V. K. Kedrinskii

Hydrodynamics of Explosion

Experiments and Models

Springer

Valery K. Kedrinskii

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Translated by Svetlana Yu. Knyazeva
With 175 Figures

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Dedicated to the memory of Academician M.A. Lavrentiev

Preface

In the past century, much progress has been made in the hydrodynamics of explosion, the science dealing with liquid flows under shock-wave loading. This area is concerned primarily with studying underwater and underground explosions, cumulation, and the behavior of metals under the action of the detonation products of high explosives (HE), which produce extreme conditions such as pressures of hundreds of kilobars and temperatures up to several thousand degrees.

This book presents research results of underwater explosions. Included are a detailed analysis of the structure and parameters of the wave fields generated by explosions of cored and spiral charges, a description of the formation mechanisms for a wide range of cumulative flows at underwater explosions near the free surface, and the relevant mathematical models. Shock-wave transformation in bubbly liquids, shock-wave amplification due to collision and focusing, and the formation of bubble detonation waves in reactive bubbly liquids are studied in detail. Particular emphasis is placed on the investigation of wave processes in cavitating liquids, which incorporates the concepts of the strength of real liquids containing natural microinhomogeneities, the relaxation of tensile stress, and the cavitation fracture of a liquid as the inversion of its two-phase state under impulsive (explosive) loading. The problems are classed among essentially nonlinear processes that occur under shock loading of liquid and multiphase media and may be of interest to researchers of physical acoustics, the mechanics of multiphase media, shock-wave processes in condensed media, explosive hydroacoustics, and cumulation.

Obviously, the formulation and solution of problems is often initiated under the influence of our teachers and colleagues. First of all I would like to mention my teachers, Prof. R.I. Soloukhin and Prof. M.A. Lavrentiev. The author is indebted to Prof. L.V. Ovsyannikov for his attention and continuous interest in some problems described in the monograph. The contacts and discussions with my colleagues and friends, Profs. V.M. Titov, V.E. Nakoryakov, R.I. Nigmatullin, E.I. Shemyakin, B.D. Khristoforov, Yu.A. Trishin, Kazujoshi Takayama, Leen van Wijngaarden, Charles Mader, Werner Lauterborn, Brad Sturtevant, David Blackstock, David Crighton, and many others, were very encouraging. Many results were obtained together with researchers in my laboratory: Drs. S.V. Stebnovsky, A.R. Berngardt, A.S. Besov, N.N. Chernobaev, M.N. Davydov, I.G. Gets, V.T. Kuzavov, E.I. Pal'chikov, S.V. Plaksin,

and S.P. Taratuta. Recent results obtained in cooperation with Profs. N.F. Morozov, Yu.I. Shokin, Drs. V.A. Vshivkov, G.I. Dudnikova, and G.G. Lazareva are also included in the book. I am grateful to Profs. V.P. Korobeinikov, B.D. Khristoforov, Fumio Higashino, Leif Bjorno, Leen Wijngaarden, Yoichiro Matsumoto, and David Blackstock for valuable comments and recommendations for publication of the English version of the monograph. For this purpose the Russian version of the monograph was considerably reworked and extended.

I would like to express my cordial thanks to Dr. S.Yu. Knyazeva for the high-quality translation of the book. I am also thankful to Dr. M.N. Davydov for technical assistance in the preparation of the camera-ready copy.

The English version of the monograph is based on the 2000 Russian edition, which has been revised and supplemented at the suggestion of the series' editorial board.

Novosibirsk,
February 2005

V.K. Kedrinskii

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Introduction

In the past century, much progress has been made in the hydrodynamics of explosion, the science dealing with liquid flows under shock-wave loading. This area is concerned primarily with studying underwater and underground explosions, cumulation, and the behavior of metals under the action of detonation products of high explosives (HE), which produce such extreme conditions as pressures of hundreds of kilobars and temperatures of up to several thousand degrees. Under these conditions, many solid media "forget" about their strength properties and rigid crystal structure and follow the classical laws of hydrodynamics.

A representative example is a shaped charge, i.e., a solid cylinder of HE that has a conical cavity (apex inside) at one end. If the surface of this cavity is lined with a metal layer (liner), the charge gains powerful armor-breaking capabilities. This idea was first patented in 1914. In the 1940s, the shaped-charge theory was developed independently by Birkhoff et al. and by Lavrentiev based on a hydrodynamic model assuming that material properties change radically under high pulse loads. According to this concept, the metal liner behaves as an ideal incompressible fluid, behind the detonation wave initiated at the charge end opposite to the cone, and incident on the cone from its apex.

Under the action of the detonation products, the liner collapses to the axis and the liner walls collide. This results in a jet flow moving in the direction of detonation-wave propagation at a velocity u_{jet} of about 10 km/s. The shaped-charge theory is based on the model of collision of free liquid jets, which is practically identical to that used in penetration theory. The theory suggests that the impact of a shaped-charge jet on armor generates a pressure $p \approx 10^3$ kbar in the deceleration region. This estimate is readily obtained from the formula $p \simeq \rho_{\text{met}} \cdot u_{\text{jet}} \cdot c_{\text{met}}$, if the density of the metal ρ_{met}, the speed of sound in it c_{met}, and the jet velocity u_{jet} are known. Jet penetration into a target is described by the model of jet interaction using reverse velocities. Comparison of results obtained using this model and experimental data confirms the "hydrodynamic origin" of these phenomena.

It is known that hydrodynamic cumulation also arises from hypervelocity (few kilometers per second) impact on a metal specimen with a hollow cavity on the rear surface. It results from the interaction of a plane shock wave generated by an impinging jet in the specimen with the free surface of the cavity, whose points are imparted different initial velocities.

Similar but low-velocity flows are observed in a liquid when its gravity plays a major role, e.g., the fall of a rain drop on a water surface or the impact of a water-filled test tube falling vertically on a table (experiment of G.I. Pokrovsky). In the first case, a hemispherical cumulative cavity on the surface is produced by penetration and spread of the drop. In the second case, the cavity as a meniscus occurs initially due to the capillary effect and wetting. Upon impact the liquid in the test tube "instantaneously" becomes heavy, which leads to cumulative flow in the cavity with jet formation, as in the case with a drop.

These physical effects can be treated as models for the formation of cumulative flows in large-scale underwater explosions. When charge weights are in excess of hundreds of kilograms and typical dimensions of a cavity with explosion products are up to tens or hundreds of meters, the gravity of the liquid can no longer be ignored: the pressure gradient between the upper and lower points of the explosive cavity, which is of the order of $\rho_{\text{liq}} g R$ (ρ_{liq} is the liquid density), becomes comparable with hydrostatic pressure.

Usually, the behavior of various media under explosive loading is studied in the so-called impulsive state. The medium is originally considered as an ideal incompressible liquid, and its flow is considered using the potential: $\mathbf{v} = \nabla\varphi$. Then, using the law of conservation of momentum,

$$\rho_0 \frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\nabla p \,,$$

and replacing v by φ, one can easily obtain

$$\nabla\left(\frac{\mathrm{d}\varphi}{\mathrm{d}t} + \frac{p}{\rho_0}\right) = 0$$

and

$$\varphi = -\rho_0^{-1} \int\limits_0^{\tau} p \,\mathrm{d}t \,,$$

where the integral defines the value of the potential on the boundary of the domain under study, τ specifies the duration of explosive loading, and, in essence, determines the initial distribution of φ. This parameter is calculated from the speed of sound in detonation products and from the geometrical characteristics of the HE charge used in each particular case. Then, the Laplace equation is solved for the known domain, and the potential distribution in this domain, its gradients, and, hence, the initial distribution of mass velocities are obtained.

The above approach is general, and the model is too "ideal" to be used without restrictions on the medium strength. For shaped-charge liners, the kinetic energy of the liner elements $\rho u^2/2$ should exceed the dynamic yield point of the liner material σ. For the problems of penetration, hypervelocity impact, or a contact explosion, the situation is not so simple: the targets, as a rule, have large volumes, and the above condition is satisfied only in a very narrow zone near the contact region.

These problems can be solved using the so-called "liquid–solid" model proposed by Lavrentiev, whose idea is extremely simple: the medium is considered an ideal incompressible liquid near the charge or in the impactor contact zone (where the mass velocity is higher than a certain critical value v_*) and in the remaining region, it is treated as an absolutely rigid body. The solution of the problem on deformation of a lead column by explosion of a superimposed charge (V.K. Kedrinskii) illustrates the application of this model in dynamics with changing "phase" boundary as the particle velocity decreases (in the zone of contact with the solid body) and particle "freezing" according to the model.

Explosive magnetic cumulation (collapse of a conducting liner) is among the problems close to the hydrodynamics of explosion. An original solution of the problem of the impact on a planet surface at space velocities (50–100 km/s) was proposed by Lavrentiev late in the 1950s to determine the crater size: the energy lost by the body upon impact is converted into heat, and in the region where this thermal energy exceeds a certain critical value, the solid body is instantaneously gasified.

Finally, we consider the models that are directly concerned with real liquids. A peculiar prototype of the problems of explosion hydrodynamics is the Besant problem (late 19th century) on the flow in an empty spherical cavity, which arises instantaneously in an ideal imponderable incompressible liquid. Now it is recognized as an adequate model for an oscillation stage of the cavity with detonation products during underwater explosion. The problem can be solved using the energy conservation law: the change in the potential energy of the liquid is equal to the increment of its kinetic energy $p_0(V_0 - V) = T_{\mathrm{k}}$. Here $V = (4/3)\pi R^3$ is the current volume of the cavity and the kinetic energy is readily determined from the expression $\mathrm{d}T_{\mathrm{k}} = (v^2/2)dm$ and has the form

$$T_{\mathrm{k}} = 2\pi\rho_0 \int_R^\infty v^2 r^2 \,\mathrm{d}r \,.$$

In the case of an incompressible liquid, the continuity equation $\mathrm{d}\rho/\mathrm{d}t + \rho \operatorname{div} \mathbf{v} = 0$ reduces to $\operatorname{div} \mathbf{v} = 0$, whence for arbitrary symmetry, we have $\partial v/\partial r + \nu v/r = 0$ and $vr^\nu = f(t)$. From the condition on the boundary of a spherical cavity, $(f(t) = R^2(\mathrm{d}R/\mathrm{d}t))$. Hence,

$$T_{\mathrm{k}} = 2\pi\rho_0 R^3 \left(\frac{\mathrm{d}R}{\mathrm{d}t}\right)^2 .$$

The energy conservation law now yields

$$\left(\frac{\mathrm{d}R}{\mathrm{d}t}\right)^2 = \frac{2p_0}{3\rho_0}\left[\left(\frac{R_0}{R}\right)^3 - 1\right] .$$

It is easy to see that as $R \to 0$, the velocity of the cavity wall $\mathrm{d}R/\mathrm{d}t \to \infty$. This is a typical example of the classical spherical cumulation. We note that in this case, the kinetic energy of the liquid generally approaches its limit – the initial potential energy U_0.

An interesting model of explosion hydrodynamics is the problem of a strong point explosion. The classical model for explosion of a powerful (for example, nuclear) device ignores the dimensions of the device and assumes that all the energy is released at a point (L.I. Sedov). Here we confine ourselves to the case of an incompressible liquid with no counterpressure, i.e., we assume that as $r \to \infty$, the pressure $p \to 0$. The governing parameters of the problem are the explosion energy E_0 and the liquid density ρ_0. Combining these parameters with the independent variable t, one can define the linear dimension of the cavity R as the lower boundary of the perturbation region $R = k(E_0/\rho_0)^{1/5}t^{2/5}$. It is obvious that the flow is self-similar and the self-similarity index is $2/5$. We assume that in our problem the explosion energy is entirely converted into the kinetic energy of the liquid (the expanding cavity is empty):

$$2\pi\rho_0 R^3\left(\frac{\mathrm{d}R}{\mathrm{d}t}\right)^2 = E_0 \ .$$

Substitution of the expressions for the radius and velocity of the explosive cavity yields the coefficient $k = (25/8\pi)^{1/5}$.

It is interesting that the above-mentioned Besant problem is also self-similar in the vicinity of the flow focusing point. Furthermore, the liquid flow near the point $R \to 0$ is completely identical to the case of a strong explosion. Let us assume that $R = a\ t^{\alpha}$ in the mentioned vicinity. Substitution of this solution into the Besant equation shows that the latter is satisfied if $\alpha = 2/5$ and the coefficient a has the form $a = (25U_0/8\pi\rho_0)^{1/5}$, where U_0 is the initial potential energy.

The hydrodynamics of explosion involves plenty of interesting models, paradoxes, and unexpected analogies. What do the fracture of a ship's bottom due to underwater explosion, cavitation erosion, and disintegration of kidney stones in lithotriptor facilities have in common? To a certain extent, this is shock-wave loading. But the main feature common to all these phenomena is the impact of cumulative jets on a solid surface under cavity collapse near it.

In the 1950s, the limiting weights of explosive charges W required to damage a ship's bottom in an underwater explosion at various distances h from the ship were studied. One would expect that beginning with a contact explosion, the weight would increase with distance from the bottom. However, experiments revealed a surprising paradox: beginning with a certain distance h_*, the function $W(h)$ "enters" a rather long (within $(2\text{–}3)h_*$) horizontal ledge (M.A. Lavrentiev). Thus, the distance increased but fracture was achieved without increase in explosive weight. In addition, the nature of fracture changed: instead of cracks over a large area, the fracture zone was highly localized.

The fracture mechanism was determined by the action of the high-velocity cumulative jet formed at the second stage of an underwater explosion – the collapse of the cavity with detonation products after its first maximum expansion. The proximity of a solid boundary disrupts the one-dimensionality of the flow even if the cavity was spherical at the moment of maximum expansion. Particles on the cavity surface remote from the wall are imparted high velocities, i.e., the classical cumulative effect occurs. The jet is thus directed toward the wall and has a velocity of hundreds of meters per second.

The phenomenon of bubble cavitation in a liquid has long been known. Already in the early 20th century, it was found that bubble cavitation on rotating propeller screws was accompanied by mechanical surface damage. Numerous studies have shown that the damage mechanism is determined by shock-wave generation and the impact of the cumulative microjets produced by the collapse of minute near-surface bubbles in the cavitation zone (bubble cluster). Microstructural analysis of specimens from vibration tests and model experiments in "shock wave–bubble–specimen" systems show that during high-velocity interaction, the microjets penetrate into a specimen at a depth comparable to their length and cause appreciable local damage.

The threshold of the power of hydroacoustic systems is also associated with the development of bubble cavitation near the radiator surface.

In recent years, there have been extensive studies of shock wave focusing in liquids as applied to problems of lithotripsy (breakup of kidney stones). In particular, the mechanism of stone crushing in the focus zone was analyzed. At first glance, the cause of breaking of a stone placed at one of the foci of an ellipse is fairly obvious: the focused wave is refracted into the kidney stone, and its subsequent internal reflection from the interface with the acoustically less rigid media (liquid) results in a rarefaction wave, whose "travel" over the kidney stone leads to the stone breakup (B. Sturtevant). It is argued that the effect of an outer cloud of cavitation bubbles around a kidney stone should be taken into account in this model. Actually, the nature of the load resulting in stone crushing may appear to be much more complex.

Indeed, when analyzing the structure of a shock wave converging to a focus, it is easy to notice that because of diffraction at the edges of a semi-ellipsoid piezoelectric converter, there is a transition in the shock-wave "tail" from the positive postshock pressure to a rarefaction phase with a fairly large amplitude and long duration. Focusing of such a wave should inevitably result in the formation of a bubble cavitation zone in the focus zone (and, naturally, on the surface of the kidney stone). Considering that in practice a series of such shock loads is required for crushing, the periodic action of cavitation cloud (as a whole) on the stone can amplify the Sturtevant effect described above. The question arises of whether in this case, too, the breakup mechanism involves the high-velocity interaction of cumulative microjets (produced by cavitative bubbles in the vicinity of stone surface) with the target.

Shock-loaded liquid still remains a puzzle. And it is difficult to solve these problems by simply writing a complete system of conservation laws in the form of differential equations and closing defining relations, or by developing unique computer programs and codes. Physical models that include all main stages and features of the processes occurring in liquids must remain a key element in research. Otherwise, it would be impossible to explain the hydrodynamic properties of metals during impulsive loading or the brittle fracture of water with fragmentation into flat spall layers due to the action of strong rarefaction waves.

Concluding this short introduction we would like to note that the problems of underwater explosions described in this monograph can be conditionally divided into four groups:

- Shock waves, equations of state, and the dynamics of a cavity with detonation products (for unbounded media)
- Shock waves (transformation and amplification) in multiphase media including a reactive gas phase
- Behavior of a liquid with free boundaries during explosive loading, microinhomogeneities in the liquid and tensile stresses, and inversion of the two-phase state of the liquid and its strength property
- High-velocity jet flows at underwater explosions near the free surface and liquid flows with unknown free boundaries

The above-mentioned lines of research are primarily concerned with understanding the physics of the examined phenomena, searching for the pertinent control mechanisms, developing experimental methods, and constructing adequate mathematical models for describing fast processes and structural changes in liquids. Interest in the problems of explosion hydrodynamics considered here was motivated by the importance of the problems, the apparent illogicality of the phenomena, and the attractiveness of the models proposed by Lavrentiev, which were frequently used as the basis for constructing general concepts.

1 Equations of State, Initial and Boundary Conditions

1.1 Equations of State for Water

Various considerations on the state of continuous media during dynamic compression, shock transition, and unloading are used to solve a broad spectrum of problems on explosions underwater and to analyze the behavior of continuous media under impulsive loading. These approaches are based on certain thermodynamic models and are aimed at providing the most exact description of the state of a medium for a wide range of temperatures and pressures.

Derivation of a unique analytical relation, for example, in the form $p(T, \rho)$, in particular for water, is not a simple task due to the complex character of the dependence of thermodynamic functions, such as pressure, on density ρ, temperature T or internal energy E.

The first known attempt to describe the state of a real medium was made by Van der Waals, who considered the effects of the attraction and repulsion of molecules. Since then the interest in this subject has remained stable not only owing to the endeavor of giving a perfect empirical description of real properties of real media, but also due to the expansion of the assortment of subjects under study, from which we will be concerned with liquids (or "liquid" states) and the detonation products of explosives.

The equations of state are usually presented in one of the following forms:

- As a sum of cooling and heating components (the Mie–Gruneisen equation),

  $$p = p_c(v) + G(v) \cdot \frac{c_v T}{v\mu} ,$$

  where v is the specific volume, p_c is the cooling pressure, $G(v)$ is, c_v is the specific heat at constant volume, μ is the specific mass.
- In a form containing a certain function of entropy s

  $$p = B(s)F(v)$$

  where $B(s)$ is the entropy function, s is the entropy, and $F(v)$ is the function of the specific volume.
- In the most common virial form

  $$\frac{pv}{RT} = 1 + \frac{B(T)}{v} + \frac{C(T)}{v^2} + \frac{D(T)}{v^3} + \dots ,$$