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Bilge and Oily Water Treatment During Operation of Vessel

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ABSTRACT: Bilge and oily water (BOW) during vessel's operation are the most large-tonnage type of waste and for their treatment all ships, in accordance with regulatory requirements [14], have to be equipped with special equipment – oily water separators. Under conditions of sea vessel operation BOW are process effluents that occur in the engine room, in cargo holds, as well as during the operation of the different equipment and deck machinery. At sea vessel's operating conditions three main directions of BOW cleaning are now used: physical, chemical and biological. In most technological cases, they are used in combination with each other. The analysis of BOW separation methods based on these three directions has shown that they all could be characterized by one common drawback - unidirectional cleaning. During separation the final product – water is only one component of multiphase flow. It is very difficult to obtain secondary petrochemical products when modern methods of purification are used on the sea vessel during separation. Because of this reason in the research, a new method for BOW separation was developed. It is based on the use of a hydrodynamic process of supercavitation with artificial ventilation of the cavitational cavern. With local origin in the flow of a supercavitating cavern, there will always be saturated water vapor inside of it. The process of permanent water vapor selection from the cavern will ultimately contribute to the production of highly concentrated mixture of those petroleum products that form the initial mixture of BOW. In research, an assessment of the spatial stability of the cavitational cavern in the range of various cavitation numbers was done. During the study of BOW separation process it was found that decreasing of the working pressure inside the working chamber of the cavitation separator have to be always compensated by an increase in the temperature of the processed multiphase flow.

1 INTRODUCTION

The problem of emergence, collection, storage and separation of a multi-phase flow of water with oil products, referred to in the operating conditions of water transport vehicles as ship's bilge and oily water (BOW) is very actual and important. BOW during vessel's operation are the most large-tonnage type of waste, and for their processing all ships in accordance with regulatory requirements [14] have to be equipped with BOW separators.

The outlet concentration of impurities in purified water should be less than 15 p.p.m. [14] and in a big number of special regions of the planet, the overboard discharge of BOW is prohibited. With a comprehensive analysis of this problem, it can be stated that from an economic point of view the secondary oil products obtained from the BOW are of great interest as a source of additional fuel resources for the ship.

2 MATERIALS AND METHODS

2.1 *Main Sources of BOW*

BOW are process effluents that occur in the engine room, in cargo holds, as well as during the operation of the deck and deck machinery under the conditions of the ship's operation.

According to the analysis fulfilled for sea vessels (bulkers, tankers, RO-RO type vessels, etc.) operation, it was found that the main generators of the components that form the basis of the BOW, which finally end up in bilge wells and tanks, are: condensed liquids from cooling systems of main and auxiliary engines; condensed liquids from starting and auxiliary compressors for compressed air supply; liquids condensated from the deck heater system; distillate from refrigeration units and compressor units servicing air conditioning systems; liquids condensated from for oil tanks (separator tank, incinerator tank, etc.) heating systems; leaks in pipelines and ship auxiliary mechanisms, in particular: sea water, fuel, oil and steam systems (in most cases, such leaks are typical for ships whose construction and operation period exceeds ten years); waste water with light chemical products after cleaning or scrubbing the decks of the engine room and pallets of ship auxiliary mechanisms; products of washing or scouring of: decks, deck machinery, process equipment and auxiliary equipment; running water for personal hygiene of workers in the engine room of large multi-tonnage vessels; drainage of rainwater from ship chimneys at the absence of separate discharge lines; cargo hold or tank washing products collected in a separate, so-called SLOP tank; products of oil spills during bunkering or during loading and unloading operations, collected in a separate SLOP tank; drains from bow, stern and central ship wells and gaters.

During operation of water transport facilities quantitative changes in the total volumes of generated BOW are determined by a combination of the following reasons: the operational intensity of the ship power plant; total power and number of auxiliary boiler equipment; non-uniform loading of the ship's holds with the same type of cargo; the quality of inspection and repair of tanks and fuel and oil supply systems, etc.

2.2 *Specific Features of BOW*

The qualitative and quantitative composition of BOW is not universal and in each case is a variable value. It directly depends and is determined by the ship technological processes that generate it. The average statistical list of the main BOW components includes: dissolved gases; oils (industrial, used machine oils, etc.) with a concentration of up to 1000 mg/l; waste oil products and their components, as well as oil sludge (concentration up to 8000 mg/l); detergents (concentration up to 5-10 mg/l); suspensions (concentration up to 300-500 mg/l); sulfates (concentration up to 200 mg/l); phenols (concentration up to 50 mg/l).

All of the above components, except for gases, are characterized by a large specific gravity compared to the same parameter for water, which is the basis for the further process for their separation from the BOW flow.

If we classify BOW components as gaseous, liquid and solid we can state that, depending on the ratio between the densities of the separately considered component ϱc and water ϱw, the following two options for the behavior of the mixture are possible:

– in a stationary state, over time at $\varrho c<\varrho w$, for a certain time during stratification, the components of the BOW will float up;
– in motion with absence of lifting forces and $\varrho c>\varrho w$, the components of the BOW will precipitate.

Considering BOW as a multicomponent flow being processed it is worth to note, that when analyzing the operation practice of separators, it was found that high purification efficiency occurs at a concentration of harmful components only up to 100 mg/l [3, 19]. Exceeding this value leads to the complication of methods used for their separation.

2.3 *BOW Separation Methods*

The general principles of technological schemes functioning intended for BOW separation are directly determined by the work processes used to separate their constituent components. Three main directions of water purification in the vessel operating conditions can be distinguished principally: physical, chemical and biological. In most cases, they are used in combination with each other [1, 3, 11, 13, 16].

The basis of the physical direction is the use of mass and less often surface forces. In this case, the mass forces include the forces of inertia, gravity, floating, etc.

The implementation of chemical processes in the BOW separation is based on the use of various reagents in combination with electrochemical oxidation of the processed flow [2, 12].

The biological direction of BOW separation implies the use of microorganisms that ensure the destruction of the constituent components of petrochemical products during the time of their life activity [20, 25].

During research, a general structural classification of existing methods for the BOW separation was developed (Fig. 1). It was done in the form of a diagram, which shows that all ship technological schemes for BOW processing are based on twelve different technologies.

The analysis of their performance indicators has shown that during the vessel's operation, separators which operate on the principle of centrifugal flow separation are most widely used. The main disadvantage of marine centrifugal separators is their limited capacity, i.e. inability to process large volumes of BOW in short periods of time. Basically, such a limitation is caused by the length of the path that particles of oily impurities have to pass by before they hit the free surface of water or stick to the contact surface of the separator.

During separation of BOW, pre-filtration of the processed multiphase flow is used always. It is based on the physical cleaning method and is founded on the use of pressure or non-pressure filtration. During filtration, a non-selective reversible process is used. It is based on the use of van der Waals forces - the forces of intermolecular interaction between the molecules of the filtering material and the molecules of the BOW components [21].

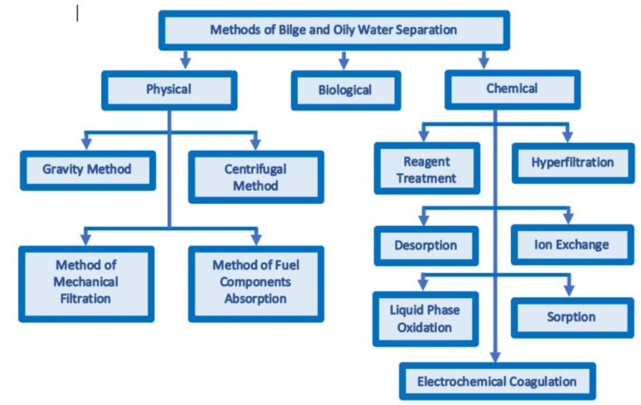

Figure 1. Methods of BOW separation

2.4 *Cavitation in BOW*

A detailed analysis of all methods for BOW separation in Fig. 1 allows to conclude, that they are characterizing by one common drawback - unidirectional cleaning. During the separation, the output product is only one mixture component - water. When using these purification methods during separation, it is very difficult to obtain secondary petrochemical products. For this reason, during the research, it was concluded that it is necessary to develop a new method for the BOW separation and the expediency of using in this case the hydrodynamic process of supercavitation with artificial ventilation of the cavity.

With local origin in the flow of a supercavitating cavern, there will always be saturated water vapor inside of it [24]. The process of continuous selection of water vapor from the cavern will ultimately contribute to the production of a highly concentrated mixture of those petroleum products that form the initial content of the BOW. An example of a supercavitational cavern for stationary water flow one can see in Fig.2 [18].

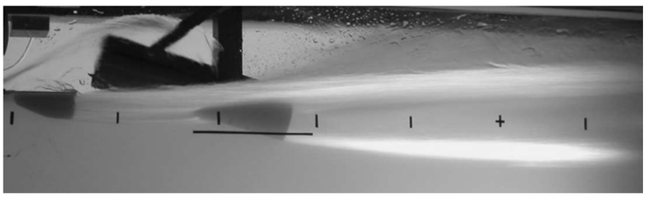

Figure 2. Stationary supercavitation cavern [18].

The main advantage of the proposed new method for BOW flow separation using the supercavitation process with artificial cavity ventilation is the possibility of purifying the flow with a high concentration of harmful impurities. This method can be used as an alternative to electrochemical separation methods, which are currently considered to be practically the only effective methods that can be used at impurity concentrations in water exceeding 1 g/l [2, 17].

2.5 *Specific of Cavitational Flows and Caverns*

The main feature of the occurrence of cavitation caverns on rigid boundaries located in a moving flow is the beginning of cavitation - the moment when the cavitation number Ω becomes equal to the minimum pressure factor C_{pmin}. On the outflowing surface, the value of this factor is determined by the position of the point (line) where the maximum rarefaction is observed [6]. Near such a region of minimum pressure, nucleation, accumulation, and association of initially formed bubbles of water vapor and gases dissolved in the liquid occur [5, 6, 10]. The influence of the design (its geometric configuration, the degree of curvature of the constituent elements, the angle of attack of the flow, the amount of overlap at the inlet and outlet, etc.) of the working chamber of the cavitation channel always increases with the development of cavitation [26, 27]. The quality of such influence is directly determined by the shape and location of the surface on which the cavitational cavern is formed.

Since cavitation in a liquid is the formation and stable existence of cavities filled with vapor and gases, the ratio of the content of gas and vapor in the cavity may be different with a local decrease in pressure.

Depending on the concentration of steam or gas inside the cavern, cavitation caverns are divided into two types - steam and gaseous [5, 18, 27].

Due to the complexity of the processes occurring during artificial cavitation, there is currently no clearly formulated theory that describes the relationship between the main characteristics of this flow and hydrodynamic forces that affect the spatial dimensions of the cavity. There are also no known data that indicate how the air flow and pressure which goes to supply cavity ventilation affect these values [15].

The value of the static pressure PSt has a direct impact on the stability of the supercavitational cavern. With an increase in the value of PSt, the decreasing volume of the cavitation cavern will perceive a large value of the absolute pressure. Accordingly, the rate of decrease in volume will be higher, other things being equal, and as a result, the pressure of the vapor-gas mixture inside the cavity will increase, eventually leading to vapor condensation.

A specific feature of supercavitation in multiphase flows is the absence of influence of the physical properties of the flow onto dynamics of the cavitation cavern existence [18]. In particular, such two important factors as the surface tension coefficient and the viscosity of the flow do not change the dimensions of the cavitation cavern with the invariance of the cavitation number of the flow. Thus, for example, the influence of viscosity begins to affect when its value exceeds by two orders of magnitude (at 100 and more times) the analogous value for pure water [28].

The spatial behavior of cavitation caverns is directly determined by the geometry of the flow in which they are formed. The cavity shape can change significantly under the influence of closely spaced hydrodynamic features [18]. In this case, depending on their intensity and location in relation to the cavitation cavern, it is possible to obtain a different degree of deformation of its boundaries. At the same time, in the case of very high relative flow velocities, the influence of the forces of gravity (weight) of liquid on the geometry of the cavitational cavern is practically absent.

The presence of rigid walls near the cavern can lead to the appearance of asymmetry of its boundaries with respect to the horizontal section. In the presence of a horizontal channel wall, the maximum length of the cavitational supercavern depends on the cavitation number. If a cavity appears behind the disk, then its length can be described by a relation [7]

$$L_{max} = \frac{1,66d}{\Omega_{min}} \tag{1}$$

d – diameter of disk, m; Ω_{min} - minimal number of cavitation.

The value of the minimum distance h between the wall and the boundaries of the cavity at which its destruction will not be observed can be described as [7]

$$h = \frac{0,375}{Fr_d^{4/3}} \tag{2}$$

Fr – Froude parameter.

According to the experimental results [7], the minimal distance h depends on the velocity of the nozzle or the main flow around the nozzles. In the practically demanded range of Froude numbers, i.e. when Fr≈5-10 the value of h should exceed 5% of the length of the supercavitational cavern. In accordance with this range, the deformation (the ratio of the abscissa in the maximum section of the cavern to the diameter of the nozzle behind which it was formed) of the cavitation cavern near a solid surface [7] is proposed to be found as

$$\overline{y_c} = 1 - \frac{0.05}{\frac{h}{L}} \tag{3}$$

L – length of cavitational cavern, m.

By analogy with thin cavitating airfoils, approximately the value of the lift force factor acting on the rectilinear thin boundary of the cavitation cavern can be determined, depending on the angle of attack of the flow, by the Betz formula

$$C_y = \frac{\pi}{2}\alpha\left(1 + \frac{2}{\pi}\frac{\Omega}{\alpha}\right) \tag{4}$$

α – angle of attack; Ω - cavitation number.

For the case when cavitation flow is formed inside a channel with rigid boundaries, formula (4) will give more accurate results if instead of the angle of attack of the flow, the angle of its bevel is used. This value is the ratio of the maximum value of the vertical velocity component at the supercavity interface to the velocity of the oncoming main flow and can be calculated as

$$\alpha = \frac{V_{y\,max}}{V} \tag{5}$$

A decrease in the number of cavitation, which is equivalent to an increase in the flow velocity, always leads to the association of finely dispersed vapor bubbles into an integral supercavitation cavern. For this reason, it is important to know the speed at which the first stage of cavitation will occur inside the working chamber of the cavitator. It corresponds to the nucleation of small bubbles filled with saturated water vapor and can be calculated as

$$V = \sqrt{\frac{P_{c.t.} + \rho g h - P_i}{\frac{\rho \xi_{max}}{2}}} \tag{6}$$

P_i - pressure along the surface of the working chamber of the cavitator, Pa; $P_{c.t.}$ - pressure in the storage tank, Pa; h - height of the storage tank location in relation to the axis of symmetry of the cavitation working chamber of the separator, m; ξ_{max} – maximal factor of local hydraulic losses of the cavitator chamber.

During cavitational separation of BOW it is important to know the amount of water vapor taken off. The vapor mass in the first approximation can be found using the Hertz-Knudsen formula

$$G = \alpha P_{s.s.}\left(\frac{M}{2\pi Rt}\right)^{\frac{1}{2}} \tag{7}$$

G - mass of vapor evaporating or condensing per unit time on a unit surface; α - accommodation factor (for water α=0.04...1.0); $P_{s.s.}$ - pressure of saturated water vapor inside the cavity, Pa; M - molecular weight of water vapor; R - universal gas constant; t - absolute temperature, °C.

For an approximate evaluation of time τ, during which a spherical cavitation supercavern with radius r will be completely filled with saturated water vapor, can be found as

$$\tau = \frac{r}{3\alpha}\left(\frac{2\pi M}{Rt}\right)^{\frac{1}{2}} \tag{8}$$

The destruction time of this spherical cavern can be calculated using the empirical Rayleigh formula

$$t = 0.915 r_{max}\sqrt{\frac{\rho}{P_\infty}} \tag{9}$$

r_{max} – maximal radius, m; ρ - initial density of BOW flow, kg/m³; P_∞ - initial pressure of the BOW flow, Pa.

When the cavity expands, the vapor pressure inside of it will not always correspond to the saturated vapor pressure. To satisfy their equality, it is necessary to accomplish an inequality

$$t_s > \frac{r_{max}}{3\alpha}\left(\frac{2\pi M}{Rt}\right)^{\frac{1}{2}} \tag{10}$$

t_s – time when cavern forms stable position, sec.

Evaluation of expression (10) shows that at a BOW temperature equals to 20 °C, the water vapor pressure inside the cavern will be equal to the saturated vapor pressure, subject to the following inequality $r_{max}/t_s \leq$ 17,8 m/sec.

Since dissolved gases are always present in the BOW, their mass must also be taken into account at the initial stage of cavity formation. For the case when the outer boundaries of the cavitation cavern are limited by a flat rectangular channel, the mass of dissolved gases is equal to

$$G_g = \frac{4}{3}\frac{C_g}{K}bL^3 \tag{11}$$

G_g - mass of gas inside the cavern at the time when it reaches a stable state; C_g - initial gas concentration in the BOW flow; K - Henry's constant; b and L – thickness and length of the cavern.

2.6 *Artificial Supercaverns*

Initially, artificial supercaverns were used in experimental studies of phenomena associated with the high-speed motion of bodies in a fluid. Artificial supercaverns, in comparison with caverns that occur during natural cavitation, have distinctive features: the flow movement in which cavitation is artificially created is always characterized by lower values of the average velocity; due to the difference in the densities of liquids and air, which is always much less than unity, artificial supercaverns always have a clear interface between the areas of the moving flow; the beginning of an artificial supercavern always has a unique spatially fixed position; the movement of the vapor-gas mixture inside the artificial supercavern can be neglected and it can be assumed that the outflowing of the cavity is provided by potential flow.

For the case of artificial blowing of air into the cavitation supercavern, in the first approximation, without considering the discontinuity of the main flow of the BOW, the dependence of the velocity at the boundary of the supercavern on the blowing velocity was estimated. If we accept that at the inlet to the working chamber of the cavitator: the values of the velocity and pressure of the BOW flow are Pbow, Vbow; the velocity and pressure of the air are Pa, Va; velocity and pressure at the boundary of the BOW flow cavern are Pc, Vc, then the flow velocity at the cavern boundary can be found as

$$V_c = V_{bow}\sqrt{1+\Omega} + \frac{\rho_a V_a^2}{2} \tag{12}$$

ρ_a - density of the air, kg/m³; V_a - velocity of the air supply, m/sec.

Since low cavitation numbers correspond to high motion velocities [7, 22], it can be written approximately that $\sqrt{1+\Omega} \approx 1+\Omega/2$. In this case, the last expression can be simplified to an approximate formula

$$V_c \approx V_{bow}\left(1+\frac{\Omega}{2}\right) + \frac{\rho_a V_a^2}{2} \tag{13}$$

Analysis of (13) allows one to make conclusion that velocity caused by the hydrodynamic features inside the cavitation channel, at the boundary of cavern, will be determined mainly by the velocity horizontal components of the air and the treated BOW flow. In this case, the prevailing contribution to the value of V_c in formula (13) comes from the term $V_{bow}\Omega/2$.

When one considers spatial and temporal stability of an artificial cavitation supercavern, the optimal air supply rate used for its ventilation is of great importance. Its value can be found if we accept the hypothesis that the air movement occurs due to the pressure drop in the end sections of the air flow. Such sections can be the cavity closure plane and the inlet section of the air channel. In this case, the optimal air flow rate is equal to

$$V_a = \sqrt{\frac{2P_{atm}}{\rho_a\left(\lambda\frac{l}{d}+\bar{P}\right)}} \tag{14}$$

P_{atm} - atmospheric pressure, Pa; $\bar{p}$ - pressure factor behind the cross-section of air inlet into the cavern; λ – hydraulic friction factor of the air supply channel; l, d – length and diameter of the air supply channel, m;

One of the main factors determining the necessity to use artificial supercavitation during BOW separation is the hysteresis in the occurrence of natural cavitation vapor bubbles [27]. It has been experimentally stated that, at the initial moment of time, the growth of bubbles occurs due to a decrease in pressure in the liquid to the threshold value P_{cr}, which is always less than the saturated vapor pressure [26]. In the future, the growth of the gas-vapor bubble is prevented by the added mass of liquid, static pressure and surface tension pressure. The non-linearity of the behavior of the phase equilibrium leads to a decrease in the average temperature of the vapor bubble relative to the temperature of the surrounding liquid. The result of such a temperature imbalance is the flow of heat from the liquid into the bubble with the evaporation of the liquid into the interior and the subsequent growth of the bubble. An increase in hydrostatic pressure leads to a decrease in the time of collapse of the cavitation cavern and an increase in the intensity of shock waves. Also, in this case cavitation erosion takes place [8].

In accordance with the experimental data [7], at moderate relative flow velocities, stable regimes of artificial supercaverns with stable hydrodynamic characteristics are observed in the range of cavitation numbers $0 \leq \Omega \leq 0.2$.

A specific feature of artificial supercaverns is their dependence on the relative velocity of the main flow in which they are formed. For a given cavitation number, a decrease in the injected gas flow rate can be compensated by an increase in the relative velocity. At the same time, at excessive flow rates of the blown gas, the cavity will be saturated with this gas with the appearance of boundary instability or complete destruction of the cavern. In accordance with experimental results [7], the critical cavitation number at which high-frequency spatiotemporal oscillations of the external contour of the cavern begin satisfies the inequality $\Omega_{cr} < 0.19\ \Omega_{nat}$.

2.7 *Cavity Dimensions and Flow Temperature Influence on Separation*

During separation of BOW flow by the proposed method of cavitation evaporation of the water component, an important question is the spatial stability of the supercavern when water vapor is removed outside from it. Due to the change in the volume of the cavitation cavity, its outer contour will constantly oscillate in the vertical plane relative to its stable stationary position. These fluctuations will be affected by the ratio between the pressure values inside the cavern and in the moving flow of the BOW. In this case, it is always necessary to make an assess of a stable equilibrium at which the cavity can return to its maximum size or vice versa will come to the state of a vapor-gas cavern that does not participate in the cavitation process.

If we consider the cavern as spherical, then the value of the critical radius of the cavitation cavern with respect to the pressure P in the main flow of the BOW will be determined as

$$r_{cr} = \frac{4}{3}\frac{\sigma}{\left(P_c - P_{cav}\right)} \tag{15}$$

σ – factor of surface tension; P_c - pressure inside the cavern; P_{cav} - threshold pressure corresponding to the occurrence of cavitation (at first approximation, it can be taken equals to the saturated vapor pressure at a given temperature).

Below the value calculated by expression (15), there is no sense to provide the process of removing water vapor during the separation of the BOW. In this case the cavity will no longer be able to recover to its original size.

The temperature factor also plays an important role during cavitational separation of BOW. With an increase in temperature, due to a decrease in the solubility of gases, their release and transfer into the interior of the cavity will be much more intense. The second factor that will influence the increase in the size of the supercavitational cavern with increasing flow temperature is the drop in the value of the surface tension factor. At a constant value of static pressure, an increase in temperature invariably will produce an increase in the dimensions of cavitation cavern.

When considering supercavitation in an ordinary homogeneous flow, the growth of the temperature factor will lead to negative consequences - the destruction of the cavitation cavern due to a quick increase in the mass of water vapor and pressure drop inside of it. From the point of view of the BOW separation process, this drawback is an advantage, since a uniform selection of water vapor will only lead to stabilization of the spatio-temporal dimensions of the cavity and an increase in the productivity of the separation process in terms of the amount of separated water.

According to the experimental results [23], the optimal temperature at which spatial stability of the cavity dimensions is observed answers the range of 55–60 °C.

According to the experimental data [9], an increase in pressure during cavitation will also lead to a shift in the flow temperature at which the cavitation process will remain stable. In particular, for pure water, the maximum cavitation effect is at 4 atm of excessive pressure was observed at temperatures 85-95 °C.

2.8 *Local Numbers of Cavitation*

The problem of stability of artificial supercaverns was considered by [7], where it was shown that air supply to a supercavitating cavern is possible in one case only - when its dimensions reach certain values. Such dimensions of the cavern correspond to its complete formation in accordance with the conditions of the experiment. With artificial ventilation, the initial air entry is accompanied by a characteristic sound click and an almost instantaneous increase in the size of the cavitational cavern with an increase in the intake air flow rate. The cavitation number drops significantly and then remains constant and does not depend on a further increase in air flow.

A good criterion in the analysis of artificial supercaverns can be an estimate of local cavitation numbers. In accordance with the experimental results [7] in unrestricted flow an integral cavitation supercavern appears when the cavitation number corresponds to the values Ω=0.5-0.3. Such caverns are characterized by the absence of clear and stable boundaries.

With a cavitation number equals to Ω=0.2, the cavitational cavern shrinks in size and, due to the occurrence of a reverse jet, can break. In the case when Ω<0.13, the dimensions of the cavern increase with the appearance of clear and transparent boundaries. The cavitational cavern in this case assumes a stable spatio-temporal state.

From the point of view of stability, cavitation caverns with Ω>0.13 are characterized by a strong dependence on the value of the dynamic pressure in the flow and are unstable.

One of the reasons for the violation of the dynamic instability of the cavern can be: exceeding the capacity of the working channel of the cavitation chamber; the appearance of a large counter pressure behind the working chamber; external dynamic perturbations.

3 INVESTIGATION OF BOW SEPARATION

3.1 *Initial Postulates*

A mathematical model describing dynamical behavior of a cavitation supercavern with consideration of the process of its artificial ventilation was developed on the basis of the following hypothesis:

- BOW flow is ideal (without any types turbulence) and has a weight;
- the flow outside the cavity is incompressible;
- the beginning and the end of the cavitation cavern are always known and correspond to the entrance and exit to the working area of the separator;
- the weight of the gas component inside the cavity can be considered by means of hydrostatic pressure.
- at the beginning of the separation process, air for cavitational cavern ventilation enters it at each point of its initial cross-section.
- the main flow of the BOW is flat and one-dimensional.

3.1.1 *Basic Equations and Calculation Scheme*

In the Euler form, the motion of the main flow outside the cavity was written in the following form

$$\frac{\partial V}{\partial t}+V\frac{\partial V}{\partial x}=\rho g y-\frac{1}{\rho}\frac{\partial P}{\partial x} \tag{16}$$

Motion of the steam-water mixture inside cavern has the analogical view

$$\frac{\partial V_{st}}{\partial t}+V_{st}\frac{\partial V_{st}}{\partial x}=\rho_{st} g y-\frac{1}{\rho_{st}}\frac{\partial P_{st}}{\partial x} \tag{17}$$

At the boundary between main BOW flow and the supercavitation cavern, conditions should be satisfied always in the following form

$$\frac{\partial P}{\partial x}=\frac{\partial P_{st}}{\partial x} \tag{18}$$

$$\frac{\partial V}{\partial x}=\frac{\partial V_{st}}{\partial x} \tag{19}$$

Rigid boundary conditions modeling the direct influence of the rigid walls of the working chamber of the cavitation channel. On rigid walls of the separator's working chamber it is necessary to fulfill the condition of complete impermeability in contrast to the free interface surface, corresponding to the outer boundary of the supercavern with the processed BOW flow, In this case, the boundary conditions for equations (16)-(17) are:

- rigid walls on the side of main BOW flow:

$$\frac{\partial P}{\partial n}=\frac{\partial P}{\partial x} \tag{20}$$

$$\frac{\partial V}{\partial x}=0 \tag{21}$$

- rigid walls inside cavitational cavern:

$$\frac{\partial P_{st}}{\partial x}=P_{s.st} \tag{22}$$

$$\frac{\partial V_{st}}{\partial x}=0 \tag{23}$$

t - time, sec; n - surface normal coordinate, m; P_{st} – pressure of the steam, Pa; $P_{s.st}$ – pressure of the saturated steam, Pa.

To describe the process of artificial ventilation of the supercavitation cavern a calculation scheme was developed (Fig. 3) in relation to mathematical model. The design of the working chamber of the cavitation channel implies a clear closure of the boundaries of the supercavern to the outlet plate (all other cases are considered as non-working). This calculation scheme for the process of extracting the water component from the BOW allows the solution of the differential equations of the mathematical model using the finite difference method.

The velocity at the cavitational cavern boundary, which in Fig. 3 is a curve connecting the inlet and outlet plates of the working chamber, is considered equals to the flow velocity in the calculated section, which coincides with the inlet plate. This condition is consistent with the experimental results [7], and in this case, the influence of non-stationary phenomena in the tail part of the cavitational cavern on the conditions of flow around its head part is absent.

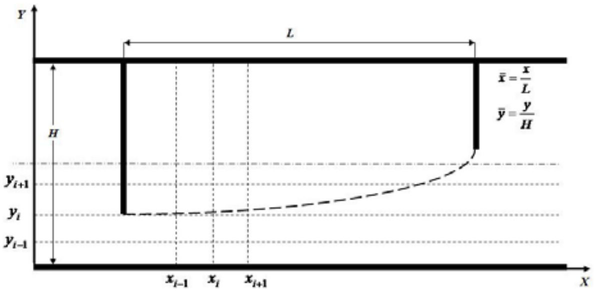

Figure 3. Calculation scheme

The advantage of the proposed design scheme is to overcome the Brillouin paradox - at the boundary of cavern, the velocity is a constant and non-zero value. In its tail part, it contains a critical point with zero velocity, which in this case physically corresponds to the upper edge of the output plate. Due to such a fixed point, the Zhukovsky-Chaplygin condition is satisfied - during the calculations, a smooth descent of the flowlines from the surface of the output plate takes place.

The finite difference method was used to solve the differential equations of the mathematical model of the BOW separation process. In accordance with calculation scheme (Fig. 3) the entire computational domain was divided into computational sections with a uniform step. The step value along the OX and OY axes was chosen on the basis of the results of preliminary calculations and was usually $(x_{i+1}-x_i)=L\cdot10^{-4}$ and $(y_{i+1}-y_i)=H\cdot10^{-6}$.

As convergence criteria during calculations was used divergence between left and right parts in equations (16) and (17). Its maximal value in all calculation points never exceeded value 10^{-8}.

All terms of the equations of the mathematical model correspond to a homogeneous continuous BOW flow. When using the finite difference method, which implies the replacement of a continuous medium by a discrete one, they were written using their differential analogs. Depending on the location of the computational point in relation to the rigid boundaries of the computational domain, central, left-sided, and right-sided differences of the second order of accuracy were used.

4 RESULTS

4.1 *Geometry of Cavitational Cavern*

During modeling the process of BOW separation, the dependence of the elongation of the cavity L in relation to the width of the working channel B of the BOW cavitation separator was determined. The calculation was carried out without considering air injection, since, in accordance with the conclusions of [7], neither the method of creating the cavitational cavern nor the shape of the body behind which it was formed affect the geometry of the cavity. The results of the calculations (Fig. 4) show that a drop in the flow rate, corresponding to an increase in the cavitation number on the plot, leads to a significant reduction in the size of the cavitational cavern. The working dimensions of the cavitation cavern answers the range of cavitation numbers from 0.1 to 0.15. In this case, the length of the cavern is from 5 to 4 calibers of the width of cavitator's working chamber.

To control the calculated data on the growth of the cavitation cavern in the cross section along its entire length, the results of [7] were used. For the case of an unbounded flow, this author proposes the use of following relation

$$\frac{D_{max}}{d} = \frac{0.955}{\sqrt{\Omega}} \tag{24}$$

D_{max} – maximal diameter of the cavitational cavern, m; d - diameter of the nozzle behind which the cavitation cavern is created, m.

During the calculations there was done an assessment of the degree of influence of the rigid horizontal boundary of the working chamber of the cavitational channel onto deformation of the lower contour of the cavitational cavern. The cavity profile ordinates were calculated for three values of the relative height $\bar{h}$ of the cavitator's inlet plate. This value was calculated as the ratio of the plate height h to the height of the cavitation channel itself H. The calculation results are shown in Figure 5, where one can see that a decrease in the value leads to the alignment of the cavity boundary to a flat shape.

The horizontal axis in Figure 5 corresponds to the relative elongation of the cavity $\bar{x} = x/L$, and the vertical axis corresponds to the change in its relative ordinate $\bar{y} = y/H$.

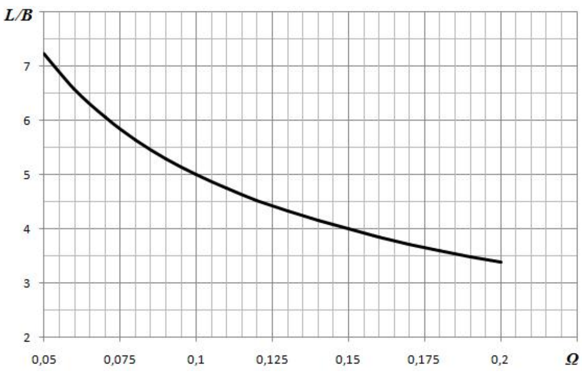

Figure 4. Influence of flow velocity onto the length of cavitational cavern

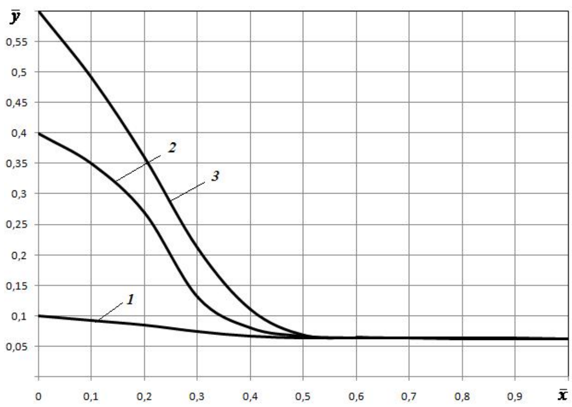

Figure 5. Influence of flow geometry onto the contour of cavitational cavern
1 – $\bar{h}$ =0.1; 2 – $\bar{h}$ =0.4; 3 – $\bar{h}$ =0.6

4.2 *Quantitative Evaluation*

A specific feature of BOW separation process is determined by the detection of BOW main physical property - viscosity. The main oil-containing components do not answer the well-known Newton's law [6]. For this reason, the multiphase flow structure must be considered as a grid containing water. This grid, in turn, consists of a set of paraffin and resin molecules randomly arranged among themselves [4, 13].

In case when the viscosity of the BOW flow is unknown, it can be found at first approximation by the values of the viscosity of the n mixture components, considering their volumetric content ai.

$$\nu = \nu_1 a_1 + \nu_2 a_2 + \ldots + \nu_n a_n \tag{25}$$

Due to the strictly expressed non-linearity of reological properties, there is always a strong resistance to tangential shear stresses in the BOW flow. For this reason, most constructions of ship's bilge water hydrodynamic separators use flat channels, inside which density stratification of the processed flow occurs [11, 19]. During calculations, an estimate was done for the value of pressure drop inside a two-dimensional flat channel, the walls of which represent two parallel planes. The values of the kinematic viscosity of the BOW flow were taken identical and equal to $\nu=2\cdot10^{-6}$ m²/sec.

For different values of the BOW flow density there was created a nomogram which depicts the dependence between pressure drop and velocity of the processed flow. It is shown in Figure 6, where one can see that during flow motion an increase in the flow density of the BOW leads to an increase in the value of pressure drop. With regard to the proposed method of hydrodynamic cavitation separation, it can be stated that ceteris paribus in this case, the beginning of the cavitation process should be expected at lower speeds. Under these conditions the value of velocity is directly determined by the value of excessive pressure. The higher the excessive pressure in the pumped mixture of BOW is the higher will be the effect of cavitation onto efficiency of the technological separation process.

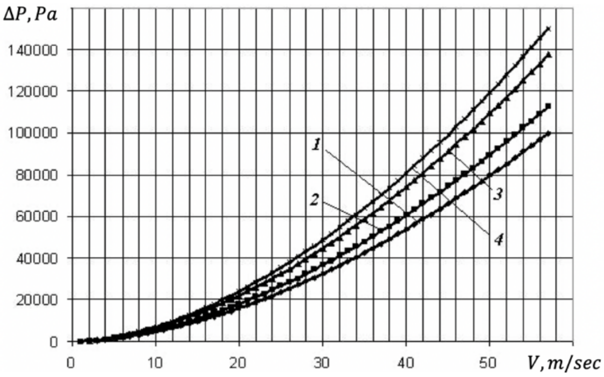

Figure 6. Influence of velocity onto pressure drop in the flow
1 – ϱ=800 kg/m^3; 2 – ϱ=900 kg/m^3; 3 – ϱ=1100 kg/m^3; 4 – ϱ=1200 kg/m^3

When in the BOW flow cavitation occurs at the hydromechanical approach the resulting cavern can be considered as local resistance. In this case it is worth to estimate the value of its resistance coefficient. This parameter can be considered as the sum of inductive and two profile resistances

$$C_x = C_{x\,ind} + C_{x\,t.w.} + C_{x\,b.l.} \tag{26}$$

$C_{x\,ind}$ - inductive resistance, depending on the elongation of the cavity and the angle of attack of the flow on it; $C_{x\,t.w.}$ - profile cavitation resistance caused by the turbulent wake behind the cavity and the non-stationary mode of closing of its boundaries; $C_{x\,b.l.}$ - profile viscous resistance, caused in the presence of rigid obstacles by the boundary layer arising on them.

All terms of expression (26) are directly determined by the processes of vortex formation at the interface of the cavitational cavern. Inductive resistance is caused mainly by longitudinal vortices at the boundaries of the cavitational cavern, and profile resistance - by transverse vortices at its boundaries.

4.3 *Experimental Evaluation of the Main Parameters*

During experimental researches, it was studied how the dynamic pressure at the inlet to the working chamber of the cavitator affects the quality of the BOW separation process. All experiments were carried out for three flow temperatures: 30 °C, 50 °C and 90 °C. A mixture of water with fuel oil in the ratio of 50% water to 50% fuel oil was used as a BOW. The main measurement results are shown in Figure 7. The graph shows that the effect of dynamic pressure growth on the cavity length l is directly determined by the temperature factor. The maximum length corresponding to the length of the working chamber of the cavitator L was observed, respectively, at:

Temperature BOW, °C	Pressure, Pa
30	406250
50	381591
90	320113

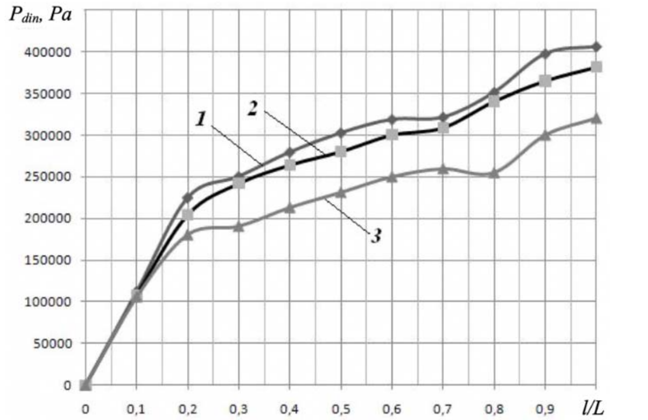

Figure 7. Influence of dynamic pressure in the flow on the relative length of the cavity
1 – temperature is 30 °C; 2 - temperature is 50 °C; 3 - temperature is 90 °C.

An analysis of the stated values allows us to draw an unambiguous conclusion - a decrease in the operating pressure must always be compensated by an increase in the temperature of the processed flow. It should also be noted that with an increase in temperature, the solubility of gases in the BOW decreases, which, as a result, are released from the treated flow at the first stage of cavitation, i.e. even before the beginning of the supercavitation process.

An increase in the temperature of the supplied BOW at a constant value of the static and dynamic pressures led to an increase in the size of the emerging supercavern and an increase in the mass of the steam inside of it. The consequence of the growth of the mass will always be a decrease in pressure inside the cavitational cavern. An increase in temperature, on the one hand, increases the cavitation zone, but on the other hand, reduces the intensity of the cavitation effect. Under normal conditions, the value of the optimal temperature at which the first factor prevails over the second, as established experimentally is 55 - 60 °C.

Despite the same nature of the change in the obtained curves in Figs. 7 one can see that at elevated temperatures, the treated BOW flow can be subjected to a separation process at a much lower pressure. As a result, the requirements for the selection of injection equipment can be reduced in terms of reducing its flowrate and pressure characteristics and the quality of materials used in the manufacture of the working chamber of the cavitation channel.

If it is necessary to increase the total productivity of a separation unit containing several working chambers, the quality of the cleaning process can be greatly influenced by their total hydraulic resistance when working on a single pipeline of the separation circuit. For this reason, during the experiments, the dependence of the volumetric flowrate of purified water on the number of simultaneously connected working chambers was studied. It is shown in Figure 8, where one can see that an increase in the number of working chambers N did not lead to a directly proportional increase in the performance of the separator. With the dimensions of cavitation channel: length 1 m, width 0.3 m and depth 0.01 m and the inlet head of the BOW flow equals to 46 m.w.h. the optimal number of working chambers should be three units. Further addition of working chambers leads to a general increase in the pressure drop across the separator and does not give a significant change in its total productivity. During the experiments, it was found that in this case, the hydraulic resistance of the main pipeline, which constitutes the main technological circuit for processing BOW, also increases.

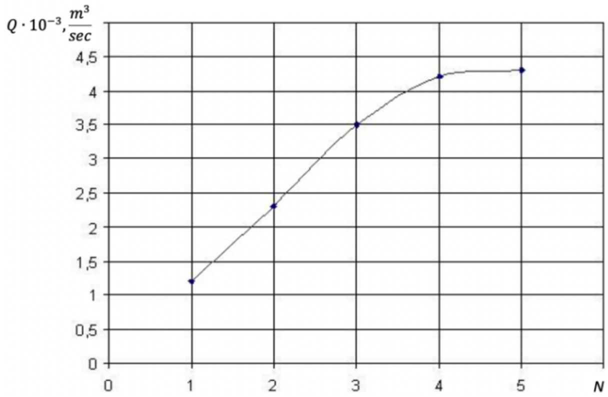

Figure 8. Dependence between performance and number of working chambers

An effective way to influence the hydromechanical characteristics of the flow is to change its structure by blowing air. In this case, artificial cavitation is created in the flow, and during the experiments it was found that air supply should start before the beginning of the second stage of cavitation, i.e. when the vapor-gas bubble-film cavitation (the first stage) passes into a continuous supercavern (the second stage).

During the experiments, there was found the dependence between resistance factor of the inlet rectangular plate in the working chamber of the cavitator and the cavitation number of the supplied flow. It is shown in Figure 9. The graph shows that starting from the cavitation number equals to 0.1, i.e. with the release of the artificial supercavern to its stationary spatial dimensions this dependence took on a self-similar character.

On the base of experimental results, it was found that hydraulic resistance during cavitation is determined by only two factors: the size of the cavitational cavern and the number of cavitation. In this case, it was concluded that hydraulic resistance of cavitational cavern does not depend in any way on the method of its creation and is identical both with natural cavitation and with creation of cavitation due to air blowing.

In artificial cavitation, the effect of the supplied air flowrate on the hydrodynamic characteristics of the resulting supercavern is important. An increase in the ventilation air flowrate leads to an increase in the dimensions of the cavity. The values of the volumetric air flowrate in experiments were respectively Q=0.00012 m³/sec and Q=0.0002 m³/sec.

During experiments, it was found out that a rapid increase in the size of the cavity up to the length of the working section of the separation chamber can be obtained in the case when the flowrate of the supplied air is in the range from 5 to 8% of the flowrate of the treated BOW flow. Exceeding the specified range led to the collapse of the cavity with negative cavitation numbers corresponding to the case when the air pressure inside the cavity exceeded the pressure at the interface between the liquid and vapor phases.

During experiments there was studied how the direction of air supply makes influence on the stability of the cavitational cavern. As one can see in Figure 10, air supply was carried out in three different ways: perpendicular to the flow of the B)W, against the main flow of the B)W and inside the cavitational cavern.

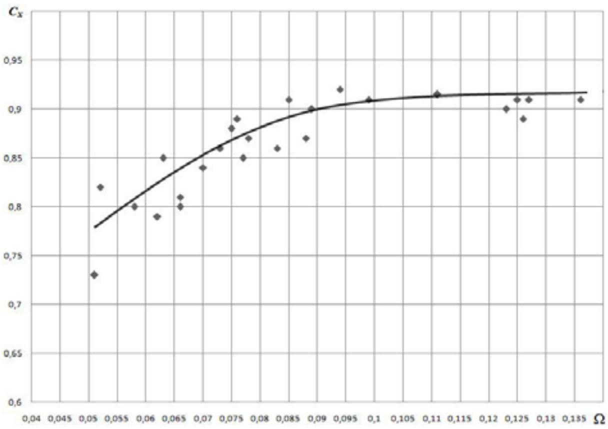

Figure 9. Drag coefficient of the inlet plate during artificial cavitation

The most stable state cavitational cavern took place in the latter case, when air was supplied into the interior of the cavity. The transition at the initial stage from partial to complete ventilation of the cavitation cavern occurred abruptly without pressure breaks in the working area of the cavitator chamber. In first two cases, during experiments, the failure and destruction of the cavitational cavern was observed practically always even at the initial stage of its inception.

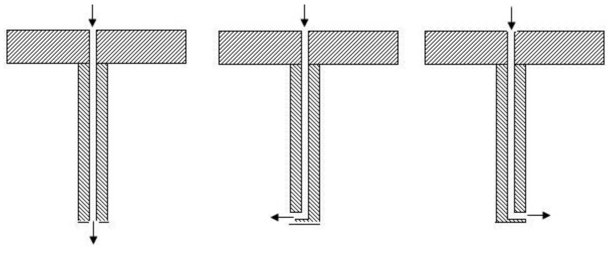

Figure 10. Scheme of air supply to the cavitational cavern

The principle of operation of the proposed cavitational method for BOW flow separation is based on the constant selection of artificially blown air and water vapor from the supercavitational cavern. In the course of experiments, it was investigated how the flowrate of the steam taken off with air Q_{ext} affects the behavior of the cavitational cavern. The main results are shown in Figure 11, where one can see that the dependence between the change in the cavitation number for various values of the flowrate of the extracted steam can be approximated by a linear law.

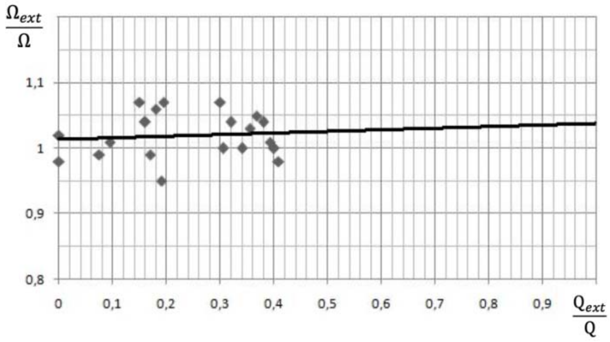

Figure 11. Influence of steam extraction on supercavity

On the base of this dependence it was concluded that the flowrate of water vapor taken from the cavitational supercavern does not have any effect on the cavitation mode existing in the working chamber. The ratio of cavitation numbers during the extraction of steam Ω_{ext} in the case of ordinary (not artificial) cavitation Ω to the ratio of the flowrate of the extracted steam Q_{ext} to the total flowrate Q obeys a linear relationship with a change within an error equals to 3.8%. A similar conclusion was obtained also on the basis of the performed experiments for the dimensions of the cavitational supercavern. The length of the cavitational cavern during the selection of steam and air from it did not change.

4.4 *Air Supply System*

The main technical questions in the implementation of the proposed method of BOW separation in the operating conditions of the vessel should be aimed at increasing its productivity. All optimal dimensions and output power of the separator should be determined by only one performance indicator - its flow capacity.

One of the perspective options to increase the productivity of separator is the use of artificial ventilation of the cavitational cavern, which is based on blowing air into the inside of the cavern. On the base of stated above results it has been established that the artificial ventilation of the supervacuity cavity has a direct impact on its dimensions and, as a result, on the final performance of the ship's separation plant.

The calculation of the air supply system should be in fact always reduced to the hydraulic calculation of a converging nozzle (cone nozzle) and to the determination of its cross-sectional area for a given flowrate and pressures before and after the nozzle. The friction of air passing through the nozzle can be neglected due to its insignificance.

When calculating the jet nozzle, the mass air flowrate should be determined by the expression

$$Q = \rho_{out} \varepsilon S_{out} V_{out} \tag{26}$$

ε- flowrate factor; S_{out} - outlet area, m²; V_{out} – velocity at the output section, m/sec.

The velocity at the nozzle's outlet can be calculated using the Bernoulli's energy equation for a one-dimensional flow

$$\frac{V_{out}}{2g} + \frac{k}{k-1}\frac{P_{out}}{\rho_{out}} = \frac{k}{k-1}\frac{P_{inlt}}{\rho_{inlt}} \tag{27}$$

and the adiabatic expansion equation

$$\frac{\rho_{out}}{\rho_{inlt}} = \left(\frac{P_{out}}{P_{inlt}}\right)^{\frac{1}{k}} \tag{28}$$

as

$$V_{out} = \sqrt{\frac{2gk}{k-1}\frac{P_{inlt}}{P_{out}}\left(1-\delta^{\frac{k-1}{k}}\right)} \tag{29}$$

$\delta = P_{out}/P_{inlt}$; P_{inlt} and P_{out} – pressure at the inlet and outlet of the nozzle, Pa; ρ_{inlt} and ρ_{out} – air density at the inlet and outlet of the nozzle (can be found from state tables or diagrams); k – adiabatic exponent.

Insertion of (29) into (26) with concerning of (28) gives

$$Q = S_{out}\varepsilon\sqrt{\frac{2gk}{k-1}P_{inlt}\rho\left(\delta^{\frac{2}{k}} - \delta^{\frac{k+1}{k}}\right)} \tag{30}$$

In expressions (27)-(30), more accurate results can be obtained if instead of the adiabatic exponent k, we use the volumetric adiabatic exponent k_v of air.

$$k_v = \frac{k\beta}{\mu_T} = \frac{k\beta}{\left[-\frac{P^2}{RT}\left(\frac{\partial v}{\partial p}\right)_T\right]} \tag{31}$$

β – air compressibility factor; μ_T - deviation factor (its diapason of change is from 0.04 to 2) depending on the gradient of the change in air volume v by means of pressure p at a constant temperature T.

To ensure high-quality air supply inside the cavitational cavern, it is necessary to provide optimal taper angles α during manufacture of a conical jet nozzle. At these angles, an irrotational flow of air supplied to the ventilation of the cavern will be provided. The dependence of the taper angle α on the ratio of the inlet and outlet diameters of the cone nozzle presented in Table 1 and Figure 12.

Table 1. Optimal values of the nozzle taper angle α

$(D_{inlt}/D_{out})^2$	1,5	2	2,5	3	3,5	4
α	28°	22°	16°	12°	9°	6°

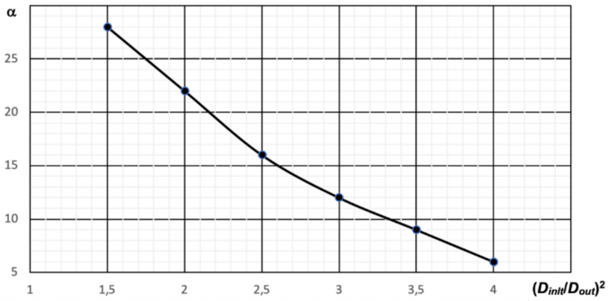

Figure 12. Optimum value of the nozzle taper angle

5 DISCUSSION

Researches described in the article were mainly directed to the solution of a very urgent problem of technical and environmental improvement in the process of sea vessels operating. The use of secondary energy resources on a vessel, in our case BOW, will always lead to additional income and reduction of environmental emissions.

On a base of all results obtained in the research of the cavitation process in application to the separation of a multi-phase flow on sea vessels, in fact, it is proposed to create a new type of separation equipment. This type of equipment has the potential to be used not only on ships, but also in other industries.

The problem of utilization of multiphase flows is very actual and will not lose its significance for many decades. The proposed separation method is universal and can be used in the future not only on sea vessels, but also for treatment facilities at energy plants, in medicine when disposing of chemically or biologically hazardous reagents, etc.

The versatility and reliability of the proposed method of hydrodynamic separation based on the cavitation process is mainly based on the invariable implementation of the basic laws of physics. In this case, the intensity of the process of evaporation of a moving stream will always directly depend on its pressure and temperature.

The main areas of further research, which still remain undiscovered, include methods for creating stable caverns in clearly spatially fixed areas of a moving flow. In this case, it is necessary to pay special attention to two areas: methods of sealing the working chamber of the cavitation channels; simplification of the technique for monitoring the vacuum value along the cavity with modern measuring equipment. Critical pressure jumps on the surface of cavitation channels from low vacuum to local zones with a pressure exceeding 100 MPa require the creation of new materials. In addition to such materials, it is necessary to create new mechanisms for producing a spatially stable cavitation zone with clearly fixed boundaries in a moving flow.

6 CONCLUSIONS

Modern methods of BOW separation on vessels have one common drawback. When they are working on a ship, the cleaning of the BOW is always unidirectional. During the separation process, only one water component is the output product, and the secondary petrochemical products with a high degree of concentration are very difficult to obtain in a pure form and cannot be used in further.

A qualitative solution to the problem of BOW disposal can be the use of a new separation method that uses a hydromechanical approach. When artificially created by blowing air into the cavitational cavern in the moving flow of the BOW, it is possible to continuously select the resulting saturated water vapor from the cavern and thus obtain the highly concentrated oily components of the BOW.

When creating an artificial supercavern by injecting air to the BOW flow, the velocity caused by the hydrodynamic features inside the cavitation channel at the cavern boundary will be mainly determined by the horizontal components of the air velocities and the processed flow of the BOW.

During the use of the cavitation process for the separation of the BOW, the operating pressure should be reduced and this reduction should be always compensated by an increase in the temperature of the treated BOW flow.

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