Explosion of aluminized mixtures in bubble column as a method of underwater compression wave enhancement

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Abstract. The results of experimental investigations of underwater explosions of ideally and nonideally detonating charges in continuous water and in water containing air bubbles are reported. Charges few tens of grams in weight were exploded in a metal reservoir filled with water. Parameters of compression waves generated by explosions in the reservoir were monitored. Based on the experimental data obtained the mechanism and the main stages of nonideal explosions as well as the nature of the effect of enhanced directed impact of blast waves on targets attained with the aid of bubble arrays are discussed.

1. Introduction

It is known that in some cases the impact of blast waves on obstacles in water can be enhanced, for example, by bubbling water ahead of the wave front. Such a phenomenon was described in [1], where the shock wave propagated under conditions when a heterogeneous medium (foam block) was located immediately nearby the object protected or contacted it. It was found in [2] that sometimes a hydro-shock wave (HSW) was amplified as a result of its passage through the bubbled layer and its subsequent impingement on a solid obstacle behind the layer. Such effect is typical for cases where the shock wave in water interacts with a bubble array of a limited volume.

On the other hand, bubbled curtains are often used in practice as a method for reducing the intensity of HSW generated by underwater explosion of high explosive (HE). For example, the experiments carried out in work [3] demonstrate that the HSW decays as it passes through the bubbled water. It was found that degree of attenuation depends on the volume, concentration of bubbles, and the charge mass. It should be noted that the underwater pressure wave significantly changes its duration after passing through the bubble array, thus the object downstream of the bubbled water experiences longer exposure. In articles [2, 4], the authors have also shown a decrease in the parameters of a HSW as it passes through bubbled water. However, as reported in [2] the bubble shield was located at some distance from the protected object so that a 0.5–1 m gap of continuous water remained between the bubbled liquid and obstacle. Therefore, when the
HSW impinges an obstacle through the bubbled layer of water, the positive compression phase duration is increased, due to deceleration of the flow of compressed heterogeneous medium.

As shown previously [5] the amplitude of an incident HSW after it crosses the bubbled water layer is much lower than that of the same wave traveling in continuous water. As demonstrated in experiments where hydro-reactive metalized mixtures were injected at high pressure and temperature into water with bubbles [6, 7], a secondary pressure pulse arose, unlike the case when explosion products are injected into continuous water. This secondary impulse is caused by interaction between the reacting heterogeneous flow and the obstacle. The experiments mentioned above demonstrate also that formation of a reacting multi-phase cloud lasts no less than 500 µs. Reaction time in continuous water is expected to be much longer than the HSW unloading time. This is why there is no secondary pressure pulse in continuous water. In the case of bubbled water, the speed of sound in heterogeneous media is much lower than that in continuous water. Therefore the HSW unloading time is increased. Moreover, an increase in the permeability of the medium for jets of detonation products leads to an increase in the dimensions of the heterogeneous cloud and mixing intensification. HSW reflected from the walls in a closed vessel or from the bottom in the open basin propagates through the heterogeneous reacting cloud. Therefore it increases the burning rate of aluminum particles in water vapor due to the increase in temperature during compression. As a result a secondary pressure wave is generated. Measurements also demonstrated at least 1.5 times longer pulse in the case of explosion in bubbled water.

The main factors, which are responsible for the enhanced impact of blast waves generated by hydro-reactive charges exploded inside a bubbled water column positioned between the charge and obstacle, are as follows:

- When a charge highly enriched with Al is exploded inside bubbled water, the detonation products are more intensively mixed with water and steam due to a higher permeability of the medium.
- The reaction of excess metal with water proceeds faster than it does in continuous water. The resulting compression waves capable of supporting the generated HSW spread through a heterogeneous medium at slower velocities than they do through continuous water.
- The vector of particle velocity in a heterogeneous reacting medium is directed towards the obstacle because the products expand predominantly along the bubble column in the directions of highest permeability of the medium.
- When the compression wave impinges the obstacle, the duration of the compression pulse also increases due to relatively slow deceleration of the compressible heterogeneous medium.
- Unreacted metal particles start to burn during deceleration of heterogeneous media and produce additional compression due to a sharp increase in the temperature. Such afterburning also enhances the pulse duration and amplitude. It is obvious that there is some optimal relationship between the mass and the composition of the charge and the dimensions of the bubble column, its parameters and the distance from the charge to the obstacle.

2. Experiments
Experiments were performed in vertical open cylindrical steel reservoir of 2 m in internal diameter and 3.5 m in height with semicircular bottom. Reservoir capacity was about 11 m³. The reservoir was surrounded with a compacted and wetted sand barrier up to its top rim. The sand barrier width was no less than 1 m at the top. The sand barrier provided the necessary inertia resistance of the reservoir walls to an internal explosion impact. The general view of the setup is shown in figure 1.
Two PS-02 piezoelectric pressure gauges were used to monitor pressure [8]. To measure the mechanical impulse imparted in a target by a compression wave, a movable obstacle in the form of a metal cylinder of 175 kg in weight was used (herein after impulse meter). Its closed end faced the charge. The impulse meter was partially immersed in water so that a compression wave acted solely on the bottom end until the rarefaction wave from the free water surface arrived. Piezoacclerometer gauge was mounted on the impulse meter to measure its acceleration after impact of the compression wave. Such technique was discussed in details in [8, 9].

3. Characterization of bubble arrays
To study the directed effect of nonideal explosion a device was devised to generate the column of uniformly distributed air bubbles in water. The device development was based on the following reasoning:

- The bubble column must be cylindrical and positioned coaxially with the reservoir, charge, and impulse meter.
- It must be as transparent for HSW as possible and preclude reduction of its amplitude.
- It is well known that air-bubble curtains are applied to quench hydro-shock waves when performing underwater explosion works [10]. Specific rate of air flow from a perforated

Figure 1. Outline of the setup with all its components arranged at the test area: $D_1$ and $D_2$ are lower and upper pressure gauges respectively.
tube positioned at the bottom per one meter of the air feeding tube length is the basic parameter characterizing efficiency of such curtains. The authors of article [11] report that wave quenching starts at \(0.24 \text{ m}^3/(\text{min m})\) of the air flow rate value. The pressure reduction coefficient in this case \(B_p = 6\):

\[
B_p = \frac{P_1 - P_0}{P_{\text{after}} - P_0},
\]

where \(P_1\) is the incident wave amplitude, \(P_{\text{after}}\) is the amplitude of the wave passed the curtains, and \(P_0\) is the hydrostatic pressure. When the present experiments were prepared, we assumed that the air flow rate should never exceed the aforesaid value.

- When the HSW interacts with bubbles, a significant fraction of the wave energy is spent to the compression of bubbles. As follows from paper [11], small bubbles about one millimeter in diameter are cooled after compression within a time interval comparable with that of their compression. It means that a significant fraction of the heat from the compressed gas is transferred into the surrounding water. Heat transfer from large bubbles is much slower. Therefore, the energy loss from the wave is much less. In addition, inasmuch as HSW propagates along the bubble column at a much lower velocity than it does in continuous water, the surrounding water shocked earlier is unloaded into the column. It leads to feeding the column area with additional energy. The larger the bubbles the more prominent is this effect because the pressure in the column equilibrates with the surrounding pressure longer. Moreover, the work done by the pressure wave against the surface tension forces within the bubble column is less in the case of large bubbles.

The main parameter specifying efficiency of HSW quenching by bubble curtains is known to be the internal energy of the gas contained in 1 m\(^3\) of the curtain. As mentioned in paper [2], if specific energy of an incident wave \(E_0 \gg (h P_1^2 \phi)/(\gamma - 1)\) (where \(h\) is the curtain width, \(\phi\) is the volume fraction of bubbles in water, and \(\gamma\) is the adiabatic exponent of air), the wave amplitude decrease is insignificant. The wave energy in our experiments ranges between about \(10^3\) and \(10^5\) J/m\(^2\). Such a value of the volume fraction of bubbles was selected in order to avoid HSW reduction. After testing of several various air disperser devices a version shown in figure 2 was selected. The disperser construction is as follows: wooden crossbar supports a spiral half inch plastic pipe 4.5 m long with perforations—250 holes spaced 1.5 or 2 cm apart.

Air compressor which provided the 120 l/min flow rate at the maximum outlet pressure of 8 bar was selected. HSW pressure attenuation coefficient was \(B_p < 6\) according to data indicated in [5]. The experiments were carried out at three various values of the bubble volume fraction

Figure 2. Outline and photo of the working air dispersing device.
Table 1. Bubble column parameters.

| Air Flow regime | Dynamic pressure in the feeding manifold, kPa | Air flow rate, l/min | Bubble lifting velocity, m/s | Volume content of bubbles in water, | Mean bubble size, mm | Average ratio of bubble diameter to its height |
|-----------------|-----------------------------------------------|----------------------|-----------------------------|-------------------------------------|----------------------|-----------------------------------------------|
| 1               | 6                                             | 10                   | 0.35                        | 0.004                               | 4–5                  | 1–2                                           |
| 2               | 24                                            | 48                   | 0.6                         | 0.026                               | 10                   | 2.5–4                                         |
| 3               | 54                                            | 120                  | 0.6                         | 0.1                                 | 10                   | 2.5–4                                         |

Table 2. Compositions of the mixtures used.

| Substance | Name in text | Component | Mass of individual parts, g | ρ, g/cc | Mass of booster, g | Al to O ratio |
|-----------|--------------|-----------|-----------------------------|---------|--------------------|---------------|
| Al+AP+NM  | 1 : 1        | AP (40 µm) | 10.79                       | 1.27    | 4                  | 1.31           |
|           |              | NM        | 4.42                        |         |                    |               |
| Al+AP+NM  | 1.5 : 1      | AP (40 µm) | 8.63                        | 1.22    | 4                  | 1.85           |
|           |              | NM        | 4.42                        |         |                    |               |
| Al+AP+NM  | 2 : 1        | AP (40 µm) | 7.19                        | 1.18    | 4                  | 2.26           |
|           |              | NM        | 4.42                        |         |                    |               |
| Ammonite  | 6JV          | AN (79%)  | 23.7                        | 1.12    | —                  | —              |
|           |              | TNT (21%) | 6.3                         |         |                    |               |

in water (regimes 1, 2, and 3 accordingly in table 1). The temperature of supplied air was same as in water in the vessel (about 5 °C).

4. Energetic materials used

Characteristics of the HE and mixtures used in the present work are listed in table 2. Ammonite was chosen as basic HE because its density is close to alumized mixtures used. Its explosion parameters served as a reference in assessing the performance of nonideally detonating mixtures. The measured detonation velocity of loose packed ammonite of 1.12 g/cm³ density is 4500 m/s, according to control measurements. The ammonite charge weight was 30 g in all tests except the test performed to calibrate the reservoir [12].

Nonideal compositions highly enriched with aluminum was discussed in the previous work [12]. As seen from comparison between table 2 and HBX-3 (high blast explosive) [13] the aluminum mass fraction of the mixtures used is much greater than that in typical underwater HE. The mass fraction of nitromethane in all mixtures used was 17%. Only Al to AP (aluminum to ammonium perchlorate) ratio were varied in mixtures from 1 : 1 to 1 : 2 (see table 2). PAP-2 (flaked aluminum powder) particles 10 × 10 × 1 µm³ in a representative particle size and ammonium perchlorate particles of 40 µm in size were used in experiments.

The metal rich mixtures were exploded in polyethylene tubes of 20 mm in internal diameter and 4 mm wall thick. The 4 g ammonite booster was used for metal rich charges.
5. Discussion of experimental results
Among the entire set of tests performed, we selected only those with unquestionable reliability. The error of pressure and acceleration measurements does not exceed 10% (in agreement with gauge manufacturer’s data).

5.1. Ideally detonating charge in continuous water
First, the reference experiment with ideally detonating charge was carried out. The depth of charge submersion was 135 cm. The experimental results are presented in figure 3.

Below we present some comments for clarifying figures 3–6. The bottom part in these figures displays the pressure profiles up to a complete unloading of gauges. Time is measured from the charge initiation instant. At the top in figures, the accelerometer signal and time histories of impulse meter velocity, kinetic energy, and absolute displacement are shown. The maximum impulse meter kinetic energy, velocity, and displacement are assessed in these figures. All the experimental results obtained are presented in tables 3 and 4.
Table 3. Summary of the experimental results from runs 1 to 6.

| Run No | 1     | 2     | 3     | 4     | 5     | 6     |
|--------|-------|-------|-------|-------|-------|-------|
| Energetic material (see table 2) | 6JV   | 6JV   | 1:1   | 1:1   | 1:1   | 1:1   |
| Regime of barbotage | —     | 2     | —     | 2     | 3     | 3     |
| Bubble source distance from the charge, m | —     | 0.5↓  | —     | 0.5↓  | 0.5↓  | 0.5↓  |
| Bubble source distance from the obstacle, m | —     | 0.7   | —     | 0.7   | 0.7   | 1.4   |
| Depth from water surface, m | 1.35  | 1.35  | 1.35  | 1.35  | 1.35  | 2.05  |
| Distance between the charge and gauge \(D_1\), m | 0.51  | 0.5   | 0.48  | 0.54  | 0.54  | 0.43  |
| \(P_{\text{max}}(D_1)\), bar | 148   | 117   | 355   | 227   | 107   | 122   |
| \(P_{\text{max}}(D_2)\), bar | 68    | 51    | 251   | 117   | 123   | 97    |
| \(I_{1\text{max}}\), bar s | 0.045 | 0.033 | 0.043 | 0.056 | 0.046 | 0.029 |
| \(I_{2\text{max}}\), bar s | 0.025 | 0.023 | 0.031 | 0.044 | 0.037 | 0.024 |
| \(e_s\), MJ/kg | 0.64  | 0.26  | 0.9   | 0.97  | 1.34  | 0.70  |
| \(V_{1\text{max}}\), m/s | 1.02  | 1.25  | 1.1   | 1.49  | 1.8   | 1.34  |
| \(V_{2\text{max}}\), m/s | 1.47  | 1.68  | 1.52  | 2.13  | 2.44  | 1.47  |
| \(E_{k\text{max}}\), J | 220   | 290   | 236   | 605   | 461   | 222   |

Note that \(I_{1\text{max}}\) is the total impulse at gauge \(D_1\), \(I_{2\text{max}}\) is the total impulse at gauge \(D_2\), \(e_s\) is the specific HSW energy, \(E_{k\text{max}}\) is the maximal kinetic energy of the impulse meter, \(V_{1\text{max}}\) is the maximal velocity at first stage of obstacle motion, \(V_{2\text{max}}\) is the maximal velocity at second stage of obstacle motion, ↓ is the bubble generator positioned below the charge, and ↔ is the bubble generator at the charge level.

Signal of the lower pressure gauge \(D_1\) was used to evaluate the decay time constant \(\tau\) for HSW shock energy calculation. Then the specific shock wave energy \(e_s\) was calculated by formula from [14]. Its values are also presented in tables 3 and 4.

We dwell on an analysis of the results obtained. The assessed shock wave energy values are qualitatively consistent with the available literature data, however the data on explosion of ammonite charge is significantly lower than its counterparts for TNT (0.94–0.99 MJ/kg in [12] instead of 1.01 MJ/kg in [13]), whereas the explosion heats of both explosives are quite similar. This discrepancy is accounted for by the low density of ammonite charges.

The signal from the accelerometer attached to impulse meter exhibits at the first glance a chaotic set of periodical oscillations. The frequency of these oscillations is identical in all tests and is about 2.1 kHz. Measurements of the natural frequency of elastic impulse meter bottom oscillations performed after the basic set of experiments showed the same value.

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Table 4. Summary of the experimental results from runs 7 to 12.

| Run No | 7     | 8     | 9     | 10    | 11    | 12    |
|--------|-------|-------|-------|-------|-------|-------|
| Energetic material (see table 2) | 1 : 1 | 1.5 : 1 | 1.5 : 1 | 2 : 1 | 2 : 1 | 1 : 1 |
| Regime of barbotage | 1 | 1 | 3 | 1 | 3 | 1 |
| Bubble source distance from the charge, m | 0.5↓ | 0.5↓ | 0.5↓ | 0.55↓ | 0.5↓ | ↔ |
| Bubble source distance from the obstacle, m | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| Depth from water surface, m | 1.35 | 1.35 | 1.35 | 1.25 | 1.35 | 1.35 |
| Distance between the charge and gauge $D_1$, m | 0.52 | 0.52 | 0.52 | 0.52 | 0.53 | 0.55 |
| $P_{\text{max}}(D_1)$, bar | 193 | 131 | 104 | 142 | 91 | 210 |
| $P_{\text{max}}(D_2)$, bar | 97 | 197 | 149 | 123 | 70 | 152 |
| $I_{1\text{max}}$, bar s | 0.035 | 0.049 | 0.047 | 0.044 | 0.040 | 0.056 |
| $I_{2\text{max}}$, bar s | 0.013 | 0.020 | 0.023 | 0.021 | 0.030 | 0.021 |
| $e_s$, MJ/kg | 0.98 | 0.92 | 0.84 | 0.66 | 0.67 | 1.02 |
| $V_{1\text{max}}$, m/s | 1.84 | 1.92 | 1.27 | 1.68 | 1.22 | 4.08 |
| $V_{2\text{max}}$, m/s | 2.55 | 2.26 | 1.83 | 1.97 | 1.92 | 3.9 |
| $E_{\text{kmax}}$, J | 663 | 513 | 369 | 389 | 341 | 1713 |

waves. After the integration of the acceleration signal, the resulting time histories of the velocity and displacement have an anticipated shape and can be interpreted. Velocity profiles exhibit also oscillations; however, a two-stage process of impulse meter acceleration is clearly seen. To eliminate the effect of elastic impulse meter oscillations on the velocity–time histories the accelerometer data were treated with a cutoff Fourier filter at a frequency equal to the previously measured natural impulse meter frequency. The resulting impulse meter velocity derived from the accelerometer signal is shown in figures 3–6 by a solid line. The two-stage motion of impulse meter is noteworthy. Some temporary deceleration is probably coupled with HSW unloading when the wave arrives at the water surface. After that the acceleration starts increasing again due to water flow from the depth directed to the surface.

5.2. Explosion in water with a bubble column

To explore the effect a bubble column present in the reservoir upon the hydrodynamic pattern of the pressure pulses generated by explosions of condensed energetic materials, we carried out an experiment in which a 30 g ammonite charge was exploded within a bubble column at a 1.35 m depth. The bubble generator was located 0.5 below the charge and operated in the second air feeding regime (see table 1). The other things were as in experiments in continuous water.

The pressure signals represented in figure 4 demonstrate a considerable decrease in the amplitudes, as compared to that recorded in the test with ammonite charge exploded in continuous water. The pressure pulse recorded by a gauge positioned near the impulse meter bottom is decreased significantly. This gauge falls into the bubbled liquid area. Thus this decrease is an evidence of shock wave suppression by a bubbled liquid discussed above. The maximum amplitude recorded with this gauge is 51 bar against 68 bar recorded in the test in
Figure 4. Pressure and impulse meter data obtained when 30 g ammonite charge was exploded at 1.35 m depth in water containing the bubble column of bubbling regime 2.

continuous water. Pressure gauge $D_1$ also shows some decrease (117 bar against 148 bar). Such behavior of the signals has been expected because the wave travels sideward through the 20 cm layer of bubbled water. The wave energy in the latter case also decreases drastically from 0.64 to 0.26 MJ/kg. As to the compression wave duration there is clear evidence of its increase when the wave traverses the bubble column. The duration of pressure pulses increases. When the charges were exploded in water with a bubble column it is virtually impossible to specify the time instant when the pressure reaches its maximum, because the signal consists of a set of periodical pulses. This becomes particularly obvious when the pressure signals were compared with their counterparts recorded in tests with no bubble column by gauge $D_1$. In the case when the bubble column is present, the relatively smoothly decaying pressure profile behind the shock front consists of a number of short pulses. Averaging of such a signal yields a decaying signal whose shape resembles that of a signal recorded in continuous water. The short pulses are most likely produced by multiple wave reflections at the bubbled column borders. Furthermore, bubble density distribution in the column is not uniform which can also be responsible for pressure pulses, due to multiple wave reflections within the bubble column. When the charge was exploded in the presence of a bubble column, the impulse meter demonstrates an increase in the maximum kinetic energy acquired by the target. Its full displacement during compression wave action indicates that the mechanical impact of the explosion was directed to the target. The nature of the velocity build up process is also two-stage as in the case of continuous water. Bubbled column extends the velocity build up time in conformity to the increased compression wave duration. Therefore, an increase in the impulse meter velocity at the second
Figure 5. Pressure and impulse meter data obtained when 30 g Al-rich charge was exploded at 1.35 m depth in continuous water.

acceleration stage is less and amounts to 35% (of first one) against 44% in the case of continuous water.

6. Explosion of an Al-rich charge
To have a reference, the charge of the basic 1 : 1 mixture in continuous water was exploded and the results were compared with their counterparts measured with ammonite explosion under the same conditions. Then the basic 1 : 1 charge was exploded in the presence of a bubble column according to the scheme of ammonite charge with the bubble column of the second bubbling regime.

6.1. Explosion of a nonideal charge in continuous water
The HSW amplitude at test in which a 1 : 1 charge (run 3 in table 2) has been exploded is more than twice as high as the one measured in the test with ammonite (355 bar against 148 bar). It is owing to the higher explosion heat of the 1 : 1 charge. The shock wave energy also increased from 0.64 to 0.9 MJ/kg. It has been expected because traction of the excess aluminum with water contributed to it. Signal from the upper pressure gauge exhibits a sharp spike of amplitude amounting to 80 bar (see figure 5). These spikes are presumably induced by very fast aluminum reaction with water initiated by the high temperature after some delay caused by premixing.

The impulse meter velocity built up as before in two steps. However, the overall rise intensity increased, while its relative value at the second step slightly dropped. The total impulse meter
Figure 6. Pressure and impulse meter data obtained when 30 g Al-rich charge was exploded at 1.35 m depth in water containing the bubble column of bubbling regime 2.

Displacement exceeded slightly its value recorded in the test with ammonite explosion. The maximum kinetic energy was also slightly increased. On the whole, the test demonstrates only a slight gain in the mechanical impact parameters compared to those in the case of ammonite explosion. Enhancement of some parameters was ascribed to reaction of the excess aluminum with water.

6.2. Explosions of nonideal charges in water with a bubble column

An Al-rich mixture charge (1 : 1) was exploded in water with a bubble column created by the airflow fed in regime 2. The data obtained are displayed in figure 6.

The pressure records demonstrate an increase in the HSW pulse duration compared to all above experiments. The shock wave energy slightly increased in comparison to the explosion of the same charge in continuous water. Shock wave front pressure was lower than that recorded in run 3 but up to two times higher than in the case of the ideal charge detonated in bubbled water. Multiple spikes were observed in the pressure profiles behind the shock front. This observation is tentatively attributed to inhomogeneous distribution of the aluminum oxidation reaction spots in the cloud. As shown in [7] the rate of water entrainment in the detonation product flow containing excess aluminum ready to react affects heavily the efficiency of aluminum–water reaction in the heterogeneous cloud behind the HSW front. The mixing process is intensified considerably in the presence of a bubble column due to jets of the products containing excess aluminum penetrating deeply into the low-density media. In addition, the compression of the
gas inclusions increases the fluid temperature and hence the aluminum oxidation rate. Gas-
dynamic perturbations within the cloud increase due to multiple reflections in the two-phase
medium. The Al–water reaction surface also increases rapidly due to break up of the jets. As a
result, intensification of the reaction and an increase in the compression wave pressure impulse is
observed as compared to run 3 where the water penetrates into detonation products mainly due
to the interface instability and by the jets formed after destruction of the charge enclosure. The
impulse meter accelerates much faster compared to both the explosion of a nonideal charge in
continuous water and explosion of ammonite in bubbled water. The two stages of velocity build
up are also observed there, but the velocity rises more smoothly than it does in the reference
tests. The relative velocity increase at the second stage is greater than that in the reference
tests, presumably because the fluid energy in the bubbled water is larger. The maximum kinetic
energy value is also greater (about 1.5 fold) compared to the reference tests.

Some interim conclusions should be mentioned:

- The presence of air bubbles in water around the charge intensifies significantly the reaction
  of excess aluminum with water.
- Directed bubble column induces redistribution of the explosion energy. As a result, the
directional effect of compression wave is observed.

7. Effects of the bubble column parameters and charge composition

7.1. Effect of bubble column length

The enhanced parameters obtained in the previous experiment raise a question how the charge
and the target should be disposed with respect to each other to provide the highest impact
parameters, when a bubble column is present in water. To answer the question we performed
comparative experiments in which a 1:1 charge was exploded in water with a bubble column (air
flow regime 3) at various depths (1.35 and 2.05 m from water surface). Regime 3 (large bubbles)
of bubble generator operation was chosen because we failed to make a 2 m long bubble column
in regimes 1 and 2. At low air flow rates the bubble column was unstable in its upper portion
where column spread throughout the reservoir cross section. Observations of the behavior of
large bubbles in a long column have shown that the radial expansion of the column did not
exceed 10%. Thus, the average density of the heterogeneous medium of water with air bubbles
was changed insignificantly. Reference experiment (run 5) demonstrates the highest kinetic
energy of impulse meter and some enhancement in other parameters. The reaction time within
the longer bubble column (run 6) can be longer than the time allotted by the unloading process
in run 5, consequently, the maximum mechanical explosion impact on the target can be greater
in the case of a longer impact time. It is clearly seen in table 2 that the HSW and impulse meter
parameters are much lower than they are in the reference experiment with a shorter bubble
column (run 5), except pressure signal at $D_1$ which was situated closer to the charge.

The comparison between the results of two experiments suggests the following conclusions:

- The optimal bubble column length was found as a function of the charge weight, target
  size, and bubble density.
- The optimal arrangement of the setup is that of test 5, therefore the further comparative
tests were carried out in the same geometry.

7.2. Effect of the bubble column properties

To investigate the effect of the bubble column properties upon parameters of nonideal directed
explosions, in addition to the above discussed tests 3, 4 and 5 (see tables 3 and 4) an experiment
with the same setup but with the lowest air flow rate (feeding regime 1) was carried out. Apart
from that, to clear up the effect of the volume fraction of bubbles in water, the experiments
with increased excess aluminum content were analyzed. They are: runs 8 and 9 in which the 1.5 : 1 mixtures were exploded with air feeding regimes 1 and 3 and experiments with the 2 : 1 mixture in which the same air flow regimes are used (see runs 10 and 11). Thus, the entire set of experiments with 1 : 1, 1.5 : 1, and 2 : 1 mixtures was obtained to compare their results at various air flow feeding regimes.

For a start, we compared the results of experiments with the 1 : 1 mixtures (runs 4, 5, and 7). Comparison of pressure profiles recorded by gauge D2 reveals an interesting peculiarity. In tests with the bubble column, the pressure signal decays behind the HSW. The pressure trace is smooth when the charge is exploded in continuous water, as distinct from explosions in a bubble column. The duration of individual pulses increased as the bubble size increases. This is presumably associated with transverse waves traveling within the column and induced by the wave spreading through the continuous water surrounding the column. The larger the bubbles size the longer the circulation period of these transverse waves because of the lower acoustic velocity in the bubbled water. The maximum amplitude of the averaged signal increases as the bubble size increases, because of the lower density of the column. Signals recorded by the lower gauge D1 behave similarly with increasing bubble size with the only one difference—the shock wave (run 5) is attenuated intensively. The highest HSV energy in water with the bubble column was obtained in the case of bigger bubbles (1.34 MJ/kg in run 5). Thus, there are some optimal bubble size and average bubble column density values at which HSW absorption is not intense and mixing of the aluminum rich products with water are most favorable for a higher fraction of aluminum burnt in water. It should be noted that the maximal kinetic energy of impulse meter was observed in the case of smallest bubbles. It means that the heat of explosion is utilized better by the array of small bubbles with larger specific contact surface between the water and air. Comparison of the results of tests where the charges contained a different amount of excess aluminum (runs 8 and 9 for the 1.5 : 1 mixture and runs 10 and 11 for the 2 : 1 mixture) have been exploded demonstrates the same behavior of the compression wave parameters as the bubbles volume fraction changes. Experiments with the 1 : 1 mixture demonstrate a similar trend, but the impulse value is at its maximum when air feeding regime 2 was used. Behavior of the impulse recorded by the lower gauge D1 can be explained by intense energy absorption when the bubble column is generated in regime 3, i.e. at the highest bubble volume fraction.

It is also necessary to explain why the impulse values that follow from the integrated pressure-time history and from impulse meter measurements differs. Integration of pressure records with respect to time yields the static momentum component, which in continuous water virtually equals the total momentum because water compressibility is very low. When a compressible fluid is present in the reservoir the situation significantly changes. The dynamic momentum component increases the more the lower the fluid density. The dynamic component of momentum is converted into pressure at a reflecting obstacle. Therefore, the impulse derived from the accelerometer signal is higher.

7.3. Mixture composition effect
To study the effect of excess aluminum in the mixture we consider two groups of tests. In the first group (runs 7, 8 and 10), the nonideal charges were exploded within the heterogeneous bubble column containing the lowest volume fraction of bubbles (regime 1). In the second group (runs 5, 9, and 11), the same charges were exploded within the bubble column generated by regime 3 with the highest air flow rate. There are three compositions with different aluminum content (1 : 1, 1.5 : 1, and 2 : 1) in each group investigated.

Parameters of the pressure waves do not depend monotonically on mixture enrichment. Thus, the shock wave impulse at gauge D1 is the highest tests with the 1.5 : 1 mixture, whereas the explosion of 1 : 1 mixture produced the highest pressure of 193 bars. As follows from the analysis of impulse meter motion this dependence reverses, that is, an increase in aluminum
concentration entails a monotonic reduction of all the parameters. The velocity rises up in two stages, which is inherent in tests with the bubble column containing small-size bubbles in a low concentration. The kinetic energy of impulse meter decreases in tests with rich mixtures. This set of experiments demonstrates that an increase in the aluminum content in the mixture is not actually beneficial, so that the 1 : 1 mixture turns out most optimal in terms of the majority of parameters. However, at the explosion of bigger charges when the explosion processes are observed longer time one can expect a more significant effect of an increase in aluminum content in the charge.

7.4. Effect of bubble generator location

In all previous experiments, the bubble generator was mounted half meter below the charge. The reason for such its position is as follows:

- Heterogeneous medium around the charge would facilitate water mixing with the Al-containing detonation products and thereby a heat release will be intensified.
- Continuous interaction between the cloud of detonation products, oxidation zone of excess aluminum, and bubble column would provide a lowest energy losses in the course of acceleration of the heterogeneous media that impact the target.

However, keeping in mind that the initial particle velocity vector was oriented predominantly upward because the charges were initiated at their bottom end, one should expect that the presence of bubbled liquid beneath the charge could lead to undesired additional unloading of the expanding detonation products and therefore to the reduction of the directed compression wave intensity. Therefore, we carried out one additional experiment where the bubble generator was mounted at the charge level. As it was expected, the presence of continuous water underneath the charge increased the heterogeneous column acceleration. The lack of unloading of the pressure pulse generated by the charge and continuous contact of the detonation products with the bubbled water supplied efficiently water vapor to Al-contained products which provided the highest impulse meter movement parameters, comparative to all experiments conducted in the present work. The velocity history curve demonstrates no stages. It means that the two stages actually merged. This implies that the directed compression wave was supported by the metal–water reactions.

7.5. Results

It should be noted that the data on mechanical impact of the directed compression waves pertain solely to the initial explosion stage limited by the 10 ms time window when the impulse was monitored by the accelerometer. The full pattern of possible mechanical impact development can be obtained after conducting larger-scale experiments with bigger charges in unconfined basins.

Comparison between experimental results obtained from explosions of nonideal charges in continuous water with those produced by ideal explosions demonstrates a significant contribution of the aluminum–water reaction especially at the first stage of expansion. These reactions increase both the HSW amplitude and its specific shock wave energy up to a factor of two.

Comparative experiments carried out have demonstrated that the HSW amplitude generated by ideal charges diminishes significantly in the tests where the wave propagates in a bubbled liquid. No any enhanced mechanical effect was observed and the process was fully conformed to the well-known fact of shock wave suppression by bubbled curtains.

When nonideal Al-rich charges were exploded inside a bubbled column, the mechanical impact produced is not only much stronger than those produced by ideal explosion, but exceeds the effect of explosion of the same nonideal charge in continuous water as well. Explosion in the
heterogeneous medium significantly intensifies water vapor admixing to the zone where excess aluminum reacts with it. Reacting heterogeneous cloud spreads preferentially along the bubble column. Intensity of the reaction in the cloud fades out gradually because of expansion and cooling with water. Analysis of all stages impulse meter motion demonstrates clearly the directed mechanical impact of the explosion.

To optimize the explosion energy distribution that provides enhanced directed mechanical impact one has to consider several effects:

- Shock wave decay in the bubbled liquid must be minimized, provided that inhomogeneity of the fluid remains at a level which warrants sufficient feeding of the reacting cloud with ambient water in order to keep aluminum oxidation going on. We believe that the optimal air flow rate is in between those in regimes 1 and 2 (closer to the latter one).
- An increase in bubble column compressibility in the experiments with the higher air flow rates would result on the one hand a more uniform target loading and on the other a possible compression wave suppression and reduction of the volume fraction of aluminum reacted, because of non-optimal water supply to the reaction zone.
- Within the present experiment arrangement (in which the surface area of the impacted plate of the impulse meter is less than the cross section of the reacting cloud) unloading of the reflected compression wave along the impulse meter walls can be a responsible for reducing the impulse meter acceleration. This effect can decrease the characteristics of the mechanical impact from explosion.
- Compression of the small size bubbles of a low concentration within the bubble column by the compression wave that spreads in ambient continuous water at a velocity which is much higher than does the wave in the bubbled column can result in enhancement of the mechanical impact. This is because the fluid density within the bubble column increases before arrival of the wave spreading through the column.

Experiments performed with the charges where Al to O ratio was varied, have demonstrated that an increase of the volume fraction of aluminum in small-size charges brought about no advantage. The 1 : 1 mixture provided the optimal values of the compression wave parameters. However, visual observations of the mechanical effects at later times allows one to hope that an increase in the aluminum content can offer some benefit in the case when explosions of larger charges are conducted in unconfined water volumes at deeper charge submersion.

The effect of the heterogeneous column position was also considered in comparative tests, where the column started 0.5 m beneath the charge, and at its level. The best results were obtained in the test when the bubble column started from the charge level. The following factors are responsible for better explosion performance in this case:

- Expansion of detonation products begins without unloading in the direction opposite to the initial particle velocity vector. Higher pressures at the initial expansion stage probably result in intensification of both mixing and aluminum–water reactions.
- All the explosion stages interact continuously.

8. Conclusion

Summarizing the findings, we can state that reaction of excess aluminum enhances appreciably the mechanical effect of explosion and that bubble column makes it possible to enhance mechanical impact in a chosen direction and to control, to a certain extent, the explosion energy.
Acknowledgments
Authors appreciate sincerely A V Savchenko for his advice and help in the experiments. The work in area of experimental investigation on directional effect in bubbled column is supported by the Russian Foundation for Basic Research (grant No. 16-29-01077). Authors also acknowledge the Federal Agency for Scientific Organizations of Russia (project 0082-2018-0002, registration code AAAA-A18-118031490034-6) for a financial support of the experimental part where explosions of Al-rich charges were compared with conventional high explosives in continuous water.

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