TRANSPORT
ISSN 1648-4142 / eISSN 1648-3480
2018 Volume 33(1): 197–207
doi:10.3846/16484142.2016.1152298

THE ASSESSMENT ALGORITHM OF TECHNOLOGICAL FEASIBILITY OF SO_x SCRUBBER INSTALLATION

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Submitted 19 December 2014; resubmitted 24 February 2015, 22 April 2015; accepted 8 July 2015;

Abstract. The problematics of installation of sulphur oxides (SO_x) scrubber becomes much relevant for today due to the new Annex VI of MARPOL 73/78 requirements, which sets 0.1% SO_x limits by 2015 in Emission Control Area (ECA) and globally to 0.5% in 2020. The research in this field becomes more significant for ship-owners. SO_x scrubber is most promising alternative because of lower operating costs and suitability to existing ships. Despite the fact that exhausts gas scrubbing is a common and proven technology on land, the conditions on ships differ significantly and still there are not enough practical knowledge of installation of mentioned equipment. In addition, speaking about existing ships there are some limitation factors of SO_x scrubber installation on-board, which will be discussed in the paper. Taking into account the size and mass of the SO_x scrubber, it can be assumed that the recalculation of ship stability will be required for most ships. Therefore, the most important task for equipment designers is selection of scrubber system location with the minimum impact on ship stability and identification of necessary changes (deadweight, additional space, etc.) in accordance with ship safety requirements. For this reason, the research was carried-out in order to create the algorithm of ship stability assessment and selection of optimal scrubber location on-board.

Keywords: MARPOL 73/78 Annex VI; SO_x scrubbers; optimal location; ship stability; heel; trim; metacentre.

Introduction

The implementation issues of SO_x scrubber are relevant for today as scrubber technology is the most realistic alternative to comply with new regulations of MARPOL 73/78, which sets certain limits on SO_x emissions from ship exhaust to 0.1% by 2015 in Emission Control Area (ECA) and globally to 0.5% in 2020 (MEPC 2008). ECA regulations are now enforced across many countries and there are further designated zones under discussion. Therefore, an increasing number of scientists are exploring mentioned issues in their researches. However, most of researches contain analysis of environmental impact of ship exhaust and ways to reduce harmful emission (Caiazzo *et al.* 2012; Fridell 2008; Kannan 2014; Lack *et al.* 2012). In the medium and long term, it can be expected that most of global trading centres will be pass through ECA zones. It is noteworthy that the regulations will be applicable not only to new building but also to existing ships. It is obvious that SO_x restrictions will bring considerable financial and technological challenges especially for modernization of existing ships. Certainly, new SO_x requirements will affect overall world fleet as well as new building and existing. However, the modernization of ship is more complicated than designing a new one. The researches of scrubber installation problematics are gaining importance as the compliance with emission limits becomes more challenging. There are several ways to achieve the compliance with SO_x requirements and many papers contain a comparison of advantages and disadvantages of technologies of SO_x reduction (Brynolf *et al.* 2014; gCaptain 2012; Glosten 2011; Kruse 2012). In addition, authors investigate methods of SO_x scrubber selection but there are still not enough recommendations suitable for pre-design phase of technology selection (Schinas, Stefanakos 2014; Glosten 2011; Tai, Lin 2013; Walter; Wagner 2012; Yang *et al.* 2012). Issues of changed ship stability are investigated only for a particular ship at the equipment design phase. In turn, the estimating methodology of SO_x scrubber effect on ship described insufficiently. For this reason, the paper analyses the assessment of scrubber installation impact on the ship stability.

In order to understand the problematics of SO_x scrubber installation, it is necessary to analyse the speci-

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ficity of installation of the entire system (Lloyd's Register 2012; Wärtsilä 2013, 2010; MEPC 2008; Wright 2000). Generally, SO_x scrubber is a device installed in ship exhaust system after the engine or boiler that treats the exhaust gas with a variety of substances including seawater, chemically treated fresh water or dry substances, so as to remove most of the SO_x emission. The installation of scrubber is complicated because of the significant weight of equipment and location high above waterline.

There are two types of scrubbers: wet and dry. Wet scrubbers are more acceptable for ships because of the lower price and smaller dimensions of units. That is why only wet scrubbers will be analysed in the paper.

Currently, the wet SO_x scrubbers reached an industrial scale and there are a number of manufacturers offering their equipment including such companies as Alfa Laval Aalborg, Clean Marine, Couple Systems, DuPont BELCO Clean Air Technologies, Green Tech Marine, MAN Diesel and Turbo, Marine Exhaust Solutions, Wärtsilä Hamworthy Krystallon. There are three main types of wet scrubbers which are offered by manufacturers: the open loop which uses only seawater; the close loop which uses fresh water mixed with caustic soda; the hybrid which has both benefits of open and closed loop (ABS 2013; DNV 2012).

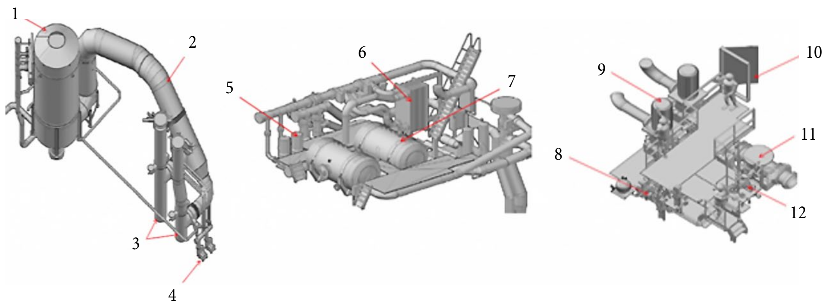
The open loop scrubber system is rather simple and cheaper than close loop. However, it cannot be operating in area with restricted water outlet criteria like Baltic Sea. In turn of hybrid system, there are no significant weight and dimensional characteristics differences between close loop and hybrid system. Mentioned types of wet scrubber are comparable then assessing the technological feasibility of scrubber installation. For this reason, the paper will consider only on close loop type of scrubber.

The working principle of mentioned close loop scrubbers of different equipment manufacturers is almost the same. It means that scrubbers are approximately the same in size and mass, in pumping capacities, caustic soda solution, etc. That is why the differences between the manufacturers are not taken into account in the paper. Regardless of the manufacturers, wet scrubber usually consists of three main block of equipment (see an example of Aalborg close loop scrubber on ferry of shipping company DFDS Fig. 1):

- casing with scrubber unit inside and exhaust manifold which are connected with existing exhaust pipes.
- equipment room with circulation tanks and pumps for water mixing with NaOH;
- pump room with pumping, NaOH and sludge storage equipment.

Regardless of the design features of the ship, a new casing should be added to the aft part of the existing casing and scrubber should be located inside the new casing as close as possible to the existing exhaust gas pipe. A new equipment room should be located at deck directly under scrubber unit. Circulation pump, tanks and cooler should be located in the equipment room. The new equipment room should be in open connection to the scrubber in the casing structure by stairs way. A new pump room should be located below the equipment room in short connection with existing sea chest. Seawater cooling/feed pump, cleaning unit, NaOH pumps sludge transfer and storage tanks are located in the new pump room. It is obvious that the whole system should be located with open access with existing engine room, new pump room and equipment room. Therefore, regardless of place planning on-board, the location of scrubber system will directly depend on the location of engines and the exhaust system.

The most significant elements of overall system on weight and dimensional characteristics are scrubber unit with casing and circulation tanks. The scrubber unit should be located as close as possible to the existing exhaust pipes to ensure efficient reduction of SO_x emission of exhaust gas and minimize the length of manifold pipes. The circulation tanks should be located as close as possible to the scrubber to ensure an efficient flow of mixed NaOH water into the scrubber and minimize the energy consumption for circulation pump operating. It is also necessary to note that these elements should be placed as close as possible to each other, which means that in most cases the gravity centre of scrubber unit and circulation tanks will be located above or close to the waterline. As the scrubber and circulation tanks are quite heavy and volumetric elements in comparison with the entire system, its location on board should be considered at the pre-design phase. To ensure the compliance with ship safety requirements (will be discussed in



Casing Equipment room Pump room

Fig. 1. The scrubber system elements: 1 – scrubber; 2 – exhaust manifold; 3 – existing exhaust pipe; 4 – sealing air fan; 5 – circulation pump; 6 – cooler; 7 – circulation tank; 8 – NaOH equipment; 9 – sea water pump; 10 – water-light door; 11 – sea strainer; 12 – sludge equipment (DFDS Seaways 2014)

the next chapter), the centre of gravity of the scrubber system should be located as close as possible to the ship centre of gravity. This will ensure the minimum impact on the ship stability. However, taking into account the specifics of ship space planning and location of engine room, usually it is impossible to ensure the location of scrubber system close to the ship gravity centre. Therefore, it is necessary to calculate the optimum possible location of the scrubber system with the minimum impact on the characteristics of ship after modernization. Taking into account significant capital costs of scrubber equipment, the mentioned changes of ship characteristics can increase costs and make the choice of scrubber technology unprofitable.

The paper presents a part of carried out research on the evaluation of economic efficiency and technological feasibility of scrubber technology applied to the exiting ships. The main task of the research was to determine possible economic and technical consequences of complying with the new SO_x requirements. The assessment of economic efficiency is presented in earlier paper (Panasiuk, Lebedevas 2014). This paper presents technical aspects of the feasibility of ship modernization by installing SO_x scrubber on-board. This paper analyses the technological assessment of SO_x scrubber installation on-board the ship.

1. The Scrubber System Configuration and Whole Elements Weight and Size Parameters

The analysis of the proposed scrubber's equipment of different manufacturers showed that there are no significant differences in system configuration, as well as in weight and volume of each component of system. Regardless of the manufacturers, SO_x scrubber selection is primarily based on particular engine characteristics of ship. More specifically, the capacity of scrubbers directly depends on exhaust gas flow. If it is single stream (separate scrubber for each engine), there is a need to calculate combustion unit power separately. In case of multi stream (one scrubber for several engines), we should take into account an overall power of combustion units. The exhaust gas flow per combustion unit power is the main parameters when choosing the required capacity of scrubber for particular ship. Depending on combustion unit's characteristics, the maximum exhaust gas flow can be calculated as follows:

$$\dot{m}_{gas} = \dot{m}_{fuel} + \dot{m}_{fuel} \cdot L_0 \cdot \alpha \cdot \beta, \qquad (1)$$

where: $\dot{m}_{gas}$ – exhaust gas flow; $\dot{m}_{fuel} = P_{emax} \cdot b_{emax}$ – nominal fuel consumption; L_0 – stoichiometric air-fuel constant (accepted 14.5 kg air/kg fuel); α – real coefficient of air excess; β – air mass flow ratio (according to Mollenhauer *et al.* (2010), can be accepted approximate value 1.45 for 2-stroke and 1.1 – for 4-stroke engine).

The most important parameter in the formula of $\dot{m}_{gas}$ calculation (Eq. (1)) is an air mass flow ratio, which determines the value of the difference between 2-stroke and 4-stroke engine. 4-stroke engines have higher exhaust temperatures than 2-stroke engines. It means that for the same volumetric flow of exhaust, more water is required for cooling and saturation. 2-stroke engines have higher volumetric flow of exhaust than 4-stroke engines, which mean that for the same power of engines volumetric flow of exhaust, more power of scrubber is required. The higher the exhaust gas flow from combustion units the more powerful scrubber is required. It should be noted that scrubber is designed for continuous operation at full specified gas flow (ISO 8178-1:2006; Mollenhauer, Tschöke 2010).

The size and mass of scrubber can be determined as dependence between combustion units power and scrubber capacity. The scrubber unit weight is primarily affected by its capacity or in other words on exhaust gas mass flow. In accordance with analysed systems, the dependence of scrubber weight and volume per its capacity has the form shown in Figs 2 and 3 (Wärtsilä 2013; MAN Diesel & Turbo 2013).

It is very important to design the scrubber system with minimum of weight, due to its high vertical centre of gravity. That is why manufacturers offer lighter reinforced plastic scrubber tank body instead of a corrosion resistant metal. Weight saving compared to metallic scrubber unit is 20–30%. In turn, a volume of scrubber directly depends on water flow required to clean exhaust gas. It means only the location of scrubber unit can be adjusted in order to find a suitable place on-board of the equipment. However, the mass and volume of scrubber unit is just a part of overall system and on the average is 10–15% of scrubber system weight. Overall, SO_x scrubber system directly depends on quantity of water and reagents required to cool the gas flow and wash out

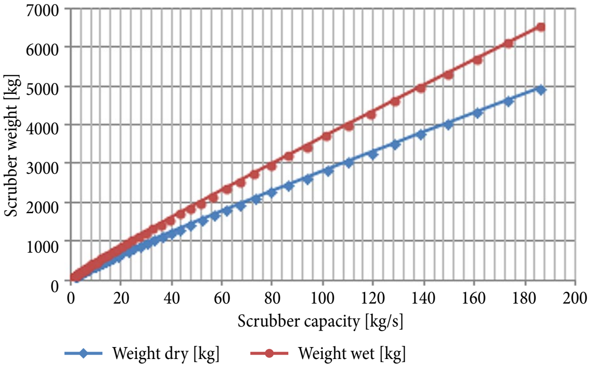


Fig. 2. Scrubber weight per scrubber capacity

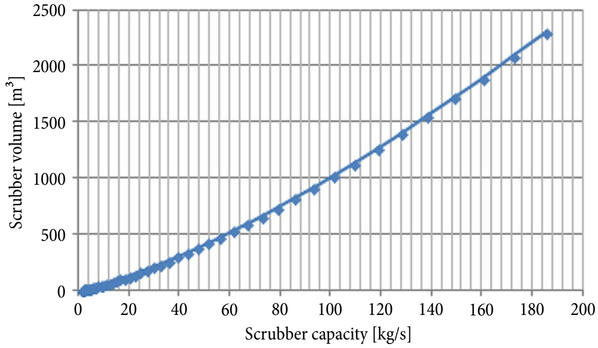


Fig. 3. Scrubber volume per scrubber capacity

the SO_x. In addition, there is some difference of unit's parameters (pipe length, etc.) depending on ship geometry. However, the deviations are insignificant and can be ignored at the pre-design phase. Thereby, the weight of each unit can be calculated as the dependence on scrubber capacity.

Mentioned dependence of scrubber system capacity and its mass and volume was taken into account to create the database of scrubbers with identified characteristic of overall system's elements. The data of scrubber parameters of specific manufacturer was taken into account in calculations. However, the further present methodology can be applied to any manufacturer by clarifying the characteristics of the systems. The complete scrubber system used in the paper is the following (Fig. 1). The exact size of the various element of scrubber system can only be determined when the system has been designed. However, on the pre-design phase we can state that each element depends on exhaust gas flow or in other words on scrubber capacity. As an example, the values of each component of particular ship's (Ro-Pax of DFDS) scrubber system mass and volume are given in Fig. 4.

As is shown in Fig. 4, there is no complete ratio on the mass and volume characteristics of each element of system. In turn of mass, the greatest impact on the ship will have such scrubber elements as exhaust fan casing, piping (especially water circulation), equipment room casing, circulation tanks and directly scrubber unit, which are located in exhaust fan casing. The volumetric characteristics of mentioned elements differ significantly. For example, the mass of exhaust casing is 24%, whereas the volume is 31% of whole system volume. Only the scrubber unit is approximately the same for both characteristics and is equal 12–14%. However, the greatest impact on the ship will have the mass and location of each elements of system, while the volumetric characteristic will be used as a limiting factor to determine the possibility of elements installation in a particular location depending on the available space on-board the ship. The mass characteristics of each element of scrubber system mainly affect the stability of ship. The location of mentioned elements directly depends on its volume. Obviously, it is not so easy to find a place on-board for sufficiently massive equipment and therefore volumetric characteristics of each element should be used to clarify the possible range of element location (Fig. 5). It means that possible range of location of a particular element will be specified depending on the necessary volume for its installation and the specific mass of element.

In addition, the specific mass per unit of volume should be taken into account when identifying the location of element, which directly affects the stability of ship. Therefore, the greater scrubber system element's specific mass per m^3 identifies the need to install it as lower as possible.

The described concept of scrubber system selection allows to state that the configuration of scrubber system directly depends on combustion unit power. This dependence allows evaluating overall system mass and volume when only combustion power is known. The capacity of scrubber determines mass and volume char-

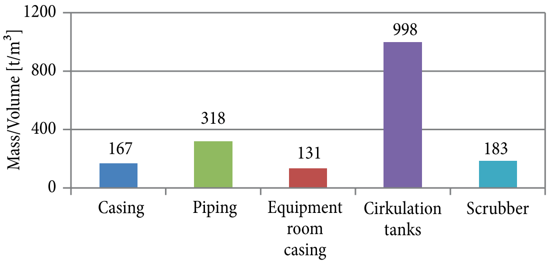


Fig. 5. Scrubber system specific mass characteristic

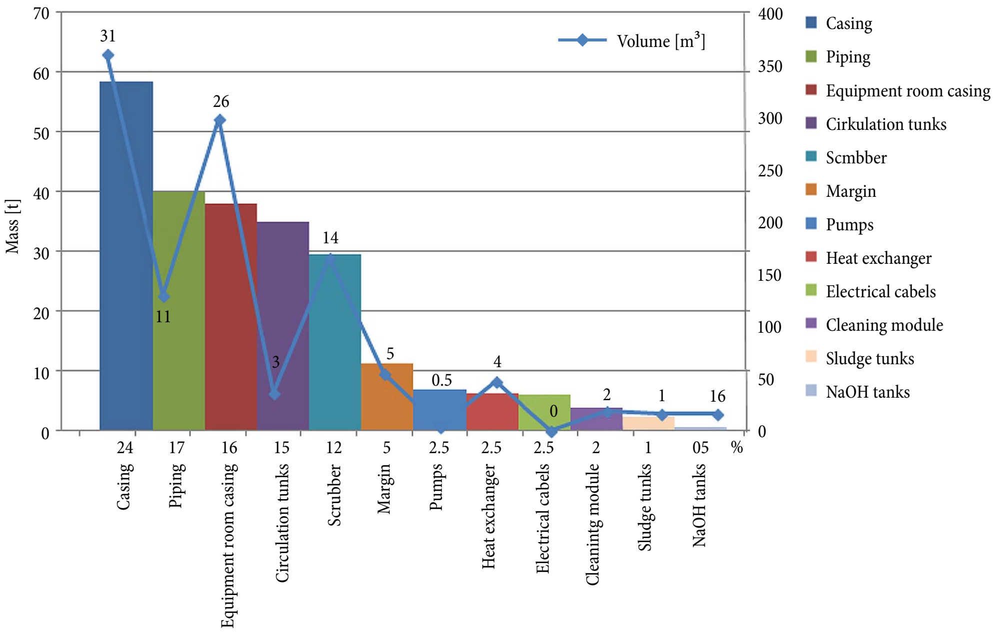


Fig. 4. The mass and volume of each element of scrubber system

acteristics of each elements of whole system. The element with the most significant mass and volume will be taken into account to optimize their location on-board. It means that exactly those elements that on mass and volume characteristic exceed 10% of the total system will be taken into account in the simulation of optimal system location. Thereby, it can be stated that the first stage of the assessment of technological feasibility of scrubber installation is the selection of capacity and configuration of whole system in accordance with the characteristics of ship combustion units. Providing that the main parameters of whole system are known, the second step of assessment (location selection) of scrubber impact on the modernized ship can be done.

2. The Algorithm of Assessment of Ship Stability Changing with Scrubber Onboard

As a rule, the main of mathematical modelling of an object is optimization of its parameters. Usually, such modelling consists of an input and output data, a function of optimization, criteria of function with limitations. The input data is needed to calculate the impact of scrubber on ship characteristics. In turn, output data are results obtained after calculations. Calculation of varying or independent parameters of optimization function allows identifying the values, which is achieved by optimum of the function.

In our case, the optimization function allows to select the optimal scrubber system location with the minimum effect on ship characteristics (Fig. 6).

However, it is obviously known that the optimal location of the scrubber should be as close as possible to the centre of gravity of the ship (in all three axes *X*, *Y*, *Z*). The implementation of optimization may be performed by limiting the analysed interval on *X*, *Y*, *Z* axis and function's optimum will be calculated in this interval. Hence, the optimization function cannot be completely formalized. Generally, the permissible interval of scrubber installation should match the engine room location on *X* axis, exhaust pipe on *Z* axis and approximately equal to ship gravity centre on *Y* axis. The optimal location of scrubber system can be calculated as minimum possible deviation of ship characteristics (draught, trim, heel, etc.) which affects its buoyancy, floatation and stability. Thereby, the technological feasibility of scrubber installation can be assessed in further stated way. First step of assessment is calculation of scrubber capacity in accordance with ship input data. The capacity of scrubber determines all parameters of system elements. As was said before, first of all, it is necessary to identify the capacity of scrubber according to ship data. After that, it will be possible to identify the mass and volume of each element. Then, after all characteristics of system are known, it is necessary to calculate compliance with ship safety requirements. If ship with changed mass does not match all limiting factors, it is necessary to identify an optimal location of scrubber system with minimum effect on limiting factors. Further, the interval of possible place of scrubber system installation on-board is identified in accordance with characteristics of ships (engine room, exhausts pipe, sea chests location, etc.) or by expert opinion of ship-owner if the changes in the existing facilities of the ship are allowed. Then, after the optimal location within the permissible interval of scrubber system (*X*, *Y*, *Z*) is identified, it is necessary to calculate consequences of scrubber system installation (decrease of deadweight, an extra ballast to compensate mass of scrubber and ensure the trim as required, etc.). The result of calculation should be provided in the form of aggregate data on necessary changes to install scrubber system and still comply with requirements.

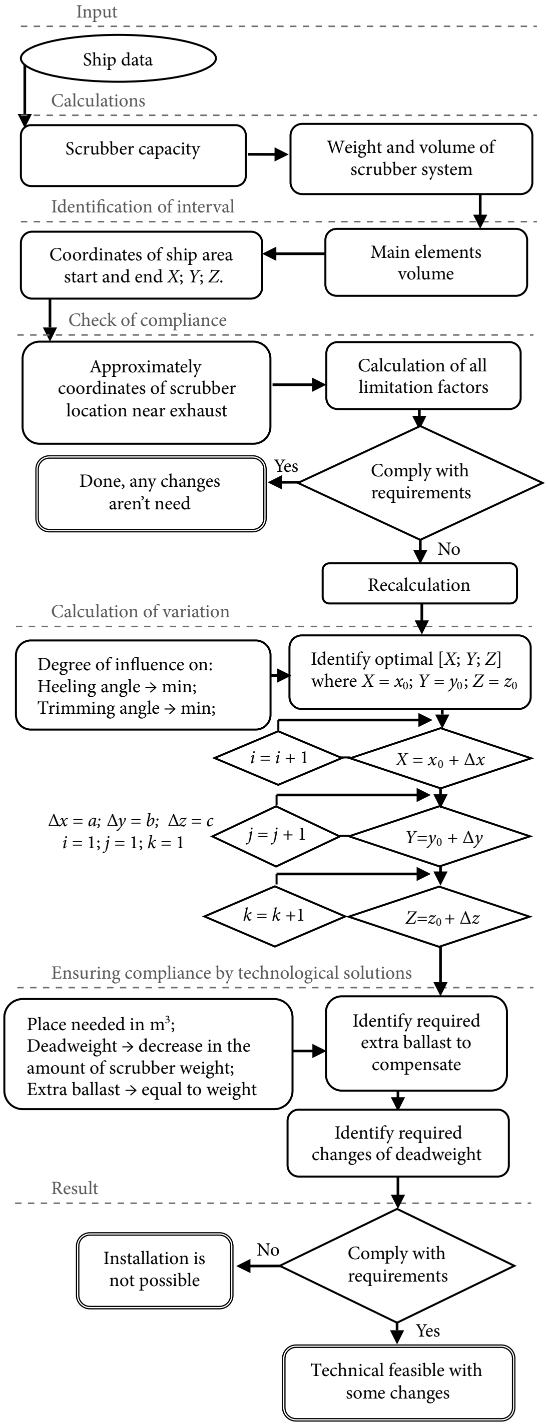


Fig. 6. The algorithm of assessment of scrubber system installation

3. The Calculation of Compliance with Ship Stability Requirements

The additional equipment of scrubbers system can be seen as a part of changed ship mass, which directly affects ship's gravity centre and hence all other parameters like draught, trim, etc. As was said before, scrubber system consists of three main blocks of equipment (Fig. 4):

- casing with scrubber, part of pipes and some margin is 46% of whole system mass;
- equipment room with circulation tanks, part of pipes and some margin is 41%;
- pump room and the other elements is 13%.

Exactly these blocks can be moved to minimize an impact of system on ship characteristics. The 3rd block can be regarded as a weight with fixed coordinates of gravity centre as its insignificant weight of about 13% and the possible location just in room of existing sea chest below the waterline. Accordingly, selection of optimal location of 1st and 2nd block of scrubber system can be done by assessing their impact on ship and finding an option with the smallest possible impact. In turn, the smallest possible impact can be assessed by using standard ship theory calculations (IMO 2004, 2005; Rawson, Tupper 2005).

It is obvious that all ships should comply with safety requirements and changing of each parameter is limiting within acceptable values. If changing of ship parameters with scrubber on-board will exceed the limitations mentioned in Table, it will be necessary to reclassify the ship to approve the compliance with classification societies, such as Det Norske Veritas, Lloyd's Register, American Bureau of Shipping (ABS 2013), etc. This leads to the necessity to make changes in the location and partial reduction of deadweight to compliance with mentioned requirements. Selection of optimal location of each element of scrubber system can be considered as compliance with ship safety requirement or ensuring the minimum possible deviations of mentioned parameters listed below:

Table. Main acceptable tolerances (IACS 2016)

Limiting parameters	Value
Lightship weight $m_{lightship}$	2%
Centre of gravity δX_{CG}	1% or max 50 cm
δY_{CG}	0.5% or max 5 cm
δZ_{CG}	1% or max 5 cm
Draught T_{MD}	1% or max 5 cm
Metacentric height $\overline{GM_L}$	1% or max 50 cm
$\overline{GM}$	1% or max 5 cm
Trimming angle θ	1%
Heeling angle φ	not allowed

Thereby, an optimal location of each element of scrubber system will be calculated by the method of selection of location with the minimum deviation of mentioned ship parameters (Table).

Under the standard conditions, such calculations are carried out by taking into account all geometric characteristics of ship. However, needed data usually are unknown. That is why the proposed methodology consist approximate calculations with the initial stability assumptions. In order to ensure the suitability of established optimization model for conceptual design phase of scrubber system selection, the simplifying assumptions will be introduced in the calculations, which will be presented in the form of functions of other variables or for example water plane coefficient, etc. As a rule, the results of such calculations have a high deviation because of using mentioned simplified assumptions. However, on pre-design phase, the resulting accuracy of the calculations will be more than enough to make a decision about the technological feasibility of the analysed scrubber technology for a particular ship.

The following calculations will be used in the assessment of compliance with requirements in Table. In accordance with acceptable tolerance, 1st limiting factor of scrubber installation is its overall mass. Consequently, there is a need to recalculate changed ship's mass:

$$m'_G = m_G + m_g \,, \tag{2}$$

where: m'_G – ship mass with scrubber; $m_G = m_{lightship} + m_{DWT}$ – total ship mass; m_g – scrubber mass.

The displacement in all loading conditions should not exceed 2%. It means that the weight of scrubber system should not exceed 2% of ship lightweight and similarly for the other limiting factors.

Next limitation is the changed centre of gravity, which is affected by additional mass of scrubber system-m_g. In other words, the additional m_g shifts the centre of ships gravity towards scrubber location (Fig. 7).

G is initial ship's centre of gravity, g is gravity centres of scrubber equipment, B is buoyancy gravity centre, M is metacentre, K is keel line. Initial G can be represented as force acting through buoyancy centre of gravity X_{CB} and $X_{CB} = X_{CG}$. In turn, the gravity centre of scrubber g is usually remote to the aft ship closer to the engine room and changed gravity centre of ship will be moved to the side of scrubber location x_{Cg}, y_{Cg}, z_{Cg}. The distance from initial to changed ship gravity centre δX_{CB}, δY_{CB}, δZ_{CB} can be calculated as follows:

$$\delta X_{CG} = \frac{m_g \cdot \left(x_{Cg} - X_{CG} \right)}{m_G + m_g} \,; \tag{3}$$

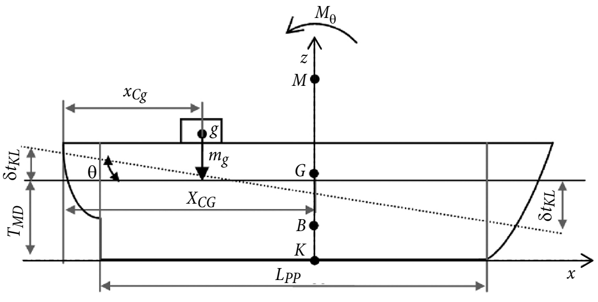


Fig. 7. Trim of ship with scrubber

$$\delta Y_{CG} = \frac{m_g \cdot \left(y_{Cg} - Y_{CG} \right)}{m_G + m_g}; \qquad (4)$$

$$\delta Z_{CG} = \frac{m_g \cdot \left(z_{Cg} - Z_{CG} \right)}{m_G + m_g}. \qquad (5)$$

Changed gravity centres of ship will affect longitudinal $\overline{GM_L}$ and transverse $\overline{GM}$ metacentric height, which can be calculated as follows:

$$\overline{GM_L} = R + Z_{CB} - Z_{CG}; \qquad (6)$$

$$\overline{GM} = r + Z_{CB} - Z_{CG}, \qquad (7)$$

where: $R = \frac{0.08 \cdot L_{PP}^2}{T_{MD}}$ and $r = \frac{0.08 \cdot B_{WL}^2}{T_{MD}}$ – approximate longitudinal and transverse metacentric radius; $Z_{CB} = \frac{T}{1 + \frac{C_B}{C_{WP}}}$ – buoyancy gravity centre; C_B and C_{WP} – block and water plane area coefficient (Biran, López-Pulido 2014).

By making the assumption of a constant of waterplane area, approximate differences between initial and changed metacentric height δGM_L and δGM can be calculated as follows:

$$\delta\overline{GM_L} = \frac{m_g}{m_G + m_g} \cdot \left(T_{MD} + \frac{\delta T_{MD}}{2} - \overline{GM_L} - z_{Cg} \right); \qquad (8)$$

$$\delta\overline{GM} = \frac{m_g}{m_G + m_g} \cdot \left(T_{MD} + \frac{\delta T_{MD}}{2} - \overline{GM} - z_{Cg} \right). \qquad (9)$$

Next limitation is the changed draught of ship (Fig. 8).

The draught is characterized by changed mean draught, trim and heel angles. It is directly affected by additional mass on-board and difference of changed draught δT_{MD} can be calculated as follows:

$$\delta T_{MD} = \frac{m_g}{L_{PP} \cdot B_{WL} \cdot \rho \cdot C_{WP}}, \qquad (10)$$

where: L_{PP} – ship length between perpendicular; B_{WL} – maximum moulded breadth at design water line; ρ – water density (1.0 for river and 1.025 for sea); C_{WP} – water plane area coefficient.

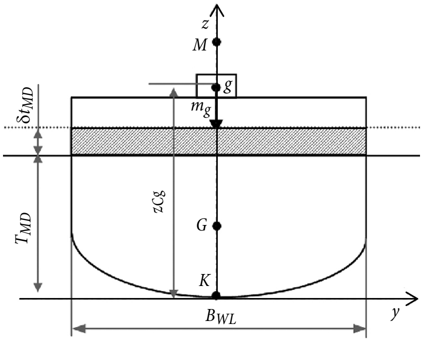


Fig. 8. Draught of ship with scrubber

If draught at the aft and fore ship on Z–O–X axis not match then appears the trim. In turn of trim, it appears only if the centre of changed gravity with scrubber equipment x_{Cg} will be not direct in the vertical line of ship's gravity centre X_{CG} (Fig. 7). It should be noted, that the trim to fore ship is not allowed. Unlike, the trim to aft is allowed, but usually undesirable. In turn, difference of changed angle of trim θ can be calculated as follows:

$$\delta\theta = 57.3 \cdot \mathrm{arctg} \frac{m_g \cdot \left(x_{Cg} - X_{CG} \right)}{\left(m_G + m_g \right) \cdot \overline{GM_L}}. \qquad (11)$$

If scrubber system is located closer to aft ship and $x_{Cg} < X_{CG}$ then trim is to aft ship and $\delta t_{KL} < 0$ otherwise the trim is to fore ship and $\delta t_{KL} > 0$. The changed trim can be calculated as:

$$\delta t_{KL} = \frac{M_\theta}{M_{TM}}, \qquad (12)$$

where: $M_\theta = m_g \cdot \left(x_{Cg} - X_{CG} \right)$ – the moment to trim with scrubber on-board; $M_{TM} = \frac{m_g \cdot \overline{GM_L}}{L_{PP}}$ – moment to change trim by one meter.

In approximate calculations, the change centre of ship buoyancy is assumed to be equal to the changed centre of ship gravity (X axis).

If scrubber system is located not direct at the centre of the ship then appears a heel (Fig. 9).

It should be noted that a heel at starboard or portside is not allowed. It means that y_s should match with y_{G_0} or it is necessary to ensure the movement of the available weight onboard (replacement of scrubber system element in place of bunker tank, etc.).The difference of changed angle of heel φ can be calculated as follows:

$$\delta\varphi = 57.3 \cdot \frac{m_g \cdot y_{Cg}}{m_G \cdot \overline{GM}}, \qquad (13)$$

where: φ – angle of heel; y_{Cg} – distance of transverse centre of gravity of scrubber system on Z–O–Y.

The key indicator of ship stability is righting arm $\overline{GZ}$, which directly depends on metacentric height (Fig. 9). $\overline{GZ}$ is a perpendicular distance between the centre of gravity G and the buoyancy force vectors. As is known the ship-righting arm $\overline{GZ}$ with small angle

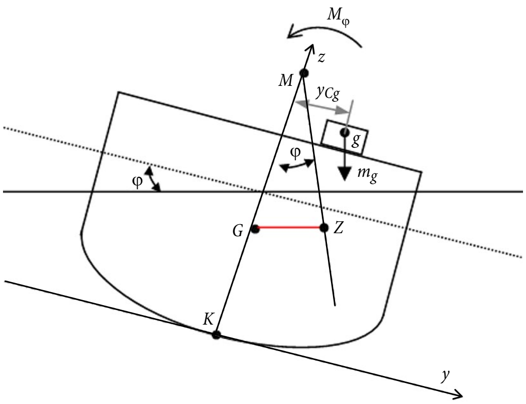


Fig. 9. The heel of ship with scrubber

inclination can be calculated as follows (Rawson, Tupper 2005):

$$\overline{GZ} = \overline{GM} \cdot \sin\varphi, \tag{14}$$

and difference of changed $\overline{GZ}$:

$$\delta\overline{GZ} = \delta\overline{GM} \cdot \sin\delta\varphi\,. \tag{15}$$

Summarizing the calculation, the compliance criteria will be as follows:

$$\begin{cases} \delta m_g \le 0.02 \cdot m_{lightship}; \\ \delta X_{CG} \le 0.01 \cdot X_{CG} \;\text{ or }\; \delta X_{CG} \le 0.5; \\ \delta Y_{CG} \le 0.005 \cdot Y_{CG} \;\text{ or }\; \delta Y_{CG} \le 0.05; \\ \delta Z_{CG} \le 0.01 \cdot Z_{CG} \;\text{ or }\; \delta Z_{CG} \le 0.05; \\ \delta T_{MD} \le 0.01 \cdot T_{MD} \;\text{ or }\; \delta T_{MD} \le T_{MD} + 0.05; \\ \delta\theta \le 0.01\theta; \\ \delta\varphi \cong 0; \\ \delta\overline{GM}_L \le 0.01 \cdot \overline{GM}_L \;\text{ or }\; \delta\overline{GM}_L \le 0.5; \\ \delta\overline{GM} \le 0.01 \cdot \overline{GM} \;\text{ or }\; \delta\overline{GM} \le 0.05; \\ \delta\overline{GZ} \le 0.05 \cdot \overline{GZ} \;\text{ or }\; \delta\overline{GZ} \le 0.05. \end{cases} \tag{16}$$

All mentioned limitations depend on whole scrubber system mass and its location on-board. It should be noted that in any case, the draught of ship should be equal to initial and it is necessary to reduce ship deadweight in the amount of scrubber's system mass.

Optimization involves setting of function, which in our case is certainly known: location of whole scrubber system should be as close as possible to ship gravity centre. Therefore, in this case, the optimization function cannot be completely formalized and some decisions should be done by expert's review of the ship-owner. In other words, we cannot get the specific coordinates of whole system location as it is limiting due to the need to locate the scrubber unit as close as possible to exhausts pipes. However, after the calculations we get a range of impact of the whole system on the ship characteristics depending on the location of each element. In turn, the ship-owner will be able to choose the location of each element in the range obtained by using the proposed algorithm.

The selection of optimal location of each element can be done by variation calculations of trim and heel angles, transverse metacentric height and righting arm with different coordinates of scrubber location on the *X*, *Y*, *Z* axis:

$$\begin{cases} \delta\theta = 57.3 \cdot \mathrm{arctg}\dfrac{m_g \cdot \left(x_{Cg} - X_{CG}\right)}{\left(m_G + m_g\right) \cdot \overline{GM}_L}; \\ \delta\varphi = 57.3 \cdot \dfrac{m_g \cdot y_{Cg}}{m_G \cdot \overline{GM}}; \\ \delta\overline{GM} = \dfrac{m_g}{m_G + m_g} \cdot \left(T_{MD} + \dfrac{\delta T_{MD}}{2} - \overline{GM} - z_{Cg}\right); \\ \delta\overline{GZ} = \delta\overline{GM} \cdot \sin\delta\varphi. \end{cases} \tag{17}$$

Thereby, the criteria of optimal location for each block of scrubber system are as follows:

- X_{CG} with $\delta\theta \to \min$. δX_{CG} affected the trim (draft at aft and fore ship not match) and changing of gravity centre should be minimal, but if it is impossible, the trim can be compensated by extra ballast on the opposite side of ship; deadweight reduction or extra ballast in opposite side of ship;
- Y_{CG} with $\delta\varphi \to \min$. δY_{CG} of changed gravity centre should be ≈0, but if it is impossible the heel can be compensated by moving each block of scrubber system to opposite direction (for example, if scrubber with casing is on starboard side, then equipment room can be moved to portside);
- Z_{CG} with $\delta\overline{GM} \to \min$. δZ_{CG} of changed gravity centre should be minimal, but if it is impossible, the changing of metacentric height can be compensated by extra ballast below the water line deadweight reduction or extra ballast in opposite side of ship;
- Y_{CG} and Z_{CG} with $\delta\overline{GZ} \to \min$. Y_{CG} and Z_{CG} changing should be compensated by reducing or extra ballast to ensure minimal $\delta\overline{GZ}$;
- scrubber's system mass and extra ballast should be compensated by reducing of ship deadweight.

The proposed algorithm allows estimating effect on ship stability and compensating deviations due to the coordinates of location of each block of system. The interval of the analysed area for each component of scrubber system installation will be coinciding with the engine room location (start and end frame or distance on *X*, *Y*, *Z* axis of engine room location). For example, the interval of engine room location can be from $\left[X_0; Y_0; Z_0\right]$ to $\left[X_n; Y_n; Z_n\right]$ then the optimal location of scrubber system will be analysed in mentioned interval. The place where scrubber system will comply with safety requirements (Table) or will have the minimal impact on the ship characteristics will be considered as optimal.

4. The Approbation of the Algorithm of Assessment of Ship Stability Changing with Scrubber Onboard

The approbation of the optimization model of selection of scrubber system location is presented on example of Ro-Pax ferry (DFDS Seaways 2014). To calculate the optimal location of whole system, there is a need to identify the configuration, mass and volume of most significant elements. As it is said before, main elements of scrubber system, which should be analysed when selecting the optimal location, are casing (exhaust and equipment room), piping, circulation tanks and scrubber unit.

It is decided to design multi steam SO_x scrubber for two main engine of analysed ship. Because of the lack of space on-board, there is only a small part of the ship where it is possible to arrange scrubber system. To ensure architectural design of ship, the scrubber can be located behind of the existing exhaust pipe. Thereby, a new casing will be added to the aft part of the existing exhaust casing and will be located above the elevator trunk from 18 to 33 frames and from 24 m to 30 m above base line. The scrubber unit will be located inside the new casing. As new equipment room should be in open connection to scrubber in new casing structure via stairway, it will be located directly under scrubber unit from 21 m to 24 m above base line. Circulation tanks, pumps, cooler and cleaning unit will be located in the new equipment room. Access to the equipment room will be from the existing corridor. As the access to the new pump room should be established from engine room, it will be located from 6 m to 9 m above base line directly under new equipment room. Accordingly, the analysed interval of calculation will be from 18 to 33 frame on *X* axis and from 6 m to 30 m on *Z* axis. As was said before, the location of the whole system should be provided right at the centre of the ship gravity on *Y* axis to avoid heel which upon the requirement (Table) is not allowed.

Using mentioned algorithm, the intervals of deviations ($\delta\theta$, $\delta\varphi$, $\delta\overline{GM}$, $\delta\overline{GZ}$) were calculated and following results were obtained (Figs 10–13).

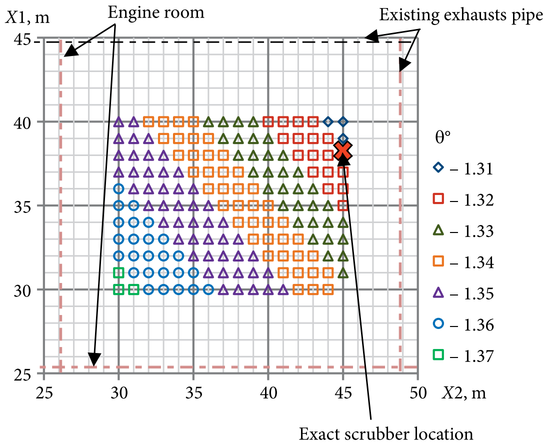


Fig. 10. The deviation of trimming angle depending on the displacement of block 1 and 2 on *X* axis

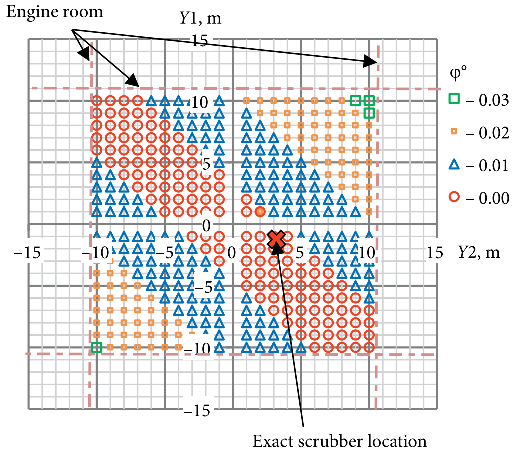


Fig. 11. The deviation of heeling angle depending on the displacement of block 1 and 2 on *Y* axis

The approbation of algorithm was done by comparing the calculation results with real project of scrubber installation on DFDS ferry. The algorithm allows to assess main criteria of ship stability ($\delta\theta$, $\delta\varphi$, $\delta\overline{GM}$, $\delta\overline{GZ}$) and compensate deviations due to the location of each block of system. As is seen in Figs 10–12 in accordance with scrubber project data (DFDS Seaways 2014) exact location of whole scrubber system (marked on the chart ✖) is within the range obtained by using the proposed algorithm. Received correspondence confirms the accuracy of the calculations and allows stating that the mentioned algorithm can be used to assess ship stability changes and predict the necessary changes to install scrubber on-board.

As is shown in Figs 10–13, the interval start point is the location of existing exhaust pipe and engine room due to the need to ensure open connection via stairway to scrubber from engine room through equipment room. For a given mass differences between 1st and 2nd block (from 46% to 41%), the impact of both blocks

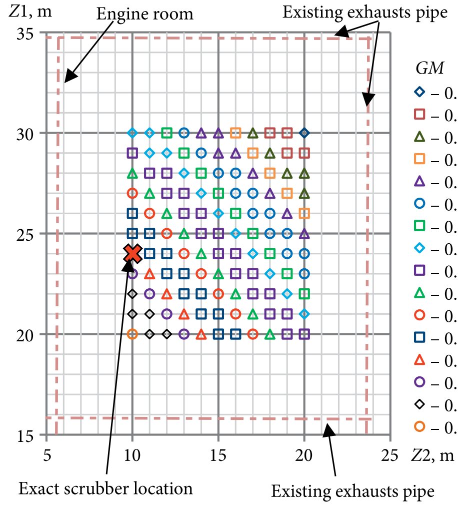


Fig. 12. The deviation of metacentric height depending on the displacement of block 1 and 2 on *Z* axis

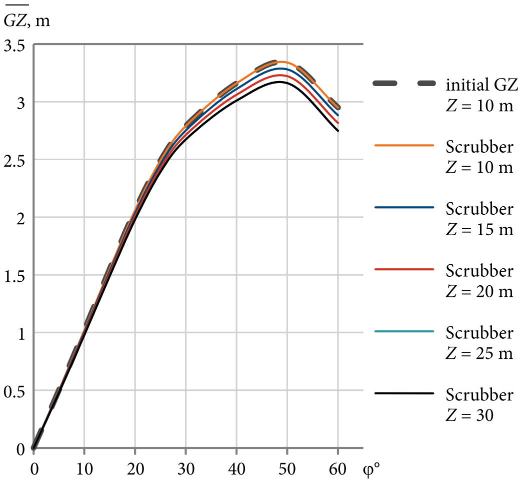


Fig. 13. The deviation of righting arm depending on the displacement of the whole scrubber system on *Y* and *Z* axis

on $\delta\theta$, $\delta\varphi$, $\delta\overline{GM}$, $\delta\overline{GZ}$ is comparable. Therefore, on Figs 10–12 is clearly seen distribution (~angle 45°) of values of mentioned criteria. In the case of other mass ratio between the blocks, charts (Figs 10–12) would have a slightly different view.

In turn of θ (Fig. 10), the intervals of 5×5 m (from 35 to 40 m) allows withstanding relatively similar deviations and adjusting the selection of system location depending on the available space on-board. In turn of φ (Fig. 11), the mentioned intervals is 2×3 m (~ from 0 to 3 m) if all block of system are located on the same side. If 1st and 2nd blocks are located on different sides, mentioned intervals expand to 4×5 m (~ from 0 to 10 m). However, this location of blocks balances only the total centre of gravity of the scrubber system. In turn, overturning moment is increased by the longer arm of 1st block. Therefore, this option is only relevant in the case of replacement of existing equipment on one of the blocks of scrubber system. In turn of $\overline{GM}$ (Fig. 12), the mentioned intervals is 4×4 m (~ from 10 to 15 m for 2nd block and from 20 to 25 for 1st block). However, the decrease of metacentric height directly affects the main parameter of stability $\overline{GZ}$ (Fig. 13) and in this case, the centre of gravity of whole scrubber system should not exceed 15 m on Z axis.

As in our case, the lightship weight changed to 2.63% and limiting factor is equal ≤2%. Regardless of whether or not the ship requires of reclassification, in any case the characteristics of ship should meet all limiting factors. This was achieved by changing of existing system or its loading capacity. Therefore, it was decided to abandon part of the ship's loading capacity in the area of system installation. To achieve the requirement, there were made some changes of ship deadweight. The maximum deadweight was reduced by 244 t (weight of scrubber system), due to the draught marks. This weight was reduced by eliminating one of the fuel tanks in place of new equipment room. The changed gravity centre was compensated by 120 t extra ballast in fore ship (125.5 m on X axis). Thus, the deadweight of ship was reduced by 370 t. An updated Trim and Stability Booklet is then going to have a departure condition with 4179 t of cargo (including crew, passengers and provision). The actual cargo loading can be higher than the 4179 t, if other dead-weights are reduced (FO, ballast, etc.). The investigation of 8 actual conditions received from the ship shows that in the worst case of these conditions, the cargo capacity will be reduced by up to 100 t.

Certainly, the algorithm of calculations is not final and there are some approximate values that are evident in settlements with limited information about the ship and its premises layout. However, fragments of the expected results cover all location decisions on X, Y, Z axis. Therefore, the algorithm allows setting the range of possible values by moving elements of the scrubber within acceptable interval. The exact location of each element of scrubber system should be refined by the expert opinion of the ship-owner. As only ship-owner can decide to redevelop the premises, reduce part of the cargo or provision, etc. In turn, mentioned range allows calculating the necessary changes in the cargo capacity of the ship, etc. then possible location is chosen by ship-owner. Thus, algorithm allows the ship-owner to plan possible changes and the expected costs associated with these changes at the pre-design phase then is possible to choose other way to comply this new MARPOL 73/78 requirements. It is very important that the mathematical modelling of the scrubber installation impact on ship allow without major design expenses choose the best solution for a particular ship.

Conclusions

1. The proposed algorithm is based on engineering method of assessment of SO_x scrubber installation impact on existing ship stability in the context of the ship safety requirements: deadweight, trim, heel, metacentre, etc.
2. The lack of common influencing factors makes it difficult to optimize the deployment of the scrubber system location coordinates. The standard formulation of function optimization through extremes calculation with specified restrictions cannot be fully used. Therefore, the proposed algorithm provides:
   - calculations of variation of ship stability parameters in accordance with technological feasibility of installation on board in the range of possible location of each element of scrubber system;
   - combined analysis of the results with experts (ship-owners) in order to minimize the negative impact of scrubber installation on ship stability.
3. The adaptation of the developed method on real results of scrubber installation project of DFDS confirms the adequacy of mentioned algorithm:
   - the achievement of optimum for all values $\delta\theta$, $\delta\varphi$, $\delta\overline{GM}$, $\delta\overline{GZ}$ are in most case an impossible task that is confirmed by the results (scrubber elements cannot be located right in optimal coordinate because of lack of space on-board);
   - however, in accordance with scrubber project data (DFDS 2014) exact location of whole scrubber system is within the range obtained by using the proposed algorithm;
   - the algorithm of assessment of scrubber impact on ship stability coincides with the DFDS project data;
   - in the analysis of the other ship can be difficult to establish the possibility of eliminating of the fuel tanks, etc.; however, the calculation will determine the mass and volume features that should be installed on board; the offered optimization model allows identifying the impact of scrubbers system on ship stability and selecting an optimal location of each element of system.

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