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Technological Perspective for Reducing Emissions from Marine Engines

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***Abstract*—Climate change and adverse impacts on the ocean environment have recently received much attention in the shipping and marine economic sectors. Preventing pollution of the marine environment from land sources through the river or atmospheric water is only possible by applying clean industrial technologies without waste and methods for rational use of natural resources. Main technical facilities to protect the sea environment from the current pollution are used to remove toxic substances from waste sources of ships. The International Maritime Organization increasingly tightens regulations on emissions with marine transport fleets, especially emissions of NOx and SOx. Therefore, many countries in the world continually improve and develop marine diesel engines in the direction of reducing emissions with different technologies. It is a tremendous necessary to enrich the technological knowledge to select new energy equipment in shipbuilding because they play a vital role in ensuring emission standards throughout the life of the ship. Indeed, technology development orientation in coastal countries' marine industry with the initial study results on the use of extraction optimization measures, alternative fuels, and output emission control solutions, it shows that we can implement some technologies to achieve NOx and SOx reduction according to IMO regulations. This paper summarizes the most important recent development technologies in the world in the field of marine engines. Also, the authors assessed the possibility of applying these new technologies to fleets of coastal countries to meet environmental requirements.**

***Keywords*—marine environment protection; marine engines; the technology of reducing emissions; SCR.**

I. INTRODUCTION

Inland waterway and sea transportation play an essential role in the operation of coastal countries' economy, where is endowed with large deltas, a long coastline, and marine resources. However, over the past 15 years, the economic conditions and environmental sustainability of these essential modes of transportation have been weakening due to insufficient investment to expand, improve and maintain the waterway transport network and critical locations such as river ports and seaports, although the country's economy has experienced rapid development. This reduces the efficiency of goods transport by waterway, less encourages shipping companies to invest in purchasing large vessels, less polluting the environment, and can increase logistics costs throughout the country[1]. Moreover, in specific markets where it is economically and operationally feasible to shift the mode of transport of goods from road to waterway, such conversion capacity has weakened.

Third world countries along the ocean are increasingly integrated into the global economy and are facing risks of climate change such as rising sea levels and unpredictable types of weather. More sustainable and efficient use of inland and maritime transport can be an economically effective, feasible way of doing so that helps both increase competitiveness, and effectively control the emissions of the pollutants and greenhouse gases. Emissions from marine diesel engines are considered a severe source of air pollution for the marine environment. Diesel engine exhaust has many toxic components, especially components such as SOx and NOx[2]. These toxic components directly affect human health and have many negative impacts on the living environment. To control environmental pollution emissions from diesel engine exhaust, the International Maritime Organization (IMO) has set out the mandatory standards in Annex VI MARPOL 73/78, amended in 2010 to regulate the standards of toxic substances in the engine exhaust, especially NOx and sulfur[3], [4].

Indeed, there are many methods and research methods to limit NOx and SOx emissions in diesel exhaust; each method has its strengths and limitations. Therefore, to choose the appropriate method, it is necessary to have thorough evaluation studies[5]. In the world, researches are being applied and tested on ships with high efficiency as an electronically controlled lubrication system was announced and commercialized by Man B&W in 2010 engine generations[6]. The amount of lubricant injected with high and controlled pressure can thus reduce the amount of lubricant, which will reduce PM and HC emissions[7]. In the early 1980s, major diesel engines studied the method of reducing NOx concentration by emulsion fuel; the results showed that for 2-stroke engines, NOx concentration drops to 10% when adding 10% water to the fuel[8]. Also, the method of reducing NOx concentration by using SCR catalysts on the exhaust line of diesel engines reduces 90-98% NOx in exhaust gas[9]. Measures to use exhaust gas reflux are also being studied and applied to large 2-stroke engines that can reduce NOx by 70% and combine with water injection tower and will reduce soot by 20-25%[10].

Coastal countries are considering to fully participate in Annex 6 - "Regulations on prevention of air pollution caused by ships" of the International Convention MARPOL 73/78. Besides, the set of indicators according to IMO standards for energy efficiency design (EEDI), which can be verified by calculating ship design parameters[11]. This set of indicators helps ship owners effectively compare designs of the same type of ship of different shipyards. Vietnam currently manages a large number of inland waterway vehicles using older generation diesel engines, so the control of emissions to ensure international regulations is becoming increasingly urgent.

In this paper, the author has carried out the research, analysis, and specific evaluation of several methods based on many different aspects to evaluate the applicability of marine diesel engines. Due to the limited scope of the topic, the authors only focused on analyzing and evaluating several solutions related directly to engine structure.

II. Materials and Methodology

A. Formation Mechanism of Emissions from Marine Diesel Engines

1) NOx emission: NOx compounds are generated by the combustion of air and fuel mixture in the diesel combustion chamber. In internal combustion engines, the large excess air coefficient, the amount of excess oxygen and nitrogen after the combustion reaction is still large. The vast majority of nitrogen that does not participate in the combustion is released from the engine cylinder by the exhaust, but a small amount of oxidized nitrogen forms various forms of nitrogen oxide and is collectively known as NOx. The content of NOx depends on the combustion temperature, the amount of nitrogen in the fuel, the amount of O_2 and N_2 of the excess air in the cylinder at the high temperature of the combustion stage. The higher the combustion chamber temperature, the stronger the activation of nitrogen and thus the greater the amount of NOx formed. Thus, all the factors that increase the combustion temperature in the engine cylinder increase the level of NO formation in exhaust gas[12].NOx in the engine combustion chamber is generated from two sources and is distinguished by thermal NOx and fuel NOx. During combustion, oxidation of nitrogen molecules produces heat and NOx molecules, while fuel NOx is formed by oxidation of nitrogen available in the fuel. However, the amount of fuel NOx is minimal because the nitrogen content in the fuel is insignificant. Unlike other types of emissions, NOx emissions are a side effect of combustion. Combining hydrogen carbon with oxygen creates power for the engine; Nitrogen in the air is only pulled into the combustion reaction [13]. The formation of nitrogen oxide is explained quite closely through the mechanism proposed by Zeldovich as follows[14]:

$$O + N_2 \leftrightarrow NO + N \quad (1)$$

$$N + O_2 \leftrightarrow NO + O \quad (2)$$

$$N + OH \leftrightarrow NO + N \quad (3)$$

$$NO + HO_2 \leftrightarrow NO_2 + HO \quad (4)$$

$$NO_2 + O \leftrightarrow NO + O_2 \quad (5)$$

$$NH + NO \leftrightarrow N_2O + H \quad (6)$$

$$NCO + NO \leftrightarrow N_2O + CO \quad (7)$$

$$N_2O + H \leftrightarrow NH + NO \quad (8)$$

$$N_2O + H \leftrightarrow N_2 + OH \quad (9)$$

In the combustion chamber of the diesel engine due to high pressure, the thickness of the flame film is negligible, almost all NO gas is formed behind the fire film. The NO reaction rate is much lower than the combustion reaction rate. Also, the NO content in the reaction area is less affected by oxygen concentration[15]. Experimental results have shown that at 20^o crankshaft angle after the top dead center of combustion, NO concentration is almost unchanged[16]. This means that all NO gas is generated at the visible fire stage with the highest pressure and maximum burning temperature. It also shows that the concentration of NO in exhaust gas depends greatly on the temperature of the combustion process[17].

Also, $NO_2$is formed from combustion in the engine cylinder; they are also formed by the oxidation of NO on the exhaust line of the engine when the exhaust flow rate is low and the presence of oxygen in the exhaust. The amount of NO_2 formed on the engine exhaust is about 5 ~ 10% of the total NO_2. There is also a significant amount of NO_2 formed when coming out of the chimney due to NO oxidation under environmental conditions[18]. As we know, the combustion process in the engine cylinder is the oxidation of chemical components in fuel, so in combustion products of diesel engines, the content of N_2O is shallow. According to statistics, the content of N_2O generated by internal combustion engines accounts for only about 7% of the total N_2O content in the environment[19].

2) SO_xemission: The SOx emissions from marine diesel engines are derived primarily from the amount of sulfur in the fuel, the content of which depends on the characteristics of the oilfield and the methods of distillation. Typically, the sulfur content in fuels used on ships ranges from less than 4.5%[20]. The process of forming SOx is complicated and depends on many factors such as temperature, pressure, composition, and amount of substance involved in the reaction. In the combustion chamber (of diesel engines, boilers, incinerators,...) under high temperature and pressure conditions, sulfur reacts with oxygen to form SOx according to the reactions[21].

$$S + O_2 \leftrightarrow SO_2 \quad (10)$$

$$2S + 3O_2 \leftrightarrow 2SO_3 \quad (11)$$

B. Regulations on Emissions from Marine Diesel Engines

Due to the serious effects of marine diesel engine emissions on the environment and human health, IMO has introduced the stringent regulations in Annex IV of MARPOL 73/78 to limit ship emissions. This annex consists of 19 chapters, detailing the prevention of air pollution caused by ships [5]. The purpose of Annex VI is to control emissions of ozone-depleting substances, NOx, SOx, volatile organic compounds and the burning of waste on ships[22]. Accordingly, all ships with a total tonnage of 400 or more, built on or after May 19, 2005, must be inspected and certified to meet the requirements of Appendix VI. For ships with a total tonnage of 400 or more, built before May 19, 2005, must be inspected and certified no later than the first on-board inspection after May 19, 2005, but not later 19/05/2008. For diesel engines of more than 130 KW, installed on or after January 1, 2000, NOx emissions measurement must be measured and an international certificate of air pollution prevention of engine (EIAPP) as required by the NOx Technical Code[23].

Due to the serious effects of SOx emissions on the environment and human health, IMO has introduced the stringent regulations in Annex IV MARPOL 73/78 to limit SOx emissions from ships. According to this regulation, from May 19, 2005, the fuel used on ships must have a sulfur content lower than 4.5%. Of the two special control areas for SOx emissions, these regulations are even stricter. These areas are called emission control zones (ECA) or SOx emission control areas (SECA). Since 2015, allowable SOx emissions in these areas should not exceed 0.1%[24].In October 2016, IMO decided to continue tightening regulations on SOx emissions, and from 2020 the 0.5% global limit will take effect. ECA emissions control regulations will not change at 0.1%. Coastal countries have not fully participated in Annex VI, MARPOL 73/78, so the compliance with the requirements of Annex VI will be conducted by the Port State Control of participating countries for vessels flying Vietnamese flags when landing at those countries' ports. Consequently, compliance with the requirements of Annex VI, MARPOL Convention 73/78 is one of the top priorities for Vietnam's fleet today.

There are many technological measures to control emissions of NOx and SOx. It can be divided into 3 categories: pre-treatment, internal treatment, and post-treatment. For the pre-treatment plan, it is expressed through alternative fuels or emulsion fuel, namely, alternative fuels such as methanol and LNG can be used. Although the alternative fuel alternative is considered to be the optimal solution, the pre-treatment solution requires time and huge costs. Furthermore, a national strategy for fuel and GHG emissions is needed.

C. Treatment solutions

Also, internal treatment solutions are considered to be less expensive and soon achieve the goal of reducing NOx and SOx emissions. One immediate solution proposed by the engine manufacturers is to equip filters and emissions treatment such as SCR and scrubber. Figure 1 shows possible technological solutions that can be applied to the emissions reduction strategy in the shipping industry.

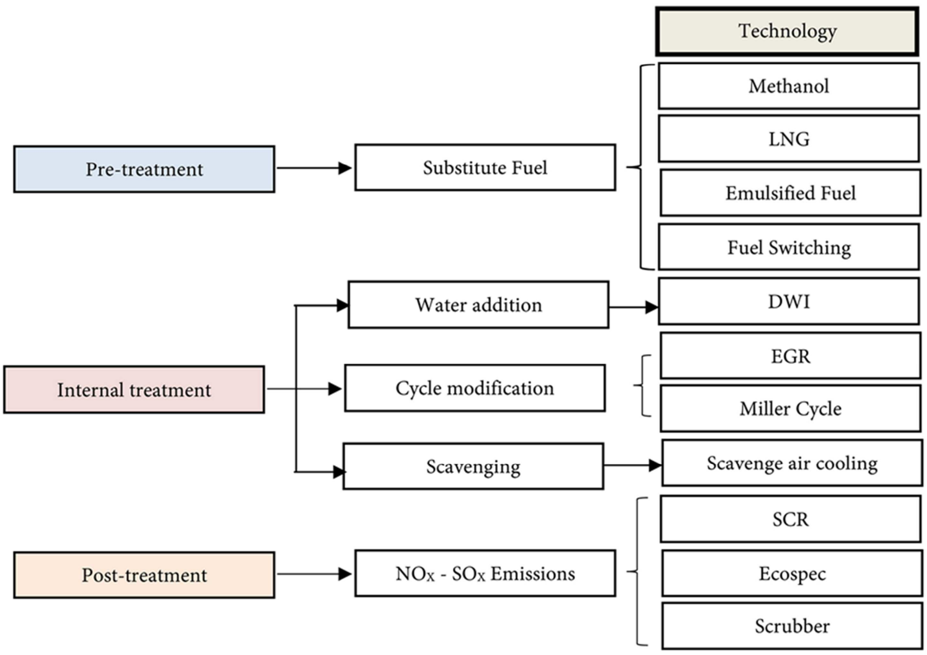

Fig. 1 Technological solutions for marine engines to reduce NOx and SOx emissions [25]

1) NOx treatment: The Variable Injection Timing (VIT) mechanism is usually fitted to MAN-B & W and SULZER engines. These engines are high-speed engines that use a port-controlled type of high-pressure pumps or helix-controlled type of high-pressure pumps to adjust the amount of fuel fed to the cycle according to the end of the cycle [22]. With the time of constant fuel injection, the high load mode will make the maximum combustion pressure in the cylinder significantly increase (can reach values of 15 ~ 17 Mpa) - this is the increases the level of NOx emissions, besides that it also increases the dynamic load acting on engine components [23]. That is the reason for equipping the VIT mechanism for these engines [24]. Figure 2 shows the structure diagram of a helix-controlled type of high-pressure pumps that have adjusted according to the end of injection in the MAN-B & W MC engines [26]. High-pressure pumps of this type have two and eight gear rods: the gear rack is linked to the plunger piston, the gear rack (plays the role of adjusting the timing of the fuel injection) associated with a cylinder of the high-pressure pump through gear wheel. When gear rack is moved, through gear wheel 6 will make cylinder move up and down so change position relative to piston plunger. Gear rack is controlled by the VIT mechanism described in Figure 2; the signal for VIT structure is taken from the governor. VIT of fuel injection timing control for SULZER RTA engine is described in Figure 3.

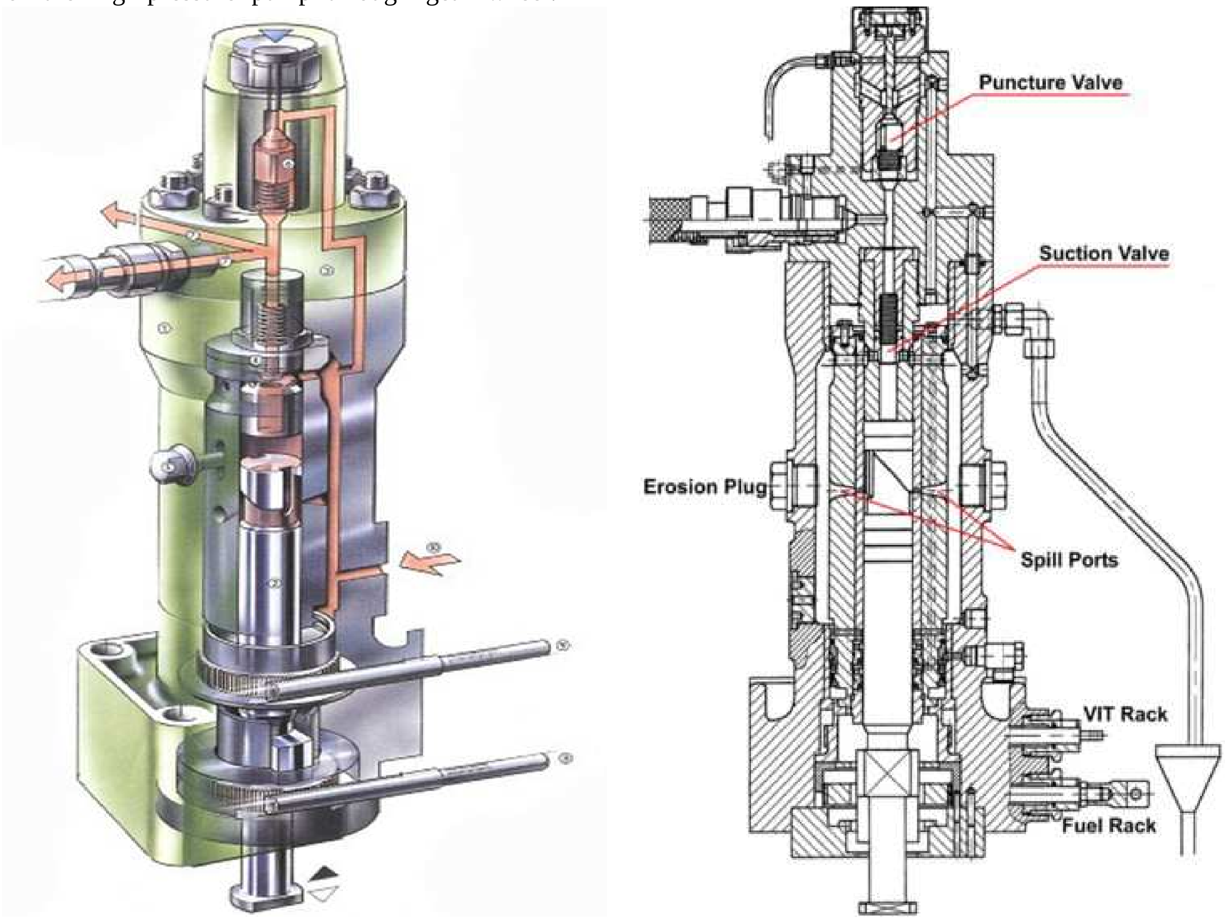

Fig. 2 The Variable Injection Timing (VIT) of MAN-B&W [26]

The high-pressure pumps used in the two cases are the type of adjustment of fuel supply by the end time by the VIT so that fuel injection time can be changed depending on the load mode of engines. For engines with common rail fuel system, or in some engines with high-pressure pumps driven by electro-hydraulic mechanism, fuel injection timing is flexibly controlled by load modes of engines according to the present program in the central control unit. The cylinder pressure during the combustion process is a necessary parameter to promote the VIT functions of marine engines. The maximum burning pressure in part-load mode is achieved quickly by the effects on the variable injection time [27]. This contributes to reduce fuel consumption and improve combustion efficiency when the engine is in partial load mode. Therefore, VIT technology has increased the maximum pressure during combustion by controlling the fuel injection time of the distribution pump [28].

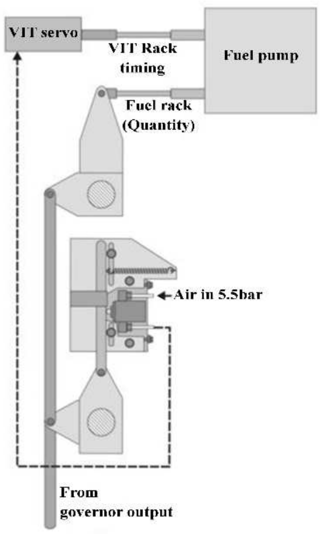

Fig. 3 The adjustment mechanism of fuel injection timing for high-pressure valve pumps of SULZER RTA-53 engines [29]

For engines not equipped with VIT devices, the timing of fuel injection is done manually. The timing of spraying is adjusted from the design specification in the technical file and cannot be changed during engine operation[30]. Depending on the structure of each type of high-pressure pump, one of the following methods may be applied: (1) - Changing the timing of fuel injection by changing the height of roller in the high-pressure pump. For removable high-pressure pumps, the fuel injection time can be delayed by reducing the height of the roller. This method is usually applied to engines using removable high-pressure pumps such as HANSHIN, AKASAKA; (2) Changing the injection time by rotating fuel cam. For engines using camshafts with removable fuel cams, the timing of fuel injection may be delayed by rotating the fuel cam in the opposite direction of the camshaft rotation at a certain angle as required. (3) Change the time of fuel injection by rotating the camshaft relative to the driven shaft. With high-pressure cluster pumps, the fuel injection time is delayed for all cylinders by separating the passive and active shafts, then relatively rotate the driven shaft of the high-pressure pump (passive shaft) in the opposite direction to the required rotation angle (Figure 4). This method applies to engines using cluster-type high-pressure pumps such as SKL, YANMAR. (5) - Changing the timing of fuel injection by changing the thickness of the rim between the cylinder of the high-pressure pump and the body of the high-pressure pump. In the case of high-pressure cluster pumps, it is also possible to adjust the timing of fuel injection for each pump by adjusting the thickness of the rim between the cylinder and body of the high-pressure cylinder. (6) - Changing the time of fuel injection by changing the thickness of the rim between the cover and body of the high-pressure pump. For high-pressure pumps installed for MAN-B & W engines, the timing of fuel injection into the engine cylinder can be adjusted late by increasing the thickness of the rim between the cover and body of the high-pressure pump (Figure 5). (7) - Changing the timing of fuel injection by changing the length of the suction in the thrust valve (for the port-controlled type of high-pressure pumps). In SULZER low-speed engines, fuel injection time can be delayed by rotating the fuel cam in the opposite direction of rotation or increasing the length of the throttle valve.

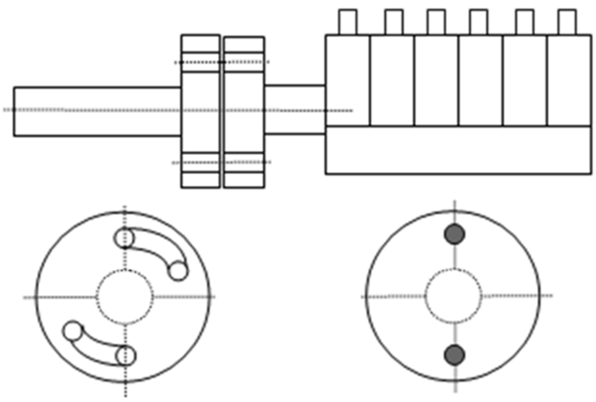

Fig. 4 Changing the timing of fuel injection by rotating the driven shaft of the high-pressure pump [31]

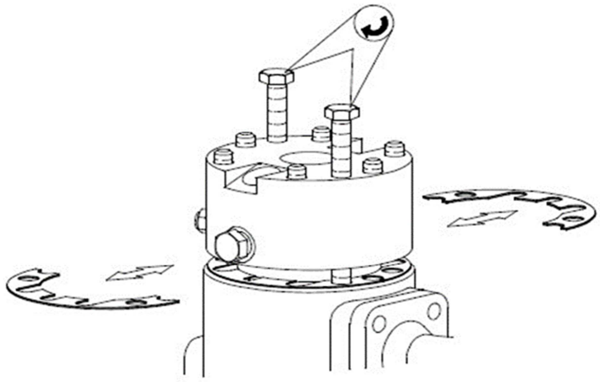

Fig. 5 Change of injection timing for MAN-B & W engines 32]

Exhaust gas recirculation (EGR) is a method to reduce the formation of NOx in marine diesel engines significantly. In the EGR system, after a cooling and cleaning process, part of the exhaust gas is recirculated to the scavenge air receiver[33]. In this way, part of the oxygen in the scavenge air is replaced by CO_2 from the combustion process. This replacement slightly increases the heat capacity of the scavenge air, thus reducing the temperature peak of the combustion and the formation of NOx. The NOx reduction is almost linear to the ratio of recirculated exhaust gas. The principle of EGR is illustrated in Figure 6.

The EGR system is arranged in two alternatives: the first is the bypass-based layout (Figure 7), the second is the T/C cut-out layout (Figure 8). The bypass layout can be applied to engines equipped with single or multi-stage turbochargers. Meanwhile, the use of T/C cut-out is selected for the multi-stage turbocharged engine. Engine manufacturers deploy ERG equipment on two-stroke marine diesel engines to improve engine stability when switching between working modes. The working mode depends on the EGR arrangement, layout of T/C cut-out or bypass.

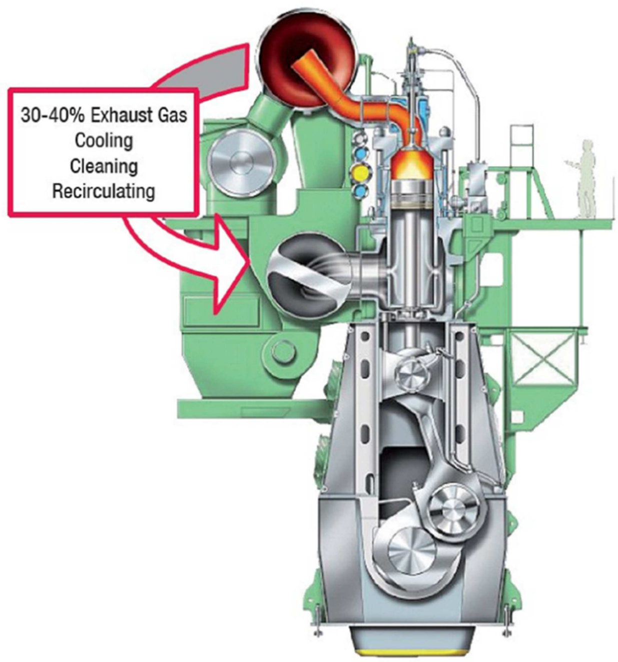

Fig. 6 Basic EGR principle[34]

When the EGR concentration changed from 0% (without using EGR) to the maximum concentration in this study was 40%, the average pressure and temperature in the combustion chamber changed significantly in the direction of concentration. EGR degree increases, pressure and temperature decrease. The main reason is that when using EGR, there will be some CO_2, H_2O and other gases in the exhaust gas returning to the combustion chamber occupying a part of the intake air volume, reducing the amount of oxygen loaded (dilution effect). The reduced amount of oxygen will slow down the combustion process of the engine, leading to an increase in delay time. As the starting point of the fire became more and more distant from the top dead center, the combustion was less intense, combined with the plunging of the plunger causing the volume to increase, resulting in both pressure and temperature decrease. Also, the presence of H_2O and CO_2, which have higher specific heat capacity than air, will absorb more heat, causing the temperature in the combustion chamber to decrease (thermal effect)[35].

The most crucial factor that contributes to the reduction of NOx of EGR is the reduction of the peak temperature of the flame because the theory has shown that NOx only forms actively when the temperature is above 2000K[36]. It is evident that when EGR concentration is increased, flame temperature decreases, NOx decreases significantly. Especially, with 40% of EGR drag reduced to 97% of NOx emissions, from $1.17x10^{-3}$g without EGR to $0.027x10^{-3}$g[37]. When using EGR on direct injection diesel engines in general and research engines, in particular, will help reduce NOx emissions, but increasing soot and in part will reduce engine power as well as increase fuel consumption. Proper use of EGR will result in good emissions efficiency and have less impact on power and fuel consumption[34].

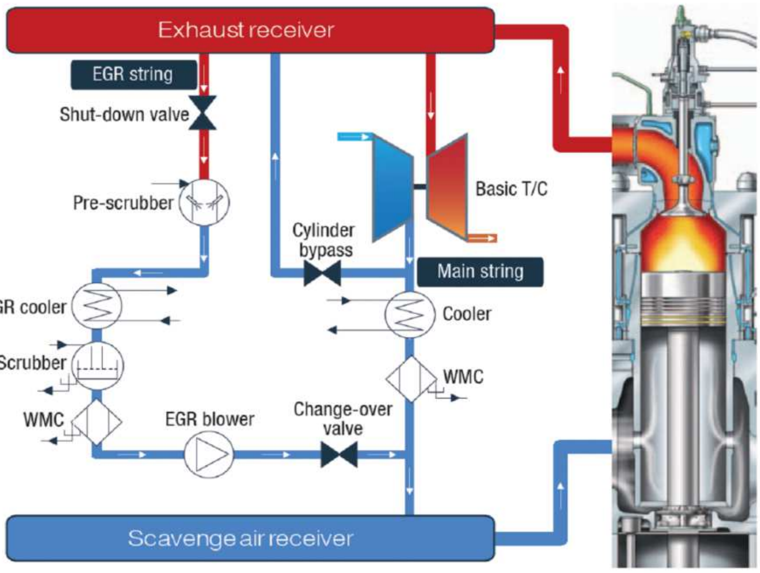

Fig. 7 EGR system with bypass layout [38]

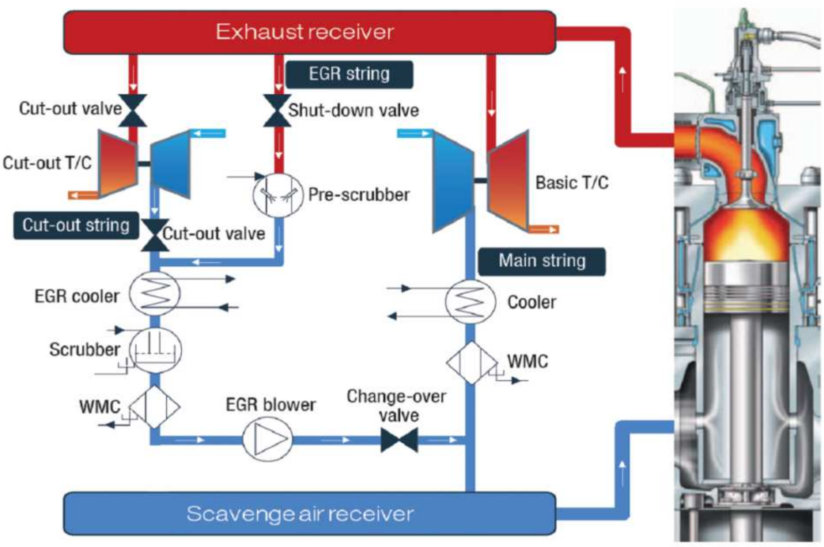

Fig. 8 EGR system with TC cut-out layout [39]

2) *SOx treatment:* To meet the IMO International standards for emissions of SOx, shipowners can choose from using low sulfur fuel or using SOx scrubber. Currently, shipowners possessing the large tonnage fleets being operated on international waters still tend to choose the utilization of the scrubber aiming to treat SOx thoroughly [40]. The wet scrubber (Figure 9) has a relatively simple structure, works effectively and has been widely used in industry and onboard for many years. A wet scrubber (Figure 10) includes a water supply system, which increases the contact between water and exhaust gas, along with the sediment filter function, water treatment equipment before discharging; sludge tank; handling quality control devices. The scrubber is often installed on a high of ships around chimneys to save space and increase handling capacity[41].

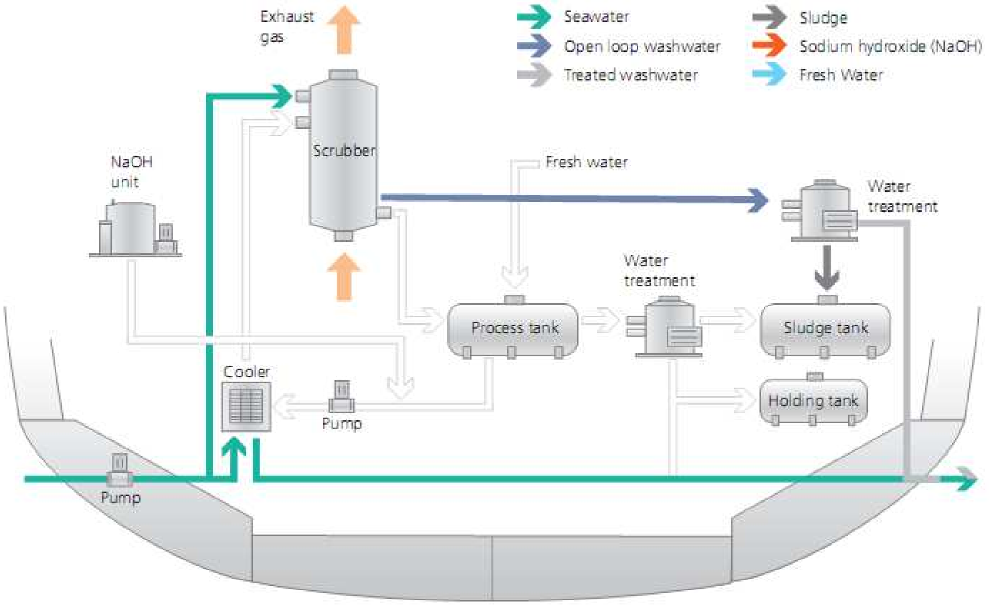

Fig. 9 Wet-type SOx absorber system, operating in an open-loop[40]

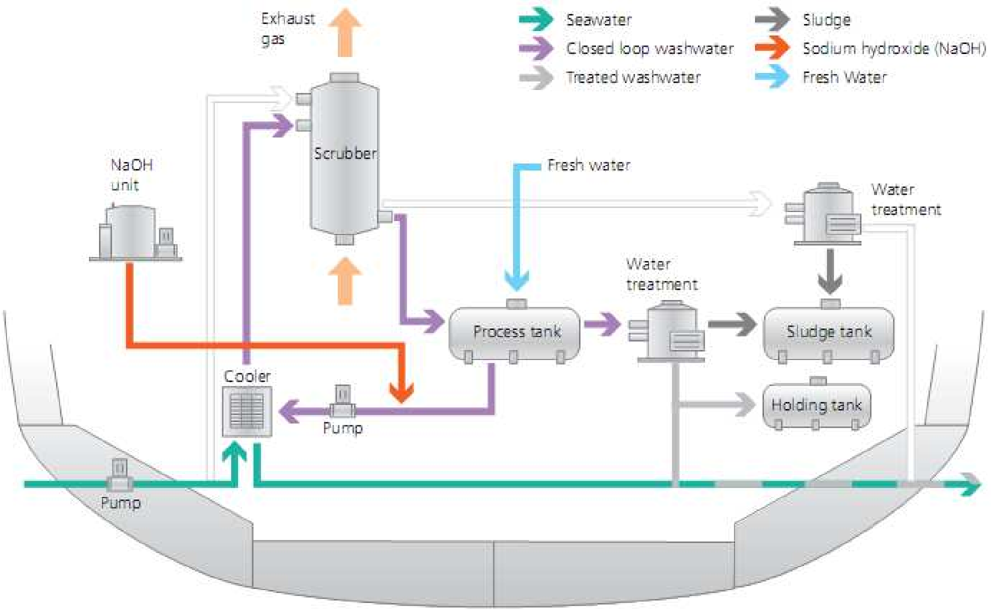

Fig. 10. Wet-type SOx absorber system, operating in a closed-loop[40]

The dry scrubber has been widely used since the 70s of the last century. In terms of structure, the scrubber consists of the filter element, also known as absorption, where the exhaust gas will come in direct contact with the slaked lime particles $Ca(OH)_2$. Unlike most wet scrubber, the exhaust is fed into the scrubber perpendicular to the direction from top to bottom of the substrate. In this method, there is no need to cool the exhaust gas before putting it into the scrubber so that the dry scrubber can be installed in advance of heat recovery equipment and exhaust gas recirculation (EGR). The slaked lime particles are fed to the engine by a compression system and then it is recovered at the holding tank. An automated control system is equipped to control the entire process of dispensing and collecting slaked lime particles, along with checking the system's SOx treatment quality[41]. Typically, the dry scrubber (Figure 11) operates in temperatures ranging from 240°C to 250°C. Limestone particles are sprayed into the scrubber with sizes from 2mm to 8mm, and quite dense concentration increases the likelihood of reaction between SOx and slaked lime. The final product in the scrubber after the primary reaction is gypsum ($CaSO_4.2H_2O$) and is stored onboard until docked to move to the next handling place[42].

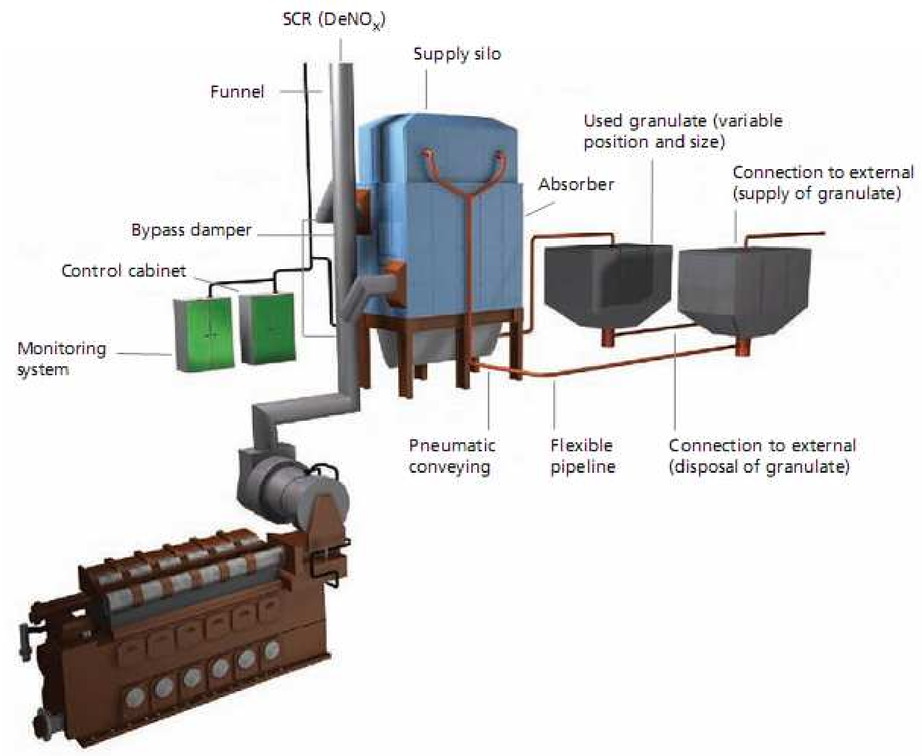

Fig.11. Dry SOx absorber system [41]

The scrubber types applied to treat SOx emissions are highly effective, whether it is wet, dry or combined. However, each type has its strengths and weaknesses when standing on different angles to compare, such as power consumption, occupancy rate, the cost for initial installation and operation[28]. Table 1 shows the results of the comparison between different types of scrubbers based on different criteria.

TABLE I
COMPARISON BETWEEN TYPES OF SCRUBBER[42]

Technology	**Wet scrubber, an open-loop system**	**Wet scrubber, closed-loop system**	**Wet scrubber, the combination system**	**Dry scrubber**
Major equipment	Scrubber; Piping systems; Water pump; Treatment equipment; Equipment for transfer sludge.	Scrubber; Piping systems; Water pump; Treatment tank; Water tank; NaOH storage tank; Treatment equipment; Equipment for transfer sludge.	Scrubber; Piping systems; Water pump; Treatment tank; Water tank; NaOH storage tank; Treatment equipment; Equipment for transfer sludge.	Absorption scrubber; Containers for clean lime water; Used lime water tanks; System of transporting lime water particles; Secondary lime water container.
Operation in freshwater	No	Yes	Yes	Yes
Do not discharge to sea	No	Yes, limited	Yes, limited	No
Weight calculated for engine 20MW	30-55T, Excluding water supply and treatment systems	30-55T, Excluding water supply and treatment systems	30-55T, Excluding water supply and treatment systems	200T, Includes fresh lime container.

Power consumption (% of diesel engine power)	1-2%	0,5-1%	0,5-2%, Depends on open-loop or closed-loop system	0,15-0,2%
Chemical consumption	No	NaOH 6l/MWh.%S	NaOH (closed-loop)6l/MWh.%S	Lime 10kg/MWh.%S
The ability to combine with Waste heat recovery systems	Yes, install after waste heat recovery equipment	Yes, install after waste heat recovery equipment	Yes, install after waste heat recovery equipment	Yes, install before or after waste heat recovery equipment
Ability to combine with catalyst NOx treatment (SCR)	No, unless drying equipment is installed behind the scrubber	No, unless drying equipment is installed behind the scrubber	No, unless drying equipment is installed behind the scrubber	Can be combined
Ability to combine with the exhaust gas recirculation system (EGR)	Yes	Yes	Yes	Yes
Handling solid particles	Yes	Yes	Yes	Yes

The comparison results in Table 1 show that open-loop and wet scrubber have the advantage in relation to the use of seawater to create SOx treatment medium. The open-loop power of consumption is similar to that of the closed-loop scrubber, combined scrubber, but it is higher than dry scrubber. This type does not need to use chemicals, it is difficult for the ship to moor in the port due to the limitation of discharge water after filtering and in the river ports which cannot work. Closed-loop scrubber applies freshwater as a treatment medium, must use chemicals, but requires a water treatment system after filtering and sludge tanks. The dry scrubber has the advantage of not discharging water into the environment, but the volume of equipment is too large and much waste. The combination scrubber (closed-loop and open-loop system) combines the advantages of closed-loop and open-loop and wet scrubber, has advantages over dry scrubber in terms of not much volume and not much waste. So, this is an excellent option to equip ships, to ensure regular operation of ships and ports, take advantage of the wet scrubber to use seawater directly when traveling at sea, and do not use chemicals. However, the price may be slightly higher than the remaining scrubbers[43].

III. Results and Discussions

A. Assessment of solutions to treat NOx emissions

The results of the theoretical analysis, as well as simulation studies, have shown that the level of NOx emission sharply decreases when delaying the time of fuel injection into the cylinder of engines. However, to evaluate the effectiveness of this option, it is necessary to consider the overall performance of the work, engine performance, emissions of other hazardous components as well as the ability to impact when changing the time of fuel injection in actual operation.

1) Considering the performance of the engine when the late time of spraying: When reducing the angle of early spraying, the starting point of burning in the cylinder will be later; the combustion will be moved towards the expansion line, reducing the speed of increasing the pressure dP/dφ, the engine will work “softer.” However, when the maximum burning pressure in the cylinder is reduced, the engine's output and torque are reduced. When the moment of spraying is too late (too close to the top dead center), almost all of the fuel supplied to the cycle is sprayed after the top dead center, the combustion will take place on the expansion line as the indicator's performance[44]. Engine reduction, engine power reduction and fuel consumption rate increased significantly[45]. According to the simulation results on the AVL 5402 engine, when reducing the early injection angle from 18^o crank angle to 4^o crank angle before the top dead center, in the mode of 60% load of engine power decreases 10.18%, fuel consumption rate increased by 10.21%; In 80% mode, engine power load decreases by 13.72%, fuel consumption increases by 15.79%[46].

2) Considering the emission of other toxic substances in the exhaust gas when being late to the time of fuel injection: When delaying the time of fuel injection, the amount of soot in the exhaust gas will change in the opposite direction: at the same loading mode, the later the time of fuel injection, the higher the amount of soot in the exhaust gas. Specifically, according to the simulation results on the AVL 5402 engine, when reducing the early injection angle from 18^o crank angle to 4^o, the amount of soot in the exhaust gas increased by 48% at 60% load mode and 286.2% at 80% load mode. Also, due to the late injection time, the starting point of the fire moving toward the expansion line also increases the CO content in the exhaust gas[12].

3) In terms of the ability to change the injection time with the engines being operated: For marine diesel engines equipped with a VIT mechanism, the injection time will be automatically adjusted to suit the engine's loading mode, and the delay effect of the fuel injection time only occurs in some modes. Engine's high load (90 ~ 100% load), these are the working modes with the highest NOx emissions. Meanwhile, in other loading modes, the injection time is reasonably adjusted, so it does not affect the engine's ability to generate power and economy. For engines not equipped with VIT devices, the adjustment of the timing of fuel injection is directly affected by hand and is almost unchanged when the engine is operating, regardless of the engine load mode. Delaying the timing of spraying in all engine modes is unreasonable, significantly affecting the performance of the engine in small load modes. Thus, the overall performance of the engine, emission level, and extraction requirements can be concluded that the engine's ability to reduce NOx emissions is based on the ability to delay injection time. Fuel is not an effective solution for every engine object. It is necessary to research and experiment with more effective solutions or use some other solutions for small diesel engines without VIT.

B. Assessment of solutions to treat SOx emissions

Before Annex VI, the MARPOL Convention 73/78 came into effect, the fuel used on ships was usually heavy fuel (HFO) and marine diesel fuel (MDO) contained relatively high sulfur content and can reach over 5% by weight. So SOx emissions from ships are huge when Annex VI comes into effect, but the solution to reduce SOx emissions is presented in this research. The most widely used method is to use distillate fuel with a sulfur content of less than 0.1%.This is a relatively simple solution. However, this type of fuel is costly and dramatically affects the operating costs of the ship and thereby increases the cost of transporting goods.

Using scrubber: Currently, to reduce operating costs, IMO agrees to allow heavy use of HFO fuel for ships and in combination with the air filtration tower application and ships allowed to operate in normal international waters (GMA-global maritime area). The scrubber has two types: wet and dry. The wet scrubber type is classified into a closed, open and combined system. For wet scrubber, seawater or freshwater is used as a solvent to wash emissions (SOx, solid sediments) in the exhaust gas before being discharged into the environment[47]. The wet scrubber is being used quite widely on ships today. The dry scrubber works according to the principle: Engine exhaust will pass through a series of clusters containing calcium hydroxide; When the exhaust gas passes through calcium hydroxide, it will absorb SOx and form gypsum. The plaster is stored onboard and will be brought ashore for processing. The dry scrubber will not produce sludge or sewage.

Using LNG liquefied natural gas fuel: replacing traditional fuel with liquefied petroleum gas will reduce greenhouse gas emissions by about 15% and 85% to 90% reduction in SOx, as well as NOx (in the case of low-pressure engines - gasoline engines)[26]. According to the forecast of the Norwegian Register (DNV), by the period from 2020 to 2025, the world will have about 1,000 vessels using LNG, thereby annually consuming from 5 to 7 million tons of LNG[48]. Moreover, LNG offers an important benefit over the current HFO in terms of the cost by about 31% per year[49].

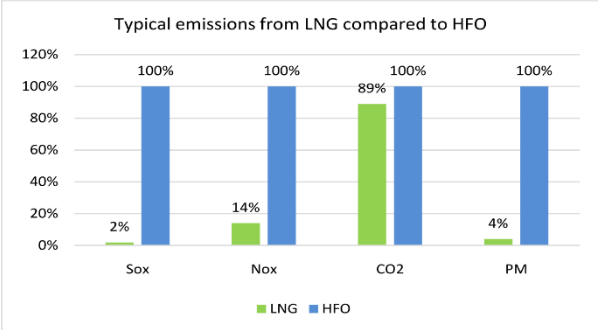

Fig. 12 Relative gas emissions for LNG and HFO [49]

The use of LNG fuel instead of HFO on Wärtsilä main engines has brought about significant benefits such as reduced annual costs of about 650 USD/kW (maintenance, lubrication, cleaning and SCR equipment)[49]. Despite these advantages, the LNG's challenge lies in its expensive installations on the one hand and is the higher sizes of its tanks which are 4 times greater than the marine diesel oil tanks[50]. While the use of methanol and LNG appears to increase over the next couple of years in ECAs, emulsified fuel, which was proposed by Professor B. Hopkin-son, consists in mixing two entirely immiscible liquids offering the advantage for better atomization and a better distribution of the fuel resulting in complete combustion. Emulsified fuel has the advantage of reducing NOx and PM emissions by an amount of 30% and 80%, respectively [51]. However, it also motives corrosion of engine components and the short common oil-water separation phenomenon[29]. Besides, emulsified fuel increases fuel consumption by 2% - 3% to achieve the same output, Figure 12. Moreover, the cost of installing the fuel system to use LNG is quite high, but in the long run, it will be offset by the lower price of LNG compared to HFO [52]. Table 2 shows a comparison between technological solutions to treat SOx emissions.

TABLE I

COMPARISON OF SOX TREATMENT SOLUTION [49]

Technology	Explain	Ability to reduce SOx	Initial investment rate [USD / kW]
Use low distillate fuel with low sulfur content	Distillate fuels with 0.5% S and even 0.1% S require use	Reduction from 80% to 90% SOx compared to HFO (2.7% S)	Fuel price increased from 1.8-2.1 times
Scrubber	Using HFO fuel combined with the scrubber installation. This method is recognized even when the vessel runs in special waters and even when fuel is required with 0.5% S at the common sea (GMA).	Reduction from 95% to 98% of SOx	- From VND 4-12 million for an operating ship; - From USD 200 - 400 / kW (main engine) for newly built ships.
LNG liquefied natural gas	Using LNG to replace traditional HFO fuel	Reduction from 95% to 100% SOx	- Costs increase from 10-15% for newly built ships; - From 800 - 3000 USD / kW (main engine) for currently operating ships.

With the three solutions to treat SOx emissions as mentioned above, it can be commented as follows: (1) Using low sulfur fuel will require the least investment and implementation is quite simple, but the cost of operating the ship is very high, which can be 2 times higher than the cost of using traditional fuel (HFO or MDO); (2) Using scrubber requires significant investment cost, but still can use traditional HFO fuel and crew's ship operating experience is not much affected; (3) Using LNG liquefied natural gas requires the highest investment, but in the long run because LNG is cheaper than HFO, it can compensate in the future.

IV. Conclusion

Diesel engines are the main driving force of ships, and they are also one of the primary sources of air pollution, especially NOx and SOx emissions, which are harmful to health and the environment. Therefore, the reduction of pollutant emissions including SOx and NOx components from marine diesel engines, is significant, being concerned all over the world. From the results of the study, analyzing the formation mechanism and the factors affecting the formation of SOx and NOx in the exhaust of marine diesel engines, we can see that: all factors affecting the mixture composition and the combustion temperature in the diesel combustion chamber both directly or indirectly affect the formation of NOx in exhaust gas. Since then, the reduction of NOx emissions in exhaust gas from marine diesel engines now has to address these two basic elements. There are many different solutions to reduce NOx emissions in the exhaust gas and can be grouped into two basic groups of solutions: impact on the combustion process in the combustion chamber and exhaust from engines before being discharged into the environment. In particular, solutions affecting the structure of engines belong to the first group of solutions.

To meet the SOx emissions standards, instead of using low sulfur fuels as recommended by the International Maritime Organization, Vietnamese vessels should be equipped with a wet scrubber and continue to use HFO fuel (2.7% S) to still be able to sail on international seas that need emissions control area (ECA) as approved in Annex VI. The solutions for energy equipment exploitation and the choice of ship types provide investors with more options, based on the harmonious view of economic benefits and environmental protection. NOx and SOx emissions reduction plans are part of an effort to make the shipping industry more environmentally friendly.

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