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Determining Properties of a Flow-Through Supercavitation Desalination Plant

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Abstract. Nowadays humanity faces an increasing problem of fresh water, the resource of which is rapidly declining because of anthropogenic activity. In this regard, the development of methods and means of purification of natural waters from various impurities, both solid and gaseous, becomes a priority. Steam extraction from the supercavitation cavity for its subsequent condensation is an obvious method of water desalination and has a number of undeniable advantages. However, numerous attempts to implement a method of cavitation desalination of water using large-scale setups have not been successful yet. The purpose of this study is to obtain experimental dependence between the temperature and flow velocity of the desalinated liquid, the pressure in the cavity and its size, the geometry of the streamlined body and the volume of steam taken from the cavity in the prototype of a supercavitation desalination plant. Analyzing obtained data made it possible to show a sharp difference between gas and steam cavitation, the performance of the experimental setup in the desalination mode has been determined. It was concluded that the steam velocity in the condensate extraction pipeline is a factor limiting the condensate output. Based on the data obtained, specific design criteria for industrial supercavitation desalination plants were determined.

Keywords: supercavitation desalination plant, cavity hydrodynamics, cavitation experimental setup, degree of steam dryness.

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Определение характеристик проточного суперкавитационного опреснителя

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Аннотация. Человечество в настоящее время все более остро нуждается в пресной воде, ресурс которой в результате антропогенной деятельности стремительно сокращается. В этой связи становятся приоритетными разработки методов и средств очистки природных вод от различных примесей, как твердых, так и газообразных. Отбор пара из суперкавитационной каверны для его последующей конденсации является очевидным методом опреснения воды и имеет целый ряд неоспоримых достоинств. Однако многочисленные попытки реализовать способ кавитационного опреснения воды с помощью крупномасштабных установок пока не увенчались успехом. Цель настоящего исследования – получить экспериментальные зависимости между температурой и скоростью течения опресняемой жидкости, давлением в каверне и ее размером, геометрией обтекаемого тела и объемом отбираемого из каверны пара в прототипе суперкавитационного опреснителя. В ходе анализа полученных данных показано четкое различие между газовой и паровой кавитацией, определена производительность работы экспериментальной установки в режиме опреснения. Установлено, что фактором, лимитирующим выход конденсата, является скорость пара в трубопроводе его отбора. На основании полученных данных определены конкретные критерии проектирования промышленных суперкавитационных опреснителей.

Ключевые слова: суперкавитационный опреснитель, гидродинамика каверны, кавитационная экспериментальная установка, степень сухости пара.

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Highlights

- Steam extraction from the cavitation cavity is possible for desalination
- The intensity of thermohydrodynamic cavitation is determined by the saturated vapor pressure
- The degree of steam dryness from the cavitation cavity decreases with increasing temperature
- The speed of the steam extraction process is proportional to the speed of sound in it
- The rate of steam extraction is a limiting factor in the performance of a supercavitation desalination plant

1. Introduction

The importance of pure water for a person is difficult to overestimate. Unfortunately, the supply of drinkable pure water is decreasing everywhere. Large industrial enterprises continue to discharge industrial water into natural reservoirs, the quality of wastewater treatment of various origins also leaves much to be desired. The problem is getting worse by the strong uneven distribution of water resources. In many countries, there is already a serious shortage of not only pure drinking water, but also fresh water in general [1]. Water supply problems are relevant for regions where there is a shortage of water or water with a high salt content is used. Modern desalination plants prepare water for the normal operation of life support systems, production needs; they are used in shipping and power plants. Desalination plants also purify wastewater from pollution, bringing its indicators up to standard. That is why technologies for obtaining fresh water are developing so rapidly. While the importance of water sources is underestimated in many parts of the world, water scarcity can pose significant challenges to sustainable development, which can contribute to political and social instability, environmental disasters, harm human health, as well as serve as a serious obstacle to economic development [2].

Desalination is carried out by methods based on various physical and chemical principles: distillation, reverse osmosis, electrodialysis, freezing, thermal desalination and ion exchange. The listed technologies have their advantages and disadvantages (deposits on the surfaces of heat exchange, membranes, high specific energy costs, environmental hazards, etc.). The choice of the method and technology of water desalination depends on the requirements for water quality and salinity, as well as technical and economic indicators. The variety of tasks and required salt compositions make it difficult to choose any one universal method.

In this regard, the issue of modernization of existing and development of new desalination plants is very relevant. Separately, there are cavitation technologies currently being developed [3–27], which are easy to implement and energy efficient. In contrast to common methods, the evaporation process in supercavitation-type apparatuses (SC-apparatuses), which can be both flow-through and rotary, is carried out by creating a developed cavitation flow when the cavitator flows around, followed by steam extraction from the formed cavity.

The use of cavitation effects in the desalination plant for the extraction of steam from the cavity of the cavity has a number of undeniable advantages. They are high intensity of the processes occurring, the absence of surfaces in the vaporization zone on which salt deposition can occur, and, consequently, the ability to work without preliminary water treatment, the compactness of the installation, high efficiency, etc.

The tasks of developing flow-through SC devices were solved in [10], where the author studies, proves the possibility of using advanced cavitation modes to intensify the processes of heating, degassing and evaporation of liquids, due to experimental and analytical studies. Much attention is paid to the dependence of the mode thermohydrodynamic characteristics of the flow and geometric parameters of the supercavitation apparatus on the evaporation rate into the cavity. A scheme of a cavitation multi-stage setup for water distillation is proposed as well as a design scheme of a device for water desalination, where corona discharges and pulsations of the evaporated liquid flow are used to intensify the modes of cavitation evaporation. The described works were carried out quite a long time ago, did not have the necessary completeness and therefore cannot be used for direct comparison with the results described in this article. Ideas proposed by V.M. Ivchenko, V.A. Kulagin, A.F. Nemchin and A.S. Machinsky [3, 10] were developed in the dissertation of T.A. Pjanykh [13]. Here, on the basis of mathematical modeling of heat and mass transfer and hydrodynamic processes in a flowing SC evaporator, results were obtained that allow us to assess the influence of control actions (concentration of impurities; degree of flow constraint; amount of steam taken from the cavity; velocity, density and temperature of the flow) on water treatment modes. The proposed method of calculation of cavitation evaporators makes it possible to determine the rational operating and design parameters of single- and multi-stage evaporation plants of supercavitating type at the stage of their design.

Significant progress in the implementation of the principle of cavitation desalination of water is associated with the development of computing technologies [4, 5, 20, 23]. In the works from different periods [6, 11, 12, 14, 16–18, 22, 26] the results of numerical simulation of rotary SC evaporators (RSCE) are presented. Steam extraction in this setup is organized through holes located in the rear of the rotating impeller. The development of research in the direction of improving the processes of thermal desalination by means of a rotary evaporator can be found in the later work of the authors [9]. This article presents the results of numerical simulation of supercavitation flows in a rotary cavitator with an optimized impeller shape. In addition to numerical studies of supercavitation flows at different rotational speeds and different sampling pressures, the effect of steam extraction on hydrodynamic characteristics and desalination performance was considered. The results described by the authors are very encouraging, but the degree of desalination obtained during the experiments is still insufficient for using such a device in practice.

The process of steam extraction in order to obtain conditioned industrial water and drinking quality water is not the only task of cavitation technology. The most important problem of our time is the treatment of industrial and domestic wastewater [28–37].

Despite the positive prospects for the use of computing technologies in the design work of the production of SC evaporators, it turns out to be impossible to do without solving the problems of physical modeling of supercavitation flows and corresponding experimental work on fine-tuning real designs of evaporation plants and systems [38]. In this regard, the Russian-Chinese International Laboratory of Cavitation Technologies of Siberian Federal University is systematically working on the development of experimental techniques in the field of supercavitation flows based on a prototype of the flow-through stage SC-evaporator [39–44].

In this paper, we have attempted to establish a connection between the hydrodynamic parameters of the flow and the thermodynamic parameters of the selected steam, thereby demonstrating the effectiveness of the supercavitation evaporator and proposing a new approach to the design of desalination plants based on steam extraction from the cavitation supercavity clearly.

As the main tasks, set in terms of our research, the following were chosen:

- demonstration of the fundamental possibility of using cavitation as a phenomenon to create an effective desalination plant;
- determination of factors affecting the maximum performance of the cavitation desalination plant;
- setting the parameters of the cavitator flow, allowing the maximum amount of steam to be taken from the cavity.

2. Materials and methods

In terms of carrying out the described works, the previously used hydrodynamic setup [39, 40] underwent significant changes, in particular, the length of the working section was increased from 170 to 450 mm (Fig. 1, 2).

To control the temperature of the experiment, the setup was supplemented with a heating element installed directly in the flow, with a power of 9 kW with a thermostat. To condensate extraction, the installation is supplemented with a plate heat exchanger with a heat exchange area of 0.5 m^2. The condensate collection tank is additionally evacuated by a single-stage rotary vacuum pump Zensen ZSJ-2S. The general schematic diagram of the experimental stand is shown in Fig. 3. The appearance of the entire experimental stand is shown in Fig. 4.

The experiment was constructed as follows: tap water was supplied to the setup, air was removed from the setup through air valves. The speed in the circulation circuit was regulated by a valve after the

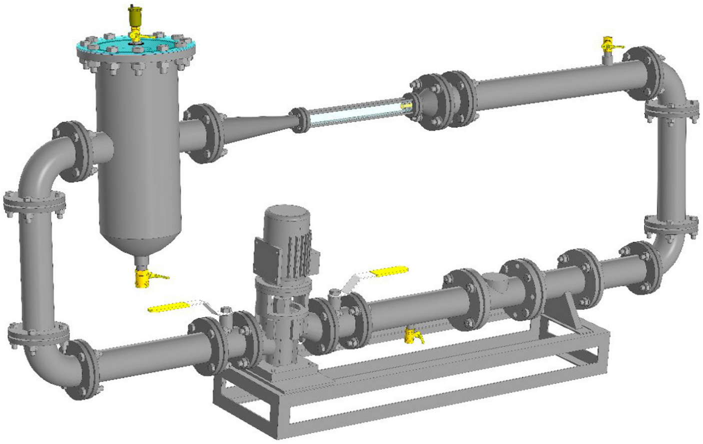


Fig. 1. Used hydrodynamic circulation circuit

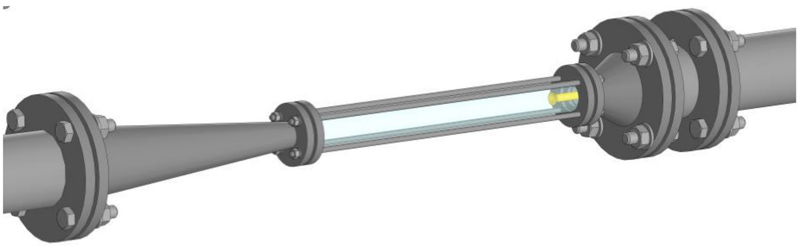


Fig. 2. Working area

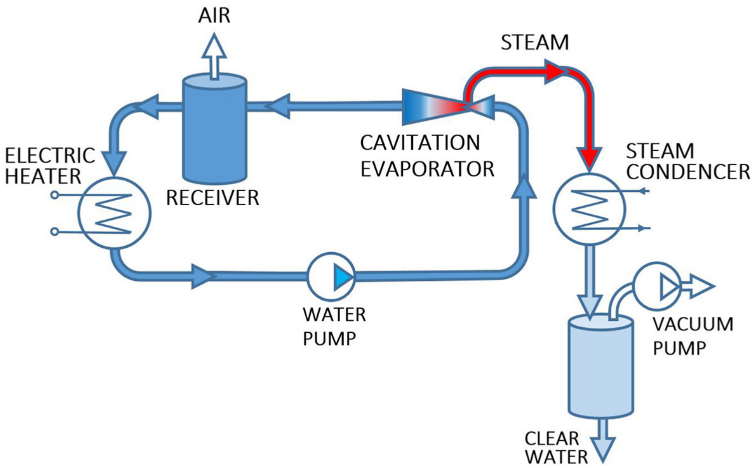


Fig. 3. Schematic diagram of the experimental stand

a) b)

Fig. 4. General view of the experimental stand: a – evaporation circuit; b – condensation circuit

pump, the maximum temperature was set on the thermostat of the electric heater. After the length of the cavity reached its maximum as a result of the temperature increase, the vacuum pump was turned on and the condensate collection line was opened.

During the experiment, the following parameters were recorded:

– water flow in the installation and cooling water flow through the heat exchanger;

– flow temperatures, steam at the inlet to the heat exchanger, condensate, cooling water at the inlet and outlet of the heat exchanger;

– pressure in front of the working area, in the cavity, at the entrance to the confuser, after the receiver, in the condensate collection tank;

– the length of the cavity;

– the volume of condensate.

In terms of described work, two series of experiments were conducted: with the flow of cones with a diameter of 15.5 mm and 27.75 mm.

3. Results

According to velocity and temperature of the flow, the cone flow took place in the mode from the flow of a continuous liquid to the formation of a supercavern up to 400 mm long. Photos of the cavern of different lengths are shown in Fig. 5

a)

b)

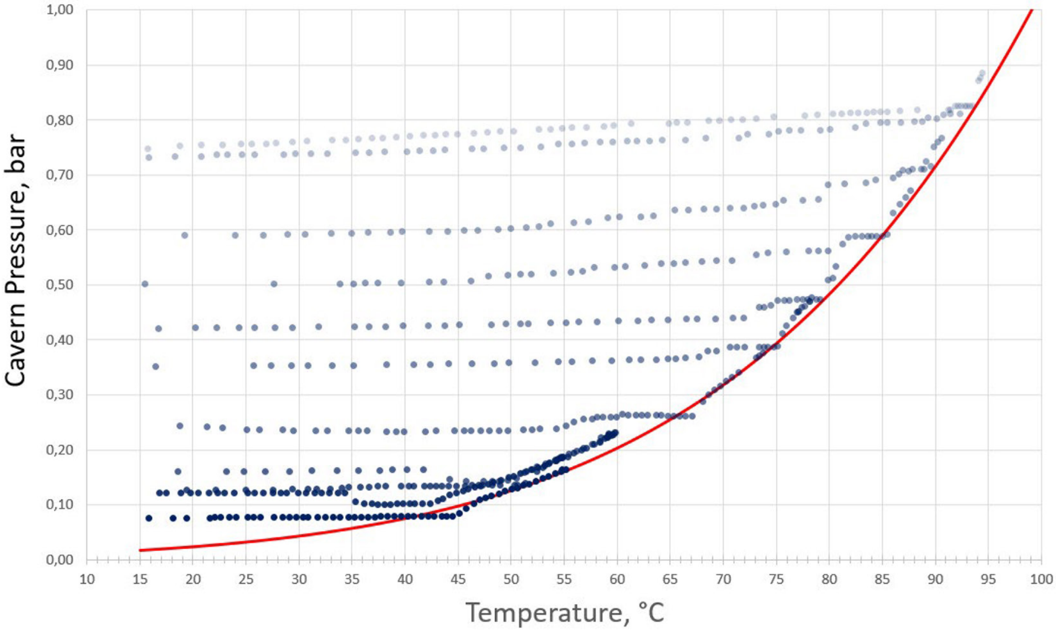
Fig. 5. An example of the geometry of a cavern when flowing around a cone with a diameter of 15.45: *a* – the length of the cavern is 30 mm; *b* – the length of the cavern is 220 mm

During the measurements, the following graphs were generated: the dependence of the pressure in the cavity on temperature for different velocities (Fig. 6), the length of the cavity on temperature (Fig. 7) and the flow velocity on temperature (Fig. 8).

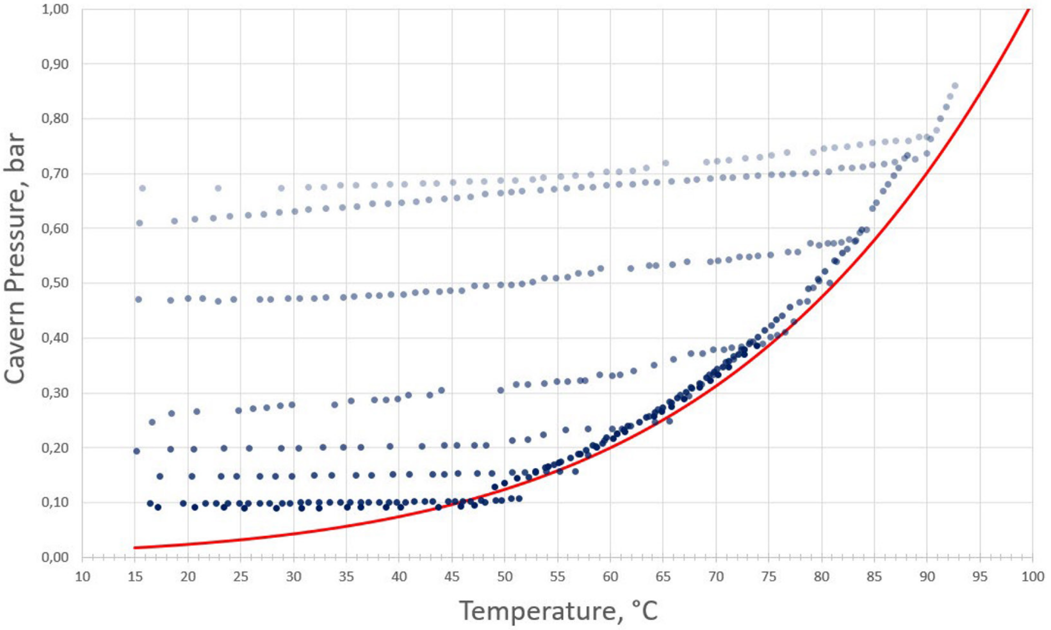
4. Discussion

The obtained data allow us to analyze the nature of the cavitation flow. Using the dependence of saturation pressure on temperature, it is possible to divide the mode of cavitation flow into steam cavitation, when the pressure in the cavity is equal to the pressure of saturated steam at the temperature in the flow, and steam-gas, when the pressure in the cavity is less than the pressure of saturated steam. The transition to steam cavitation is clearly visible in Fig. 6 and corresponds to the inflection point of the presented dependencies, which quite accurately correspond to the saturation line shown on the graphs. The data obtained in this way are transferred to the graphs in Fig. 7 and 8.

The obtained data on the amount of collected condensate (Fig. 9) allowed us to determine the steam velocity. Figure 10 shows the steam velocities through steam pipelines with a cross section of 3 and 5 mm. The resulting velocities are perfectly approximated with the speed of sound at the same temperatures. The lower steam velocity (approximately 4.5 times) is explained by the local and linear hydraulic resistances of the steam main.

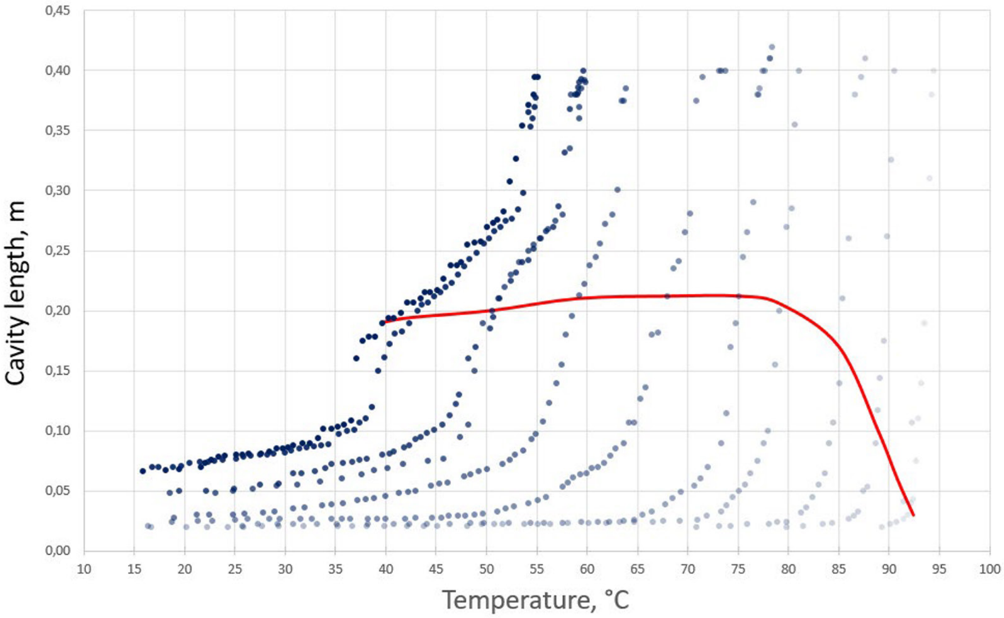


a)



b)

Fig. 6. Dependence of cavity pressure on temperature: *a* – a cone with a diameter of 15.45 mm, *b* – a cone with a diameter of 27.75 mm. Markers with more intense coloring correspond to a higher flow rate. Red line – saturated vapor pressure (reference data)



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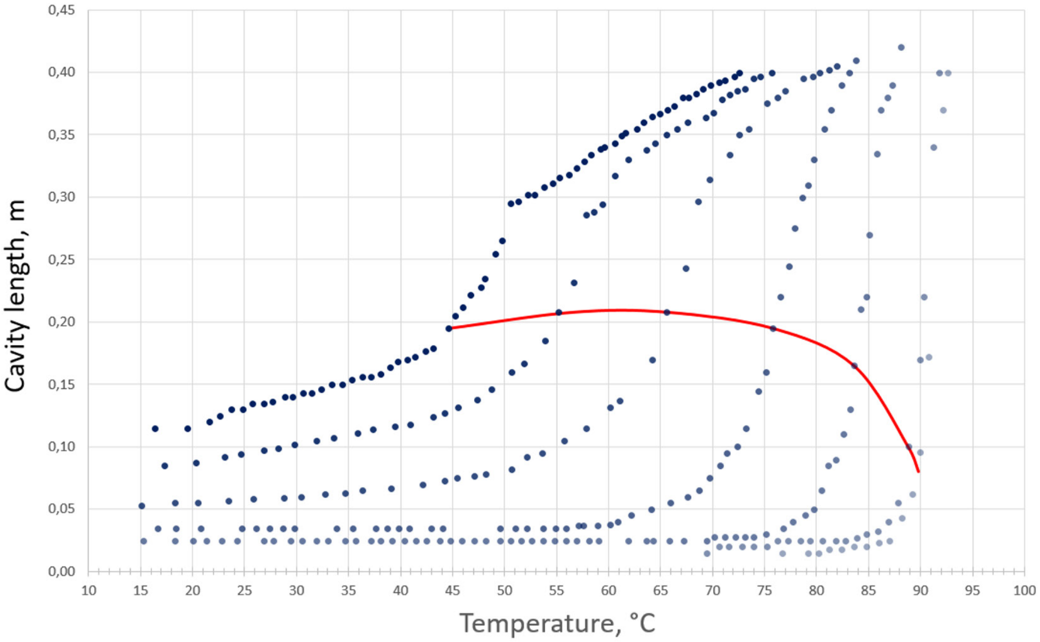
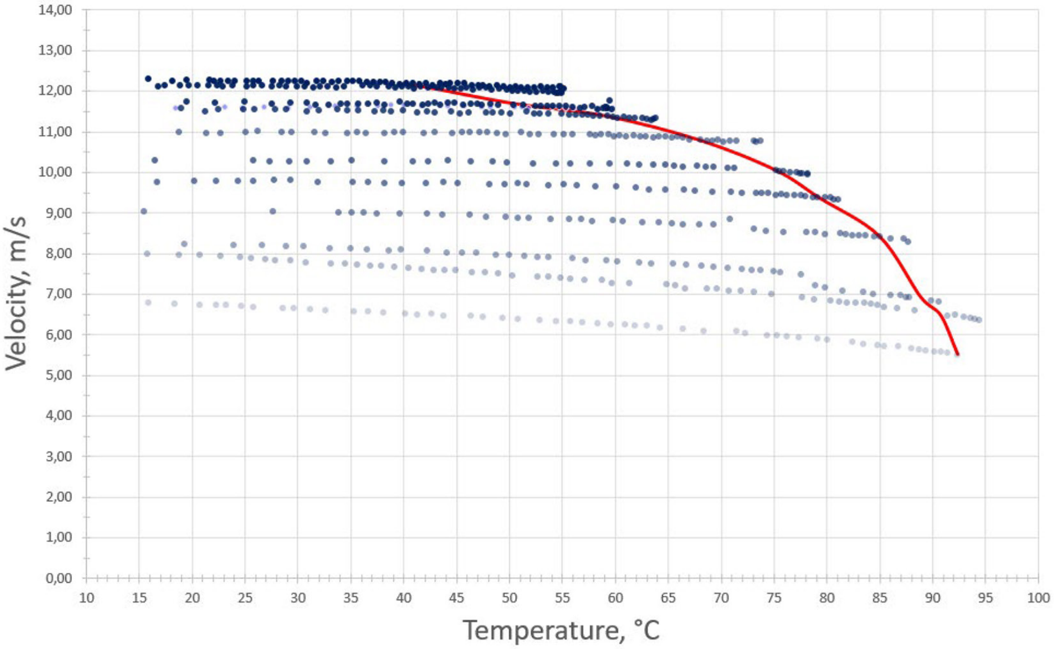
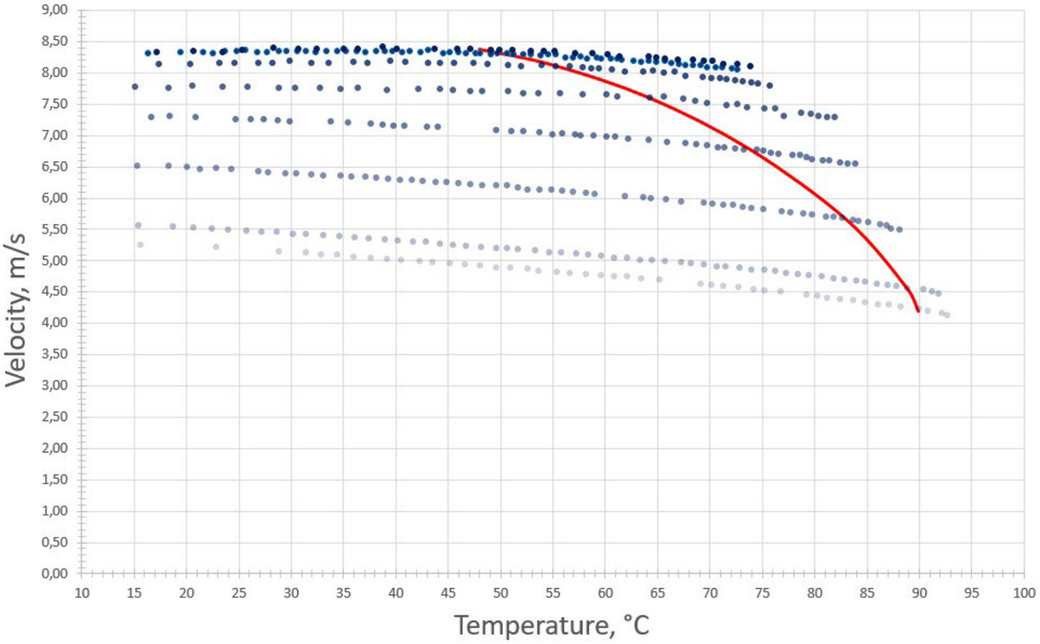


b)

Fig. 7. Dependence of cavity length on temperature: *a* – a cone with a diameter of 15.45 mm, *b* – a cone with a diameter of 27.75 mm. Markers with more intense coloring correspond to a higher flow rate. The red line is the conditional boundary between the gas (bottom) and steam (top) stages of cavitation



a)



b)

Fig. 8. Dependence of flow rates on temperature: *a* – cone with a diameter of 15.45 mm, *b* – cone with a diameter of 27.75 mm. Markers with more intense coloring correspond to a higher flow rate. The red line is the conditional boundary between the gas (bottom) and steam (top) stages of cavitation

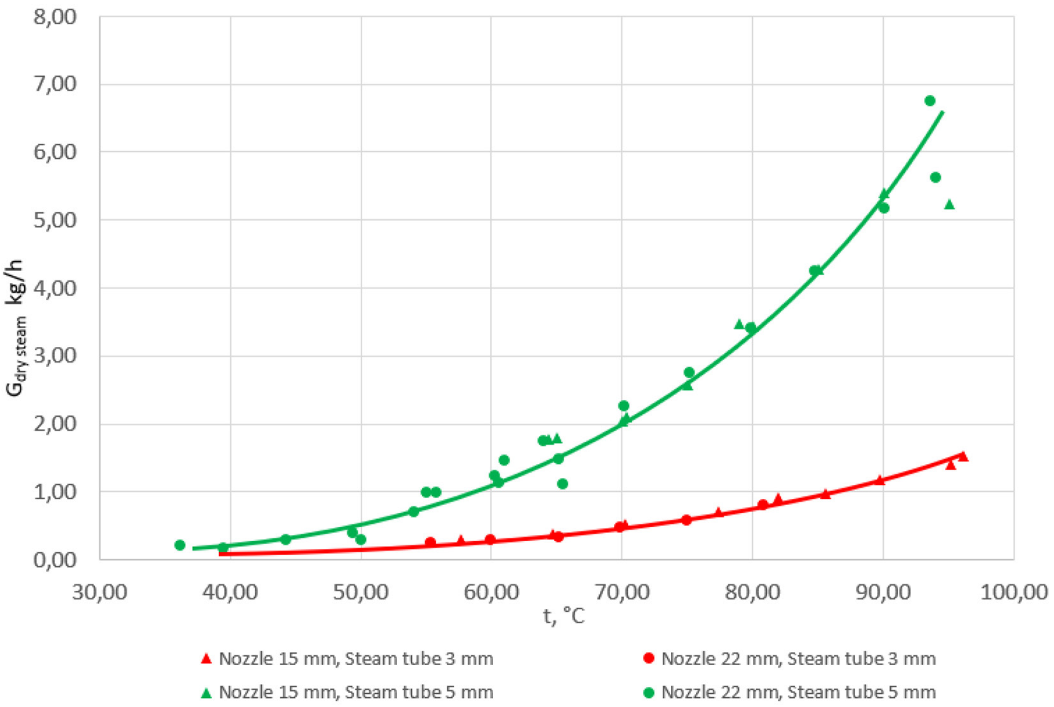


Fig. 9. The amount of steam taken from the cavity

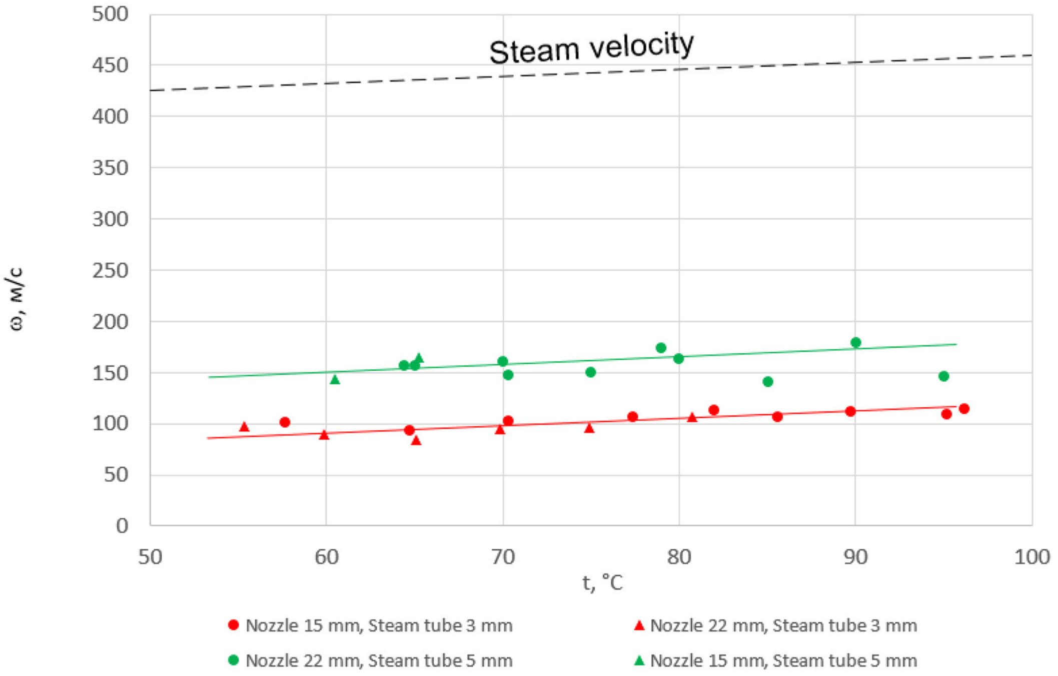


Fig. 10. Steam velocity in the steam line with a section of 3 mm

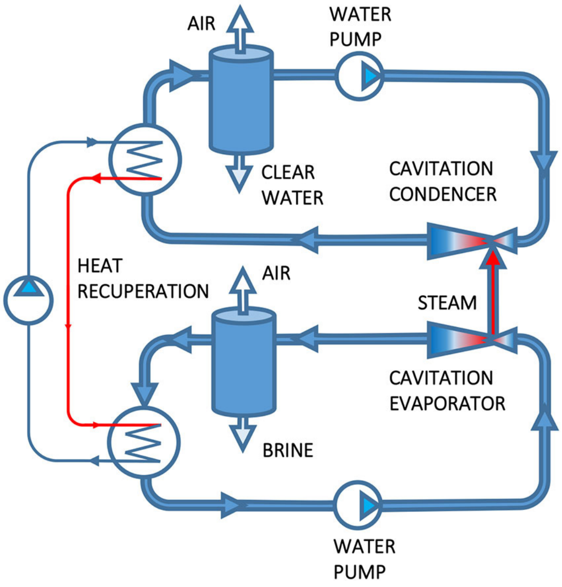


Fig. 11. Scheme of desalination plant with cavitation condensation and heat recovery

5. Conclusion

Each of the lines shown in Fig. 6, illustrating the dependence of pressure in the cavity on temperature, can be divided into a part corresponding to the stages of gas and steam cavitation: when the saturation parameters are reached, the slope of the curve changes dramatically.

The conducted research has clearly shown that hydrodynamic cavitation can be considered as a phenomenon with great potential for use in the design of an effective desalination plant. Figure 11 shows one of the possible schematic diagrams of such an installation. The authors suggest that in addition to the cavitation steam generator, it is possible to use cavitation, including for steam condensation. The diagram shows two circuits: evaporative and condensing. The heat of vaporization chosen in the evaporation circuit can be returned from the condensation circuit by the recovery system.

Supercavitation has been a topic of interest globally owing to its diverse applications such as torpedo, underwater transport, wastewater treatment, and desalination. The supercavity dimensions decide the amount of vapor generated and is of vital importance in the desalination of water [45]. The temperature of the liquid plays an important role in the supercavity geometry, accordingly, studies are conducted on supercavity properties at various operational liquid temperatures. The simulations are conducted using ANSYS Fluent [46] at fixed cavitation number and operational liquid temperature in the range of 22–50 °C. The working fluid employed is water as the experimental study mentioned. The results show that the increase in temperature is associated with an increase in the vapor generation rate. It is observed that on increasing the liquid temperature the supercavity maximum diameter and half-length also increases. As compared to the liquid temperature of 22 °C, an increase of 53 % in supercavity diameter was observed at 50 °C.

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