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# SHOCK WAVES IN LIQUIDS CONTAINING GAS BUBBLES

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**Abstract**—Results of theoretical and experimental studies on shock wave propagation in boiling and nonboiling liquids with gas bubbles are reviewed. The structure of shock waves, their reflection and attenuation in two-phase gas–liquid media are considered.

## 1. INTRODUCTION

Most of the features specific to shock wave propagation in two-phase gas–liquid media are due to the fact that the bulk of the mass is concentrated in the liquid phase while the compressibility of the media is totally determined by the compressibility of the gas in bubbles. There is no doubt that various forms of two-phase media occupy an important place in the general class of continuous fluids. Two-phase systems include all media having a normal density in excess of $\rho = 1$–$1.5\,\mathrm{kg/m^3}$, as in most gases, and up to $\rho = 800$ to $1600\,\mathrm{kg/m^3}$ as in solids and continuous fluids. In this rather broad range of densities it is possible to single out bubbly liquids as well as their limiting states such as gas–liquid foams, plug train flows and flows having an annular or dispersed-annular structure, sprays. Relative densities of liquids containing bubbles may range from 1 to 0.7 of the density of a continuous fluid.

The density of a gas–liquid mixture may vary, depending on its void fraction from $10^{-2}$ of that of continuous fluid (for foams with a very high void fraction) and up to $10^{-1}$ for foams with a low void fraction. A special place among the two-phase media is occupied by those in which it is possible to vary the mass fraction of the gas component in a considerable range by passing through the system a pressure or rarefaction wave. Systems of this type are largely different from those containing insoluble or non-condensable gases (which have been the systems mostly dealt with in the research carried out to date) for which one may assume without much error that the mass fraction of gas is constant and use in calculations only the variable volume fraction of gas in liquid.

The mass and volume gas fractions are the most general parameters for any two-phase system. Other parameters that are often used in calculations are found as a rule to be applicable only to a rather narrow range of systems. A parameter which is now popular among the researchers is the distance between the adjacent gas or liquid inclusions in the gas or liquid phase respectively. In some theoretical models they make this parameter subject to limitations; for example, a requirement is imposed on the dispersed inclusion size that it be negligible by comparison with their spacing. This requirement confines that range of systems that can be treated under such assumptions to those containing a very small volume ratio of gas. Differentiation of systmes according to the spacing of the dispersed inclusions improperly breaks up into different classes those systems which otherwise have similar properties, e.g. systems containing bubbles are set apart from gas–liquid foams. The first, which has a volume concentration $\beta < 1\%$, $ld^{-1} > 10$, and the second always have $ld^{-1} \ll 1$, where $l$ and $d$ are the size and spacing of dispersed inclusions, respectively. Howbeit, foams, and bubbly systems exhibit similar dynamic behavior in certain or even most cases.

The research in this field and analysis of the practical problems involving two-phase systems both stipulate a wider utilization of such media in practical applications. The latter no doubt include the technical problems of using two-phase media as blast and shock wave energy transformers, of safety and environment protection measures involving explosion operations either in air or underwater. Other problems which relate here are those of safe service of steam or cryogenic pipelines, safety precautions in operation of laboratory and commercial equipment, and others.

## 2. PROPAGATION VELOCITY AND PRESSURE OF THE SHOCK WAVE

We will now consider the state-of-art in investigations of the propagation dynamics of medium–strong and strong shock waves in a two-phase medium. In keeping with the terminology which is currently common in the theory of shock waves in gases, the two above terms will refer to shock waves characterized by a Mach number of greater than 2. As in gas, Mach number is the ratio of shock wave velocity $D$ to the low-frequency sound speed in an unperturbed medium $a$. In a two-phase system, the term "a strong wave" should be understood to refer to waves with a pressure ratio before and behind the wavefront $P_1P_0^{-1} > 3$–$4$. Thus if the liquid contains more than 0.1% by volume of gas bubbles, a wave characterized by a pressure of $P_1 = 0.4$ MPA in front of and $P_0 = 0.1$ MPA behind the wave front must be regarded as a strong one for this medium.

We will here briefly review the recent results in the field of the dynamics of strong (as implied herein) shock waves in liquids containing gas bubbles. Historically, the first data obtained (Campbell *et al.* 1958) were concerned with wave parameters having a pressure drop of $P_1P_0^{-1} < 6$ across the wave front in bubbly systems prepared from water–glycerine solutions. The experiments were carried out in a 3 m long tube. Next, a series of works appeared (Noordzily 1973) reporting on waves with $P_1P_0^{-1} < 5$ at $p_0 < 0.1$ MPA in a 4.5 m long tube in water and water–glycerine solutions containing air or nitrogen bubbles. These data were in close agreement with the similar data obtained by a team of the Institute of Thermophysics, the Siberian Department of the U.S.S.R. Academy of Sciences (Kuznetsov *et al.* 1978). A little earlier or nearly simultaneously appeared the publications (Neshchimenko & Suvorov 1972) concerned with waves having $P_1P_0^{-1} < 2$ to 4 in tubes 100 and 273 mm in dia. and 6 m long. Little attention was paid in these works to the substantially nonlinear properties of two-phase systems and it was the structure of pressure waves which was studied most attentively. A theoretical treatment of certain of the prior results was described in a work of Nigmatulin *et al.* (1974). Strong shock waves with $P_1P_0^{-1}$ of between 3 and 50 as well as blast waves from detonation of high explosives in a two-phase medium were studied under $P_0 = 0.1$ to 1, 2.5 MPA in wroks of Gelfand *et al.* (1973, 1978). Strong shock waves in foam two-phase systems were studied by the teams of the Institute of Electric Welding of the Ukranian Branch of the U.S.S.R. Academy of Sciences and Institute of Chemical Physics of the U.S.S.R. Academy of Sciences in 1.2–4 m long tubes (Kudinov 1976, 1977, 1978). Simulated foam experiments were carried out by Japanese researchers for pressure waves with $P_1P_0^{-1} < 2$ (Mori *et al.* 1975, 1976). The same researchers used 2 m long tubes to investigate pressure wave propagation in water containing nitrogen bubbles with $P_1P_0^{-1} < 5$. The most recent experiments with waves having $P_1P_0^{-1} < 25$ were reported by Deksnis (1978). Also a short time ago was published a report of American investigations into the structure of a shock wave in a bubbly mixture carried out in a 18.5 m long tube (Padmanabhan *et al.* 1978). In all the above references the investigators dealt with long-duration shock-wave perturbations in which the positive compression phase lasted more than one millisecond. In connection with the problem of protection of water basins from the effects of blast waves, experimental data have been published recently on the dynamics of shortwave perturbations in a two-phase medium. The term "short-wave perturbations" is used herein to imply pressure waves (generated by blasts or other sources such as electrodynamic (e.g. Družining *et al.* 1978), with a gradual pressure drop behind the wavefront of less than millisecond duration.

Analysis of the literature reviewed above shows unambiguously that the research into the dynamic processes in two-phase mixtures is still very far from completion. A major portion of work has been concerned with very weak waves with $M < 2$ and $P_1P_0^{-1} < 4$ in which the nonlinear effects which will be discussed below manifest themselves too weakly. Another fact which calls attention is the variance between the small number of experimental works and the large number of theoretical models in the dyanmics of two-phase media. The majority of theoretical models have not been actually backed up by any experiments, so that it does not

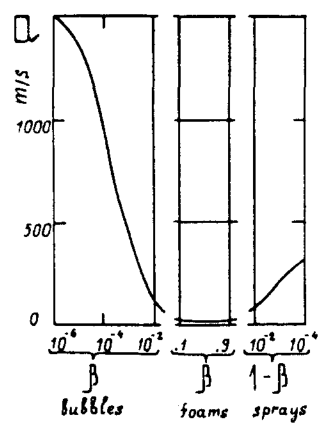

Figure 1. Relationship between equilibrium sound speed in two-phase mixtures and volume fraction of gas in liquid.

seem possible to assess the validity of the proposed models or judge about the generality of the advanced conceptions. Most of the available models are *a priori* confined to the region of very weak pressure waves—which discourages any predictions in the perturbation intensity range which is of particular practical interest.

When considering the experimental results for two-phase media one should always keep in mind that the speed of propagation of weak low-frequency perturbations (with a frequency below 50 kHz) i.e. sound speed, is lower than that in either the gas or liquid. The speed of sound varies in two-phase gas-liquid media in a manner shown in figure 1. The diagram also shows points for different mixture types. The validity of the conventional formulas for sound speed in two-phase mixtures has been verified (Gelfand *et al.* 1975) for an initial pressure of 4, 0 MPA and gas volume ratio in the liquid $\beta \approx 0.1$ to 1% using the method of determing the rarefaction wave head velocity behind the reflected shock front.

In the most-general case the speed of sound can be calculated for a low-frequency perturbation from the formula:

$$a^2 = \gamma p a_L^2 [(1-\beta)^2 \gamma p + \beta[1-\beta]\rho_L a_L^2]^{-1}$$

where $a_L$ is sound velocity in liquid, $\gamma$ is the ratio of the specific heats in gas. Very important from the point of view of various practical applications is the relationship between the shock propagation velocity and pressure drop across the wavefront. Figure 2 summarizes all the

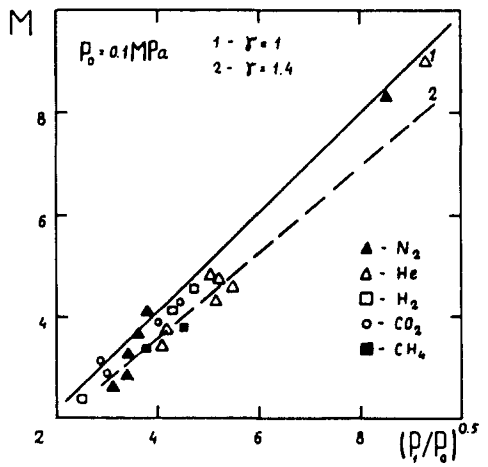

Figure 2. Relationship between pressure drop and shock wave velocity in a liquid containing gas bubbles. Curve 1—isothermal conditions; curve 2—adiabatic conditions; points: ▲$^1$—nitrogen in water; △$^2$—helium in water; □3—hydrogen in water, ○4—carbon dioxide gas in water; □5—methane in water.

available experimental results for the relation between these two values. Curves 1 and 2 refer to the isothermal and adiabatic behavior of gas bubbles compressed in shock waves. The respective analytical formulas for cases 1 and 2 are:

$$Da^{-1} = M = (p_1 p_0{}^{-1})^{0.5}$$

$$Da^{-1} = [(p_1 p_0{}^{-1} - 1)\gamma^{-1}(1 - p_0 p_1{}^{-1})^{-1/\gamma}]^{0.5}.$$

Points 1–5 in figure 2 were obtained by blowing nitrogen, helium, hydrogen, carbon dioxide gas and methane through water.

It is seen from the figure that the differences of the thermophysical properties of the gas in bubbles, which as regards density and temperature conductivity may vary within a factor of 10, has no effect on the type of the relationship $M = M(P_1 P_0{}^{-1})$ when the pressure $P_0 = 0.1$–1, 2 MPA and volume concentration of gas $\beta = 1$–20%. Representative of the nature of pressure variation in a wave traveling in a gas–water mixture are the curves of figure 3 plotted for a hydrogen–water bubbly mixture. The time scale is 600 microseconds per reading of the horizontal scale. The pressure wave is seen to have a steep enough pressure rise which is followed by intense pressure oscillations. The latter are particularly well pronounced in gases having a lower temperature conductivity coefficient and sound velocity than hydrogen or helium, as well as when the initial pressure is low ($P_0 < 0.1$ MPA). Although the analysis of these oscillations is of but secondary importance for practical purposes, it has been shown by Gelfand *et al.* (1975) that even for weak waves the oscillation period is other than that of resonance frequencies of the radial waves of solitary gas inclusions. We will now compare the experimental results of shock wave velocity in bubbly mixtures with the data for foams for the case of a two-phase medium having a 100 times smaller density. We will only note in advance that two types of waves have been found to exist in foams in both vertical and horizontal shock tubes. The pressure profiles in such waves are exemplified by the photos of figure 4. The first wave type has a clearly defined two-wave configuration. This wave type is generated in cases where the wave velocity is less than the sound velocity in the gas contained in foam cells. In figure 4(b) the gas filling water foam cells is hydrogen (sound velocity 1300 m/sec) and the wave velocity is about 700 m/sec. Foam density is 10–12 kg/m$^3$. The scale of oscilloscopic traces was 600 m/sec per division. When the wave velocity exceeded that of sound in the gas in voids, pressure waves were propagating along the tube which had a steep enough pressure rise front. In figure 4(a) the density of the two-phase system was 7 kg/m$^3$ and wave velocity 400 m/sec. In the foam cells is notrogen for which the sound velocity is 340 m/sec. The time scale of oscilloscopic traces was 600 microseconds per reading.

Figure 5 illustrates the relationship between shock velocity in foam and pressure drop across wavefront. Both qualitatively and quantitatively the relationship is similar to that existing in a bubbly two-phase structure.

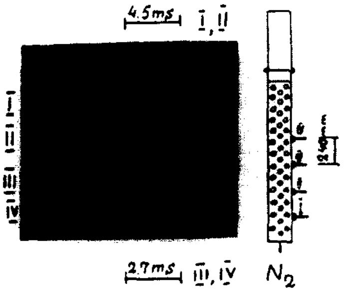

Figure 3. Oscilloscopic traces of pressure in a compression wave travelling in a liquid containing gas bubbles.

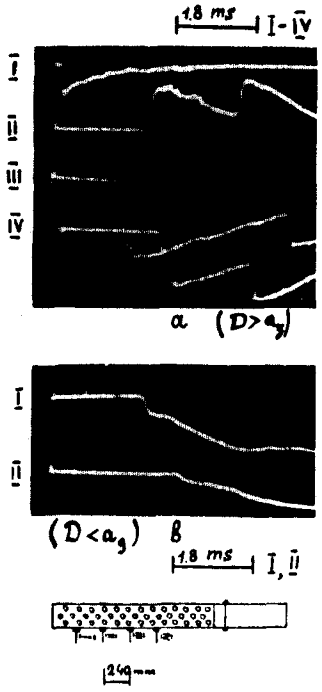

Figure 4. Oscilloscopic traces of pressure in waves travelling in foam (a) $D > a$; (b) $D < a$.

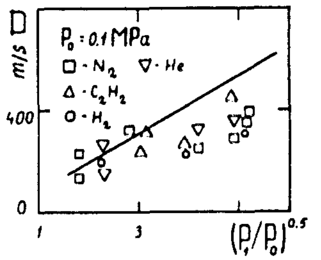

Figure 5. Pressure drop as function of shock wave velocity in foam. □, $N_2$; Δ, $C_2H_2$; O, $H_2$; ∇, He.

There are, however, some differences between wave behaviors in foams and liquids containing gas bubbles.

In foams one never observes substantial pressure fluctuations behind the shock front. Shock waves having a pressure drop $p_1p_0^{-1}$ of 25 to 30 were found to deviate from the relationship $p_1p_0^{-1} = M^2$. An increase of a pressure drop to above 25–30 results, in tube sizes realized thus far, in a saturation behavior of the function $D = f(p_1p_0^{-1})$. It was not possible to obtain experimentally shocks traveling at more than 800 m/sec in a water–air foam when the high-pressure section of the shock tube was up to 1.2 m long. The reason was the difficulty of obtaining an equilibrium of the two-phase medium in strong shock waves. Further investigations are necessary to verify the relationships for very strong shocks in foams suggested earlier. The experiments performed to date show convincingly that for most practical applications a two-phase system, such as liquid containing gas bubbles or a foam, may be considered as an imaginary isothermal gas having a density equal to that of the two-phase system in question without making any further assumptions concerning its inner structure. The relaxation times for heat transfer between phases is small due to the break-up of bubbles in shock waves. In strong shock waves the break-up results in formation of the secondary bubbles with sizes about 30 times smaller than that of the parent bubble. Treatment of a two-phase medium as an isothermal continuum when compression rates are small and as a continuous fluid when the sound has about the same velocity in the two-phase system and continuous liquid represents a simple enough model of the physical processes occurring in two-phase systems. Prior attempts to describe motion of a two-phase system with the help of the Tait equation (e.g. Družinin *et al.* 1978) necessitated evaluation of the exponent of the density ratio which is dependent upon the volume fraction of gas in liquid and appears to be unreasonably high (about $10^3$). Description of two-phase media via this type of equation hampers analysis of the behavior of the shocked two-phase medium and also fails to account for the real situation in a better way than the simple consideration of a standard shock in an equivalent gas. For this reason, we cannot regard the approach of (Druzinin *et al.* 1978) as anything more than a probing effort. Unfortunately, their effort did not crown itself with a model which would better account for the behavior of a two-phase medium than the conventional shock-wave approach.

## 3. REFLECTION OF PRESSURE WAVE IN TWO-PHASE MIXTURE

Well known in gaseous media is the phenomenon of nonacoustic reflection of shock waves at the interfaces. A feature which characterizes this phenomenon is that the ratio of pressures in the reflected and incident shocks calculated relative to the initial pressure appears to be greater than in the acoustic case where $p_2 - p_1 = 2(p_1 - p_0)$; here, $p_2$ is pressure behind the reflected shock. The same thing occurs in gas–liquid mixtures as well. Apparently the first to pay attention to the possibility of a non-acoustic behavior of shocks near a rigid wall were Campbell *et al.* (1978). Unfortunately, the imperfections of the measuring instruments did not allow this to be demonstrated unquestionably. Results of detailed investigation of pressure rise behind the reflected shocks (incident normally against a wall) are given in figure 6 based on the data reported by Gelfand *et al.* (1973, 1974, 1978). All possible cases are covered by figure 6. Curve 1 has been plotted under the isothermic assumption without allowance for water compressibility (e.g. Campbell *et al.* 1958). Curves 2–4 relate to $\beta = 5$, 3 and 1% respectively, and allow for liquid compressibility. Curve 5 represents a relationship between pressure ratios on the reflected and incident shocks in a noncompressible liquid. The points were obtained in experiments for water containing bubbles of helium, hydrogen, nitrogen, argon and methane. For ease of comparison, the relationships between the coefficient of wave pressure rise on reflection from a rigid wall, and gas concentration and initial pressure in the mixture are shown in figures 7 and 8, respectively. In figure 8 the curves 1–3 have been plotted for $p_0 = 0.1$, 0.5 and 1.0 MPA. It is clearly seen that the pressure rise in the reflected shock decreases as the gas–liquid ratio decreases, initial pressure increases and incident shock intensity increases. A reason primarily responsible for this behavior is that all these factors cause the increase of the velocity of sound in the two-phase medium behind the reflected wave

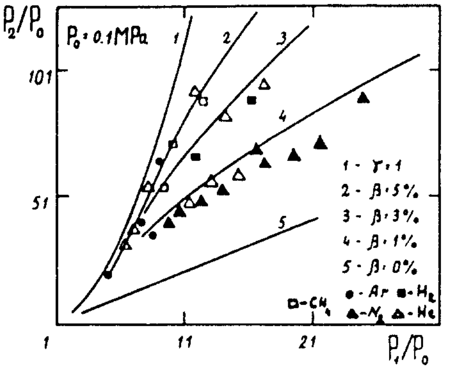

Figure 6. Pressure drop in a reflected wave as function of the incident wave parameters in a gas–liquid mixture. Curve 1—isothermal conditions; curve 2—$\beta = 5\%$; curve 3—$\beta = 3\%$; curve 4—$\beta = 1\%$; curve 5—incompressible liquid. ▲, $N_2$; △, He; □, $H_2$; ●, Ar; □, $CH_4$.

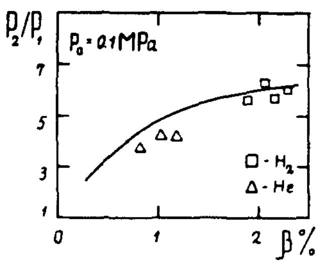

Figure 7. Reflected wave parameters as function of volume fraction of gas in liquid.

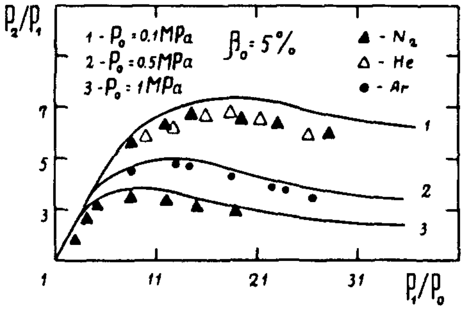

Figure 8. Reflected wave parameters as function of initial pressure in fluid at $\beta$ = 5%; curve 1 $p$ = 0.1 MPA; curve 2 $p$ = 5MPA; curve 3 $p$ = 10 MPA. ▲, $N_2$; Δ, He; ●, Ar.

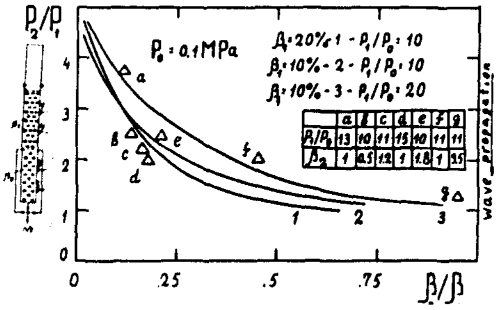

Figure 9. Relationship between reflected wave parameters and gas concentration at the interface. 1 – $p_2 p_0^{-1}$ = 10, $\beta$ = 20%, 2 – $p_1 p_0^{-1}$ = 3 – $p_1 p_0^{-1}$ = 20, $\beta$ = 10%, $\beta_1$ = 10%.

(i.e. decrease the compressibility of the fluid). Reflected wave velocities then approach the value of the acoustic velocity in the continuous liquid.

The extent of pressure rise in reflection depends on the impedance ratio of the barrier and the two-phase medium. Till now we have been implying the case of an infinite acoustic resistance of the barrier. Nonlinear effects become blurred if we replace an absolutely rigid wall by a liquid, and even more so if it is a two-phase medium. Figure 9 illustrates how the coefficient of pressure rise in a wave reflected at an interface decreases with gas concentration ratio in adjacent volumes of the two-phase system. Most of the conclusions have been verified by Mori *et al.* (1976) and agree totally or fairly with the calculations carried out by Gelfand *et al.* (1973, 1974, 1978). Qualitatively similar results for shock reflection parameters have been obtained in experiments with aqueous foams. Figure 10 relates pressure ratios in the reflected and incident shocks in nitrogen-, acetylene-, hydrogen or helium-filled foams. Curves 1–4 in figure 10 have been plotted for a gas with $\gamma$ = 1, 1.24, 1.4 and 1.66, respectively. Again we are confronted with the fact of a substantially nonacoustic pressure rise in shock reflection by a wall.

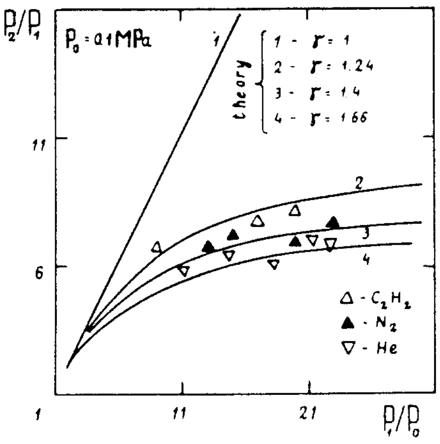

Figure 10. Reflected wave parameters as function of pressure drop in travelling waves in foams. Curve 1 $\gamma = 1$; curve 2 $\gamma = 1.24$; curve 3 $\gamma = 1.4$; curve 4 $\gamma = 1.66$.

All the above results were obtained for systems containing gases which are poorly soluble in water. As the gas solubility in liquid increases or if we consider a system containing a condensable gas the picture of wave propagation and reflections at interfaces becomes somewhat different. An example of a system with a potentially variable mass ratio of gas is water containing carbon dioxide bubbles which tend to leave water as the pressure is dropped. A pressure variation oscillogram for such a case is given in figure 11. The wave velocity and wavefront pressure variation curves are shown as curves 1 and 2, respectively, in figure 12. In

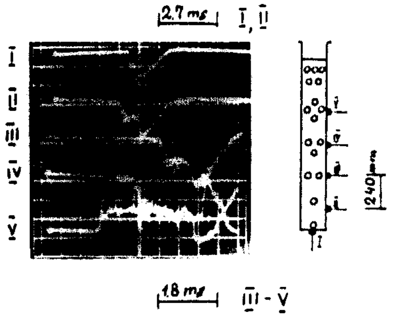

Figure 11. Oscilloscopic traces of pressure variations behind a shock wave in water containing bubbles of soluble gas.

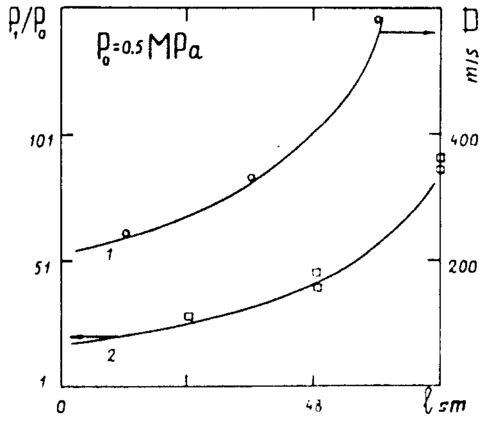

Figure 12. Wave velocity and pressure variations in case of a nonuniform gas concentration distribution over a liquid column height.

the case in question, wave travels in the mixture towards the decreasing gas concentration. In motion, the wave has to encounter an ever increasing acoustic resistance of the medium where the volume gas ratio decreases. In accordance with the conventional gas dynamics laws, the wave intensity should be expected to increase continuously, which is in fact observed in experiment. Over a distance of 1 m the pressure drop increases from 1.6 to 8.0 MPA and after reflection from a rigid wall becomes as high as 16.0 MPA. If the two-phase system we are dealing with contained bubbles with an insoluble gas, the pressure in the reflected wave would not go above 8.0 MPA. The observed increase of pressure in a medium containing a soluble gas has shortened the compression period of the reflected shock compared to an insoluble gas. The effect of gas solubility on the reflected shock parameters has also been observed in a saturated carbon dioxide solution in water. In this latter case the incident shock velocity was constant. However, direct measurements have shown that the pressure increase at the reflected wavefront in the water/carbon dioxide gas system may be as high as 12–14 times. Under comparable conditions an increase of pressure in a nitrogen gas bubbles/water system is only 4.5. It is quite obvious that the obtained pressure rise values in a reflected shock are not maximum because it was impossible to dissolve gas completely behind the front of the reflected and incident shock. Total disappearance of gas-filled voids in a liquid is apparently possible only for steam (cavitation) bubbles. It is in this case that the most intensive reflected wave may be expected. This has first been verified in Borisov *et al.* (1977) experiments dealing with the propagation and reflection of shock waves by a barrier in a cryogenic liquid-nitrogen and Freon-12, in which the factors $p_2 p_1^{-1} = 5$–$50$ were obtained for $p_1 p_0^{-1} = 1.5$, to 4. Later investigations of shock wave reflection in boiling water showed that already at $p_1 p_0^{-1} = 1.1$ to 2 a pressure $p_2 = 2.0$–$20.0$ MPA arises on the wall, which corresponds to $p_2 p_1^{-1} = 20$–$100$.

With a view to explain this result a simple model of total disappearance of vapor inclusions in any weak wave has been considered under the assumption of constant liquid parameters (density and sound velocity at different temperatures). This approach yields unduly high reflected shock pressures but the formula:

$$p_2 = p_1 + \rho_L (a_L + u) u$$

where $u$ is velocity of liquid behind the incident shock, is quite suitable for simplified engineering calculations.

Figure 13 summarizes the results of investigations. Curve 1 (experimental) here relates to the pressure recorded at the shock tube end. Curve 2 describes reflected shock pressure in a liquid containing uniformly distributed bubbles of an insoluble gas. Curves 3, 4 have been obtained for an initial vapor concentration $\beta = 90\%$ and 60% in water, and curves 5 and 6 for

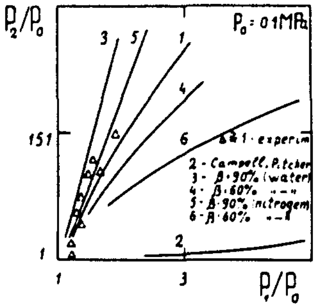

Figure 13. Reflected wave parameters as function of incident wave pressure drop in a system containing a soluble or condensable gas: Curve 1, experiment; curve 2, calculation as reported in the paper of Campbell; curve 3, calculation with allowance for disappearance of bubbles in water at $\beta = 90\%$; curve 4, calculation at $\beta = 60\%$ in water; curve 5, calculation with allowance for disappearance of bubbles in a liquid gas at $\beta = 90\%$; curve 6, calculation at $\beta = 60\%$ in liquid nitrogen.

$\beta = 90\%$ and 60% in boiling liquid nitrogen. Under the conditions of these experiments the reflected pressure must be noted to decrease with a decrease of liquid rigidity.

Since constancy of vapor concentration along the liquid column could not be assured in the experiments, so far we may only speak of a qualitative agreement between theory and experiment. Borisov *et al.* (1977) met with considerable difficulty in determining the gas–liquid volume ratio and it was difficult to determine the inner structure of the boiling cryogenic liquid.

## 4. ATTENUATION OF THE SHOCK WAVE IN TWO PHASE MIXTURE

The above characteristic features of two-phase systems, together with their quasi isothermal behavior in pressure shocks and sharp decrease of sound velocity under a minor decrease of density are the reasons responsible for the peculiar behavior of shock waves as they pass from a continuous liquid into a two-phase mixture, when the explosion products expand in the two-phase medium. Some of the peculiarities of behavior have already been revealed. One of the most common and simplest examples is the passing of a pressure shock from water or another continuous liquid into a two-phase medium. The amplitude of the traveling wave was found to be decreasing in close agreement with the reduction of the acoustic resistance in the two-phase medium compared to bulk water, as it is shown in figure 14. Depending on the actual conditions, the amplitude may be attenuated by a factor of 3–5. It should be always kept in mind, however, that, apart from the possible pressure wave steepening at an interface with an increasing acoustical resistance, a very special situation arises in a two-phase medium when the latter contacts a rigid barrier. In figure 3 this case is illustrated separately. Despite shock wave attenuation as it passes from water to a liquid–gas bubbles mixture, the pressure at the rigid wall is always the same as if there were no bubbles near the wall at all. A similar effect is observed in passing of shock waves through air-bubble attenuating screens in basins. If, on the other hand, the screen were in contact with a rigid wall, its attenuating properties would be largely reduced. It has been found besides that the ratio of shock wave attenuation and steepening coefficients at the front and rear frontiers of a gas–liquid screen is such that the effect of a screen on long plane pressure waves is quite meagre. The problem of protective screen location must be solved in each particular case with due regard to the actual conditions. It would be safe to say, in any case, that such screens are effective enough attenuators of shortwave perturbations having a compression phase duration of less than $10^{-3}$ sec. But even for such short waves the screens are not entirely opaque and attenuate effectively only within a rather narrow range of intensities $p_1p_0^{-1} \approx 5$–20 at $p_0 = 0.1$ MPA. As the shock intensity increases and the gas volume fraction decreases to below 1%, the protective effect of such screens is considerably lowered. The effect may be different if the shocks attack the screen front at an angle and bring about a nonregular wave reflection at the two-phase medium/liquid interface. So far the problem of oblique wave propagation and parameters in a two-phase medium has not been studied thoroughly either experimentally or theoretically.

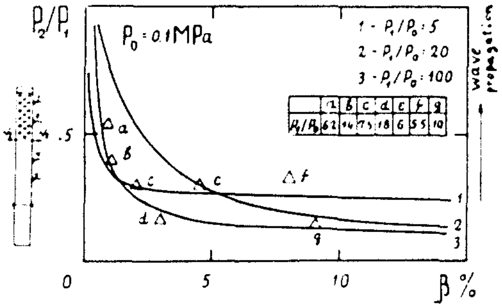

Figure 14. Wave attenuation in transition through an interface towards a decreasing accustic resistance. 1. $p_1p_0^{-1} = 5$; 2. $p_1p_0^{-1} = 20$; 3. $p_1p_0^{-1} = 100$.

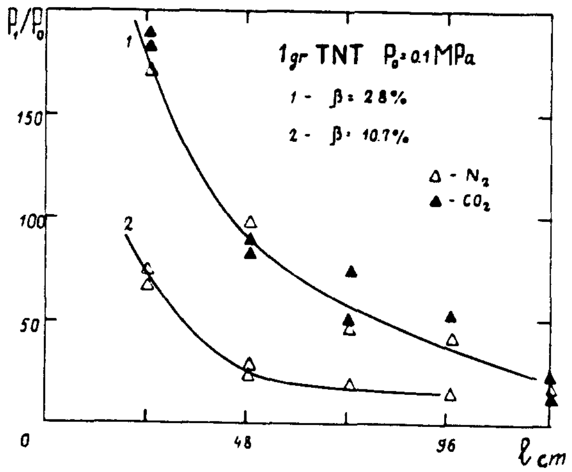

Figure 15. Shock wave parameter variations in case of explosion in a two-phase medium in a shock tube. 1, $\beta = 2.8\%$; 2, $\beta = 10.7\%$. ▲, $N_2$; Δ, He; ◆, $CO_2$.

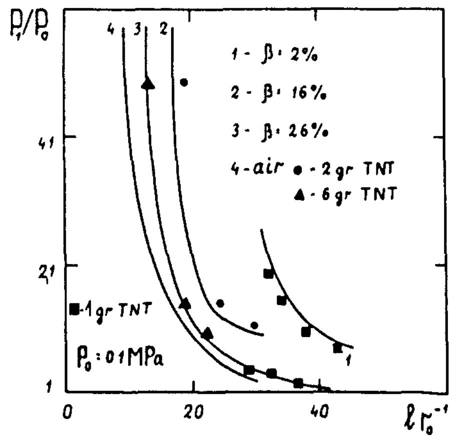

Figure 16. Spherical shock wave parameter variations in case of explosion in a two-phase medium. Curve 1, $\beta = 2\%$; curve 2, $\beta = 16\%$; curve 3, $\beta = 26\%$. Points: ■1, 1 gram, ●2, 2 gram, ▲3, 6 gram; curve 4, explosion in air.

In experiments directed to investigations of shock wave interaction with an interface it has been found that the most effective attenuation of a blast wave in a two-phase medium is attained when the disturbance source, i.e. an explosive charge, is located within the two-phase medium itself. Figure 15 is an illustration of blast wave attenuation on blowing up of a 1 gram explosive charge in a shock tube of 50 mm in dia. using a two-phase mixture containing various concentrations of nitrogen bubbles suspended in water. In water, an explosion like that would be expected to cause at similar distances shock waves with a pressure drop of above 50.0 MPA. Figure 16 presents measured pressure drops in spherical shock waves. Curves 1–3 in this diagram were obtained for gas contents of 2%, 16% and 26%. Points 1, 2, 3 correspond to 1 gram, 3 gram and 6 gram explosive charges. Compared to explosions in water, the shock amplitude is attenuated by a factor of 20–60. Curve 4 in figure 16 gives measured shock wave parameters in air generated by explosion of a 1 gram charge. A rapid increase of the positive compression phase of a shock wave is observed as it moves in a two-phase system, especially in a tube. Appearance of pressure waves having a square or trapezoidal pressure profile at long range from a source depresses the attenuating potential of two-phase screens in a closed vessel or a continuous liquid.

Maximum shock wave attenuation effect is achieved when an explosive is blown up in a bulk of foam surrounded by air, in which case the acoustic resistance of foam is higher than

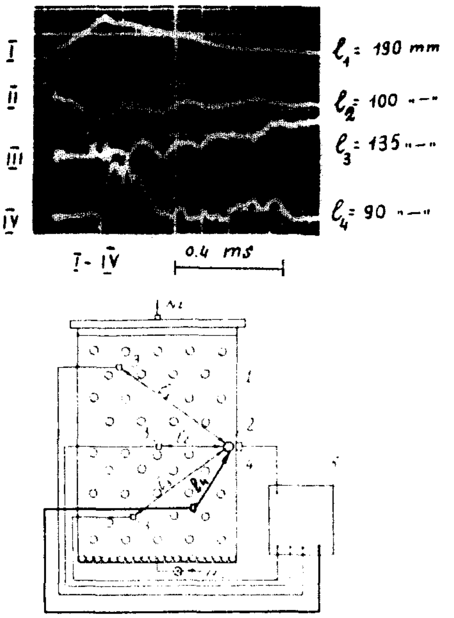

Figure 17. Shock wave profile due to explosion in foam.

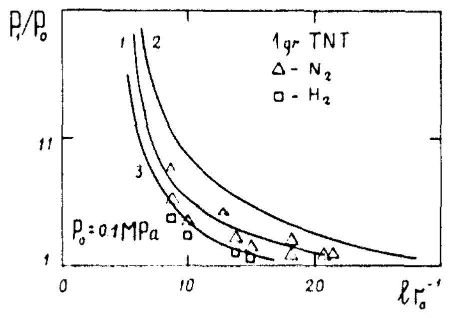

Figure 18. Spherical shock wave parameters in foam (1) and air (2).

that of the environment. Figure 17 shows the shape of a spherical shock wave propagating in foam. If one can still perceive a likeness of a shock wave at a short range from the explosion zone, at distances of several dozens of source radii no pressure wave could be detected. Figure 18 presents comparative results for shock waves in a foam and air. A relationship for shock waves in air derived by Korotkov & Adushkin (1961) is plotted as curve 1. The variation of pressure drop in a blast wave in an air-filled foam is given by curve 2 and that in hydrogen-filled foam by curve 3. Liquid concentration in foam was 10 kg/m$^3$. By now, the validity of these relationships has been verified for charges of from 1 g–3 kg. It can be seen from figure 18 that the larger the explosive charge the larger volumes of foam should be used to attenuate explosions. These results have been recently verified by Winfield *et al.* (1977). The appearance of long waves remotely from a source can make probable the nonlinear wave reflections by interfaces with an increasing acoustic resistance which we mentioned earlier in this paper.

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