Carbon dioxide extraction from marine engine exhaust gases by the method of adsorption

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Abstract. The purpose of the article is to analyze a method of marine engine exhaust gases carbon dioxide purification by means of adsorption which proceeds in parallel with the process of steam condensation formed during the combustion of fuel in a diesel cylinder. The scheme of a facility of advance efficiency for marine engine exhaust gases purifying is given. This facility works with the use of granulated slag pumice as an adsorbent for exhaust gases harmful components and ozone as an oxidant in order to accelerate the purification process. A full-scale test was conducted in order to check the efficiency of the facility and evaluate its effectiveness in engine discharge gases purifying. A formula is received for a conduction of a calculation of the carbon dioxide purifying degree in the experimental facility which contains in the engine exhaust gases depending on a crankshaft rotation speed.

Keywords: Environmental Safety, Marine engine, Exhaust Gases, Carbon Dioxide, Extracting, Adsorption.

1. Introduction

The extension of the mandate of the International Maritime Organization (IMO) to protect the atmosphere in 1986, the development and entry into force of Annex 6 to the Convention MARPOL 73/78 in 2005 marked the beginning of a systematic work of all countries in order to improve the air environmental safety[1]. Maritime transport is responsible for approximately 2.5% of global greenhouse gas emissions and about 940 million tons of carbon dioxide CO₂ annually[2]. The International Maritime Organization has announced the Strategy to reduce greenhouse gas emissions from ships in order to contribute global efforts to reduce greenhouse gas emissions. The aim of the Strategy is to reduce CO₂ emissions from international maritime transport by at least 40% by 2030, and to reach 70% by 2050 compared to 2008. The Strategy has introduced the Energy Efficiency Design Index – EEDI as an indicator of the carbon intensity of the vessel [3,4]. The EEDI is an index that indicates the vessel energy efficiency. The EEDI is measured in grams of CO₂ (generated) per ton-mile (transported cargo) calculated for the specific initial operating conditions of the vessel.

The decrease of the EEDI is divided into three stages, which will come into force in 2015-2019, 2020-2024 and 2025. The reduction of the EEDI in comparison with the initial EEDI for these stages is 10%, 20% and 30 % [5]. The shipbuilding industry, ship owners and operators have already faced the requirements of the EEDI, and soon they will have to meet even higher standards of navigation.

Various solutions are available to the shipping industry to improve the energy efficiency of new vessels (in other words, to reduce the EEDI index). The easiest way to decrease emissions is to reduce the speed. This way does not require modifications or investments.
This study [6] shows that a decrease in the delivery speed cuts costs under certain conditions. This encourages to take such measures. The majority of companies and shipowners have been using speed reduction since 2008 in order to reduce carbon emissions and improve the efficiency of ships. This has led to a significant reduction in water transport CO$_2$ emissions[7].

This article estimates the opportunities to reduce the project energy efficiency index for ships through introduction of the carbon capture system from the exhaust gases of ship power plants. The method of CO$_2$ capturing is successfully used in land-based industries characterized by high CO$_2$ emissions, for instance, fossil fuel-fired power plants[8]. The advantage of this method is that there is no need to change the engine room layout, as the gas purification system is placed after the power plants.

2. Description of method and main assumptions

Our research demonstrates the method of exhaust gases purification in order to reduce carbon dioxide emissions. The purification process is based on using of CO$_2$ adsorption process by a solid substance. The CO$_2$ purification facility is developed [9]. The exhaust gases of a marine engine are subject to purification.

This facility works with the use of granulated slag pumice as an adsorbent for exhaust gases harmful components and ozone as an oxidant in order to accelerate the purification process. Due to the high reactivity of ozone, a significant part of nitrogen monoxides NO contained in exhaust gases is oxidized to NO$_2$ dioxides; sulfur dioxides SO$_2$ - to sulfur anhydride SO$_3$; carbon monoxide CO – to carbon dioxide CO$_2$. The exhaust gas flow gets on the surface of the granules and inside the granules. Than it is purified from harmful admixtures NO$_x$, SO$_x$, CO$_x$, which settle on the surface and inside the granules. Moreover, the fine particles such as soot settle on the surface and in the pores of the granules. Than the purified exhaust gases are emitted into the atmosphere.

If the activity of the granules decreases, they are subjected to regeneration. The process of regeneration is based on cleaning the surface and pores of granules from fine particles and absorbed molecules of harmful admixtures. The cleaning is done by washing the granules with water.

A pilot facility was made to study the possibility of implementation of the proposed method of CO$_2$ exhaust gases purifying. It is a single-section complex facility shown in figure 1 [10].

There is a tray and a chamber with a purifying section inside the facility. There are vertical zigzag-shaped containers with perforated side walls and bottom which form zigzag-shaped channels. The zigzag-shaped containers are filled with pumice granules.
3. Natural experiment and its results

The combustion injection engine is an experimental object for conducting a full-scale experiment. Engine volume is 2.7 L. Motor capacity is 105 kW. The engine is controlled using a standard microprocessor control system. The operation of engine is controlled according to the following main parameters: crankshaft rotation speed, fuel consumption, mass air consumption, parameters of the exhaust gas flow.

The portable gas analysis instrument testo 350 is used for the selection and analysis of the exhaust gases composition. According to the information provided in the certificate of gas analysis instrument, it does not require additional calibration with calibration gas. The processes of nulling and calibration are performed automatically within 30 seconds before starting operation. The device is approved by the German expert organization TÜV SÜD and meets the requirements of the European standard EN 50379.

The parameters of the exhaust gas flow were measured by a device (the Pitot tube, which is a part of gas analysis instrument testo 350) for determining the gas velocity in automatic mode. A probe diameter is 7 mm. A probe length is 350 mm.

The measurements of the gas flow parameters and sampling for analysis are carried out in the center of the sampling point. The results of the obtained experimental data are presented in Table 1.
Table 1. The results of an experiment of determining the efficiency of purifying the marine engine exhaust gases by the method of adsorption (entry-exit)

| Test number | 1     | 2     | 3     | 4     | 5     |
|-------------|-------|-------|-------|-------|-------|
| Crankshaft rotation speed, min⁻¹ | 2000  | 2500  | 3000  | 3500  | 4000  |
| Exhaust gas velocity in gas bypass, m s⁻¹ | 4.3   | 6.5   | 8.6   | 11.9  | 14.8  |
| Exhaust gas consumption, m³ h⁻¹ | 19.5  | 29.2  | 38.9  | 53.9  | 66.9  |
| Outside temperature, °C | 36    | 35.8  | 36.1  | 36.2  | 35.6  |
| Exhast gas temperature, °C | 102/  | 127.2/| 156/  | 189.3/| 223.7/|
| NO concentration in exhaust gases, ppm | 81    | 172   | 330   | 749   | 1527  |
| NO₂ concentration in exhaust gases, ppm | 0.3/  | 0.2/  | 0.2/  | 1.1/  | 4.1/  |
| NO₅ concentration in exhaust gases, ppm | 23.8  | 15.2  | 8     | 4.7   | 7.7   |
| SO₂ concentration in exhaust gases, ppm | 167.3/| 248.2/| 430.2/| 808.1/| 1635/ |
| O₂ content in exhaust gases, % | 2.17  | 1.66  | 1.5   | 1.39  | 1.48  |
| CO concentration in exhaust gases, ppm | 5876/ | 3475/ | 3497/ | 4186/ | 6528/ |
| CO₂ content in exhaust gases, % | 4164  | 3377  | 3225  | 4004  | 6292  |
| Degree of CO₂ purification in the facility, % | 10.88/| 11.67/| 12.12/| 12.39/| 12.47/|
|                     | 7.74  | 8.09  | 8.31  | 8.46  | 8.50  |
|                     | 28.9  | 30.7  | 31.4  | 31.7  | 31.8  |

Figure 2 shows the functional connectivity of the carbon dioxide CO₂ content in the engine exhaust gases at the entry and exit of the experimental facility depending on the engine crankshaft rotation speed. The analysis of figure 2 allows us to conclude the following: the minimum carbon dioxide content in the engine exhaust gases will be 10.88%, at the entry of the experimental cleaning facility, if the
Engine crankshaft rotation speed is 2000 rpm. The maximum carbon dioxide content in the engine exhaust gases will be 12.47 %, if the engine crankshaft rotation speed is 4000 min.

The approximate formula for calculating the carbon dioxide content in the engine exhaust gases depending on a crankshaft rotation speed would be as follows:

\[ y = 1.0 \cdot 10^{10} \cdot x^3 + 1.0 \cdot 10^6 \cdot x^2 + 0.0061 \cdot x + 3.235; \quad R^2 = 0.999, \]

where \( x \) – crankshaft rotation speed, min.; \( y \) – the carbon dioxide content of the gases at the engine exit, %; \( R^2 \) – R-squared value.

The degree of CO\(_2\) purification of exhaust gases is determined by the method of adsorption in the experimental facility.

The degree of purification is based on a formula:

\[
 e = 100 \left( \frac{y_f - y_i}{y_f} \right), \%
\]

where \( y_i \) – initial CO\(_2\) content in exhaust gases, %; \( y_f \) – final CO\(_2\) content in exhaust gases, %.

Figure 2. The dependences of the carbon dioxide content in the exhaust gases at the entry and exit of the experimental installation from the engine crankshaft rotation speed.

The analysis of the graphical dependences presented in figure 3 allows us to conclude that the minimum degree of carbon dioxide purification of exhaust gases will be 28.9 % if the crankshaft rotation speed is 2000 min. The maximum degree of carbon dioxide purification of exhaust gases will be 31.8% if crankshaft rotation speed of the engine is 4000 min.

The approximate formula for calculating the degree of carbon dioxide purification of exhaust gases depending on the crankshaft rotation speed would be as follows:

\[ y = 6.0 \cdot 10^{10} \cdot x^3 - 6.0 \cdot 10^6 \cdot x^2 + 0.0236 \cdot x + 2.9214; \quad R^2 = 0.9994, \]

where \( x \) – a crankshaft rotation speed, min.; \( y \) – the degree of carbon dioxide purification of engine exhaust gases in an experimental facility, %; \( R^2 \) – R-squared value.
4. Conclusion

This study offers the granular slag pumice of metallurgical production as an adsorbent of harmful components of fuel combustion product. A high basicity factor M > 1 promotes the process of harmful substances sorbing (carbon, nitrogen and sulfur oxides) on the surface of the slag granules. The harmful substances are present in gas flow. The study offers to perform preliminary oxidation of carbon, nitrogen and sulfur oxides to $\text{CO}_2$, $\text{NO}_2$ and $\text{SO}_3$ with an active oxidizer - ozone for the purpose of increasing the speed of adsorption process and reducing the volume of granular slag.

This research has developed the construction of the pilot facility and its operating principle. The pilot facility provides an opportunity to implement the exhaust gases purification of power equipment plant by means of carbon oxides adsorption.

As a result of the conducted experiments it is established that the minimum degree of carbon dioxide purification of exhaust gases will be 28.9 % if a crankshaft rotation speed of the engine is 2000 min$^{-1}$. The maximum degree of carbon dioxide purification of exhaust gases will be 31.8% if a crankshaft rotation speed of the engine is 4000 min$^{-1}$.

The carbon dioxide contains in the researched engine exhaust gases. The approximate formula for calculating the carbon dioxide purifying degree $y$, % in the experimental facility depending on a crankshaft rotation speed $x$, min$^{-1}$ would be as follows: $y = 6.0 \cdot 10^{-10}x^3 - 6.0 \cdot 10^{-6}x^2 + 0.0236x + 2.9214$.

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