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Development of cavitation applications for the remediation of contaminated water

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1. Introduction

The objective of this paper is to develop understanding of the reactions of organic and nonorganic water compounds in the presence of high intensity cavitation.

The development of applications of cavitation for remediation of the contaminated water is presented. Performance data, such as scale control, corrosion and bacteria reduction, are presented. The screw propeller-type, piston-type and membrane-type cavitators were developed and investigated [1 - 5].

Minerals such as calcium and magnesium can form damaging scale deposits when exposed to the conditions commonly found in water supply systems with heat exchangers. The results of chemical and quantitative analyses of water after hydrodynamic cavitation showed the sharp decline of dissolved salts such as calcium, magnesium, etc.

The solid precipitate is easily removed from the water through the use of a cyclonic separator or filtration system. While scaling is prevented through the precipitation of calcium carbonate and its subsequent removal by filtration, the hydrodynamic cavitation minimizes the potential for oxidation and corrosion of metal surfaces of heat exchangers by removing oxygen, CO_2 and other dissolved gases from the water [6 - 8].

Because both calcium bicarbonate and calcium carbonate are simultaneously removed from the water, the solubility limit of calcium carbonate is not reached and scaling is inhibited.

The hydrodynamic cavitation treatment [9, 10] of the water also controls biological fouling. According to the obtained results, high temperatures and changing pressures generated by the cavitation process are sufficient to destroy the microorganisms that would otherwise cause bacterial, algal, and fungal blooms. No additional chemical inputs are required.

Raw and melt water has got different structures, what *inter alia* depend on the type of diluted minerals, organic elements and other additives, including the mechanical ones, that function as open, dynamic and structurally complex systems where the steady-state condition may be easily destroyed by external forces. Cavitation is one of such hydro mechanical forces that makes water discharge of dissolute gases, and forms bubbles between hardly compressible turbulent water flows. Continual stirring changes density of the water – light, easily compressible air-gas bubbles rise to the top and burst increasing water density underneath. At the same time, the water exposes different pH levels as before and after stirring, depending on consistency of hardness salts; this happens due to the junction of mineral ions with gases and diluted anions forming hard residual salts on surfaces involved. Such reactions happen more intensively under the increased temperature or low pressure conditions that are common around a screw propeller.

2. Experimental investigation

Simulation of cavitation effect has been performed using specially designed equipment. See Fig. 1 exposing the layer of vacuum cavitator.

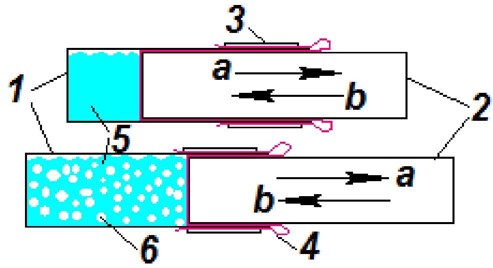

Fig. 1 Vacuum cavitator, where *1* – sleeve, *2* – pistons, *3* – sleeve gasket, *4* – elastic polyurethane pocket, *5* – water, *6* – gas bubbles

Water *5* is situated in the sleeve *1* which is closed with a retaining piston *2*. A standstill condition is achieved using elastic polyurethane pocket *4* tightly attached to the body of sleeve *1* through a sleeve gasket *3*. The equipment must be completely hermetical.

Principle of operation. When the piston *2* is moved along the sleeve *1* in direction *a*, and contact between the sleeve *1* and the piston *2* remains completely hermetical, the water is discharged and, due to cavitation bubbles appearing during gas phase *6*, it comes to boil at a room temperature. At this moment, dissolute salts join oxygen and inspire nonreversible chemical reactions resulting in disintegration of hydrocarbonates and formation of solid insoluble calcium and magnesium sulphates and carbonates (basic components of hard water salts). The piston moves backwards, in direction *b*, automatically under the effect of vacuum.

After 2 - 3 moves of the piston *2* a researcher can notice residue of insoluble hard salts in the water.

Chemical qualitative and quantitative analysis of the water before and after the cavitation exposed significant reduction of dissolute hydrocarbonate and other salts. At the same time the water becomes less alkali; filtrated becomes more transparent and freezes more quickly;

melted is suitable for drinking.

The main element of another experimental equipment this equipment was a membrane pump. The empty space *5* is filled with unclean water that is pressed with a membrane *4* fixed on a sliding cylinder *3* using an alternate differential *2* eccentric *1* (Fig. 2). After several discharges in area *5*, residual salts appear. Then surface water flows into the opening sleeve *6*, accumulates in tube *7*, travels through valve tray down the sliding cylinder *8* and lifts a shutter *9*. The equipment is powered by a motor *10*.

Vibrations generate cavitation effect and reduce the level of hardness salts. Experimental rig is shown in Fig. 3.

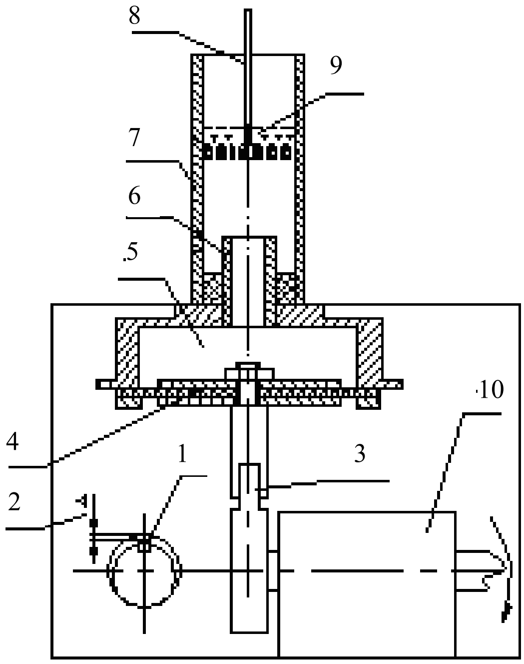

Fig. 2 Membrane cavitator

Fig. 3 Picture of cavitator equipment

3. Quantitative evaluation of cavitation

Separated according to [5], the cavitation can arbitrarily be into three stages: generation (formation of supercritical bubbles); development, and disappearance (collapse of bubbles). The stages of appearance and development of the cavitation are a function of physicochemical properties of the liquid, the presence of solid or gaseous contaminants (nuclei) in it, the temperature and pressure in the cavitation zone, and a number of other factors.

If static pressure in the liquid suddenly increases to above the pressure of its saturated vapors that fill the cavitation bubbles in any way after the first two stages, condensation of these vapors on the walls of a bubble and collapse of the bubble are almost instantaneous. According to the data in [6, 7], cumulative stream lines arise when a bubble collapses as a result of nonspherical compression, and energy is released in the vicinity of the site where the bubble disappears. The temperature can attain 104 K and the pressure can reach 200 - 400 MPa at the point of collapse of the bubble. The appearance of cumulative stream lines and extremely high values of these parameters are probably also the cause of local perturbations of propeller shaft blades, turbine blades, etc. [5, 6].

We performed a quantitative energy assessment for the possibility of using cavitation for cracking of hydrocarbons in petroleum feedstock.

According to [5], when a cavitation bubble collapses, the energy released is

$$E_c = \frac{4}{3}\pi(R_0^3 - R^3)p_\infty \tag{1}$$

where R_0, R are initial and current radii of the bubble, m; p_∞ is pressure of the liquid far from the cavern, Pa. Since radius of the bubble R returns to zero when the bubble collapses, Eq. (1) becomes

$$E_c = \frac{4}{3}\pi R_0^3 p_\infty \tag{2}$$

For a quantitative estimation of the energy released when a cavitation bubble collapses, we set R_0 = 1 mm, p_∞= 106 Pa. Then according to Eq. (2), we will have:

$$E_c = 4\cdot 10^{-3}\,\text{J} \tag{3}$$

The energy E_b of breaking some chemical bonds for one mole of several types of compounds is reported in [8]. As we see, that for breaking a bond of the C – C type in one molecule, for example, of paraffins, it is necessary to consume:

$$E_{mb} = \frac{E_b}{N_A} = \frac{332000}{6.022\cdot 10^{23}} = 5.5\cdot 10^{-19}\,\text{J} \tag{4}$$

where N_A is Avogadro's number. The number N of molecules in which a bond can be broken when one cavitation bubble collapses is thus

$$N = \frac{E_c}{E_{mb}} = \frac{4\cdot 10^{-3}}{5.5\cdot 10^{-19}} \approx 10^{-16} \tag{5}$$

That is, when one bubble with a radius of R_0 = = 1 mm collapses, sufficient energy is released for cracking 10^{16} molecules of hydrocarbons.

Collapse of N_μ bubbles is required to break bonds of the C – C type in each of the molecules in 1 mole of hydrocarbons

$$N_\mu = \frac{N_A}{N} = \frac{6.022 \cdot 10^{23}}{10^{16}} \approx 10^7 \qquad (6)$$

Such a number of bubbles will occupy the volume

$$V_{bub} = \frac{4}{3}\pi R_0^3 N_\mu \approx 4 \cdot 10^{-2}\,\mathrm{m}^3 \approx 40\,\mathrm{l} \qquad (7)$$

Let the volume fraction of cavitation bubbles in the stream of a petroleum product be 10% of the total volume. Then for cracking 1 mole of hydrocarbons, it will be necessary to "pump" 360 liters of petroleum product through the cavitation apparatus. If we assume that the molecular weight of the hydrocarbons is μ = 100-300 and their density is ρ = 700-900 kg/m^3, then after 360 liters of petroleum product has been pumped through the cavitator, approximately 0.1-0.3 kg of hydrocarbons can be cracked. The possibility of cracking petroleum hydrocarbons by hydrodynamic cavitation was thus demonstrated. To increase the yield of cracking products it will be necessary by the cavitation apparatus to ensure a multicyclic cavitation process and create cavitation bubbles of the maximum density in the petroleum product stream.

Experimental research shows that the cavitation treatment changes hardness of water as presented in Fig. 4.

Thereby water pH level changes too (Fig. 5).

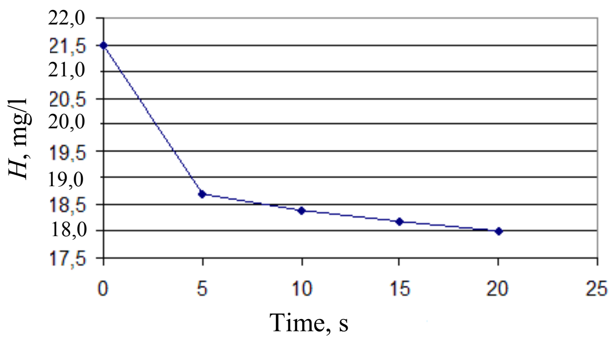

Fig. 4 Cavitation effect on hardness of tap water

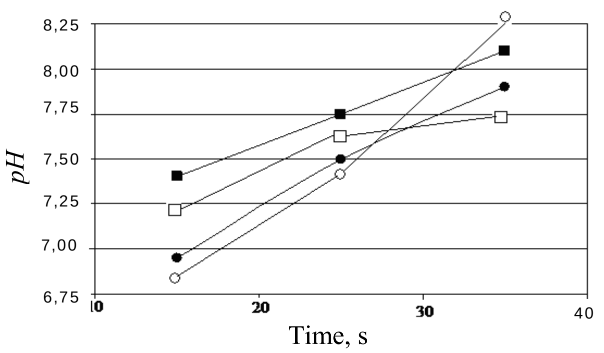

Fig. 5 Water pH *vs* cavitation time after cavitation and magnetization(■), ultrasonic treatment (●), membrane cavitation (□), and mixing with a propeller (○)

Cavitation treatment helps to clean water from various biological substances. Fig. 6 shows the changes of bacteriological water level depending on cavitation time.

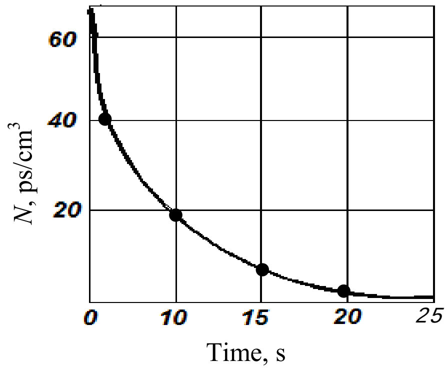

Fig. 6 Bacteria colony in water *vs* cavitation time

Examination of residue in ordinary mineral water and that after the cavitation (using electronic scanning microscope JSM-U3) showed significant differences. For instance, in ordinary mineral water, residual particles are scalenohedral (shapeless); most of them adsorb organic and biological elements and compound polydisperse environment with particles from 3 nm to 100 mμ and larger ones. Some particles reached even 1 mm. After cavitation residue gets monodisperse structure, the size of particles is between 0.3 and 10 mμ, and the particles have clear shape of trigonal crystals $CaCO_3$ corresponding to that of calcites, aragonites, and bicarbonates. Such conclusion was made on the basis of differential thermal, X-ray-graphic and X-ray phase analysis using Paulik-Erdey type derivatography and DRON-0,3 X-ray equipment, Gondolyfi type cameras, and general methods of determining phase structure in solid residue.

4. Conclusions

In conclusion we assume that cavitation leads to stratification and activation of water, destroying cluster structures and saturating it with mono particles.

In medicine, stock breeding and crop raising such water is called *live*. Foremost it activates metabolic processes and encourages the discharge of biological waste products; second, monoparticles of water remain chemically active in regards to crystal hydrates, for example, junctions of calcium carbonate ($CaCO_3$). In result salty residue falls to small pieces and, under the effect of activated water, is easily removed from a live body or artificial system.

Therefore the outboard water around a screw propeller, where the cavitation reaches the highest level, is mostly suitable for cooling the surface of marine motors and using in sea water distillation equipment.

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KAVITACIJOS NAUDOJIMO UŽTERŠTIEMS VANDENIMS VALYTI TYRIMAS

R e z i u m ė

Straipsnyje pateikti vandenyje virpesių sukeltų kavitacinių efektų tyrimai, Tyrimų metų mineralizuotas vanduo laivų sraigtų arba specialiai sukurtų kavitatorių aplinkoje buvo veikiamas jame ištirpusių druskų. Atlikta kiekybinė ir kokybinė vandens cheminė analizė parodė, kad dėl kavitacinių reiškinių labai sumažėja ištirpusių hidrokarbonatų druskų kiekis ir vandens rūgštingumas. Po filtracijos vanduo praskaidrėja, greičiau užšąla, o atitirpęs tinkamas vartoti gėrimui. Pateikta metodika kavitacijos proceso efektyvumui įvertinti, naudojant jį hidrokarbonatams šalinti iš vandens.

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DEVELOPMENT OF APPLICATIONS OF CAVITATION FOR THE REMEDIATION OF THE CONTAMINATED WATER

S u m m a r y

The development of cavitation applications for the remediation of contaminated water is presented. Performance data, such as scale control, corrosion and bacteria reduction, are presented. The screw propeller-type, piston-type and membrane-type cavitators were developed and investigated. Chemical qualitative and quantitative analysis of the water before and after the cavitation exposed significant reduction of dissolute hydrocarbonate and other salts. At the same time the water becomes less alkali; filtrated, becomes more transparent and freezes more quickly; melted is suitable for drinking. A quantitative energy assessment of the possibility of using the cavitation for cracking of the hydrocarbons in water feedstock is performed.

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ИССЛЕДОВАНИЕ ПРИМЕНЕНИЯ КАВИТАЦИИ ДЛЯ ОЧИСТКИ СТОЧНЫХ ВОД

Р е з ю м е

В настоящей работе представлены исследования по изучению поведения растворенных солей в минерализованной воде в области гребных винтов судов или в специально созданных опытных кавитаторах, моделирующих такие условия. Химический, качественный и количественный анализ воды до и после опыта с явлением кавитации показал резкое снижение растворенных солей в виде гидрокарбонатов и других солей. При этом снижается щелочность воды, а после фильтрации она становится более прозрачной и быстрее замерзает, а после оттаивания становится пригодной для питья. Представлена методика количественной оценки эффективности кавитации, используемой для очистки воды от гидрокарбонатов.

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