Attenuation of Shock Waves in Bubbly Media

To cite this article: S A Gubin 2018 J. Phys.: Conf. Ser. 1099 012016

View the article online for updates and enhancements.
Attenuation of Shock Waves in Bubbly Media

S A Gubin$^{1,2}$

$^1$National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoye shosse 31, Moscow 115409, Russia
$^2$State Center «Interphysica», 31, Kashirskoye shosse, Moscow, 115409 Russia
e-mail: gubin_sa@mail.ru

Abstract. Experiments on the attenuation of spherical shock waves were carried out in a vessel and a shock tube filled with a two-phase gas bubble–water mixture with a gas volume fraction of $\beta = 2.3$‒26%. The attenuation of the spherical blast wave generated by a charge directly into a two-phase medium proved to be more effective than in the case of using bubble screens. Experiments have shown that, at $\beta = 2.3\%$, the intensity of spherical shock waves decreases 20-fold, whereas at $\beta = 26\%$, by a factor of 40–50. A bubble layer enhances the dynamic effect on the barrier for extended waves and weakens it in the case of short-pulse disturbances. The degree of attenuation or amplification of the blast wave depends on the thickness of the layer, pulse duration, and volume fraction of bubbles.

1. Introduction

Gas-liquid bubbly systems are used to attenuate blast waves. The development of technologies for cutting, welding, and processing of materials by explosion, as well as the need to carry out blasting operations during the liquidation of the consequences of accidents in oil and gas transport pipelines and in performing underwater explosions, requires the development of effective methods for attenuating the intensity of blast waves in the surrounding medium. Methods for localizing the effect of an explosion and diminishing explosive loads are mainly based on the use of compressible two-phase systems capable of efficiently absorbing the energy of blast waves. To do this, bubbly media are used, a high compressibility of which provides significant dissipative losses due to the interaction between phases during the propagation of shock waves in gas–liquid mixtures.

Two-phase bubbly mixtures arise because of cavitation in rarefaction waves arising during accidents on pipelines. Studying the dynamics of shock waves in such environments is important for predicting the consequences of accidents on pipelines.

Analysis of the parameters of shock waves in gas–liquid mixtures and investigation of the characteristics of reflection of wave pulses in bubbly liquids makes it possible to determine optimum modes of shock impact on objects. The results obtained can be used in preventing emergencies during blasting operations, creating effective protective barriers capable of localizing the energy of the explosion and reduce the consequences of accidents on pipeline transport.

The complexity of describing the propagation of shock waves in gas–liquid systems and the limited number of experimental studies on the attenuation of blast waves in bubbly media motivates studies on the dynamics of shock wave processes in liquid containing gas bubbles.
Shock waves in bubbly media have been studied experimentally and theoretically [1‒14]. The results are overviewed in the monographs [2, 3]. It was experimentally shown [4‒8] that bubbly liquids are an effective means of attenuating the intensity of shock waves. It was established that the characteristics of shock waves in a bubbly liquid are determined by the intensity of the wave and are dependent on the parameters of the bubbles, such as the gas volume fraction, bubble size, and viscosity of the liquid. When a shock wave propagates in a bubbly liquid, gas bubbles can break up [9].

The effect of the solubility of the gas in the bubbles on the structure and amplification of shock waves in two-phase bubbly mixtures was studied in [13]. An anomalous increase of the pressure in shock waves reflected from a rigid wall in bubbly media was observed [4, 11, 14]. Thus, the question arises, under what conditions blast waves are significantly attenuated and under what conditions a high pressure of reflection of shock waves reduces the efficiency of attenuation of incident shock waves in bubbly liquids.

The aim of the present work is to examine the experimental data from [4] on the dynamics of the variation of the shock wave parameters with the distance at various contents of gas babbles in water. We have studied the attenuation of incident and reflected blast waves generated in bubbly media.

2. Experimental setup

Experiments on the attenuation of spherical shock waves were carried out in three- and one-dimensional geometries in the apparatuses schematically displayed in figures 1a and 1b. In the 3D case, spherical shock wave 2 was generated by a charge at the center of cylindrical vessel 1 (figure 1a). In the one-dimensional case, shock wave 2 was generated in the upper part of a tube 1, 50 mm in diameter and 1.3 m in length (figure 1b); the pressure behind the wave was measured with piezoelectric sensors. The volume concentration of the gas, $\beta = 2.3–26\%$, was determined from the height of the rise of the liquid after it was bubbled with nitrogen or carbon dioxide. The experiments were carried out under normal conditions. The experimental setups were described in detail in [4].

![Figure 1](image-url)

**Figure 1.** Schematic representations of installations for the investigation of (a) spherical and (b) one-dimensional blast waves in bubbling media.
The parameters of spherical shock waves in the vessel with the two-phase medium were measured by three knife pressure piezosensors 3 located at distances $l_1 = 219$ mm, $l_2 = 134$ mm, and $l_3 = 180$ mm from the charge (figure 1a). The sensor located at the distance of 180 mm measured the pressure in the shock wave reflected from the bottom of the vessel. The pressure behind the shock waves in the tube was recorded by four piezosensors 3 mounted in the walls of the tube 0.24 m apart (figure 1b).

3. Results

The structure of the spherical shock wave changed with the distance it traversed in the two-phase medium. The positive phase of compression of the triangular pulse of the spherical shock wave increased with the distance traveled by the wave in the two-phase medium. The region of constant average pressure in the shock wave widened. Oscillograms exhibited pressure fluctuations in the incident shock wave [4, 11]. The pressure in the incident shock wave was observed to increase with the volume fraction of bubbles (figure 2).

![Figure 2](image_url)

**Figure 2.** Dependences of the pressure decrease in spherical shock waves in bubbly media at various weights of the charge (1) 1, (2) 3, and (3) 6 g.

![Figure 3](image_url)

**Figure 3.** Variation of the wave front process with the distance along the tube length for (1) N$_2$ ($\beta = 2.8\%$) and (2) CO$_2$ ($\beta = 10.7\%$).

Figure 2 shows the change in the maximum pressure at the front of the incident blast wave $\Delta P$ as a function of the dimensionless distance $l/r_0$ ($r_0$ is the radius equivalent to the weight of the spherical HE charge). Points 1, 2, and 3 correspond to experiments with 1-, 3-, and 6-g charges and gas volume fractions of 2.3, 16.6, and 26%. The accuracy of determination of the excess pressure of spherical shock waves did not make it possible to reliably distinguish between the experimental data obtained at $\beta = 16.6$ and 26%. At distances greater than (30–40) $r_0$ (points 3, 2 in figure 2), the pattern of change of the maximum pressure at the blast wave front with increasing distance in media with a volume fraction of bubbles of 16.6–26.0% is comparable with that for shock waves in air [15].

The degree of attenuation of the blast wave depended on the intensity, duration of the positive compression phase of the spherical wave, distance traveled by the wave in the bubble medium, and volume fraction of bubbles. The attenuation of a blast wave generated directly inside a two-phase medium turned out to be more significant than in the case of using bubbly screens [1]. Experiments have shown that, at $\beta = 2.3\%$, the intensity of spherical blast waves decreases approximately 20-fold, whereas at $\beta = 26\%$, by a factor of ~50.

A strong attenuation of blast waves in a liquid with gas bubbles occurs due to the specifics of the expansion and interaction of the gaseous explosion products with the two-phase medium. The rate of formation and expansion of explosion products in a two-phase bubbly medium differs from the conditions of formation of the domain of explosion products in a homogeneous gas or liquid. The
products of an explosion expand non-isentropically in a two-phase medium. The detachment of the shock wave from the explosion products occurs at a shorter distance than in a gas medium.

The pressure pulse of a blast wave generated in the tube (figure 1b) acquired the form of a step with a constant average pressure at a distance of ~0.3 m. The propagation velocity of incident shock waves decreased with increasing gas volume fraction in the bubbly medium and increased with the shock wave intensity. Figure 3 shows how the pressure at the wave front changes along the tube length (curve 1, $\beta = 2.8\%$; curve 2, $\beta = 10.7\%$). Just as in the spherical case, the pressure at the wave front decrease with increasing volume fraction of gas bubbles (figure 3). Points 1 and 2 were obtained for nitrogen- and carbon dioxide-filled bubbles. No influence of the thermophysical properties of the gas on the attenuation of strong shock waves in bubbly media has been revealed.

4. Discussion

As the intensity of the blast wave decreases, so does the extension of its positive compression phase. For an initial blast wave pulse shorter than the thickness of the bubble layer, it weakened, producing a lesser effect on the obstacle. With increasing shock wave intensity, the extent of the positive phase of compression of the blast wave increases. When the length of the initial blast wave pulse is greater than the thickness of the bubble layer, the intensity of the wave pulse decreases little. In all the experiments performed in [9], the mass velocity and dynamic thrust of parameters of the blast waves were high enough to break up the bubbles.

The average pressure in the blast wave reflected from the rigid wall increased by a factor of 3–4. The pressure of the reflected wave increased noticeably with the intensity of the incident wave, so that the impact on the barrier was greater.

The reflected shock waves propagated through a finely dispersed medium of small bubbles, already fragmented in the incident wave (with an average size of $d_{10} = 0.05d_0$, where $d_0$ is the diameter of the initial bubbles.) The amplification of the reflected shock wave occurs because the secondary bubbles are rapidly compressed during the compression phase of the shock wave, with the kinetic energy of the radial motion of the liquid transforming into the potential energy of the gas pressure in the compressed bubbles. The compression of gas bubbles behind the shock wave front is accompanied by the generation of numerous pressure pulses, which produce an increase in the amplitude of the reflected shock wave.

Note that the fragmentation of bubbles sharply increases their surface area, thereby enhancing the intensity of heat transfer between the phases. However, a relatively weak compression of the small secondary bubbles in the shock wave (due to a sharp decrease in the size of the initial bubbles during breakup) does not allow the gas to become very hot during the compression of the secondary bubbles behind the shock wave. The fragmentation of bubbles in the shock wave prevents a significant heating of the gas in them. This makes the process of compression of the secondary bubbles in the shock wave isothermal. Experimentally, no intensification of heat transfer between the phases on the parameters of the shock wave during the fragmentation of bubbles was detected. Under conditions that impede the fragmentation of bubbles (powerful short pulses, a high viscosity of the liquid, and a high initial pressure), the intensity of the heat exchange between the phases decreases, and the broken-up bubbles contract adiabatically. The weak influence of the thermophysical properties of different gases in bubbles on the parameters of the shock wave, found in [4], is indicative of the isothermal compression of bubbles in shock waves. This conclusion was confirmed in [11, 12].

The solubility of the gas further enhances the intensity of weak reflected shock waves [3, 13]. The solubility of gases is accelerated by the fragmentation of bubbles, a process that intensifies the mass transfer between the phases (large interphase gas–liquid surface area) and convective diffusion due to the relative turbulent movement of the gas bubbles and the liquid behind the wave. The amplification of the reflected shock wave can be explained by sharp pulsations of pressure in the liquid generated by gas bubbles collapsing because of their complete dissolution.

It was shown [14] that the energy of the pressure pulse accumulates in the bubbly medium zone if its duration exceeds the time of propagation of the wave through the bubbly liquid area. A similar effect
of energy accumulation is used in nanoporous medium–incompressible fluid systems for attenuating pressure pulses [16, 17].

5. Conclusions
In view of the foregoing, it can be expected that the intensity of incident and reflected shock waves in media with cavitation-prone bubbles will be higher than that in media containing air bubbles. The amplification of shock waves in two-phase media containing cavitation-prone bubbles occurs because the bubbles completely dissolve during the compression phase, thereby producing the high-velocity radial motion of the liquid and, consequently, a sharp increase in pressure during bubble collapse, which explains the significant increase in the amplitude of the incident and reflected shock waves. This effect of amplification of incident and reflected shock waves must be taken into account when analyzing the risk of the accidental destruction of pipelines accompanied by cavitation of liquid products (hydrocarbons).

Thus, for the protection of objects from blast waves by means of bubbly media, it is necessary to take into account the transformation of shock waves in the protective medium and to correctly estimate the real parameters of the incident and reflected shock waves at various distances and volume fractions of the gas by using an isothermal or adiabatic model.

Acknowledgments
This work was supported by the Russian Science Foundation, project no. 16-19-00188.

6. References
[1] Kudinov V M, Palamarchuk B I, Vakhnenko V A 1983 DAN SSSR. 273 1080
[2] Kedrinsky V K 2000 Hydrodynamics of explosion. The experiment and model (Novosibirsk: SB RAS) p 434
[3] Nakoryakov V E, Pokusaev B G, Schreiber I R 1990 Wave dynamics of gas - and vapor-liquid media (Moscow: Energoatomizdat) p 238
[4] Gelfand B E, Gubanov A V, Gubin, S A, etc. 1977 Izv. AN SSSR Mech. Zhidk. i Gaza 1 173
[5] Gubaidullin A A, Ivandaev A I, Nigmatulin R I 1976 DAN SSSR 226 1299
[6] Ohtani K, Sugiyama H, Mizobata K, Sasaki Y 2017 Proc. Conf. Hokkaido Branch doi.org/10.1299/jsmehokkaido.2001.41.188
[7] Frolov S M, Avdeev K A, Aksenov V S, etc. 2017 Int. J. Multiphase Flow 92 20
[8] Avdeev K.A., Aksenov V.S., Borisov A.A. etc. 2015 J. Phys. Chem. B 9 895
[9] Gelfand B E, Gubin S A, Nigmatulin R I etc. 1977 DAN SSSR 235 292
[10] Sugiyama H, Ohtani K, Mizobata K, Ogasawara H 2005 Shock Waves 1085
[11] Sichev A I 2010 Zh. Tekh. Fiz. 80 31
[12] Surov V S 1998 Zh. Tekh. Fiz. 68 12
[13] Donshtov V E 1998 Zh. Prikl. Mech. Tekh. Fiz. 39 19
[14] Agisheva U O, Bolotnova R Kh, Buzina V A, Galimzianov M N 2013 Fluid Dynamics 48 151
[15] Adushkin V 1963 Zh. Prikl. Mech. Tekh. Fiz. 5 107
[16] Belogorlov A A, Borman V D, Byrkin V A, Paryohin D A, Tronin V N 2016 J. Phys. Conf. Ser. 751 012031
[17] Borman V D, Belogorlov A A, Tronin V N 2018 Colloids and Surfaces A: Physicochemical and Engineering Aspects 537 540