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Efficiency Evaluation of Cavitation Heat Generator Used for Desalination of Saline Solutions

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ABSTRACT

Nowadays, the issue of efficient desalination and treatment of seawater for its further use in various domains of human activity is of much interest worldwide. There are plenty of known treatment techniques. This research paper discusses the method of hydrodynamic cavitation treatment in a heat generator in various modes and proves the performance efficiency of this method. The process of treating saline solutions of different concentrations and registration of electric conductivity of solutions are studied. The possibility of changing the concentration of salt in the solution by treating it in a vortex cavitation heat generator is undertaken. The efficiency of the cavitation process depends on the temperature of the working environment: with the temperature increase, the desalination intensity decreases. Two possible scenarios of the process are revealed, i.e., the decrease in the concentration of salt in the solution or its increase in the presence of a salt source. When working on depleted solutions with a salinity of 1÷5 ‰ at high temperatures, the reverse diffusion of previously adsorbed salts from the internal surfaces into the solution takes place. When working on solutions of elevated concentrations in the same high-temperature range, the reverse diffusion decreases and at a salinity of 67 ‰, its effect ceases, since the concentration of salts on the inner surfaces becomes comparable to the concentration of the solution. The hypothesis of centrifugal separation of salts from water is experimentally proved.

Keywords: Seawater; Hydrodynamic cavitation; Diffusion; Desalination; Separation; Cavitation bubble; Cavity; Electric conductivity

INTRODUCTION

Freshwater is one of the most indispensable substances for life. Nowadays, its shortage becomes evident more often. For instance, along the coasts, where the surface water is not sufficient for life, and the groundwater is saline due to the proximity to the seawater. There are different methods to desalinate the saltwater: evaporation, freezing, ion exchange, electrodialysis, reverse osmosis and direct osmosis; hydrodynamic and electrochemical techniques, etc. (Esmaeilion, 2020; Knust et al., 2014).

Up to this date, none of the demineralized water generators is full-fledged to ensure the vital activity of people, animals and plants (Darre & Toor, 2018). In this regard, those countries that recourse to desalination of the seawater, use the treated water only for technical needs, while the drinking water gets exported. The desalinated water is not balanced in its composition and structure. Therefore, the risk of cardiovascular disease increases by 6% in the areas of its consumption (Al-Basheer et al., 2017; Melak et al., 2019).

On the other hand, human society possesses considerable knowledge, and yet continues to understand nature at an increasing pace, for instance, in the nanoscale direction. Thus, the emergence and subsequent development of novel physical principles of action imply the emergence of various applied potentials to solve emerging and existing problems (Di Vincenzo et al., 2020).

In the course of previous experimental studies, a change in some properties was established for the water (its acquisition of additional biological and chemical activities) upon undergoing the cavitation treatment (Kulagin et al., 2014). Saline solutions are more complex physical substances than pure water. Therefore, a drastic change in the properties and qualities of the solutions undergoing the cavitation treatment seems likely. There are multiple ways to explain the mechanism of cavitation for the desalination of saline solutions. Evaporation of water into a cavity through cavitation with further separation of steam from the liquid phase and final condensation is considered to be the simplest (Alhashan et al., 2018).

Another assumption states that the bubbles collapse in a very short time. This determines a non-equilibrium thermodynamic state with the bubbles collapsing, which causes the dissolved elements to become solid because the process of nucleation separates these previously dissolved solid particles from the fluid medium (Morch, 2009). There is yet another assumption suggesting that in the course of hydrodynamic cavitation the localized overheating, stratification and activation of water occur, with the cluster structures getting destroyed, and the saturation with nanoparticles occurs (Kanthale et al., 2005). At the same time, at the stage of collapse, cavities change shape until they turn into needle jets (Shipilov & Yakubov, 2018), which results in localized energy compaction, and, hence, in the increase in the variety of energy transition forms.

There are different designs of cavitators as regards of the implementation this scenario (Tao et al., 2016):

- piezoelectric and magnetostrictive cavitators with low performance due to power restrictions because of the possibility of destruction occurring in emitters;
- hydrodynamic cavitators with the power of the order of hundreds kW (Fujisawa et al., 2018). In these devices, the emitters of the sound field can be either of the following: periodically appearing and collapsing areas of the detachment of poorly streamlined bodies at a flow rate of $V \geq 30$ m/s; periodic hydrodynamic tear-off processes in diffusers; mechanical systems with the required frequency of natural oscillations subject to the run-around flow; hydraulic sirens; annular jets forming the dome-shaped periodically collapsing cavities; flooded jets, the periphery of which in the initial area emits an acoustic field into the surrounding fluid volume; sound shock waves; super cavitating caverns; hydraulic systems with competing flows, as well as hydrodynamic systems like reducing nozzles or perforated diaphragms suggesting the presence of zones with constant vacuum pressure in the flow, where the cavitating caverns originate and then collapse downstream, etc.

The vortex-type cavitators started to be employed in production processes relatively recently, i.e., in the 1990s (Potapov & Fominsky, 2000). The key advantage of cavitators under study is that the pressure pulses are created in their vortex chambers (Figure 1). In their cylindrical housing, the pulses and signals from other sources (areas of separation, tuning fork, engine vibrations) are selected as per the divisible frequencies with consideration to the pulse length and standing wave, and get amplified almost twofold (Liu & Yang, 2017).

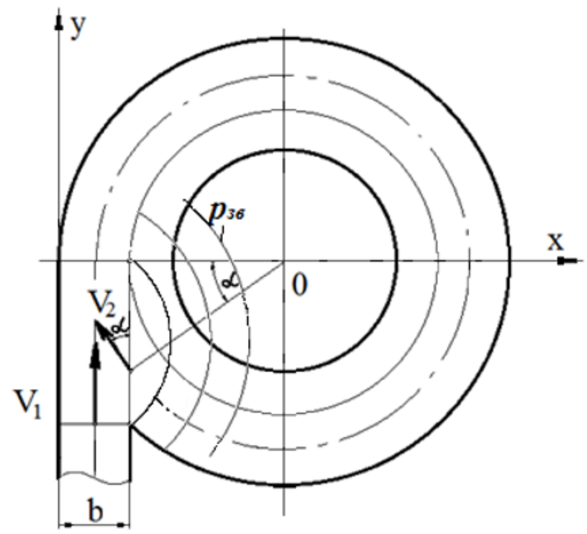


FIGURE 1. Acoustic pulse generation mechanism

Another advantage of this design is represented by the vortex technique to create acoustic pulses, which additionally accounts for the use of its separating capacities (Padhi et al., 2019). For an effective combination of the stated vortex cavitator features, as well as for recognition of the desalination procedure, it is reasonable to get familiar with the organisation of flows in the device.

The organisation of flows in the generator housing has been already studied in sufficient detail. The papers by Akhmedov & Akhmedov (2016) and Akhmedov et al. (2018) outline the organization of flows in the vortex chamber. Still, these papers discuss the device with a volume elongated in the direction of the rotation axis; besides, the flows interaction area is not yet sufficiently studied. The paper by Ivanov (2014) demonstrates the effect of the axial input of the transit flow. The paper by Rafiee & Sadeghiazad (2016) presents the results of a three-dimensional simulation of vortex pipe. The papers by Matsuno et al. (2015a) and Matsuo et al. (2015b) discuss a vortex chamber in conjunction with a cylindrical body, for which the organization of flows is described. Additionally, the latter ones of these devices run on gases, and this does not imply cavitation. Predominantly, the distribution of velocities in the vortex chamber running as part of the water intake device is considered in the research study by Athar & Srotriy (2018). However, the range of velocity criteria for the water movement does not correspond to the start of cavitation.

It is noteworthy, that the initial cavitator design is experiencing constant development, both as regards the reduction of energy intensity of cavitation, and adaptation of the cavitator to various production tasks. It is rational to review and evaluate the identified engineering solutions in terms of their application for the purposes of desalination. It is obvious, that the cavitation technologies domain extends to the pharmaceutical industry (Sivakumar et al., 2014), as well as to the chemical and steelmaking industries enabling the dispersion and homogenization of mixtures. Over the past few years, the cavitation technologies have been adjusted to meet the needs of the agricultural sector (Tarasov & Veselov, 2018; Hmelova, 2009). When seeds and plants are watered with the water treated through cavitation, germination, vegetation and growth of plants is boosted significantly (Zalepuhin, 1987).

The designs of cavitators for wastewater treatment and treatment of water for heating systems are extensively improved both by Russian scientists, such as Evstigneev (2010) and Kulagin (2007), also in foreign studies by Bagal & Gogate (2014). These developments are based on the research results produced by Nigmatulin & Afanasyev (2013) and were further developed as the supercavitation hydro wave method (Zheng et al., 2019). Cavitation heat generators represent the foundation of this method. However, the type of cavitation heat generator required for use in line with this technology is not yet fully defined, because the range of such devices is not yet fully developed.

Using Potapov's heat generator (2000), which combines the cavitation process with the possibility of hydrodynamic separation of the working fluid as per its densities, higher quality and efficiency of both desalination and mineralization of components of the treated medium is ensured. This heat generator in itself represents a liquid whistle, i.e., a geometrically similar copy of a regular air whistle.

In order to verify the stated assumptions, the experiments were carried out given treatment of saline solutions of different concentrations and at various exposures using a vortex cavitator (Figure 1), along with taking samples from the central part and peripheral areas of the device.

The purpose of this research paper is to evaluate the efficiency of the cavitation treatment of saline solutions using the Potapov cavitation heat generator, to evaluate the compatibility of the treated water with vital activities of bio-objects (seeds and plants grown from them), i.e., for further use in the agricultural sector.

It should also be noted, that the experimental data discussed in this research paper is obtained using a vortex cavitator of general use. Thus, the achievement of better results is constrained by radial waves, which stir the treated solution and partially exclude radial centrifugal resources from the working process. Consequently, this research paper only reveals the fact of the desalination of saline solutions. When it comes to higher efficiency, the topic of discussion shall pivot around an advanced cavitator model equipped with a rotating housing (Ivanov et al., 2016).

METHODOLOGY

The design specifics of the cavitator under consideration (with the following dimensions: 2600x600x750) is that of a vortex type, meaning that a sound wave is created by competing components in the vortex flow (Figure 1). This also implies, in addition to the cavitation effect on the saline solution, there is also a hydrodynamic effect.

The essence of a hydrodynamic action consists in the fact that a flow entering a vortex chamber at the speed of V=30 m/s is swirled into the vortex flow. In this case, each liquid particle experiences a centrifugal force with an acceleration of a=1000 g. If one of the particles possesses a higher density (like salt), it shall tend to move to the periphery. Consequently, less dense particles (like water) shall be pushed towards the centre. Thus, by taking samples from the central part of this device, it is possible to get more demineralized water and devoid of salts to a greater extent (Figure 2).

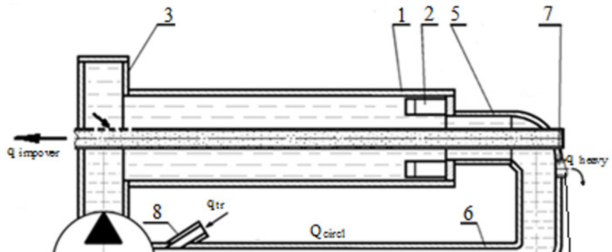


FIGURE 2. Sampling circuit for the desalinated part of the saline solution

1 – cavitator housing; 2 – 8-cantilever-petal camertone (25x85x6 mm); 3 – scroll; 4 – pump (with 50 m3/h supply and 50 m pressure head); 5 – cavitator outlet nipple; 6 – reverse circulation pipeline with Qcircl flow rate; 7 – central pipe that enables sampling from the desalinated solution with Qimpover flow rate; 8 – inlet nipple of Qtr transit flow providing for the inflow of solution; 9 – heavy fraction selector with Q heavy flow rate.

Prior to and after the treatment, each sample is measured for the concentration of solutions with threefold repeatability. The measurement is carried out using the Cond./TDS AZ8361 unit (manufactured by AZ INSTRUMENT CORP, CHINA, No. 359813, 2018). Its principle of operation is based on changes in the electric conductivity of the solution of different concentrations.

In order to prevent friction between the working fluid and the inner surface of the housing, it is suggested to design the cavitator housing of a rotary type (Figure 3).

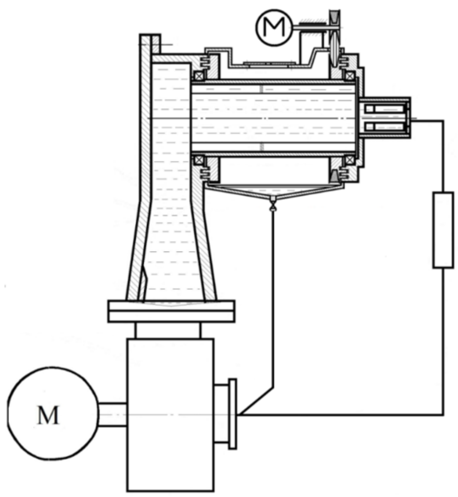


FIGURE 3. Schematic diagram of the vortex cavitator with motorized rotating housing

In this case, together with the housing, the working fluid rotates as a solid body with minimal friction between the layers and with a minimum of macro mixing (Ivanov et al., 2016). In this case, the heavier (dense) components, uniformly penetrating the less dense and relatively non-moving water quantities, move to the periphery, with the pure water quantities gradually replacing the free space in the axial part. At the same time, an auxiliary active gear allows adapting the device to different materials and process tasks, including the reverse process, i.e., mineralization in two ways, notably owing to the outward diffusion from the donor surfaces, as well as through the separation of flows.

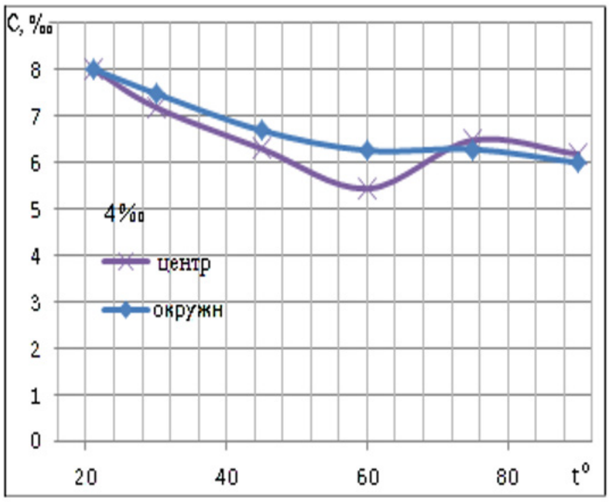
Evaluation of the evidence, or refutation of the assumption as stated, narrows down to the treatment of each of the solution portions in the heat generator in the closed circulation mode, sampling from its central part and its periphery (for every portion and mode), followed by measuring the concentrations in three independent ways: indirectly through changing the electric conductivity of the solution; directly utilizing the evaporation method and employing the bio testing method. The analysis of results obtained for each of the methods in conjunction with the results of the other two remaining for each sample makes it possible to evaluate the action of change for the value of salt concentration by reducing the amount of salt in the sample solution, by modifying the composition of salts and their properties through modification of the water properties respectively.

The process of treating the solution implies filling the heat generator (Figure 2) with a salt-based solution of concentrations S0 = 1; 2; 3; 4; 5 ‰ in the first series of experiments, and S0 = 0; 16; 33; 50; 67 ‰ in the second series of experiments, as well as involving the cavitator and treatment of each of the portions (concentrations) at different duration (exposure). At that, the exposure, which preconditions the number of circulation cycles for the solution to pass within the circuit and the amount of cavitation zones, is determined by the intensity of heating the fluid medium, that is up to the temperatures of 30^o; 45^o; 60^o; 75^o; 90^o. In this case, a proportional relationship is observed, i.e., the longer the exposure, the more times the water quantity passes through cavitation zones, and up to the higher temperature, it gets heated up.

The conducted empirical research is limited as regards the fact that the salt used for the solutions under study is table salt, which is safe, accessible, and inexpensive; and still, in terms of solubility, it is comparable with the key properties of other salts (for instance, sea salt, salts used in electroplating industry, etc.).

RESULTS

The assumption of the cleaner water from the centre of the cavitator underwent an experimental examination. For all concentrations (C = 1 ÷ 5 ‰), the samples taken from the central part have a lower concentration of salt versus the samples taken from the periphery. This fact is supported both by the outcome of the evaluation of changes in electric conductivity (Figure 4), and when evaluated at the outcome of direct evaporation.



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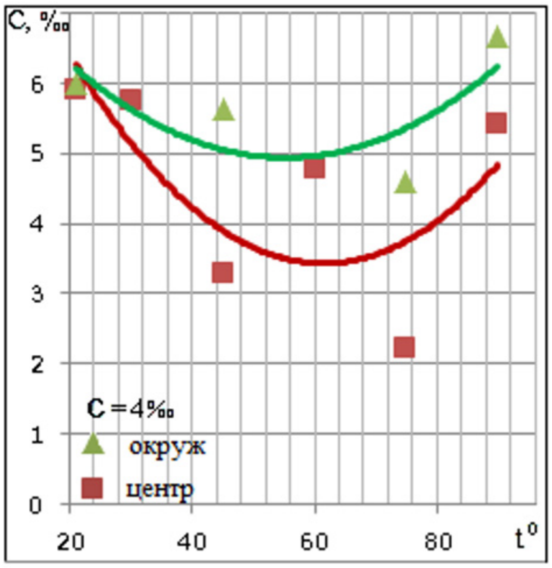


b)

FIGURE 4. Comparison of concentrations in different zones of the heat generator, i.e. in the centre and at the periphery: a) based on electric conductivity; b) obtained through evaporation

It is noteworthy that the results obtained throughout the experimental studies reveal a spread in values. It is related to the fact that there is high turbulence and transient currents within the heat generator housing, which causes the throw of the peripheral volumes of the working fluid (saline solution) to the smaller radii of rotation. This aspect significantly reduces the efficiency of the process of desalination and its centrifugal component in particular.

Figure 5 gives the outcome of the experiments by way of sampling from the centre of the device. The concentration values correspond to parts permille (‰).

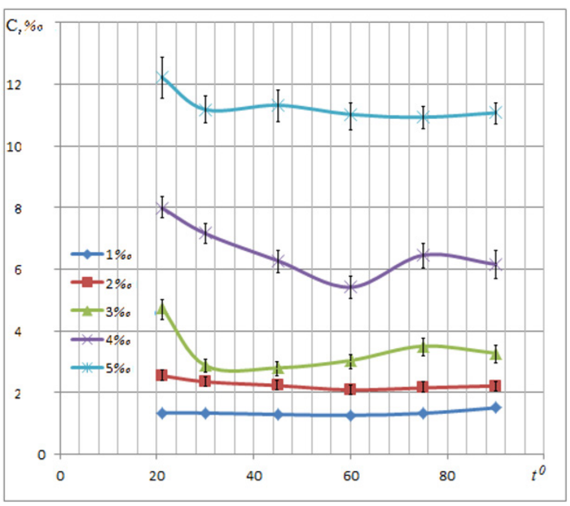


FIGURE 5. Pattern of change in salt concentration in the solution depending on the degree of treatment for different initial concentrations of C_0 = 1 5 ‰ when sampling from the centre of the device

In order to evaluate the possibility of using the vortex constituent of the solution flow in the cavitator, the samples of the working fluid are taken from the peripheral sections of the housing, with their concentrations being higher than those of the samples taken from the centre. Figure 6 shows the dependence of different concentrations on the degree of treatment and initial concentration values when sampling from the periphery of the device.

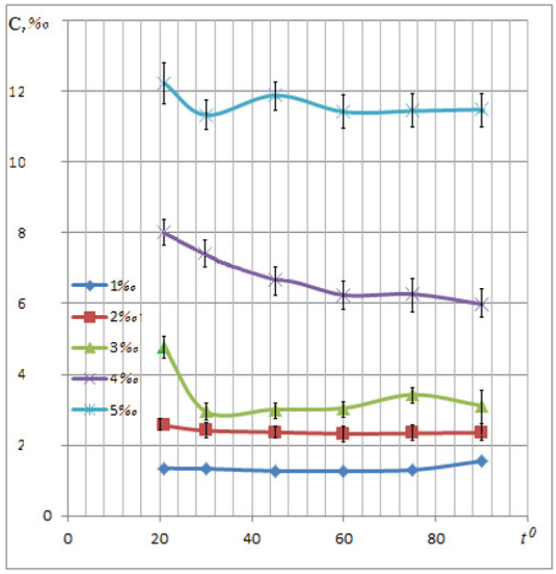


FIGURE 6. Pattern of change in salt concentration in the solution depending on the degree of treatment for different initial concentrations C_0=1÷5 ‰ when sampling from the periphery of the device housing

In order to increase the validity of the measurement results, the evaluation of concentrations was carried out through direct evaporation employing the known techniques. The obtained outcome is shown in Figure 7 (from the centre of the cavitator) and in Figure 8 (from the periphery of the cavitator housing).

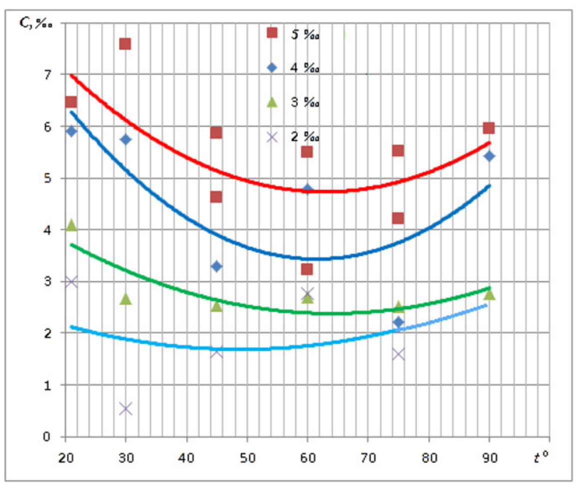


FIGURE 7. Pattern of change in salt concentration in the solution depending on the degree of treatment for different initial concentrations C_0=1÷5 ‰ when sampling from the centre of the device

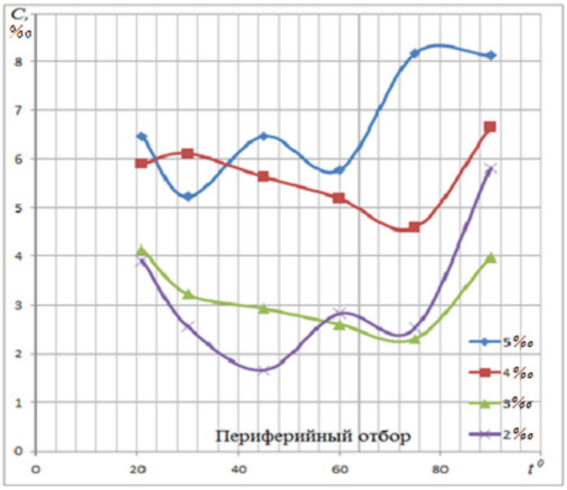


FIGURE 8. Pattern of change in salt concentration in the solution depending on the degree of treatment for different initial concentrations C_0=1÷5 ‰ when sampling from the periphery of the device housing

Figure 9 gives the results of the research study of the concentrations of saline solutions as per the averaged values in relation to the initial values for various operation modes of the heat generator and based on a series of experiments and at the increased initial concentrations (C_0 = 16 ‰, 33 ‰, 50 ‰, 67 ‰).

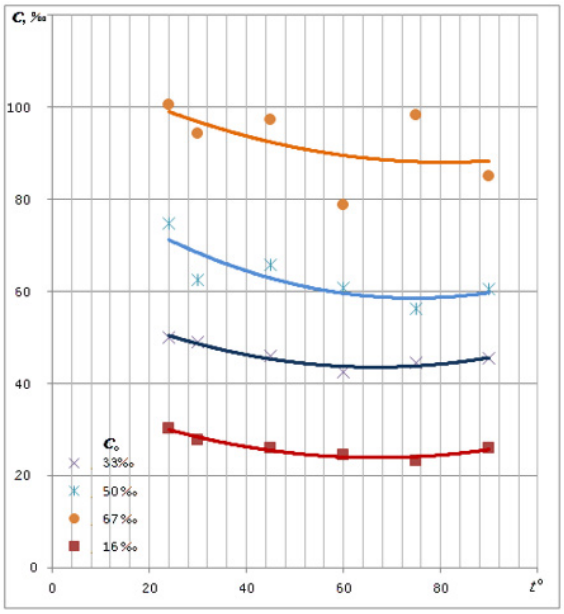


FIGURE 9. Pattern of change in concentration of table salt depending on the exposure to cavitation treatment at different initial concentrations C_0

In order to identify the specifics of each of the compared scenarios and using the known techniques with the triple repeatability n = 3, the confidence intervals are defined as follows:

$$X \pm t\gamma\ S\ \sqrt{n},$$

at the level of significance γ = 0.95 (t_γ = 0.315) of each of the compared patterns by sequentially calculating the variance D, reduced variance S^2=n D/(n−1), and confidence interval.

DISCUSSION

Comparison of the results of solution concentrations measurement (Figures 5-8) reveals that measuring the concentration by evaporation provides a higher value even at the initial stage if compared to the probable concentration after a certain quantity of salt is dissolved. This instance is justified by the fact that in the course of the research the tap water is used, with its default content of salt based on the water treatment done at the water intake station. When measuring the concentration of the saline solution from the peripheral part, the increased concentrations, if compared to the initial concentration values, are also recorded. This can be explained by the ability of the vortex cavitator to fractionate the solution components by their densities, as well as by the transition of a denser, more concentrated solution constituent towards the greater, in fact, peripheral, radii. With increasing concentrations, the readings of the device grow by an even higher degree than the quantity of the dissolved salt. This fact can be explained by the presence of more active types of substances added to the water at the water intake station during its treatment than the salt used in the course of experiments.

Based on the obtained experimental findings, it may be affirmed that the assumption about the possibility to desalinate saline solutions in Potapov´s cavitation heat generator using the cavitation effects on the salt components and their subsequent centrifugal separation from water is confirmed. At the same time, the behaviour of these processes in different modes of heat generator operation is ambiguous (Figure 10).

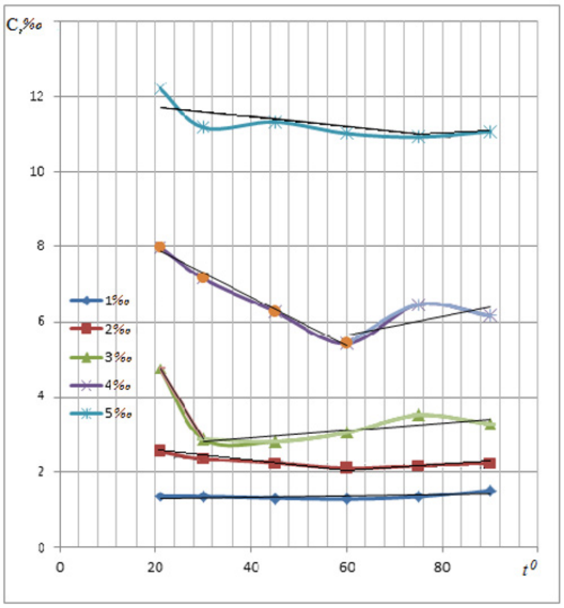
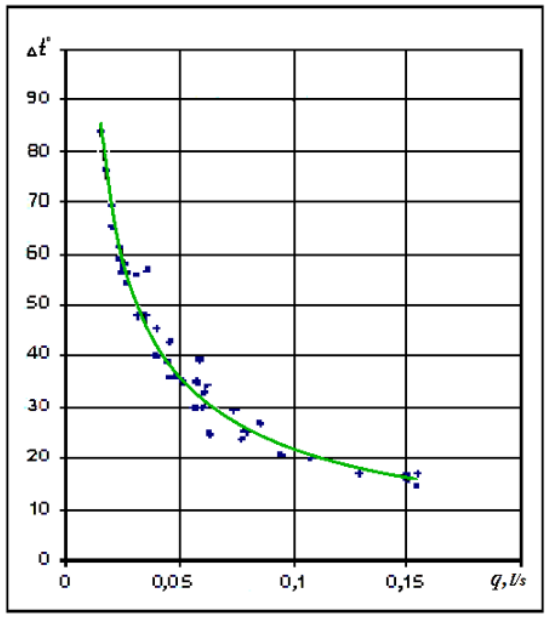


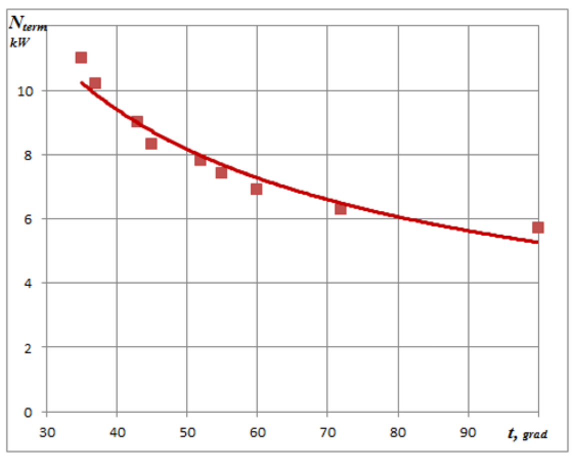
FIGURE 10. Pattern of change in concentration of the solution depending on the cavitation treatment mode (based on the evaluation outcome employing the method of electric resistance with sampling from the centre)

Each of the patterns C=f(t⁰) for different initial concentrations C_0 has two areas: 1) with a decreasing salt concentration; 2) with an increasing salt concentration in the final section at t = 90⁰. The decrease in salt concentration in the recessive area is justified by the straightforward evidence of the cavitation process. In such a case, it is possible to observe a direct effect from collapses of cavitating caverns upon the components of salt, as discussed in the papers (Evstigneev, 2010; Esmaeilion, 2020), as well as their active diffusion towards the internal surface of the heat generator, and particularly into the microcavities and micro cracks. This instance is proved by the outcome of the evaporation concentration experiments (Figure 7). At t ≈ 20⁰ ÷ 60⁰, the immediate decrease in the amount of salt in the solution under study is observed. Consequently, the functional factors of the low-temperature stage of treatment of the saline solution through cavitation are as follows: aggregation of the salt fragments with cavitation nuclei; adsorption of the salt molecules (ions) onto the internal contour surfaces of the heat generator; possible modification of properties of the salt molecules (ions) owing to multiaxial deformations, deep compression, high heating, magnetic and electrical effects; formation of the chemical compounds of salts with the material of housing, as well as with the pollutants under the cavitation conditions and acquisition of new qualities and properties by the water (Kulagin et al., 2014); decomposition of salts into components with their subsequent interaction with the material of the housing and pollutants in the collapse zones, etc.

As a result, with the increase of the number of cycles through which the working fluid passes the circulation circuit of the heat generator, which is equivalent to the increase of the treatment time, the concentration of salt in the solution decreases. Nonetheless, in the second section of curves C=f(t⁰), the concentration of salt in the samples increases because the default specifics of the cavitation heat generator working process means the increase in the temperature of solutions together with the increase in the number of cycles, or the prolongation of exposure (equivalent to the decrease in transit flow q) with continuous use of the heat generator (Figure 11, a). This reduces the efficiency of cavitation processes, and the production of thermal energy in particular (Figure 11, b).



a)



b)

FIGURE 11. Calorific efficiency of Potapov's cavitation heat generator: a) by the difference in temperatures from the transit flow; b) by the generated thermal power in relation to the operating process temperature

The studied specifics are determined by the fact that at the high temperature of the solution, more intense change in physical states occurs, i.e., from fluid to steam, and the transition of the dissolved air to free state. That was also observed in the paper by Tao et al. (2016). Consequently, during the formation and growth of the cavity, its space shall contain a greater number of vapours and gases, which, in the event of its collapse, shall reduce the speed of the counter-movement of the walls and shall not provide the required reduction in volume. Thus, the required energy density in the collapse volume shall not be ensured. As a result, there shall be no change in energy forms, and there shall be no required effect, both on the fluid being the basis of the solution, and on components thereof. The same fact is the decrease in the efficiency of heating surfaces of the heat generator in the heating mode (Figure 11, b).

In order to overcome this constraint, certain excessive external pressure is created. Given the reduction in the growth time of the cavity, the pressure reduces steam and gas release into the cavity and increases the speed of counter-movement of the walls during the collapse. The cavity volume shrinks at the final stage of collapse.

With the increasing duration of cavitation treatment in a certain mode t, the decrease in salt concentration in the solution stops. Dynamic equilibrium occurs when the number of adsorbed molecules is equal to the number of molecules diffused into the solution from the internal surfaces of the heat generator. Further increase in the temperature leads to the increase of diffusion of the salt components from metal surfaces into the solution. The salt concentration in the solution at $t = 90^0$ has a localized maximum. The working process of the depleted solution in all modes, including the low-temperature ones, involves the diffusion of constituents of the material and pollutants into the depleted solution.

With the increase in initial concentrations of solutions of $C = 17 \div 67$ ‰, the effect of the reverse diffusion of salt into the solution ($t = 90^0$) decreases (Figure 9) because the difference in concentrations in the metal of the heat generator and the solution reduces owing to the maximum permissible saturation of the metal surfaces with possible formation of a salt layer on their surfaces. It would follow from this fact that the design of the heat generator of this kind, unlike the one discussed in the paper by Fujisawa et al. (2018), is facilitated by the presence of the auxiliary separating ability within the centrifugal force field (Figure 8), which results in the excessive concentration in the wall-adjacent area if compared to the initial solution.

CONCLUSION

Within the framework of this research study, there was an establishment of the relationship between the intensity of the desalination process and the temperature of the working fluid, and the external overpressure. Taking into account these factors significantly increases the performance and quality of desalination (mineralization). The positive effect of the concomitant desalination through cavitation and centrifugal desalination was also revealed. Nonetheless, the previously recorded radial waves in the generator housing reduce the efficiency of coupling these two desalination methods. This aspect serves as grounds for further development of the design, and in particular development of a rotating housing with either passive or active rotation controlled by a servo drive.

The obtained results are of relevance because the application of the cavitation heat generator under study in its current design in the agricultural sector enables the advancement of the agrotechnical opportunities for the mildly saline solutions of $C_0 = 1 \div 4$ ‰, and, thus, compensation for deficiency of freshwater by means of treating the underground saltwater through cavitation. The obtained experimental results serve as grounds for decision-making on the feasibility of further research to identify the laws of desalination through cavitation, and to improve the device design. The statement and evaluation of the effect of the working fluid temperature on the processes of cavitation and collapse are sufficient to improve the desalination processes, as well as other technological processes through cavitation.

Directions for further research may be the development of a cavitation heat generator with a rotating body; research into the desalination process for saline solutions through cooling down the cavitation areas; research into the desalination process for saline solutions employing the method of creating excess pressure in the working volume of the cavitation heat generator; research into the desalination process using the cavitation heat generator integrating all of the above-stated scenarios.

In conclusion, the macro tools were identified to manage the molecular processes provided implementation of a specific useful function is ensured, i.e. the removal of the soluble and insoluble components from the water. Further advancement of these processes shall provide the basis for the preparation of the nutrient solutions in greenhouse farming, irrigation of the agricultural crops under freshwater deficiency (alongside the sea coasts), artificial revegetation of the saline areas, both after man-induced processes and through natural heritage.

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DECLARATION OF COMPETING INTEREST

None.

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