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Exhaust Gases Cleaning Technology for Vessels

Valerii V. Aftaniuk, Oleksiy V. Kiris, OleksiyV. Malakhov, Mikhail O. Kolegaev, Boris A. Garagulya

***Abstract**: The present investigation aims to propose results of development of an effective system for the purification of exhaust gases that are emitted to the environment by ship power plant from sulfur oxides (SO_x) and solid particles. Numerical simulation of a combined scrubber with vortex plate based on the developed theoretical approach was performed. Mathematical model of aerohydrodynamic and heat-mass transfer processes contains five interconnected modeling blocks.*

There was investigated the influence of the scrubber's geometric characteristics onto the quality of its work. As a result, for the elements of vortex plate the rational design parameters were determined (the angle of blades installation for the swirls β=60-90°, the ratio between internal and outer radius of the swirls R_1/R_2=0,6-0,7).

The interaction of gas aerosol with water foam was studied during numerical simulation. It was done with consideration of hydrodynamic regime on the surface of a vortex plate. As a result, for the scrubber rational design and operating parameters were formulated (inlet flow velocity V=18-25 m/s, the height of foam layer H=70-150 mm, inlet dust concentration 40-50 g/cub.m of the gas to be cleaned, cross-sectional area of the purification unit up to 2 sq.m).

Computer-based solid-body scrubber model was created during numerical simulation. CFD modeling of the main hydrodynamic processes based on this model was carried out. It was done for all developed structural solutions for scrubber elements. The main results obtained during CFD modeling of the scrubber operation make it possible to analyze the technology of its use and to achieve a reduction in energy costs while maintaining the quality of gas cleaning.

The developed theoretical model of a scrubber gives an ability to simulate the flow of a gas-dust stream considering all changes that were done in the geometry of the scrubber. The very model can also be used to optimize the scrubber's design depending on the type of production and parameters of the gas to be contaminated. During research works there was formulated a conclusion about the necessity to take into consideration the uneven distribution of the field of velocity when modeling the process of gas purification and cooling inside a scrubber.

In order to determine the efficiency of heat transfer process inside the scrubber, heat transfer coefficients were found out. They were compared with characteristics of a traditional scrubber's model based on a perforated plate. Calculation data have shown an excess of the heat transfer coefficient of the vortex plate by 5-7%. It was stated also that the value of the heat transfer coefficient depends on average velocity and moisture content of the gas to be supplied.

The rational design and operational parameters of the scrubber obtained on the models made it possible to develop a pilot industrial model of the scrubber and method of engineering calculation.

During experimental studies of the scrubber, new scientific results were obtained. They allow one to establish the technological range of irrigation density values, at which the maximum efficiency of trapping solid particles and sulfur oxides (SO_x) is ensured.

Experiments were carried out that reveal the relationship between the angle of blades installation of the swirl and the height of the installation of the baffle plate onto the efficiency of foaming and total resistance of the vortex plate.

***Keywords** : scrubber, cleaning of vessel's flue gases, solid-state model, dust removal, scrubbing technology for ship power plant, modelling of vessel's exhaust gas cleaning system.*

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* Correspondence Author

Valerii V. Aftanuk* , Professor, Department of Ship's Thermal Energy at the National University "Odesa Maritime Academy" (Odessa City, Ukraine),

Oleksiy V. Kiris, Head of the Chair of Ship's Thermal Energy and Full Professor in the National University "Odesa Maritime Academy", Odessa City, Ukraine.

Oleksiy V. Malakhov, Professor, Chair of Ship's Thermal Energy in the National University "Odesa Maritime Academy", Odessa City, Ukraine.

Milhail O. Kolegaev, Professor, National University "Odesa Maritime Academy", Odessa City, Ukraine.

Boris A. Garagulya , Assotiate Professor, Chair of Ship's Thermal Energy in the National University "Odesa Maritime Academy", Odessa City, Ukraine.

I. INTRODUCTION

All ships on the planet during operation of their engines generate flue gases. In technology for diesel fuel burning and the subsequent processing of the flue gases obtained during combustion, one of the important issues is the improvement of scrubber's technology. This technology is used for removal of soot and sulfur oxide (SO_x).

Ship-based emissions treatment systems in accordance with Annex VI to the MARPOL Convention of 2020 should be used practically all over the world [1].

The International Maritime Organization (IMO) has taken the initiative to promote the efficient use of energy on all vessels, both from a structural point of view and during their operation. Therefore, leading manufacturers of marine engines (MAN, Diesel, Wärtsilä, etc.) are developing and improving scrubber systems for SO_x purification [2], [3], [4].

Scrubbers are used widely in the operation of ships. Most of all they are used in the systems of: air dehumidification, inert gases and technical ventilation. With the use of ship systems which include scrubbers, it is possible to obtain the necessary parameters of the gas-air environment in different spaces of the vessel. General principles of scrubber operation, their design features and technologies which they use were described by Baum [5], Dicenson [6], Bank [7] and Rurchass [8].

To improve the quality of the cleaning technology can be recommend the use of Hybrid Scrubber System.

Such scrubbers use technologies that consistently combine several methods of exhaust gases purification from SO_x [9].

II. PROBLEM STATEMENT

Significant number of different deposition mechanisms that facilitate particle trapping, as well as the variety of forms of hydrodynamic interaction of gases and liquids in scrubbers, does not allow to develop an accurate analytical method to calculate their efficiency. That is why only several approximate calculation methods have been used in practice [10], [11], [12].

Among scrubbers from a technical point of view, one of the best is a construction with vortex plate. For further design of the very construction, a very important issue is the development of a block mathematical model. It should describe a separation of solid particles (soot that appears during heat and mass transfer processes) within a combined scrubber's working chamber.

On the basis of this model can be provided investigation of the influence between separation efficiency and main construction and operating parameters of scrubber's working chamber. Evaluation of this influence will give an ability to develop new technical solutions to change the flow rate of by-pass solid particles and hydraulic resistance of the scrubber.

The principle of the scrubber's operation with vortex plates is based on the process of interaction of soot particles with water foam. All particles can be considered as a dust aerosol. Water foam is formed due to the floating of air bubbles.

Vortex plates according to [13] and [14] are used to improve the conditions of separation and organization of fluid circulation. Their canvas base is equipped with twisting devices. The installation of the twisting devices shown in Figure 1 exactly on the canvas can extend the range of stable operation of the vessel's scrubber. Their operation provides an intensive recirculation and liquid dispersing on the canvas plates, as well as reducing a hydraulic pressure loss inside the plant.

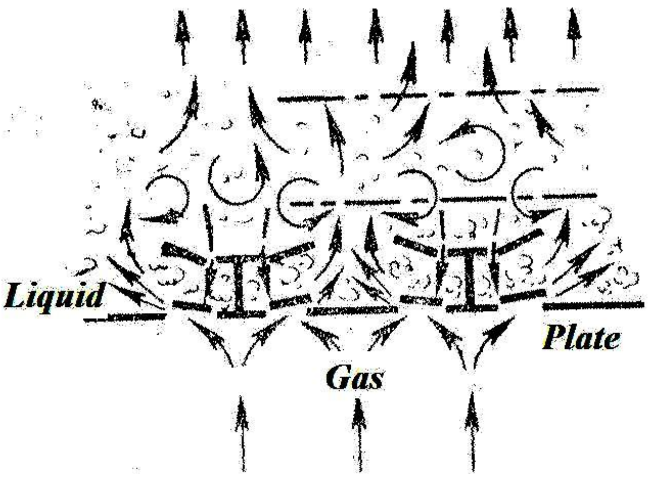


Fig. 1 Ship technological scheme
1 –plate in scrubber; 2 –flue gases; 3 – water.

For this reason, a mathematical model describing the operation of scrubber should take into account the energy parameters of this interaction process. It is also always necessary to consider the physical features of the foam formation process.

One of the perspective technologies for vessel's SO_x purification is the use of seawater. In this technology, the alkalinity of water is the main driving factor for SO_2 neutralizing.

Actually, on the base of the stated above, main problem of research works was formulated in the following way – depending on the proposed construction of the scrubber's vortex plate should be stated its heat exchange effectiveness.

This parameter will give an ability to intensify the heat exchange due to the active interaction of the gas-liquid system inside the working chamber of the scrubber. Exactly, on the base of heat exchange efficiency, it is possible to carry out comparative analysis of a new scrubber's construction in comparison with constructions that are used already.

III. METHODOLOGY

The gas that is moving through the scrubber during purification is cooled generally down to 40-50 °C. During the process it is usually moistened to a saturation state. Mainly, the gas velocity inside the scrubber should be equals 0.8-1.5 m/s. The specific consumption of water per scrubber is usually belong to diapason 3-6 l/m^3 of gas to be purified [15].

The amount of heat Q, kW which is transmitted inside the scrubber from gas to water, neglecting the heat loss to the surrounding space, can be found as

$$Q = V_{d.g.}(I_1 - I_1) = V_{d.g.}\left[C_p(t_1 - t_2) + x_1(i_1 - i_2)\right]10^{-3}$$

$V_{d.g.}$ – volumetric flow-rate of dry gases, m^3/s; I_1 and I_2 – enthalpy of gases at the inlet and outlet of the scrubber, kJ/m^3; C_p – heat capacity of dry gases at constant pressure, $kJ/(m^3K)$; t_1 and t_2 – initial and final temperatures of gases, ^0C; i_1 and i_2 – enthalpy of water vapor that is contained in gases, kJ/m^3; $i_1=(2480+1.96t_1)$; $i_2=(2480+1.96t_2)$; x_1 – initial moisture content in gas, kg/m^3.

The volume of the scrubber's working chamber can be determined when considering the heat exchange between water and gas

$$W = Q/K_0 \cdot \Delta t$$

The required value of water flow-rate for flue gases treatment inside the scrubber can be found as

$$Q_w = Q/\left[\varphi(i_v - i_s) + (1-\varphi)\left(i_v - i_f\right)\right]$$

φ – factor of water evaporation (at first approximation can be taken equals φ=0,5); i_v – enthalpy of saturated steam at the temperature t_2, kJ/kg; i_s , i_f – initial and final enthalpy of water, kJ/kg.

For preliminary estimation of scrubber's efficiency, the fractional efficiency curve can be expressed in the form of exponential dependence between penetration of scrubber's working chamber and the diameter of the particles [16]:

$$P_d = exp\left(-A_1 d_i^{A_2}\right) = 1 - \varepsilon$$

A_1 and A_2 – constant; d_i – size of the particle of the *i-th* numbered fraction; ε – efficiency, in fractions of one.

For hollow type scrubber main energy spending for gases purification are related to the sprinkling of irrigation fluid. Specific energy spending for liquid spraying, with the use of perfect atomizer designs, can be calculated as

$$A = P\frac{V_l}{V_g}$$

P – pressure of fluid before the nozzle, Pa; V_l, V_g – flow rate of irrigation liquid and gas to be cleaned, m^3/s.

In general, the hydraulic resistance of scrubbers with liquid use for cleaning can be described by equation [17]:

$$\Delta P \approx \Delta P' + \Delta P'' + \Delta P_{w.c} + \Delta P_{g.d.} + \Delta P_{d.c.}$$

$\Delta P'$, $\Delta P''$ – hydraulic resistance at the inlet and outlet of the scrubber, Pa; $\Delta P_{w.c.}$ – hydraulic resistance of the contact zone (working area of the scrubber) between gas and liquid, Pa; $\Delta P_{g.d.}$ – hydraulic resistance of the gas distribution device, Pa; $\Delta P_{d.c.}$ – hydraulic resistance of the built-in drop-catcher, Pa.

The hydraulic resistance of the gas-liquid contact zone for two-phase flow can be calculated in the following way

$$\Delta P_P = \zeta_g \frac{V_g \rho_g}{2\varphi^2} + \zeta_l \frac{V_l^2 \rho_l}{2(1-\varphi)^2}$$

ζ_g and ζ_l – factor of hydraulic resistance caused by gases and liquid respectively; V_g and V_l – linear velocity of gases and liquid respectively, m/s; φ – part of working chamber that is filled with gas.

An expression that relates the linear velocity of gas flow attributed to the full cross-section of the scriber's working chamber, with the geometric parameters of the plant and the production load on gases and liquid for counter-directed flows can be written in a form

$$\frac{V_g^2}{S_0^2 d_e g} = f\left[\left(\frac{w_l}{w_g}\right)^{2-n}\left(\frac{\mu_l}{\mu_g}\right)^n\left(\frac{\rho_l}{\rho_g}\right)\right]$$

$\frac{V_g^2}{S_0^2 d_e g}$ - an analogue of the Froude parameter; S_0 – part of the free cross section inside the contact device, m^2/m^2; d_e - equivalent diameter of the cross section inside the contact device, m.

According to operation experience, the optimal ratio between the height of the scrubber H and its diameter D equals 2.5.

In order to determine the optimal mode of scrubber operation during experimental researches a pilot industrial specimen was designed, manufactured and tested.

Technological layout of the scrubber with a vortex plate was chosen for experiments as the most promising. On the base of this construction in combination with a mathematical model further results that indicate the feasibility of such scrubbers for vessels were obtained.

A new combined scrubber design was developed to intensify the vessel's flue gases treatment system. During its operation, the sulfur oxide (SO_x) and soot solids can be double-purified. The scrubber works using a vortex plate. Its common scheme is shown in Figure 2.

The vortex plate of the scrubber was realized in the following way: the swirling flow can be formed by means of axial-blade swirlers (Fig. 2-a), to improve the circulation of the fluid in the sediment area was created a channel with holes (Fig. 2-b).

Production of swirling elements in the form of axial-blade channels allows to achieve a high degree twisting for the flows. Their twist ratio is very high because it exceeds the value equals 0.6. Due to such twisting and uniform phase distribution, heat exchange inside the working chamber of a scrubber can be intensified [18]. This allows to use working surface in a more productive mode and to reduce at the same time the hydraulic resistance of the vortex plate.

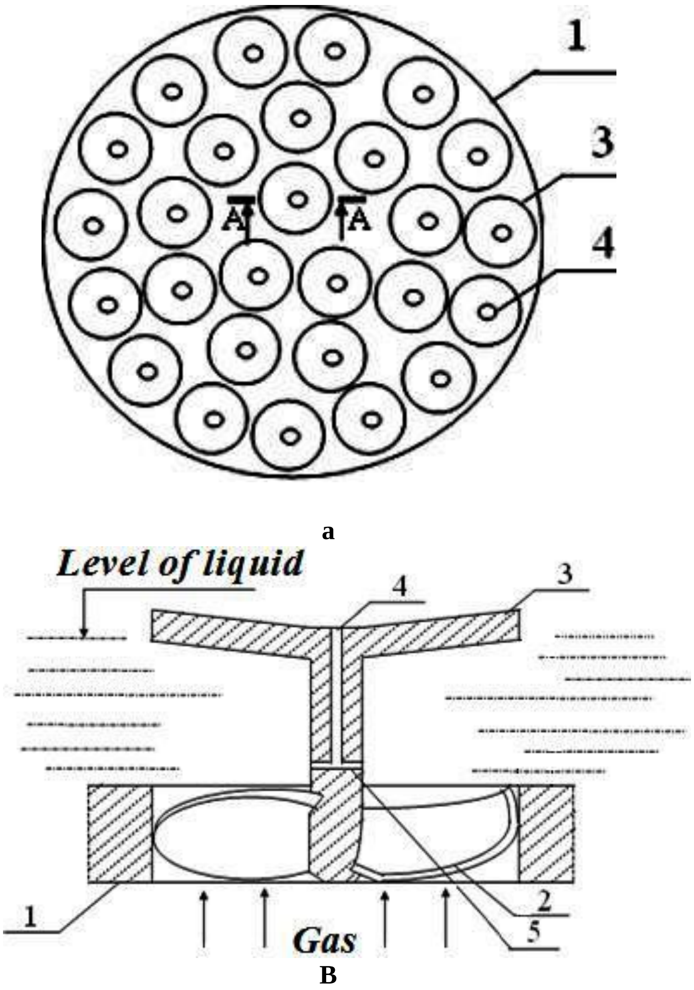


Fig. 2 Vortex plate

a – top view of axial-blade swirlers; b – swirling channel. 1 –plate; 2 –unit for flow swirling; 3 – stopper; 4 – channel; 5 – hole.

IV. RESULTS

To provide numerical simulation of the work of a combined scrubber with a vortex plate the following operations were performed:

1. The analysis of all known constructions was carried out, as well as the methods of calculation of their technological parameters are analyzed.

2. The aerodynamic characteristics of the free swirling jet were calculated in order to ensure the optimal aerodynamic structure of the swirling stream.

3. The aerodynamic characteristics of the swirling jet with polydisperse solid phase were calculated.

4. For the process of contaminated aerosol interaction with a foam a mathematical model was formulated. This model allows to consider the energy parameters and basic principles of foam production.

5. Mathematical model of the heat and mass transfer process inside the working chamber of the scrubber unit with a vortex plate was developed.

On the base of all these five operations during research works new scientific results were obtained.

Depending on the trajectory of movement of dust particles inside the scrubber, its performance would be changing. Actually, it is directly determined by the degree of flow swirling. For particles with different diameters plots in Figure 3 show the trajectories of their motion. They all were calculated for two levels of swirl intensity. The coordinate $r/r_0=1$ corresponds to the area of particles inflow into the common stream, and $r/r_0=2$ corresponds to the boundary dimensions of the swirling jet.

As one can see, in both cases of the flow swirling at the beginning of the process small particles separates first and then down the flow begins separation of larger ones. It happens due to the inertia of large particles and their slower involvement in rotational motion.

Twist intensity σ produces the significant influence onto the particle removal distribution. For modes of scattering to narrower fractions optimal are regimes with small values of the σ parameter.

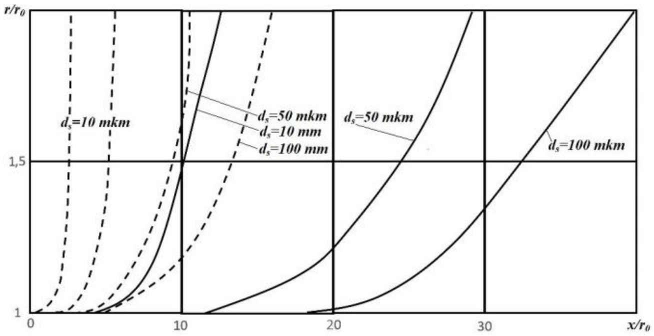


Fig. 3 The trajectories of particle motion at ω = *const*. Solid line - σ=0, 2; Dashed line - σ=1;

According to the calculation results data it is evident that when technology for particles inlet uses initial rotation, they all separating fairly quickly.

The β angle of blades installation on the swirler affects both the gas purification from dust and the aerodynamic parameters of the scrubber.

Separation of solid particles from the gas flow occurs most intensively when blades installation angle equals β=90°. At smaller values of angles, the tangential velocity of gas increases, and hence the tangential velocity of the particles increases too. Increase of this tangential velocity leads to a decrease of the value of inertia force that favors separation. As the β angle of blades installation decreases, the value of the Coriolis force of inertia, which is perpendicular to the blade surface, decreases too. Because of this reason, the common deposition rate of dust particles decreases.

Figure 4 and Figure 5 show the results, that are reflecting the influence effect of the β angle of vortex blade installation and the relative flow rate of the purified gas onto the total factor of particle transmittance E_0 and their maximum diameter δ_{cr}. As one can see from these plots, with the increase of the β angle of blades installation from 60^0 to 90^0, the factor of particle transmittance E_0 decreased by 1,8 times. The maximum diameter of the missed particles δ_{cr} decreased by 1,5 times too.

The θ angle of blades inclination affects onto the quality of the dust separation process too. The efficiency of dust separation inside the scrubber could be increased when the vortex plate blades are bent inverse to the flow main direction. Their angle of inclination should be $\theta < 0^0$. In this case, according to the calculations performed, the values of tangential velocities of gases and solid particles inside the scrubber decrease. As a result, there takes place an increment in the values of forces of inertia that increase the common level of the flow purification inside the plant.

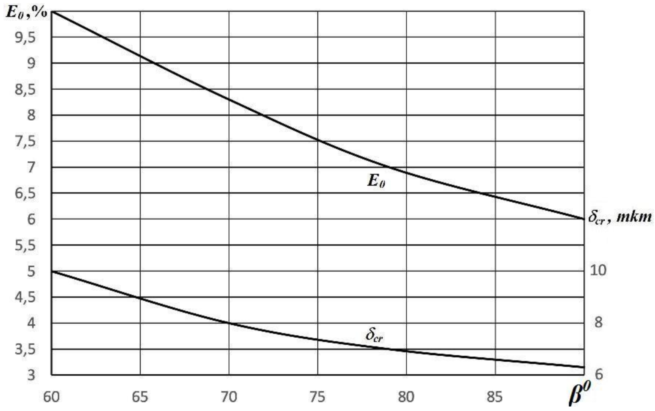


Fig. 4 Influence of the β angle of the blade's installation onto the total factor of particle transmittance E_0 and their maximum diameter δ_{cr} inside the vortex plate of the scrubber.

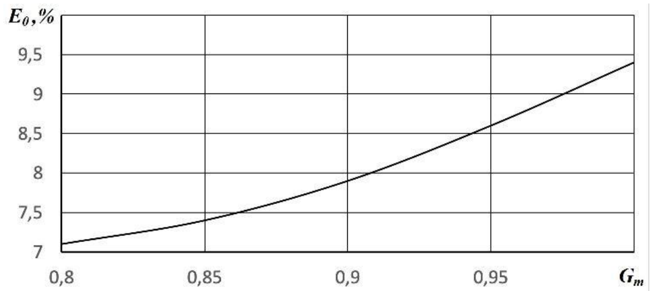


Fig. 5 Influence of the relative G_m flow rate of the purified gas onto the total factor of particle transmittance E_0.

The changes in the number of blades on the vortex plate produce insignificant effect onto the dust pass. During numerical calculations with the use of vortex plate model it was stated that increase in the number of blades from 45 to 90 units gives a decrease in the value of the total transmittance by 1,15 times.

All numerical calculations have shown that intermediate optimum values for gas purification and energy consumption could be obtained with the use of radial blades. In this case, their angle of tilt remains the same and equals the value θ=0^0.

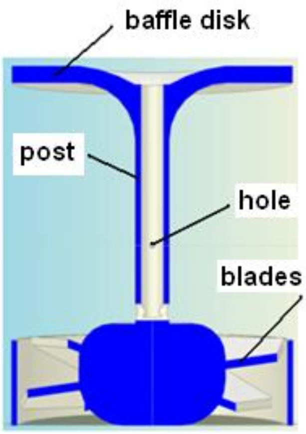
It is well known that change in the fluid temperature in the foam layer depends on the value of the initial moisture content. At low moisture content in gases (x_1=25 g/m^3), the fluid temperature can slightly decrease. It happens due to the evaporation process. At high humidity of gases (x_1=300 g/m^3), a significant increase in the fluid temperature in the foam layer can be observed (40–50% higher than the initial temperature).

The operational experience of marine diesel engines shows that the humidity of gases from the main engine can reach the value from 8 to 11%. This in its turn, significantly affects onto the processes of the heat transfer and purification of gas emissions.

To intensify the processes of heat transfer and cleaning, one can use forced humidification of the gas before it is fed into the scrubber.

One of the main factors affecting the density and porosity of the foam is the degree of swirling of the gas flow passing through the swirlers.

To model aerodynamics process on the surface of swirl plate a solid-state model was developed. It was done for both a single swirl element (Fig. 6, a) and the entire swirl plate with a complete set of swirling elements (Fig. 6, b).



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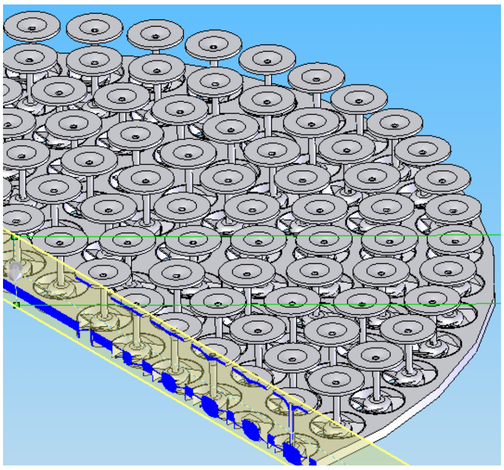
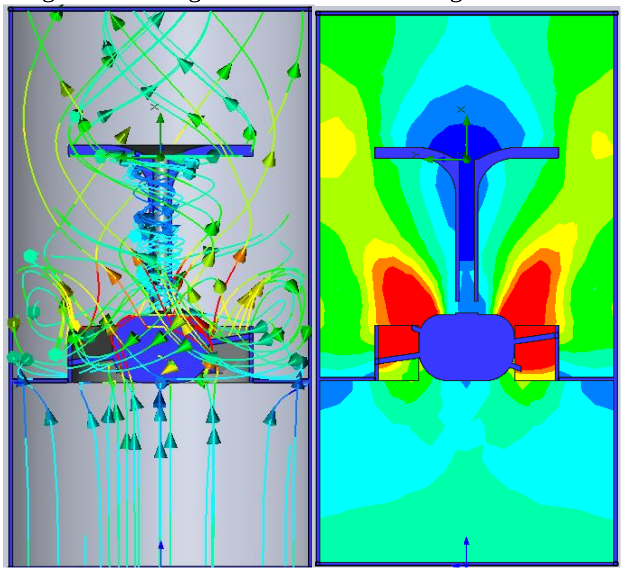


b

Fig. 6 Solid-state models.
a – swirling element; b – swirling plate of combined scrubber

The results of the velocity distribution inside the scrubber's working chamber are shown in Figure 7. As one can see, the swirler provides a high degree of swirling of the gas flow around the rack of fender disk (Fig. 7-a). Areas of reduced gas velocities are observed in the center of the disc and in the cavities of the holes (Fig. 7-b). Formation of these areas makes influence onto the process of liquid suction from the surface of the disc and its displacement to the swirling flow. In this case, the internal circulation of the liquid is actually provided with stable foam layer formation.

Visualization of pressure distribution during gas flow through the swirling element is shown in Fig. 8. As one can



a b

Fig. 7 Simulation of gas flow (field of velocity) inside the swirling element of a combined scrubber.
a – flow lines; b – cross-sectional view

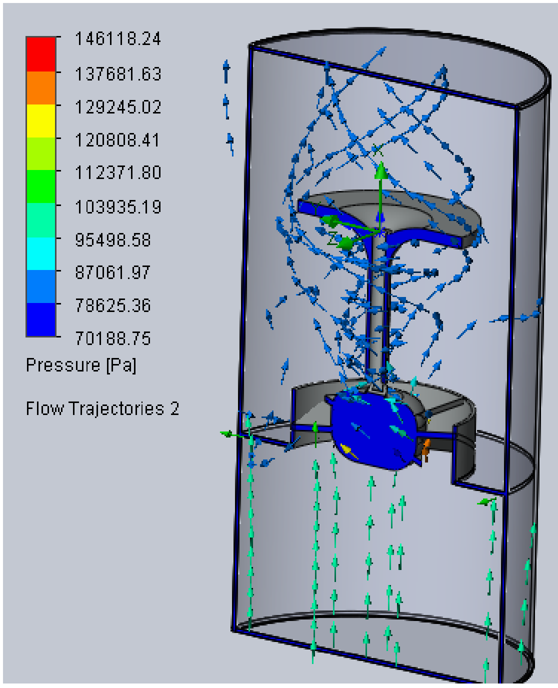


Fig. 8 Field of velocity inside the swirling element of a combined scrubber

see the pressure distribution inside the vortex element essentially repeats the trajectories of the flowlines. An area of reduced pressure can be observed in that part of the disc, which is locally located after the swirling element. This can be explained by the higher values of velocity and turbulisation of the flow at this area.

The efficiency of scrubber using and determining of its optimal design and operational parameters was tested experimentally on the plant, which is shown in Figure 9.

Quartz sand was used to model a dust of solid particles. The average median diameter of sandy particles was equals 5±0,3 micrometers. The initial concentration of dust z_p in the air was equals 2 g/m^3 ± 20 %.

The air temperature during experiments was not the same and answered to diapason from 15 to 25 °C. Its relative humidity was 50–75 %.

All experiments (when installation angle of swirling blades equals β=85°) indicated that increase of gas velocity (in the inlet pipe) from 5 to 15 *m/s* produces increase of cleaning efficiency. As one can see in Figure 10, the efficiency curve bends in the velocity diapason from 12 to 15 *m/s*. When velocity exceeds this diapason, the growing rate of efficiency factor starts to decrease sharply.

Fig. 9. Experimental plant

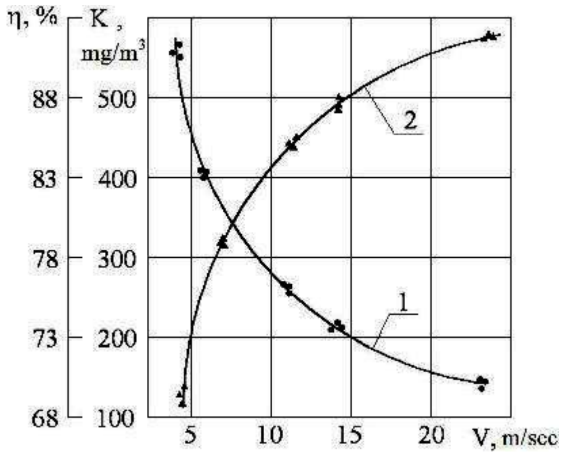


Fig. 10. Influence of gas velocity *V* onto residual dust concentration *K* (curve 1) and purification efficiency η (curve 2).

V. DISCUSSION

Results of provided research works show that during design process of the scrubber the optimal organization of the vortex structure on the surface of its vortex plate should be directed for simultaneous solution of two technological problems.

The first problem concluded in the fact, that for the scrubber's effective functioning the created airflow structure should provide a uniform aerodynamic load. Actually, the very uniform load can be obtained by means of uniform distribution of the flow's body of velocities along the entire surface of the vortex plate.

The second problem connected with realization of the process of the maximum possible pre-separation and coagulation of harmful substances when contaminated gas flow enters the foam-fluid layer.

Results of all provided experiments has shown that efficiency and hydraulic resistance of foam scrubbers are significantly influenced by the following indicators: initial dust concentration in the gas for cleaning, fractional efficiency of the scrubber which allows to design the devices with considering the characteristics of harmful emissions of various technological processes; the rate of contamination of the working fluid.

In order to ensure high efficiency of gas purification from harmful substances, it is worth to use for blades of swirling unit that is used in the middle of the scrubber's working chamber an installation angles close to 90°. In this case, it is possible to obtain optimal values for the factor of dust transmission. At the same time, it should be considered that increase of the β angle will lead to an increase in the loss of flow energy. For example, the change of the β angle of blades installation from 60 to 90 degrees produces an increase in the flow energy losses approximately at 9%.

A smaller number of blades reduces activity of their influence onto the gas flow. In this case, the gas pressure at the outlet of the vortex plate and the energy consumption inside the scrubber become smaller. Actually, as it follows from the described above research results an increase of the number of blades may be appropriate in one case only. This is the case when it is necessary to increase the gas pressure at the outlet of the swirler. It should be considered that increasing the number of blades is not a rational way to improve gas purification efficiency.

VI. CONCLUSION

The formation of a uniform aerodynamic load on the entire surface of the vortex plate can be provided by the use of optimally oriented swirl blades and the installation of fender disks of the vortex elements.

Among main parameters that affect onto the separation of solid particles are the dust particles concentration in the air at the inlet to the scrubber and the cross-sectional area of the plant.

To maintain the constant efficiency of solid particles separation, it is necessary to maintain the contamination of the liquid in the working volume of the scrubber at the level of 35-45% of the maximum amount of contamination.

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AUTHORS PROFILE

Valerii V. Aftanuk Full Professor of the Department of Ship's Thermal Energy at the National University "Odesa Maritime Academy" (Odessa City, Ukraine), received his PhD and DSc degrees in engineering scinces (scientific speciality is engineering thermal physics & industrial heat power generation) from Odessa National Polytechnic University (Odessa City, Ukraine) in 2000 and 2010, respectively. He has extensive experience in both teaching and researching (more than 25 years). His today's research interests include developing the simulation models of HVAC systems for different ship's spaces by means of methods of computional fluid dynamics (CFD); solving the problems of closed fluid flows; designing new technologies for auxiliary systems and equipment to be installed on ships.. ORCID: 0000-0002-6945-142X. E-mail: aftaniuk@smf.onma.edu.ua Mobile:+380506524909

Oleksiy V. Kiris, Professor and PhD. He is currently working as Head of the Chair of Ship's Thermal Energy and Full Professor in the National University "Odesa Maritime Academy", Odessa City, Ukraine. He has graduated from Odessa State Maritime Academy (1971). He earned his PhD degree (1975) from National University "Odesa Maritime Academy", Odessa City, Ukraine. His research interests include new methods and technologies for thermocombustion processes in ship disel engines. He is working with scientific problems, that implement on vessels new technologies for fuel treatment, fluid dynamics processes in aplication to liquid and gas treatment during vessel's operation, design of new technologies and technical units for vessels. He is the author of more then two hundred scientific articles and two scientific books for maritime students. ORCID: 0000-0003-4228-8295. E-mail: alexkiris48@gmail.com Mobile:+380936624690

Oleksiy V. Malakhov is currently working as Full Professor at the Chair of Ship's Thermal Energy in the National University "Odesa Maritime Academy", Odessa City, Ukraine. He has graduated from Odessa Polytechnic University (1992). He earned his PhD degree from Odessa National Polytechnic University (1995), Odessa City, Ukraine and Doctor of Science in Physics and Mathematics degree from National Transport University (2000), Kyiv. Ukraine. His research interests include maritime technologies for different types of vessels, fluid and gas dynamics, hydrodynamics of confined flows, CFD, design of new technologies and equipment for vessels, complex analysis of different technical operations and complex plunts on ships. ORCID: 0000-0002-5003-8715. E-mail: a_malahov@yahoo.com. Mobile:+380674810599

Milhail O. Kolegaev Chief Marine Mechanical Engineer. Currently working as Dean of Ship Mechanical Department and Full Professor in the National University "Odesa Maritime Academy", Odessa City, Ukraine. He has graduated from Odessa State Maritime Academy (1983) and earned his PhD degree (1997) from National University "Odesa Maritime Academy", Odessa City, Ukraine. His research interests include new methods and technologies for vessel's energy systems, new methods of fuel treatment and combustion processes, fluid dynamics of multiphase flows, safety technologies for vessel's operation, marine dredging technologies. A number of his scientific articles exceeds one hundred. He is the author of two scientific monographs. ORCID: 0000-0002-9328-182X. E-mail: smf@onma.edu.ua Mobile: +380676541504

Boris A. Garagulya Associate Professor and PhD. He is currently working as Assotiate Professor at the Chair of Ship's Thermal Energy in the National University "Odesa Maritime Academy", Odessa City, Ukraine. He has graduated from Moskow Energy Institute (1973) and earned his PhD degree (1985) from Moskow Energy Institute. His research interests connected with diffenet flows of gases under varible conditions, fluid and gas dynamics of confined flows including supersonic jets, CFD and new methods for flow modelling. Presently he is working in scientific area that include new methods and technologies for thermocombustion processes in ship disel engines, new technologies for improvement of fuel combustion on vessels and stable modes of ship operation under complicated boundary conditions and in channals with complicated geometry. He is the author of more then one hundred scientific articles and one scientific monograph. ORCID: 0000-0003-0637-038X. E-mail: boris.garagulya@gmail.com Mobile:+380637251075