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Review

The Breakup of Gas Bubbles by a Shock Wave: Brief Historical Background

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Abstract: A gas-hydrate method of CO_2 gas storage is one of the modern technology for reducing it emissions into the atmosphere. The breakup of gas bubbles by a shock wave is an actual area of scientific and technological research. However, it is little known that such research began in the late 1950s in the USSR. The article presents the main discoveries related to the destruction of gas bubbles in a liquid under the influence of a shock wave, made more than 60 years ago. Looking back: study the past to understand the present.

Keywords: gas bubble in liquid; cumulative jet; shock compression; gas-bubble fragmentation

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I. Introduction

An increase in the methane, CO_2 (carbon-dioxide) and nitrous oxide concentration in the atmosphere is one of the key factors of Earth's climate change [NAS 2020, Friedlingstein 2022, Lan 2022]. CO_2 is a greenhouse gas that radiates and absorbs heat [Pandey 2022]. The solution to the problem of reducing CO_2 emissions into the atmosphere is provided for by the Kyoto Protocol [Rosen 2015]. A promising way of CO_2 recycling is its conversion into a gas–hydrate state [Kuang 2022, Rehman 2022]. Today a gas-hydrate method of natural gas storage and transportation is the profitable and modern for gas and oil fields of natural gas [Gudmundsson 2002, Takaoki 2008, Kezirian 2017].

At the same time, in the USSR, the beginning of these studies was laid in the pioneering works of Prof. Vladilen F. Minin [Minin 2023] since the mid-1950s (Figure 1). V.F. Minin was a founder, general director and chief designer of the Order of Red Banner of Labour Institute of Applied Physics, Novosibirsk (1966–1996); a founder and a president of Urals-Siberian branch of Russian Academy of Technological Sciences; laureate of the USSR State Prize, holder of the Order of Lenin (for foundation of the Institute of Applied Physics and achievements in the development of science), the Order of the Red Banner of Labour, and many medals. However, his work in these fields were little known for a number of reasons, and the purpose of this article is to fill this gap and provide a brief historical background of the origins of such research.

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Figure 1. Prof. Vladilen F. Minin: in 1961 (left) and in 1994 (right).

II. Brief history

The hypothesis of the possibility of the breakup of gas bubbles by a shock was intimated in 1957 [Hartunian 1957]. Almost 15 years later in theoretical work [Noordzii 1973] on the structure of a shock wave in a two-phase mixture of a gas bubbles in liquid the behavior of the bubbles has been described following by the papers of Rayleigh. The displacements of the bubble surface have been regarded as spherically symmetric and small. It was observed that bubbles preserve their integrity in waves with small pressure in a shock front [Jensen 1973, Soloukhin 1961]. The breakup of gas bubbles under a pressure step has been demonstrated in [Hermans 1973].

At the same time Prof. V.F.Minin as early as at the late 1950 - early 1960 have propose a new method of intensification of gas-hydrate formation under the shock wave in liquids. He for the first time experimentally shown [Minin 1961] that the shock-wave gas-bubble fragmentation [Kuznetsov 1961] is the main mechanism providing the intensification of the hydrate-formation process, which leads to a significant reduction in the size of gas inclusions due to an increase in the interfacial surface [Minin 1961]. For example, Academician V. Kuznetsov in 1961 was mentioned [Kuznetsov 1961] that (excerption) "*Vladilen Minin, a scientist of the Institute of Hydrodynamics, put forward an idea to dissolve hardly-soluble gases in liquid by explosion. When the shock wave passes through the liquid with gas bubbles, the latter break into small ones. Thus the area of gas-liquid contact grows, with dissolution being sharply accelerated.*"

In contrast to [Jensen 1973, Soloukhin 1961], V.F. Minin discovered for the first time the effect of the formation of a cumulative jet directed along the path of the wave when a gas bubble is collapsed asymmetrically [Minin 1961] that is the key mechanism for the fragmentation of gas bubbles in a liquid under the action of a shock wave. He have shown that a cumulative jet of liquid cuts through the bubble interior accompanies the inception of breakup of the bubbles. It has been shown that the speed of liquid particles on the surface of the bubble depends not only on the pressure at the wave front, but also on the angle of its incidence on the interface. It was found that real bubbles with a diameter of more than 1 millimeter do not have a spherical shape and are elongated in a direction perpendicular to the direction of ascent, i.e., in the direction of the shock wave approach, which significantly affects the nature of their compression. It is quite clear that the nose of the bubble will receive a speed several times greater than the side walls, where the angle of incidence is close to zero. Since different points on the surface of the bubble have different velocities at the initial moment, the bubbles are compressed asymmetrically. The compression process is unstable and the asymmetry increases during collapse. In the case of a symmetrical round bubble, this leads to the formation of a cumulative water jet that pierces the bubble, and in the case of a lenticular bubble, the jet turns into a strip (knife cumulative jet), cutting the bubble into two parts if the dimensions of the bubble are small enough (Figure 2).

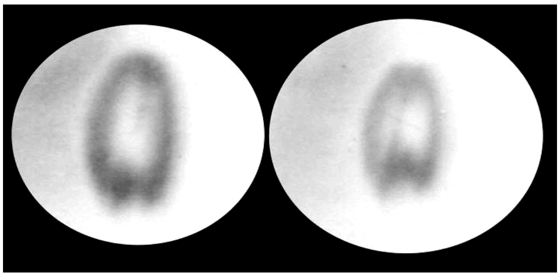

Figure 2. Example of breakup of the bubbles by shock wave. 1958. Adapted from [Minin 1961]. The front half of the bubble collapsed, forming a cumulative jet, which then interacted with the rear wall of the bubble.

The process of destruction of gas bubbles in a liquid is accompanied by turbulization of the liquid, which significantly reduces the time of gas dissolution. Five years later, Benjamin & Ellis in

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1966 [Benjamin 1966] demonstrating the existence of a liquid jet induced towards the wall at bubble collapse near the rigid wall.

III. Shock waves in Bubble Media

Experimental analysis of the propagation and attenuation of shock waves of different amplitudes in bubble screens with different acoustic properties in these years were begun by V.F. Minin [Minin 1961]. He also examined a sequence of alternating flat one-dimensional gas and liquid layers as the first convenient model of a screen. The experimental transformation of strong and weak shock waves through a layer of liquid with gas bubbles has been studied and analyzed, the role of gas (oxygen, nitrogen, hydrogen, carbon dioxide) inside the bubble on the characteristics of shock wave transformation has been studied.

The experimental analysis of the behavior of the shock waves interaction with a gas layer have allow for the first time unquestionably lend insight into the physics of shock transformation in bubbly media. For example, carbon dioxide was chosen as the bubble gas, since this gas makes it possible to obtain bubbles that are similar in diameter. The pressure oscillogram when a shock wave passes through a single-layer bubble screen is shown in Figure 3. It has been shown that after passing through the layer of bubbles, the pressure at the wave front dropped, and the wave itself split into two, following each other.

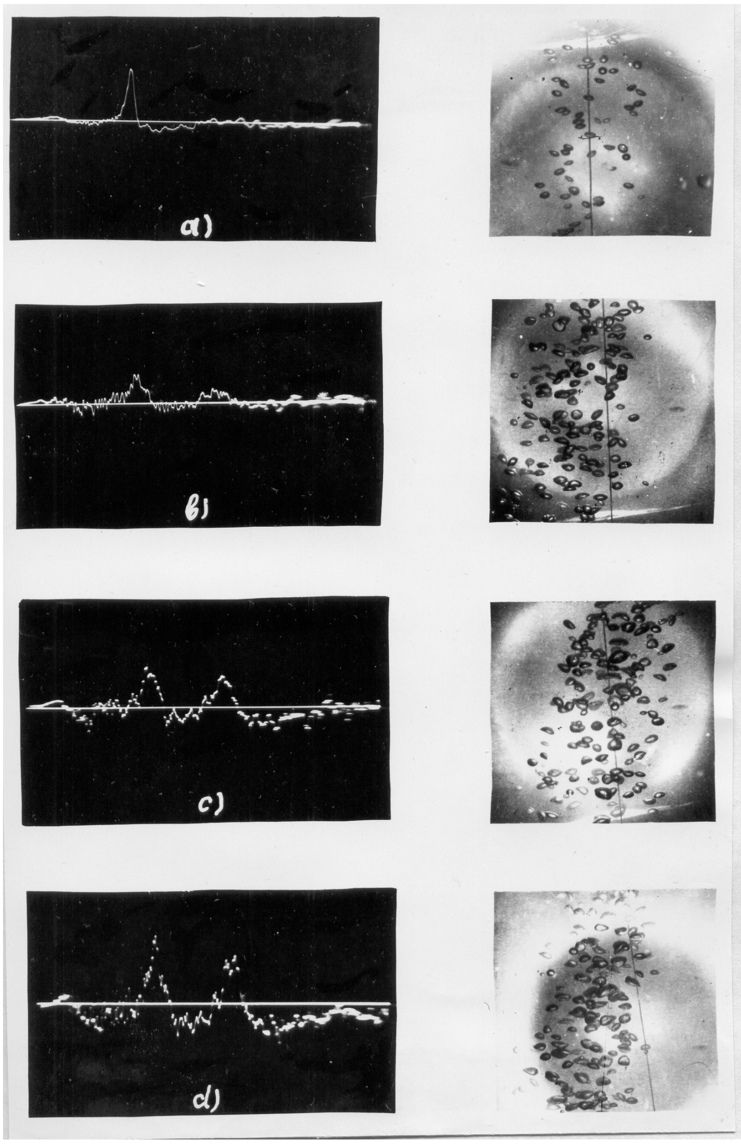

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Figure 3. Shock wave interaction with a cloud of gas bubbles with different air concentrations: C = 0.6% (a); 2.8% (b); 4.7% (s); 5.8% (d). Adapted from [Minin 1961].

Experimental results clearly shown the stratification of the initial shock into two ones: a shock wave transformed by the layer, and later radiation from the deformed layer. It has been shown that the linear scale of transmitted shock pulse are comparable with the bubble spacing.

In this case the gas-liquid medium can not to describe as a "continuum" medium because the shock in such medium as scattered as absorbed by individual bubbles. The second wave are the radiation of wave energy that have absorbed by gas-liquid layer. This second wave dissipates during the interaction with the gas bubbles. The energy of such second wave transforming into the internal energy of the compressed gas and kinetic energy of radial pulsations. As the result, all the energy absorbed by the bubbles layer becomes localized in the compressed gas at the moment of the bubbles collapse. Thus, the collective effect of compression determines both the parameters of dissipation and the amplitude of the radiation of shock wave. Moreover, the time delay of inception of the radiation maximum is determinates by inertial character of the collapse process (see short review in [Minin 2011]). It was found to exist such the bubbles layer parameters, which completely absorbs the shock wave energy. This energy is re-emitted in the form of pulsations, decaying at its own frequency.

As the bubble size increases, the period of pressure pulsations increases. Thus, with bubble sizes of about 8 mm, the periodic structure of pressure waves passing through a cloud of bubbles is shown in Figure 4.

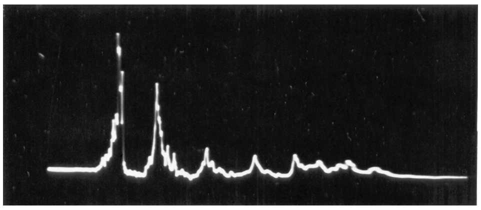

Figure 4. Periodic structure of pressure waves passing through a cloud of bubbles. Adapted from [Minin 1961].

V. F. Minin shown that strong attenuation of the shock wave in the mixture occurs due to various reasons. These include the fragmentation of bubbles during compression of the medium, the dissolution of gas contained in fragmented small bubbles, turbulization of the liquid flow during compression and other processes. The existence of a series of precursors with the distinct periodic structure of the resultant signal was discovered in the experiments. The maxima of secondary waves are determined by the parameters of the bubbles layer and are observed with a time delay relative to the precursor.

IV. Explosion near and on a free surface

Amongst studies of surface effects we should call attention to the problem of modeling of an explosion near and on a free surface. V. F. Minin in his graduate work, made in 1956-1958 in Moscow Institute of Physics and Technology, tested the schemes with one and two dischargers (disruptive distances). The results of this test (estimation of the acid brick destruction extent) showed that the destruction with one discharger was equal to that with the two. Thus, he concluded that the discharge in water is an underwater explosion. The destruction resulting from the discharge in water is of the same level as that due to the underwater explosion [Smirnov 2019].

The formation of a discharge in water and the dependence of current and voltage on the conductivity of water were studied in details. It is shown that from the moment voltage is applied to the spark gap, gas bubbles spread from the anode to the cathode. When a gas bubble approaches the cathode, a water breakdown occurs. The moment of breakdown is clearly visible in the photograph taken with tenfold magnification (Figure 5). As a bubble streamer propagates, a glow is observed at the sharp end of the bubble [Minin 1961] (Figure 6).

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Figure 5. Formation of a discharge in water (from left to right), Photo exposure $5*10^{-6}$ sec. 1957. Adapted from [Minin 1961].

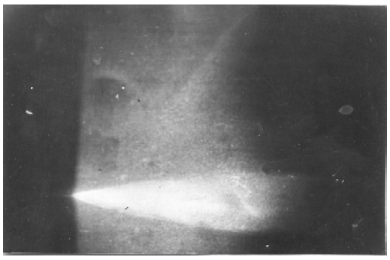

Figure 6. The glow of the bubble and the shock wave from the electric discharge in water. Adapted from [17].

Interesting that in 1960, Jarman proposed the theory of sonoluminescence phenomenon. He concluded that sonoluminescence might possibly arise from shocks with the collapsing cavities [Jarman 1960]. But at that time Prof. Minin do not know this hypothesis.

Note that the first studies devoted to the application of two-phase models to various formulations of erosion effects were carried out in [Minin 1961]. Experiments with electric discharge in liquid have shown that a bubble cluster develops in the discharge gap because of the action of tensile stresses in rarefaction phases. Analysis of the interaction of a bubble with a shock wave made it possible to explain the mechanism of damage to a solid surface due to the impact of shock waves and cumulative jets that arise during the collapse of a gas bubble.

Under an underwater explosion near free surface, an anomalous growth of the first pulsation amplitude of a gas bubble and shock wave leads to the formation of lateral and vertical localized liquids jets (so called "sultan" – see Figure 7) on a free surface. In the USSR, the role of the gas bubble and shock wave to the physics of sultan formation for the first time was investigated experimentally by V. F. Minin.

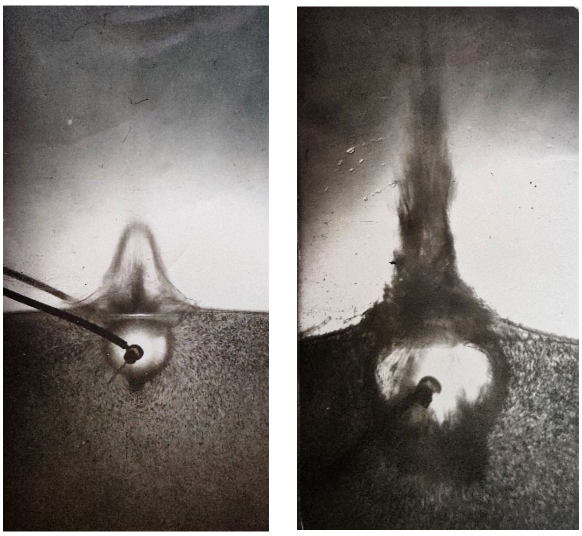

Figure 7. Dynamics of a plume (sultan) formation during an electrical explosion near the surface of a liquid. 1958.

It was shown that at the initial moments of time part of the liquid above the gas bubble contains an upward vertical impulse with a maximum velocity perpendicular to the liquid surface. At the subsequent time, this part of liquid moves inertially and is transformed into a sultan (cumulative jet). Moreover, the maximal pressure of the first pulsation is determinates by the variation in the gas bubble shape collapsing near the free surface. During the initial position of the underwater charge moves to the direction of a free surface, the maximum amplitude of the first pulsation is nonlinear - first it decrease and then fastly increase up to a amplitude exceeding the maximum value for infinite liquid. This phenomenon is due to the gas bubble collapses at this depth are accompanied by the cumulative jet formation directed from the free surface deep into the liquid.

Accurate experiments, performed later by V.F. Minin [Minin 1964] shown that cavity growth in electrical explosion near the surface of water proceeds according to a law close to the law of self-similar motion at constant energy. The flow arising is self-similar with indicator equals 0.38 and 0.47 for point and cylindrical explosions, respectively [Minin 1964]. This fact allow introducing the energy transferred to the ground and estimating its value by comparing the mechanical action parameters of contact and slightly submerged charges. The shock wave from the explosion forms on the free surface a cumulative cavity. Flow into the cavity with velocity field orthogonal to its surface leads to development of a cumulative jet.

It is noteworthy that these studies have not lost their relevance - to some extent, the phenomenon of the boundary point explosion problem near the surface in initial stage is similar to the laser-induced displacements of the liquid surface [Emmony 1976]. In both cases, the displacement of the initial hemispherical shape develops evolves to produce a closed bubble under the surface.

Later [Minin 1970] an experimental study of an explosion close to a free surface (sultan) was continued. Principles connected with the penetration depth of the discharge were established. It was shown that the nonsymmetry of the explosion bubble compression produced by the free surface leads to the formation of vortex motion during bubble compression. Experiments were conducted under laboratory conditions using an electrical discharge and explosive charges of 1 g. Under natural conditions, charges up to 10 kg were detonated. For the plane case under laboratory conditions a fluid velocity field and particle trajectories were obtained.

V. Conclusion

The phenomenon of bubble collapsing are popular up to today due to the often presence of gas bubbles in our world. For example, in nature gas bubbles are often present in clouds. However, despite the passage of time, many of the physical effects briefly described above still continue to be studied and "rediscovered." These phenomenon's can be exploited for energy generation, medical treatment, for enhancing or initiating chemical activity and gas conversion into a gas–hydrate state, etc.

In common, V.F. Minin for the first time investigated the problems of explosion in water (both by electrical discharge and by explosive), surface explosion, ball- and beaded lightning, *explosive acoustic sources; shock waves propagation in water with gas bubbles; explosive plume formation in water, etc. According to academician M. Lavrentyev, "no other laboratories of the Institute were working on the comparable problems at that time."* (Figure 8).

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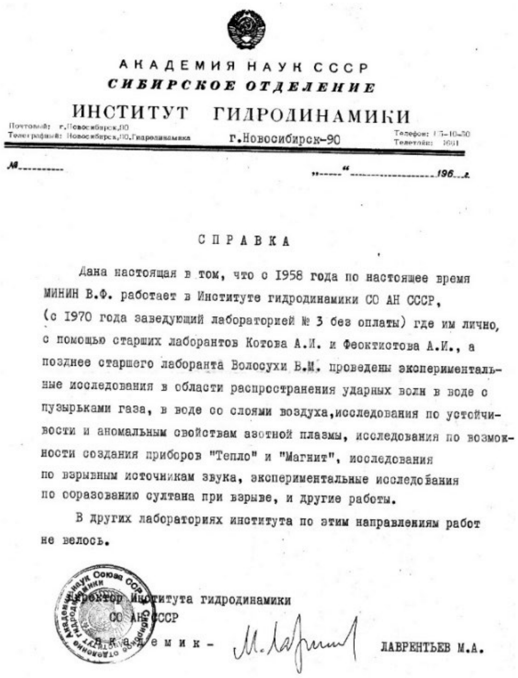

АКАДЕМИЯ НАУК СССР
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СПРАВКА

Дана настоящая в том, что с 1958 года по настоящее время МИНИН В.Ф. работает в Институте гидродинамики СО АН СССР, (с 1970 года заведующий лабораторией № 3 без оплаты) где им лично, с помощью старших лаборантов Котова А.И. и Феоктистова А.И., а позднее старшего лаборанта Волосухи В.М. проведены экспериментальные исследования в области распространения ударных волн в воде с пузырьками газа, в воде со слоями воздуха, исследования по устойчивости и аномальным свойствам азотной плазмы, исследования по возможности создания приборов "Тепло" и "Магнит", исследования по взрывным источникам звука, экспериментальные исследования по оразованию султана при взрыве, и другие работы.

В других лабораториях института по этим направлениям работ не велось.

Директор Института гидродинамики
СО АН СССР
академик - ЛАВРЕНТЬЕВ М.А.

Figure 8. Certificate from Academician M.A. Lavrentiev about the pioneering works of V.F. Minin.

Lavrentyev wrote: "Since 1958, V.F. Minin personally, and later with the help of laboratory assistants Kotov, Feoktistov, Volosukha, carried out experimental work in the field of propagation of shock waves in water with gas bubbles, in water with layers of air, studies on the stability and anomalous properties of nitrogen plasma. ... research on explosive sound sources, experimental studies on the formation of a plume (sultan) during an explosion and other works.

No other laboratories of the Institute were working on the comparable problems.

Director of the Institute of Hydrodynamics of the Siberian Branch of the USSR Academy of Sciences, academician M.A. Lavrentyev."

Today, research in this area continues intensively throughout the world [Vedadi 2010, Siew-Wan 2015, Apazidis 2016, Minin 2016, Wu 2017, Bempedelis 2020, Zhang 2023, Rawat 2023]. For example, the experimental studies of the shock-induced collapse of bubbles in liquids was studied in 1983 [Tomita 1983], who also consider multiple gas bubbles [Tomita 1984]. However, all these (and other) authors were apparently unfamiliar with the pioneering research briefly described above. And many modern "discoveries" were discovered much earlier. To create the future, we must know and study the past.

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