, No. 6. 655–677 (1988).
62. B. G. Pokusaev, E. S. Vasserman, I. I. Mullyadzhanov, and N. A. Pribaturin, "Collapse and breakup of bubbles during propagation of pressure waves in a two-phase medium," in: *Unsteady Processes in Two-Phase Flows* (Collected scientific papers) [in Russian], Inst. of Thermal Phys., Novosibirsk (1989), pp. 3–27.
63. B. G. Pokusaev, N. A. Pribaturin, and E. S. Vasserman, "Dynamics of shock-wave propagation in a bubble vapor–liquid medium," in: *Problems of Hydrodynamics and Heat Exchange in Atomic Power Engineering*: Materials Int. School-Seminar, Inst. Heat- and Mass Transfer, Belarus Acad. of Sci., Minsk (1989), pp. 36–44.
64. V. E. Nakoryakov, E. S. Vasserman, B. G Pokusaev, and N. A. Pribaturin, "Increase in shock-wave amplitude in a vapor–liquid bubble medium," *Teplofiz. Vys. Temp.*, **32**, No. 3, 411–417 (1994).
65. B. G. Pokusaev and N. A. Pribaturin, "Dynamics of shock wave propagation and interphase process in liquid–vapor media," in: Proc. 7th Int. Meeting on Nuclear Reactor Thermal-Hydraulics "NURETH-7," USA (1995), pp. 45–55.
66. V. E. Nakoryakov, B. G. Pokusaev, N. A. Pribaturin, and I. I. Mullyadzhanov, "Interaction between a shock wave and a gas slug," in: *AIP Conf. Current Topic in Shock Waves*, New York (1990), pp. 915–920.
67. V. E. Nakoryakov, B. G. Pokusaev, N. A. Pribaturin, and I. I. Mullyadzhanov, "Interaction between a shock wave and a gas slug," *Dokl. Akad. Nauk SSSR*, **311**, No. 4, 826–830 (1990).
68. B. G. Pokusaev and N. A. Pribaturin, "Influence of perturbation pressure on the slug flow stability," in: *Multiphase Flow'91*: Proc. Int. Conf., Vol. 2, Tsukuba (1991), pp. 199–202.
69. V. E. Nakoryakov, B. G. Pokusaev, and N. A. Pribaturin, "Interphase heat transfer in nonstationary vapor–liquid flows," *Heat Transfer*, **5**, 317–322 (1990).
70. B. G. Pokusaev, N. A. Pribaturin, Z. S. Mesarkishvili, and O. Yu. Schetinsky, "Condensation study in a vertical slug regime," *Russ. J. Eng. Thermophys.*, **1**, No. 4, 333–357 (1991).
71. B. G. Pokusaev, N. A. Pribaturin, and E. S. Vasserman, "Increase in amplitude of shock waves of moderate intensity in a vapor–liquid medium. Feature of slug flow," in: *Dynamics of Continuous Media* (Collected scientific papers) [in Russian], Novosibirsk, **100** (1991), pp. 176–185.
72. B. G. Pokusaev, N. A. Pribaturin, and E. S. Vasserman, "Moderate shock wave propagation in vapor–liquid slug flow," in: *Proc. 18th Int. Symp. on SWST*, Vol. 1, Sendai, Japan (1991), pp. 62–65.
73. N. A. Pribaturin, "Amplification of shock waves and failure of vapor- and gas–liquid media," Doct. Dissertation in Tech. Sci., Novosibirsk (1994).
74. S. V. Stebnovskii and N. N. Chernobaev, "Effect of the dynamics of loading of a fluid volume on the mechanism of its failure," *Prikl. Mekh. Tekh. Fiz.*, **28**, No. 5, 134–138 (1987).
75. S. V. Stebnovskii, "Mechanism of pulsed breakdown of a liquid volume," *Prikl. Mekh. Tekh. Fiz.*, **30**, No. 2, 126–132 (1989).
76. V. K. Kedrinskii, A. R. Berngardt, and N. N. Chernobaev, "Behavior of a liquid under dynamic loading," in: *Proc. IUTAM Symp. on Waves in Liquid-Gas and Liquid-Vapor Two-Phase Systems*, Kluwer Acad. Publ., Dordrecht (1995), pp. 429–438.
77. V. K. Kedrinskii, "Hydrodynamic shock tubes and their applications," in: *Proc. 18th Int. Symp. on Shock Waves*, Vol. 2, Sendai, Japan (1991), pp. 1039–1044.
78. V. K. Kedrinskii, "Nonlinear problems of cavitation failure of liquids under explosive loading (review)," *Prikl. Mekh. Tekh. Fiz.*, **34**, No. 3, 74–91 (1993).
79. V. K. Kedrinskii, "Liquid fracture at explosive loading," in: *Proc. 19th Int. Symp. on Shock Waves*, Vol. 3, Marseilles (1995), pp. 233–238.
80. A. R. Berngardt, V. K. Kedrinskii, and E. I. Pal'chikov, "Evolution of the internal structure of a liquid destruction zone under impulsive loading," *Prikl. Mekh. Tekh. Fiz.*, **36**, No. 2, 99–105 (1995).

81. S. V. Stebnovskii, "Shear elasticity of liquids containing bubbles," *Fiz. Goreniya Vzryva*, **26**, No. 3, 127–128 (1990).
82. S. V. Stebnovskii, "Instability of bubble structures in a liquid medium," in: *Dynamics of Continuous Media* (Collected scientific papers) [in Russian], Novosibirsk, **100** (1991), pp. 192–201.
83. V. K. Kedrinskii and N. N. Chernobaev, "One-dimensional projection of a liquid shell by an explosive charge," *Prikl. Mekh. Tekh. Fiz.*, **33**, No. 6, 90–96 (1992).
84. V. K. Kedrinskii, "Bubbly cavitation in intense rarefaction waves and its effects (plenary lecture)," in: Proc. 20th Int. Symp. on Shock Waves, Pasadena (1995).
85. V. K. Kedrinskii, "A role of cavitation effects in mechanisms of destruction and explosive processes," *J. Shock Waves*, **7**, No. 2, 63–76 (1997).
86. V. K. Kedrinskii, "Role of bubbly cavitation in mechanisms of fracture," in: Abstr. 19th Int. Congress on Theor. and Appl. Mechanics, Kyoto, Japan, Aug. 25–31, 1996.
87. V. K. Kedrinskii, A. S. Besov, and I. É. Gutnik, "Inversion of a two-phase fluid under dynamic loading," *Dokl. Ross. Akad. Nauk*, **352**, No. 4, 477–479 (1997).
88. S. V. Stebnovskii, "Behavior of suspensions under dynamic loading," *Prikl. Mekh. Tekh. Fiz.*, **35**, No. 5, 68–77 (1994).
89. S. V. Stebnovskii, "On building a rheological model of cavitating dispersed liquid media," *Prikl. Mekh. Tekh. Fiz.*, **37**, No. 1, 129–138 (1996).
90. S. V. Stebnovskii, "A rheological model of volume extension of Newtonian liquids," *Prikl. Mekh. Tekh. Fiz.*, **39**, No. 1 (1998).
91. S. V. Stebnovskii "Axisymmetrical explosive loading of cylindrical liquid volumes," in: *Dynamics of Continuous Media* (Collected scientific papers) [in Russian], Novosibirsk, **99** (1990), pp. 110–116.
92. S. V. Stebnovskii, "Dynamics of formation of parameters of a gas–droplet flow under explosive dispersion of a liquid volume," in: *Dynamics of Continuous Media* (Collected scientific papers) [in Russian], Novosibirsk, **104** (1992), pp. 40–75.
93. S. V. Stebnovskii, "Particle-size analysis of gas–droplet systems formed under explosive fracture of liquid volumes," *ibid.*, pp. 76–95.
94. I. G. Gets and V. K. Kedrinskii, "Dynamics of explosive loading for a finite volume of a dense two-phase mixture," *Prikl. Mekh. Tekh. Fiz.*, **30**, No. 2, 120–125 (1989).
95. V. K. Kedrinskii, "Propagation of disturbances in a liquid containing gas bubbles," Candidate's Dissertation in Phys.-Math. Sci., Novosibirsk (1968).
96. V. K. Kedrinskii, "Shock waves in a liquid containing gas bubbles," *Fiz. Goreniya Vzryva*, **16**, No. 5, 14–15 (1980).
97. O. G. Derzho and N. V. Malykh, "Formation of strong pressure pulses reflected from water–bubble layers," *Archive Mech.*, **42**, Nos. 4 and 5, 463–473 (1990).
98. N. V. Malykh, "Wave form of short shock waves reflected from bubble layers in water," *J. Phys. IV, Colloque C5*, **4**, 1121–1124 (1994).
99. N. V. Malykh "'Resonance solitons' in a bubbly liquid," in: *Proc. 19th Int. Symp. on Shock Waves*, Vol. 3, Marseilles, France (1993), pp. 147–150.
100. V. K. Kedrinskii and S. I. Plaksin, "Rarefaction wave structure in a cavitating liquid," in: *Proc. 11th Int. Symp. on Nonlinear Acoustics*, Vol. 1, Novosibirsk, USSR (1987), pp. 51–55.
101. A. S. Besov and V. K. Kedrinskii, "Dynamics of bubbly clusters and free surfaces at shock wave reflection," in: Proc. IUTAM Symp. on Bubble Dynamics and Interface Phenomena (Birmingham, U.K., Sept. 6–9, 1993), pp. 93–103.
102. A. S. Besov, V. K. Kedrinskii, and E. I. Pal'chikov, "On threshold cavitation effects in pulse rarefaction waves," *Pis'ma Zh. Tekh. Fiz.*, **15**, No. 16 (1989).
103. A. S. Besov, V. K. Kedrinskii, and E. I. Pal'chikov, "On threshold cavitation effects in pulse rarefaction waves," in: *Proc. 13th Int. Congress on Acoustics* (Beograd, Yugoslavia, Aug. 26–30, 1989), Vol. 1, pp. 355–358.

104. V. K. Kedrinskii and V. A. Stepanov, "Cavitation effects in thin films," in: Proc. 12th Int. Symp. on Nonlinear Acoustics, Austin (1990), pp. 470–475.
105. V. K. Kedrinskii, "Two-phase models in problems of physical acoustics," in: *Boundary-Value Problems of Mathematical Physics* (Collection of papers) [in Russian], Naukova Dumka, Kiev (1990), pp. 94–110.
106. V. K. Kedrinskii, "Bubble cluster, cumulative jets, and cavitation erosion," *Prikl. Mekh. Tekh. Fiz.*, **37**, No. 4, 22–31 (1996).
107. V. K. Kedrinskii, "On relaxation of tensile stresses in cavitating liquids," in: *Proc. 13th Int. Congress on Acoustics* (Beograd, Yugoslavia, Aug. 26–30, 1989), Vol. 1, pp. 327–330.
108. V. K. Kedrinskii, "Hydrodynamics of explosion: experiment and models," in: Proc. IUTAM Symp. on Adiabatic Waves in Liquid–Vapor Systems (Goettingen, Aug. 28–Sept. 1, 1989), pp. 395–405.
109. S. P. Kiselev, G. A. Ruev, A. P. Trunev, et al., *Shock-Wave Processes in Two-Component and Two-Phase Media* [in Russian], Nauka, Novosibirsk (1992).
110. S. P. Kiselev, "An elastoplastic model of deformation of a porous material," in: *Filtration of Multiphase Systems* [in Russian], Inst. of Theor. and Appl. Mech., Novosibirsk (1991).
111. S. P. Kiselev,"Shock-wave processes in an elastoplastic porous medium," in: Abstracts of 8th All-Union Conf. on Theoretical and Applied Mechanics, Moscow (1991).
112. S. P. Kiselev and V. M. Fomin, "Model of a porous material considering the plastic zone near the pore," *Prikl. Mekh. Tekh. Fiz.*, **34**, No. 6, 125–133 (1993).
113. S. P. Kiselev and V. M. Fomin, "Modeling of shock-wave processes in elastoplastic porous media," in: *Simulation in Mechanics* (Collected scientific papers) [in Russian], Comp. Center–Inst. of Theor. and Appl. Mech., Sib. Div., Acad. of Sci. of the USSR, **5**, No. 3 (1991), pp. 40–75.
114. V. M. Fomin and S. P. Kiselev, "Shock wave processes in porous elastoplastic materials," in: *Shock Waves, Proceedings*, Vol. 1, Sendai, Japan (1991).
115. S. P. Kiselev and V. M. Fomin, "Shock wave processes in porous elastoplastic materials," in: *Problems of Protection of the Earth from Collision with Hazardous Cosmic Objects* (SPE-94): Abstracts of Int. Conf., Part 2, Snezhinsk (1994).
116. S. P. Kiselev, "Numerical modeling of propagation of elastoplastic waves in a porous material," Preprint No. 6-94, Inst. of Theor. and Appl. Mech., Russ. Acad of Sci., Novosibirsk (1994).
117. S. P. Kiselev, "On propagation of a shock wave in a porous material upon collision of plates," *Fiz. Goreniya Vzryva*, **31**, No. 4, 79–83 (1995).
118. S. P. Kiselev and V. M. Fomin, "A rarefaction shock wave in a porous material," *Dokl. Ross. Akad. Nauk*, **341**, No. 5, 630–631 (1995).
119. S. P. Kiselev and V. M. Fomin, "A rarefaction shock wave in a porous material," *Prikl. Mekh. Tekh. Fiz.*, **37**, No. 1, 28–35 (1996).
120. S. P. Kiselev and V. M. Fomin, "On the problem of formation of cold particle layer upon explosive compaction of powders, in: *Simulation in Mechanics* (Collected scientific papers) [in Russian], Comp. Center–Inst. of Theor. and Appl. Mech., Sib. Div., Acad. of Sci. of the USSR, **4**, No. 6 (1990) pp. 49–53.
121. V. E. Panin, M. P. Bondar', N. A. Kostyukov, et al., "Dynamic compaction of titanium mononickelide," *Izv. Vyssh. Uchebn. Zaved., Fiz.*, **30**, No. 9, 35–39 (1987).
122. N. A. Kostyukov, "Structure of a flow of binary mixtures of solid particles under conditions of two-dimensional shock-wave loading," *Prikl. Mekh. Tekh. Fiz.*, **29**, No. 3, 54–58 (1988).
123. N. A. Kostyukov, "Approximate calculation of the critical parameters of shock-wave reflection in condensed media," *Fiz. Goreniya Vzryva*, **24**, No. 1, 72–75 (1988).
124. N. A. Kostyukov and F. A. Sagdiev, "Determination of critical SW reflection parameters in powder composite materials," *Fiz. Goreniya Vzryva*, **25**, No. 1, 82–88 (1989).
125. Yu. V. Zagarin, G. E. Kuz'min, and I. V. Yakovlev, "Measurement of pressure and temperature with shock loading for porous composite materials," *Fiz. Goreniya Vzryva*, **25**, No. 2, 129–133 (1989).

126. A. A. Vertman, O. G. Epanchintsev, Yu. I. Zvezdin, et al., "Preparation of high coercivity materials of the system Mn–Al–C by explosive compaction," *Fiz. Goreniya Vzryva*, **25**, No. 6, 120–124 (1989).
127. N. A. Kostyukov, "Physical causes and mechanisms of the formation of boundary regions in the two-dimensional explosive compaction of powder materials," *Prikl. Mekh. Tekh. Fiz.*, **32**, No. 6, 154–161 (1991).
128. N. A. Kostyukov and I. V. Yakovlev, "Powder material flow near impurity inclusions under shock loading" *Fiz. Goreniya Vzryva*, 28, No. 2, 109–111 (1992).
129. N. A. Kostyukov, G E. Kuz'min, and V. M. Shatalin, "Powder material flow in the shock wave branching region," *Fiz. Goreniya Vzryva*, **30**, No. 5, 118–122 (1994).
130. S. P. Kiselev, V. M. Fomin, and Yu. A. Shitov, "Numerical modeling of the recoil of a porous cylinder from a rigid obstacle," *Prikl. Mekh. Tekh. Fiz.*, **31**, No. 3, 100–104 (1990).
131. A. I. Gulidov and I. I. Shabalin, "Numerical modeling algorithm for supercritical fracture upon collision of plates, in: *Simulation in Mechanics* (Collected scientific papers) [in Russian], Comp. Center–Inst. of Theor. and Appl. Mech., Sib. Div., Acad. of Sci. of the USSR, No. 4 (1990).
132. A. I. Gulidov, "Implementing computation processes and structure of data in numerical solution of dynamical problems of the mechanics of continuous media," in: *Simulation in Mechanics* (Collected scientific papers) [in Russian], Comp. Center–Inst. of Theor. and Appl. Mech., Sib. Div., Acad. of Sci. of the USSR, **5**, No. 3 (1991), pp. 127–141.
133. A. M. Gladyshev, A. I. Gulidov, V. M. Kovenya, et al., "Explosive acceleration, aerodynamics, and impact of a solid body. Numerical experiment," in: *Simulation in Mechanics* (Collected scientific papers) [in Russian], Comp. Center–Inst. of Theor. and Appl. Mech., Sib. Div., Acad. of Sci. of the USSR, No. 2 (1991), pp. 7–19.
134. A. I. Gulidov and I. I. Shabalin, "The method of free elements. Application to the solution of problems of fracture of elastoplastic bodies during collision," Preprint No. 9-94, Inst. of Theor. and Appl. Mech., Sib. Div., Russ. Acad. of Sci. (1994).
135. A. I. Gulidov and I. I. Shabalin, "The method of free elements for the solution of problems of high-velocity interaction of bodies," in: IV Zababakhin Lectures, Abstracts of Int. Conf., Snezhinsk, Oct. 16–20, 1995.
136. A. I. Gulidov and I. I. Shabalin, "Calculation of contact boundaries with allowance for friction in the dynamic interaction of deformable bodies, in: *Numerical Solution of Elastic and Plastic Problems*, Materials of 9th All-Union Conf., Novosibirsk (1988).
137. A. I. Gulidov, G. A. Sapoznikov, and V. M. Fomin, "Numerical solutions of collisions of high-speed bodies," in: *Proc. 2nd Japan–Soviet Union Joint Symp. on Computational Fluid Dynamics*, Vol. 1, Tsukuba, Aug. 27–31, 1990.
138. A. I. Gulidov, "Numerical simulation of high-velocity impact for a three-dimensional case," *Lavrent'ev Readings on Mathematics, Mechanics, and Physics*: Abstracts of 4th Int. Conf. (Kazan', Russia, 3–7 July, 1995) [in Russian], Inst. of Hydrodynamics, Novosibirsk (1995).
139. A. A. Deribas, A. I. Gulidov, B. S. Zlobin, et al., "On the oblique collisions of the metallic plates at extreme conditions," in: Proc. 13th Int. Conf. on High Pressure Science and Technology, Bangalor, India, Oct. 7–11, 1991.
140. S. P. Kiselev and V. M. Fomin, "Accelerations of a shell under the action of detonation products with allowance for air counter pressure," in: *Physical Gas-Dynamics of Reacting Media* [in Russian], Nauka, Novosibirsk (1990).
141. E. N. Sher, "Dynamic development of a radial crack zone during a camouflet explosion," *Prikl. Mekh. Tekh. Fiz.*, **29**, No. 1, 164–167 (1988).
142. A. G. Chernikov and E. N. Sher, "A quasi-static model for a camouflet explosion of a concentrated charge in a mass and in an individual block," *Fiz. Tekh. Probl. Razrab. Polezn. Iskop.*, No. 4 (1990).
143. E. N. Sher, "Dynamics of development of a grinding zone in an elastoplastic medium during a camouflet explosion," *Fiz. Tekh. Probl. Razrab. Polezn. Iskop.*, No. 5 (1996).

144. E. N. Sher, "Taking into account the dynamics in description of fracture of brittle media by an explosion of a cord charge," *Prikl. Mekh. Tekh. Fiz.*, **38**, No. 3, 174-183 (1997).
145. G. V. Basheev, P. A. Martynyuk, and E. N. Sher, "Effect of the direction and magnitude of an external stress field on the trajectory of a star-shaped system of cracks," *Prikl. Mekh. Tekh. Fiz.*, **35**, No. 5, 147–159 (1994).
146. P. A. Martynyuk and E. N. Sher, "Effect of the biaxial field of rock pressure on the shape of the fractured zone for an explosion of a cord charge in a brittle media," *Prikl. Mekh. Tekh. Fiz.*, **39**, No. 1 (1998).
147. V. P. Efimov and E. N. Sher, "Calculation of rigid wedging parameters for a specimen with a cut," *Fiz. Tekh. Probl. Razrab. Polezn. Iskop.*, No. 1 (1989).
148. V. P. Efimov, P. A. Martynyuk, and E. N. Sher, "Consideration of the effect of vertical forces during wedging," *Fiz. Tekh. Probl. Razrab. Polezn. Iskop.*, No. 3 (1992).
149. T. A. Alekseeva and P. A. Martynyuk, "Paths of crack emergence on a free surface," *Fiz. Tekh. Probl. Razrab. Polezn. Iskop.*, No. 2 (1991).
150. P. A. Martynyuk and E. N. Sher, "Crack propagation near an annulus with allowance for the external field of compressing stresses," *Fiz. Tekh. Probl. Razrab. Polezn. Iskop.*, No. 6 (1996).
151. V. P. Efimov, P. A. Martynyuk, and E. N. Sher, "Emergence paths of cracks on a free surface during wedging," *Prikl. Mekh. Tekh. Fiz.*, **36**, No. 6, 142–152 (1995).
152. S. N. Ishutkin, G. E. Kuz'min, and V. V. Pai, "Thermocouple measurement of metal temperature under pulsed deformation conditions," *Prikl. Mekh. Tekh. Fiz.*, **32**, No. 1, 137–143 (1991).
153. V. S. Teslenko, A. I. Zhukov, and V. V. Mitrofanov, "Multizone electric-arc discharge in a liquid," *Pis'ma Zh. Tekh. Fiz.*, **21**, No. 18, 20–26 (1995).
154. V. S. Teslenko, "Shock-acoustic breakdown in a liquid. Kinetics of induced acoustic dissipation during shock-wave focusing," *Pis'ma Zh. Tekh. Fiz.*, **20**, No. 5, 51–56 (1994).
155. S. D. Gilev, "Electrical conductivity of highly porous aluminum under shock-wave loading," in: *Dynamics of Continuous Media* (Collected scientific papers) [in Russian], Novosibirsk, **99** (1990), pp. 105–109.
156. S. D. Gilev, "Electrical conductivity of a highly porous nickel sponge in a shock wave," *Zh. Tekh. Fiz.*, **65**, No. 6, 84–93 (1995).
157. S. A. Zhdan, "Numerical modeling of the explosion of a high explosive charge in foam," *Fiz. Goreniya Vzryva*, **26**, No. 2, 103–110 (1990).
158. V. P. Chistyakov, "Calculation of gas cumulative jet parameters," in: *Dynamics of Continuous Media* (Collected scientific papers) [in Russian], Novosibirsk, **80** (1987), pp. 139–148.
159. S. A. Kinelovskii and K. K. Maevskii, "Penetration of a strong barrier by a shaped-charge jet," *Prikl. Mekh. Tekh. Fiz.*, **30**, No. 2, 150–156 (1989).
160. S. A. Kinelovskii, "Concept of elastic–inelastic interactions of jet flows and collision of jets of an ideal incompressible liquid," *Fiz. Goreniya Vzryva*, **30**, No. 3, 75–86 (1994).
161. V. V. Pai, G. E. Kuz'min, and I. V. Yakovlev, "Approximate evolution of loading parameters in composite materials with strong shock waves," *Fiz. Goreniya Vzryva*, **31**, No. 3, 134–138 (1995).
162. V. F. Nesterenko, *Pulsed Loading of Heterogeneous Materials* [in Russian], Nauka, Novosibirsk (1992).
163. R. I. Nigmatulin, *Dynamics of Multiphase Media*, Vols. 1 and 2, Hemisphere, New York (1991).
164. A. A. Gubaidullin and R. K. Gazizov, "Amplification of shock waves in a bubble liquid with a gas-concentration gradient," *Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza*, No. 1 49–54 (1988).
165. R. I. Nigmatulin, V. Sh. Shagapov, and N. K. Vakhitova, "Manifestations of the compressibility of a carrier phase during shock-wave propagation in a bubble medium," *Dokl. Akad. Nauk SSSR*, **304**, No. 5, 1077–1081 (1989).
166. R. I. Nigmatulin, V. Sh. Shagapov, and N. S. Khabeev, "Anomalous effects of composition in the acoustics of boiling solutions," *Dokl. Akad. Nauk SSSR*, **304**, No. 6, 1323–1328 (1989).
167. V. Sh. Shagapov and N. K. Vakhitova, "Waves in a bubble system in the presence of gas-phase chemical reactions," *Fiz. Goreniya Vzryva*, **25**, No. 6, 14–22 (1989).

168. A. A. Gubaidullin, "The peculiarity of nonlinear wave evolution in bubbly liquids," in: *Physical Acoustics: Fundamentals and Applications*, Plenum Press, New York–London (1991), pp. 347–351.
169. A. A. Gubaidullin, "Shock wave phenomena in bubbly liquids," in: *Proc. 2nd Int. Conf. on Multiphase Flow*, Vol. 1, Kyoto, Japan (1995), pp. PH2 and PH3–PH8.
170. R. I. Nigmatulin, V. Sh. Shagapov, and N. K. Vakhitova, and R. Leikhi, "A method of ultrastrong compression of a gas bubble in a liquid by the aperiodic action of a moderate-amplitude pressure wave on the liquid," *Dokl. Ross. Akad. Nauk*, **341**, No. 1, 37–41 (1995).
171. R. I. Nigmatulin, I. Sh. Akhatov, and N. K. Vakhitova, "Liquid compressibility in the dynamics of a bubble medium," *Dokl. Ross. Akad. Nauk*, **348**, No. 6, 768–771 (1996).
172. R. I. Nigmatulin, A. A. Gubaidullin, A. T. Akhmetov, et al., "Experimental and theoretical modeling of the effect of anomalous amplification of shock waves in highly viscous liquids," *Dokl. Ross. Akad. Nauk*, **346**, No. 1, 46–50 (1996).
173. N. A. Gumerov, "Long waves of finite amplitude in polydispersed gas suspensions," *Prikl. Mekh. Tekh. Fiz.*, **31**, No. 4, 157–161 (1990).
174. D. A. Gubaidullin and A. I. Ivandaev, "Dynamics of low-amplitude pulse waves in vapor–gas–droplet systems," *Prikl. Mekh. Tekh. Fiz.*, **32**, No. 2, 108–113 (1991).
175. N. A. Gumerov, "Weakly linear oscillations of the radius of a vapor bubble in an acoustic field," *Prikl. Mat. Mekh.*, **55**, No. 2, 256–263 (1991).
176. B. S. Kruglikov and A. G. Kutushev, "Attenuation of air shock waves by layers of dusty gas and lattices," *Prikl. Mekh. Tekh. Fiz.*, **29**, No. 1, 51–57 (1988).
177. A. G. Kutushev and U. A. Nazarov, "Numerical modeling of nonstationary shock waves in vapor–gas–droplet mixtures," *Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza*, No. 4, 67–75 (1992).
178. A. G. Kutushev and S. V. Rodionov, "Propagation of shock waves in polydisperse gas suspensions," *Prikl. Mekh. Tekh. Fiz.*, **34**, No. 2, 24–31 (1993).
179. A. G. Kutushev and D. A. Rudakov, "Numerical study of the action of a shock wave on an obstacle screened by a layer of a porous powder material," *Prikl. Mekh. Tekh. Fiz.*, **34**, No. 5, 25–31 (1993).
180. A. I. Ivandaev, A. G. Kutushev, and S. P. Rodionov, "Explosive generation of heterogeneous detonation waves in aerocolloids of a unitary fuel," *Fiz. Goreniya Vzryva*, **31**, No. 3, 83–91 (1995).
181. A. I. Ivandaev, A. G. Kutushev, and D. A. Rudakov, "Numerical investigation of throwing of a powder layer by a compressed gas," *Fiz. Goreniya Vzryva*, **31**, No. 4, 63–70 (1995).
182. A. G. Kutushev and O. N. Pichugin, "Influence of the spatial nonuniformity of particle distribution in a screening layer on the suppression of a detonation wave in a monofuel–air suspension," *Fiz. Goreniya Vzryva*, **32**, No. 4, 107–109 (1996).
183. A. G. Kutushev and S. P. Rodionov, "Numerical study of shock initiation threshold of detonation burning in a monofuel gas suspension," *ibid.*, pp. 110–112.
184. A. G. Kutushev and O. N. Pichugin, "Mathematical modeling of dispersion of a compressed burning monofuel gas suspension in a shock tube," *Fiz. Goreniya Vzryva*, **32**, No. 1, 85–95 (1996).
185. A. A. Gubaidullin and R. I. Nigmatulin, "Linear waves in saturated porous media," *Transp. Porous Media*, **9**, Nos. 1 and 2, 135–142 (1992).
186. A. A. Gubaidullin and S. F. Urmancheev, "Compression waves in gas-saturated porous media," in: *Proc. 1st Russian National Conf. on Heat Exchange* [in Russian], Vol. 7, Moscow (1994), pp. 71–77.
187. A. A. Gubaidullin and O. Yu. Kuchugurina, "Spherical and cylindrical linear waves in liquid-saturated porous media," *Teplofiz. Vys. Temp.*, **33**, No. 1, 108–115 (1995).
188. A. A. Gubaidullin and O. Yu. Kuchugurina, "One-dimensional linear waves with axial and central symmetries in saturated porous media," *Transp. Porous Media*, **22**, No. 1, 73–90 (1996).