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# PHYSICAL FUNDAMENTALS OF ULTRASONIC DEGASSING

One of the key benefits of hydraulic system is its rigidity. It lets the signal to be transmitted from the source to the recipient with no loss. Positioning accuracy of actuators significantly depends on the rigidity. The higher the rigidity, i. e. volumetric elasticity modulus, the more accurate performance of hydraulic actuators. The presence of free and dissolved air in liquid is one of the key properties that affect the rigidity. Means of degassing discussed in the paper show a good potential for the mechanical methods, especially for the cavitation technologies. Based on the physical aspects of degassing, the authors recommend to use high- and low-amplitude ultrasonic oscillators to remove air from reservoirs of hydraulic systems. Experiments with degassing of various liquids: water (density $\rho = 1000$ kg/m$^3$); hydraulic oil (density $\rho = 860$ kg/m$^3$); engine oil (density $\rho = 844$ kg/m$^3$) were mainly focused on the amount of extracted air depending on the duration of oscillations. Comparative analysis of degassing velocities at liquid settling technique and ultrasonic degassing technique proved that the latter one has a better potential. A great deal of attention was paid to the problem of the degassing of hydraulic reservoir, directly at suction line of the pump. The removal of dissolved and free air significantly influences the non-cavitational operational mode of the pump. Which, in turn, prevents the equipment from early failure.

**Keywords:** ultrasonic degassing, hydraulic system, density, ultrasonic cavitation method, suction line of the pump, liquid.

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# ФІЗИЧНІ ОСНОВИ ПРОЦЕСУ УЛЬТРАЗВУКОВОЇ ДЕГАЗАЦІЇ

Одною із переваг гідравлічних систем є її висока жорсткість. Ця якість дозволяє з високою швидкодією передавати сигнал від джерела до споживача. Втрати при цьому мінімальні. Від жорсткості системи безпосередньо залежить точність позиціонування виконавчих пристроїв. Чим більше жорсткість, показником якої служить об'ємний модуль пружності робочої рідини, тим точніше операції, що виконуються гідравлічними приводами. На цей параметр має значний вплив наявність в робочій рідині розчиненого і нерозчиненого повітря. Розглянуті в статті варіанти дегазації рідини показали перспективність механічних способів, зокрема застосування кавітаційних технологій. Спираючись на фізичні основи протікання процесу дегазації, авторами було запропоновано використання високоамплітудних і малоамплітудних ультразвукових випромінювачів для видалення повітря з бака гідравлічної системи. Наведені авторами експериментальні дослідження процесу дегазації різних рідин: води (щільність $\rho = 1000$ кг/м$^3$); масла гідравлічного (щільність $\rho = 860$ кг/м$^3$); моторного масла (щільність $\rho = 844$ кг/м$^3$), стосувалися питань кількості виділеного повітря в залежності від часу озвучування рідини. Порівняльний аналіз швидкості дегазації рідини із застосуванням ультразвукового методу і методу, заснованого на відстоюванні рідини, наочно показав перспективність застосування ультразвукового кавітаційного методу. Особливу увагу автори приділили проблемі видалення повітря з гідравлічного бака безпосередньо в лінії всмоктування насосу. Видалення розчиненого і нерозчиненого повітря з лінії всмоктування впливає на безкавітаційний режим роботи насосу, що в свою чергу запобігає передчасному виходу обладнання з ладу.

**Ключові слова:** ультразвукова дегазація, гідравлічна система, щільність, ультразвуковий метод кавітації, лінія всмоктування насоса, рідина.

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# ФИЗИЧЕСКИЕ ОСНОВЫ ПРОЦЕССА УЛЬТРАЗВУКОВОЙ ДЕГАЗАЦИИ

Одним из преимуществ гидравлических систем является повышенная жёсткость. Это качество позволяет с высоким быстродействием передавать сигнал от источника к потребителю. Потери при этом минимальны. От жесткости системы напрямую зависит точность позиционирования исполнительных устройств. Чем больше жёсткость, показателем которой служит объемный модуль упругости рабочей жидкости, тем точнее операции, выполняемые гидравлическими приводами. На этот параметр оказывает огромное влияние наличие в рабочей жидкости растворенного и нерастворенного воздуха. Рассмотренные в статье варианты дегазации жидкости показали перспективность механических способов, в частности применение кавитационных технологий. Опираясь на физические основы протекания процесса дегазации, авторами было предложено использование высокоамплитудных и малоамплитудных ультразвуковых излучателей для удаления воздуха из бака гидравлической системы. Приведенные авторами экспериментальные исследования процесса дегазации разных жидкостей: воды (плотность $\rho = 1000$ кг/м$^3$); масла гидравлического (плотность $\rho = 860$ кг/м$^3$); моторного масла (плотность $\rho = 844$ кг/м$^3$), касались вопросов количества выделенного воздуха в зависимости от времени озвучивания жидкости. Сравнительный анализ скорости дегазации жидкости с применением ультразвукового метода и метода, основанного на отстаивании жидкости, наглядно показал перспективность применения ультразвукового кавитационного метода. Особое внимание авторы уделили проблеме удаления воздуха из гидравлического бака непосредственно в линии всасывания насоса. Удаление растворенного и нерастворенного воздуха из линии всасывания влияет на безкавитационный режим работы насоса, что в свою очередь предотвращает преждевременный выход оборудования из строя.

**Ключевые слова:** ультразвуковая дегазация, гидравлическая система, плотность, ультразвуковой метод кавитации, линия всасывания насоса, жидкость.

**Statement of a problem.** The efficiency of many processes depends on the quality of the power fluid used in the hydraulic actuating systems. The quality of the power fluid is significantly affected by the dissolved and undissolved air content. Undissolved air reduces the volumetric modulus of elasticity of the power fluid. Normally, the content of such air in hydraulic systems is 0,5–5 %, but this value can even be as high as 15 %. Dissolved air does not affect the modulus of elasticity during normal operation of the hydraulic actuator. However, when the pressure drops, e.g. at the pump inlet, if the suction filter is fouled, air is vented and bubbles form, which results in a higher content of undissolved air in the power fluid. As a result, the volumetric modulus of elasticity of the working fluid decreases, significantly increasing the probability of cavitation phenomenon with its destructive consequences for elements of the hydraulic system. The main nucleating center of cavitation in this case, as a rule, are undissolved air bubbles. Undissolved air also accelerates the oil ageing process in hydraulic systems. Therefore, the issue of fluid degassing is very relevant to ensure efficient and long-lasting operation of hydroficated process equipment.

**Physics of the degassing process.** Chemical, mechanical and physical methods of degassing liquids are known [1, 2].

When degassing liquids by chemical method reagents that bind gases dissolved in the liquid are used. For example, sulphur dioxide, sodium sulphite or steel wool are used for oxygen removal. Chlorine is used to remove hydrogen sulphide from water. The reaction produces sulphur crystals, which precipitate.

Mechanical methods of degassing operate on the principle of mechanical separation of the gas-liquid mixture by separation and filtration. These methods include centrifugal and filtration methods.

Degassing liquids physically involves influencing the physical properties of the liquid, usually by creating conditions in which the solubility of the gas in the liquid is close to zero, for example by heating, vacuuming or settling.

Physical methods of degassing also include widely known in practice technologies of cavitation degassing used in various industries in the food and chemical industries, power generation, metallurgy, etc. Cavitation technologies are implemented by means of hydrodynamic or ultrasonic cavitation. The acoustic or ultrasonic method of degassing is very common and consists in the introduction of intense ultrasonic vibrations into a liquid [2–4].

The mechanism of ultrasonic degassing occurs when nucleating centers of cavitation present in liquid in the form of stable gas bubbles and gas micro-bubbles on the surface of particles suspended in liquid under the influence of ultrasonic waves begin to vibrate intensively and increase in size at half-period of rarefaction and decrease in size at half-period of contraction. The increase in the bubble size is due to the fact that the internal pressure of the vapor-gas mixture in the rarefaction phase exceeds the external pressure of the liquid due to gas diffusion into the bubble from the liquid, as well as due to liquid evaporation from the inner surface of the bubble and an increase in the mass of vapor in the bubble [5–7]. The predominance of one or the other mechanism of bubble size growth depends on wave frequency, pressure and gas saturation of the liquid.

At high oscillation frequencies in a low gas saturated liquid at temperatures far from the boiling point, the main factor for bubble growth is the periodic excess of the internal bubble pressure over the external one.

The diffusion mechanism is the main one in the region of low vibration frequencies, when there is a low rate of pressure change in a liquid with significant gas saturation. As the concentration of gas in the bubble decreases due to a gradual increase in its size, gas diffuses from the liquid into the bubble. At the half-period of increasing pressure, the size of the bubble decreases and gas diffuses from the bubble into the liquid. Since the amount of gas, diffusing is proportional to the surface area of the bubble, which is larger in the bubble growth phase, in general during vibrational period due to the rectified diffusion process an increase of gas mass in the bubble and corresponding gradual growth of its size takes place [8]. Due to the described mechanism, cavitation bubbles either collapse with formation of spherical blast waves and intense microflows or they have time to rise to the liquid surface with increased size due to the growing ejection force and are released from it.

The main characteristics of degassing process are rate of change of gas concentration $C$ in liquid $dC/dt$ and equilibrium gas concentration $C'_p$, which is established in liquid in presence of ultrasonic field after some time interval. The change in gas concentration in the liquid in the acoustic field during the irradiation time is determined by the expression:

$$C = C'_p + (\mathrm{C}_0 - C'_p)e^{-b}, \tag{1}$$

where $C_0$ – initial concentration; $b$ – a parameter that is determined by acoustic characteristics – sound intensity and frequency.

There are two modes of ultrasonic degassing - pre-cavitation and cavitation.

In the first case speed of concentration change is proportional to intensity of sound, and its dependence on frequency f, obtained by generalization of experimental data, has the following form:

$$\frac{dC}{dt} = B \cdot f^n \cdot e^{-k}, \tag{2}$$

where $B$, $n$, $k$ – other empirical constants.

For the water degassing process (by air) at ultrasonic intensity $I = 0{,}03$ W/cm$^2$ the constants have the following values: $B = 2{,}3 \cdot 10^{-13}$, $n = 1{,}43$ and $k = 6{,}7 \cdot 10^{-6}$. And the rate of change in concentration is maximum at a frequency of $f = 200$ kHz. The value $C'_p$ is independent of the ultrasonic intensity and frequency.

If the ultrasonic intensity is sufficient to cause cavitation in the liquid under given conditions, the rate of change in gas concentration is also proportional to the sound intensity, but increases with increasing sound intensity faster than in the pre-cavitation mode, i.e. cavitation contributes to accelerating gas removal from the liquid. The gas removal rate remains at a value corresponding to pre-cavitation conditions. Only at very high sound intensities can an oscillation mode of cavitation bubbles be realized, at which a further increase in intensity causes a decrease in degassing rate.

The use of low-amplitude and high-amplitude ultrasonic emitters is recommended for introducing ultrasonic vibrations into the liquid. Low-amplitude transducers are used when it is necessary to obtain intensity of ultrasonic vibrations in liquid up to 6–8 W/cm$^2$. In this case, the mechanism of pre-cavitation and degassing is activated in the liquid due to the elastic vibrations. With increasing intensity of oscillations to the threshold of cavitation in the rarefaction phase began to actively form a large number of small vapor-gas bubbles, which are practically not visible to the naked eye (Fig. 1) [9]. Having made one or more oscillations with a change in size and accumulated energy, the bubbles collapse during the contraction phase. In this case, if the bubble is remote from neighboring bubbles or solid surfaces, its shape is close to spherical and its slamming occurs with the formation of spherical shock waves. Otherwise, the bubble shape is distorted and, due to radial unbalance of forces, the bubble collapses to form a cumulative jet directed towards the nearest surface. Shock waves and cumulative jets cause erosive destruction of solid surfaces. However, the slight oscillation of the bubbles and the diverging shock waves generate only minor microleaks in the liquid volume, which does not contribute to intensive degassing.

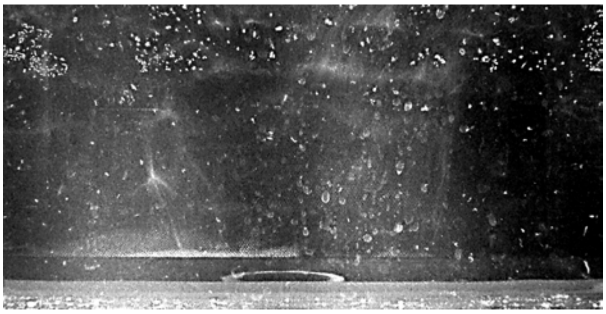


Fig. 1. Cavitation area formed by an ultrasonic low-amplitude transducer mounted on the bottom surface of the cavitation chamber

When the intensity of ultrasonic vibrations exceeds 6–8 W/cm$^2$ in the rarefaction phase cavitation bubbles are formed, which due to large amplitude values of sound pressure do not have time in the compression phase to slam shut, but continue to oscillate in time with the ultrasonic wave, gradually increasing in size to the size that can be observed with the naked eye (Fig. 2). At the same time, intensive cavitation pulls formed by steam-gas bubbles depart from the radiating surface. Fluctuations of these bubbles cause intensive microfluidic flows in the volume of the process fluid. The liquid enters a quivering, dynamic state. This is when the degassing process reaches its maximum intensity.

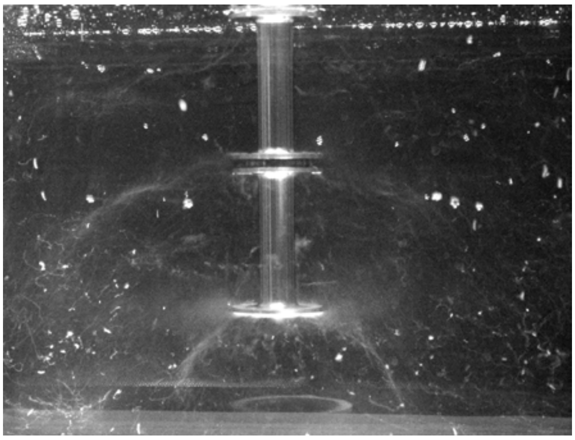
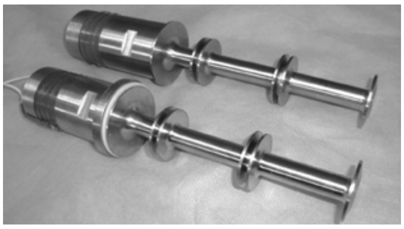


Fig. 2. Picture of the cavitation region created by a high-amplitude transmitter with a developed emission surface

In ultrasonic emitters high amplitude vibrations are achieved through the use of oscillating speed transformers (Fig. 3, *b*).

*a*



*б*

Fig. 3. Ultrasonic emitters:
*a* – low-amplitude; *b* – high-amplitude with developed surface

Attempts to increase the vibration intensity more than the specified limits for low-amplitude and high-amplitude emitters leads to disproportionate increase in losses when introducing high-frequency vibrations into the liquid. This is caused by the formation of a cavitation layer on the emitting surface, which is a cluster of steam-gas bubbles (Fig. 4). This two-phase layer causes scattering and absorption of ultrasonic energy. The need to increase the productivity of the degassing process requires the introduction of ultrasonic energy of sufficiently high power into the liquid. For this purpose a developed radiation surface is used (Fig. 3, *b*), and if necessary to increase the ultrasonic intensity different methods of concentration of ultrasonic energy in liquid are applied [10, 11].

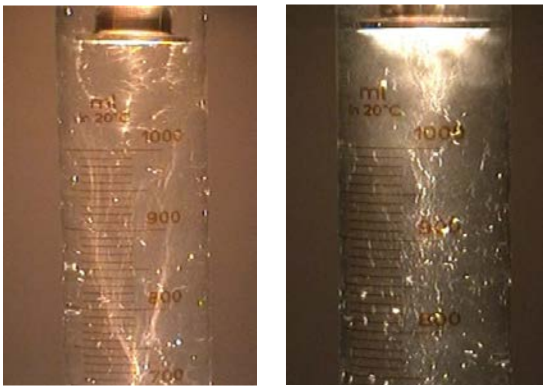


Fig.4. Formation of a cavitation layer on the radiation surface when the vibration intensity increases

**Experimental study of the degassing process.** For experimental investigation of degassing of liquids the volumetric method was chosen, which consists in investigation of change of liquid volume due to removal of air.The ultrasonic degassing method and the sedimentation method were chosen for comparison.

The experiment was carried out with the help of an experimental bench (Fig. 5).

A measuring tube 5 was used to investigate the change in liquid volume during degassing.

Water and two different oils were chosen for the experiments:

- water ($\rho = 1000$ kg/m$^3$);
- hydraulic oil Envirologic 3046 ($\rho = 860$ kg/m$^3$);
- motor oil Shell Helix Ultra 0w40 ($\rho = 844$ kg/m$^3$).

Water saturation with air was carried out by actively stirring the tank with liquid for 30 sec. To prevent the liquid from heating up under the influence of ultrasonic vibrations, this degassing method was investigated for no more than 1 min.

The intensity of the ultrasonic vibrations on the radiation surface is 12 W/cm$^2$. Power consumption – 100 W, temperature – 19 °C.

Fig. 6 shows how, due to degassing, the liquid becomes more transparent, the distribution 2 into a transparent degassing volume 3 of liquid and the volume 1 of the two-phase, air-saturated liquid are clearly defined. The volume of air removed reduces the liquid level in the measuring tube.

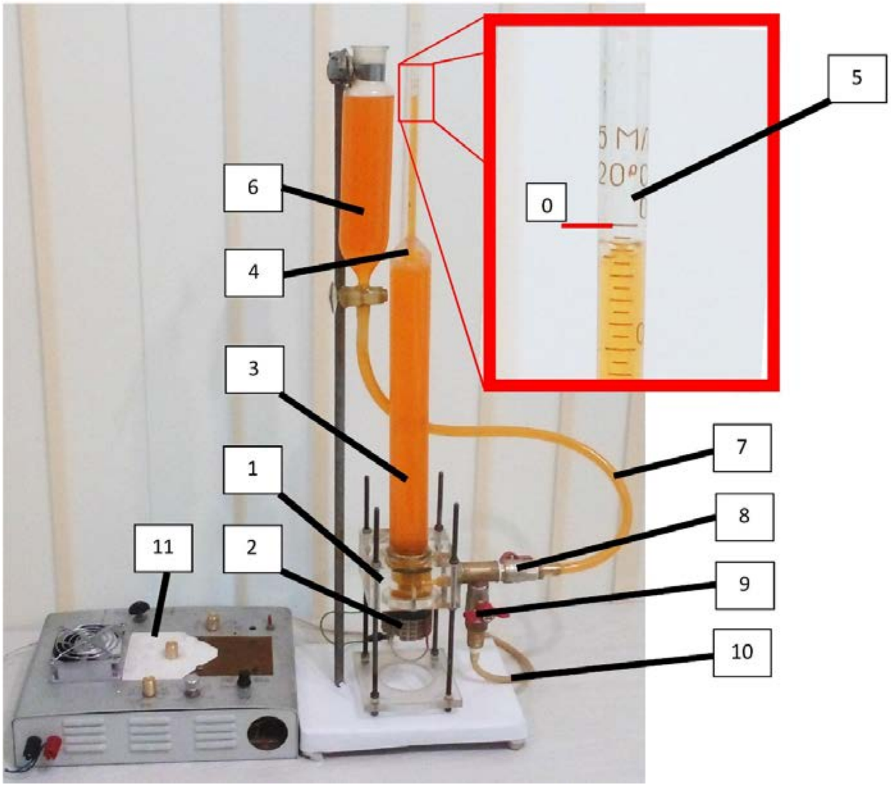


Fig. 5. Experimental unit for investigation of degassing liquids:
1 – body; 2 – high amplitude ultrasonic radiator; 3 – tank for investigation; 4 – cover; 5 – measuring tube; 6 – tank for pouring; 7, 10 – liquid inlet and outlet pipes; 8, 9 – inflow input and drain liquid valves; 11 – ultrasonic excitation generator

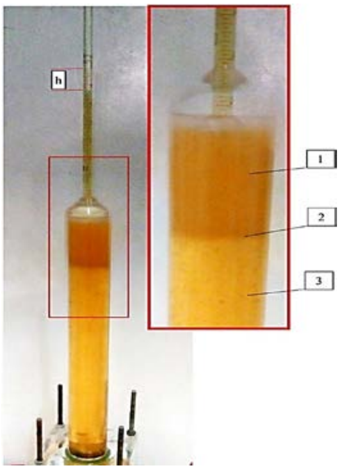


Fig. 6. Photo of the experimental setup during the experiment:
1 – gas-oil mixture; 2 – environment limit; 3 – degassed liquid; *h* – change in research liquid level

The results of the experiments are presented as graphical relationships (Fig. 7).

The study of the degassing process by sedimentation was carried out on the same experimental setup at 190 °C. Liquid volume changes were recorded after 15, 35, 60, 120, 180 min. and 12:00 after the start of counting.

The results of the study are presented as graphical relationships in Fig. 8.

Fig. 9 shows a graphical comparison of the effectiveness of ultrasonic degassing and sedimentation degassing.

**Conclusion.** When comparing ultrasonic degassing with sedimentation, one can conclude that the former method is highly effective. After all, one minute of ultrasound is equivalent to about 20 minutes of sedimentation. With time, as it is possible to see on graphs, intensity of air release from liquid decreases, therefore for full degassing at sedimentation it was required about 12:00, the same effect by means of ultrasound at the applied parameters can be reached in 4–5 minutes.

In future, it is reasonable to carry out tests at substantially higher intensity of ultrasonic vibrations, using high-amplitude radiator with developed emission surface and at increasing temperature of technological liquid.

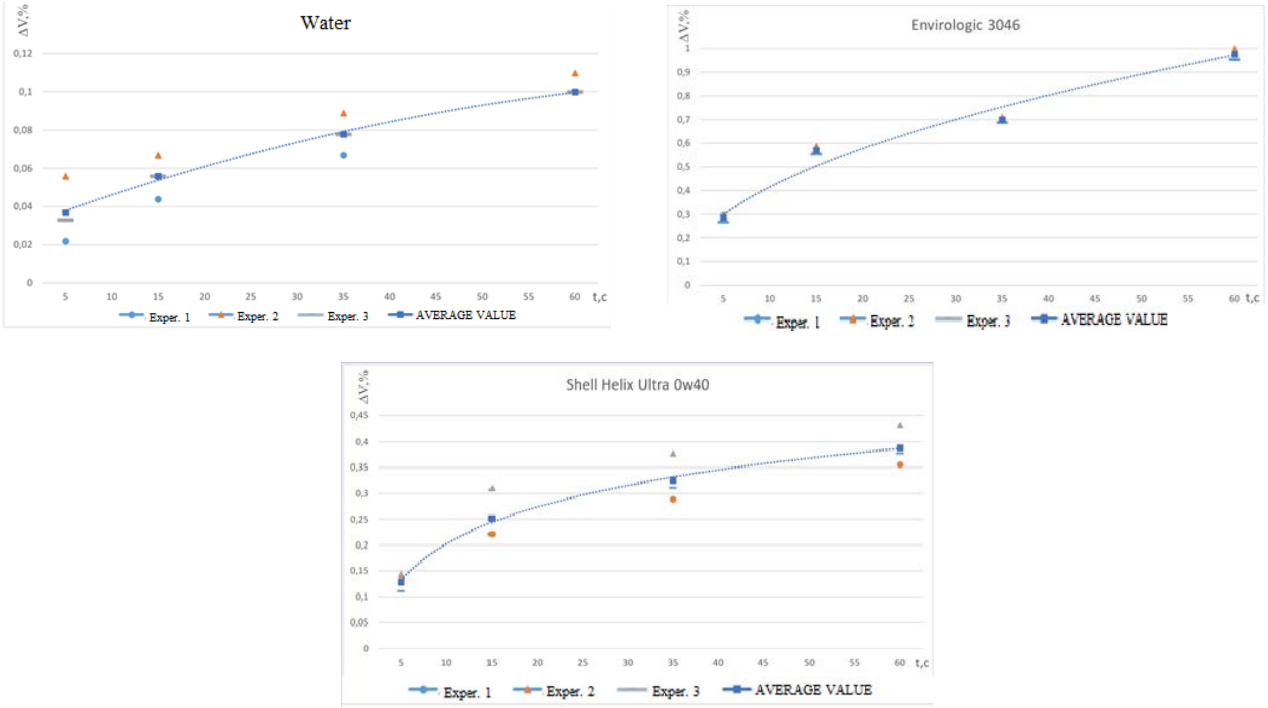


Fig. 7. Graphical relationship between air volume removed and ultrasonic degassing time

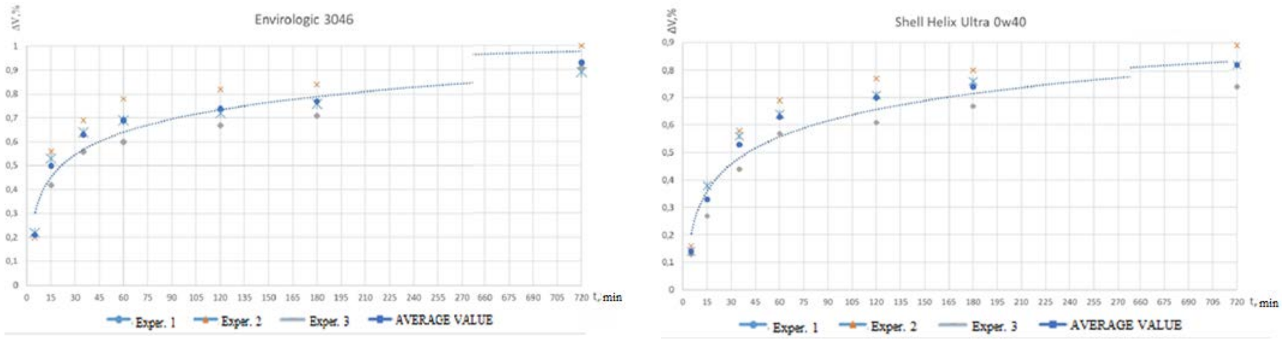


Fig. 8. Graphical relationship between the volume of air removed and the time of degassing by sedimentation

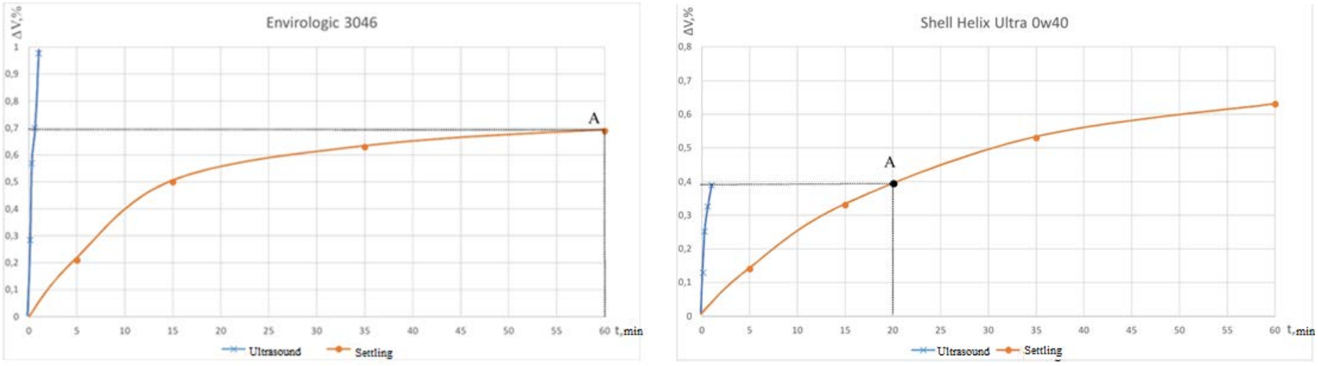


Fig. 9. Comparison of the effectiveness of ultrasonic degassing and sedimentation degassing

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