ХОЛОДИЛЬНА ТЕХНІКА ТА ЕНЕРГОТЕХНОЛОГІЇ

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The recirculate exhaust gases cooling method of the marine low-speed engine by the aerothermopressor

***D. V. Konovalov*[1]*, M. I. Radchenko*[2]*, V. I. Maksymov*[3]**
[1, 3] Admiral Makarov National University of Shipbuilding (Kherson branch), Ushakov Avenue, 44, Kherson, Ukraine
e-mail: dimitriyko79@gmail.com
[2] Admiral Makarov National University of Shipbuilding, Heroes of Ukraine Avenue, 9, Mykolaiv, Ukraine
e-mail: nirad50@gmail.com
ORCID ID: [1] 0000-0001-7127-0487, [2] 0000-0001-6301-5857, [3] 0000-0001-6301-5857

There are many ways and methods to reduce exhaust gases emissions on modern ships. One of the most effective ways to reduce NOx and SOx emissions is to use of exhaust gas recirculation (EGR technology). The EGR system disadvantage is an increase in back pressure through additional pressure losses in the scrubber and heat exchanger, which entails an engine fuel efficiency deterioration. Creating a reliable and efficient heat exchanger for cooling recirculation gases is a complex task due to deposits and pollution emitted by these gases. In the present work, the jet apparatus effectiveness named aerothermopressor is analyzed in the scheme with exhaust gases recirculation of the ship low-speed two-stroke engine. Aerothermopressor is a two-phase jet for contact disperse cooling, in which by increasing the heat from the gas stream the gas pressure and cooling are increased. The calculation of the characteristics of the engine was carried out, both in nominal, and in operating modes and in all possible range of partial loads. The installation of the aerothermopressor before the scrubber is proposed, which allows reducing engine thermal load. Increasing the pressure in the aerothermopressor by 0.2-0.4 · 10^5 Pa (6-12%) allows reducing the back pressure in the gas exhaust system and thus reducing the load on the exhaust gas recirculation fan and when the engine load is higher than 75% in the cold zone, the fan is not needed, which additionally allows to reduce the specific fuel consumption. The parameters of the exhaust gases that are going to be recirculated and the processes of their gas-dynamic cooling in the aerothermopressor are based on the developed technique and program using the thermodynamic and gas dynamics equations. The proposed scheme-design solution allows at a high environmental friendliness of the existing exhaust gas recirculation system to provide a certain reduction in specific fuel consumption. It was determined that the engine specific fuel consumption has been decreasing when the aerothermopressor is used to Δg_e *= 2.5-3.0 g/(kW·h) (1.5-1.7%).*

Keywords: *Aerothermopressor, Thermogasdynamic Compression, Recirculation, Exhaust Gases, Specific Fuel Consumption, Internal-Combustion Engine*

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1. Introduction

Modern technologies of ecologization of heat engines are in conflict with their energy efficiency, because measures to reduce emissions require additional external costs (both energy and resource costs). For example, features of the formation of such deleterious gases as nitrogen oxides NOx require reducing the maximum temperature of combustion of the fuel, which entails to reduce the energy efficiency of the internal combustion engine (ICE).

Considering this, the creation of such environmental and energy efficient technologies that would ensure a reduction in emissions into the environment and at the same time level the negative impact on the fuel and energy efficiency of the internal combustion engine is very important.

Today a promising direction is to use of thermal spraying jet technologies [1, 2], which are based on the use of a process of thermogasdynamic compression, which, in turn, will provide cooling and simultaneous increase in gas flow pressure in scheme-design solutions to neutralize harmful substances in the engine exhaust gases.

2. Literature Review

Leading engine-building firms in the world, such as MAN Diesel, Wartsila, Caterpilar, and others, are conducting ongoing research to identify the environmental impact of harmful toxic substances found in exhaust gases of marine engines, as well as looking for effective ways to reduce these emissions. Fundamental practical research was presented in [3-8].

The main harmful components in exhaust gases are carbon dioxide CO_2, nitrogen oxides NOx and sulfur oxides SOx.

Nitrogen oxides are formed in areas with high temperature, which take place in the phases of kinetic and diffuse combustion. The highest temperature occurs in local zones during kinetic combustion, when the probability of occurrence of such zones is highest. Therefore when the temperature of the combustion process is higher, as a rule, the nitrogen oxides are more [9-12].

International requirements for emissions of nitrogen oxides NOx, sulfur oxides SOx and particulate matter are determined by the MARPOL Convention (Annex VI – "Regulation on the Prevention of Air Pollution from Ships") [13]. According to the rules, NOx emissions from any diesel engine installed on a ship built after January 1, 2016, must be equal to the Tier III level when operating in the NOx control zone.

There are many ways and methods to reduce exhaust gases emissions on modern ships. These methods differ in the effectiveness of the removal of certain components. As a comparative analysis shows, the most effective way to reduce NOx and SOx oxides is using exhaust gas recirculation (EGR technology): reducing NOx emissions by 70%, reducing SOx by 19%, but increasing CO_2 emissions by 2-3% [14].

For ship two-stroke diesel engines two basic schemes is used for EGR technology [13, 15]:

1) bypass recirculation system with one mounted turbocharger (used for engines with cylinder diameter up to 700 mm);

2) recirculation system with two or more co-compressors (used for engines with a cylinder diameter of more than 700 mm).

One of the drawbacks of the EGR system is the increase in back pressure through additional pressure losses in the scrubber and heat exchanger, and this, in turn, contributes to the deterioration of the engine fuel efficiency.

It should be noted that in the EGR system there is another very important element – the heat exchanger gas cooler. Creating a reliable and efficient heat exchanger for cooling recirculate gases is a complex task due to the deposition and pollution released by these gases [16-18].

The promising heat exchangers-coolers that could be used in the exhaust gas recirculation system should include contact heat exchangers of the jet (gas-dynamic) type - thermopressors (or aerothermopressors) [2, 19, 20]. The advantages of such heat exchangers are compactness and simplicity of design, moreover, they provide, in addition to cooling, some increase in pressure [21-23], which can reduce the effect of back pressure in the recirculation system and reduce the cost of additional compression of the recirculation gases in the fan (or electric compressor).

The aerothermopressor is a two-phase jet apparatus for contact disperse cooling, in which, by removing heat from the air flow, the air pressure and air cooling are increased. With proper organization of the processes of evaporative contact dynamic cooling, the effect of thermogasdynamic compression (thermopression) is occurred - a phenomenon in which there is gas pressure increased in the process of instantaneous evaporation of water injected into the gas (air) flow and accelerated to a speed close to sound. At the same time, the heat from the gas (air) is removed to the water evaporation and gas temperature is decreased.

The purpose of the study is to analyze the effectiveness of the exhaust recirculation gases cooling method by the aerothermopressor for the ship low-speed diesel engine.

3. Research Methodology

The effectiveness of the proposed solution was analyzed and the comparison was carried out on the basis of the basic scheme with recirculation of exhaust gases, shown in fig. 1. These schemes are used to reduce harmful emissions of gases (CO_2, NOx, SOx) for low-speed engines of the company MAN (according to the terms of Tier III). The exhaust gases part bypassing is applied, followed by cooling and simultaneous condensation (purification) of ecological non-furnace gases in the scrubber. Then aftercooling is done in the heat exchanger-gas cooler to a temperature equal to the air temperature in the receiver. The system includes a scrubber, a cooler, a water mist separator, a fan, and a support system for the NaOH solution with a pump and tank. Water supply to the previous spray in the scrubber in front of the chiller is a part of the water treatment system.

The bypass recirculation system (fig. 1) works as follows: exhaust gases in the amount of up to 30-40% through the valve from the receiver of the exhaust gases are entered to the scrubber, where they are partially cooled and cleaned by water sprayed with special nozzles. Then the gases are cooled in the heat exchangers - gas coolers, the condensate is discharged into the condensate tank, and the purified and cooled gas is entered to a fan or an electric compressor in the air receiver, where it mixes with fresh air [13].

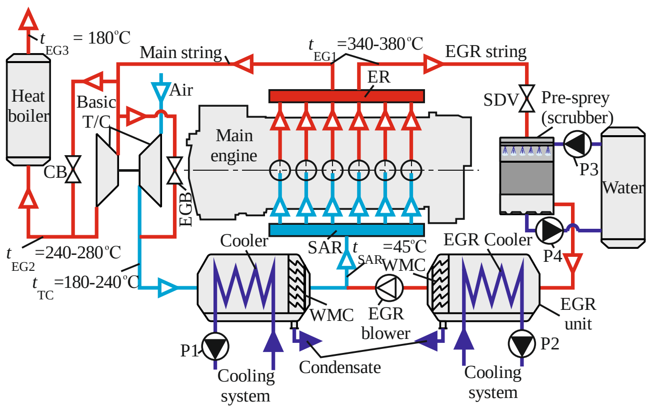

***Figure 1** – Scheme of EGR-technology with bypass matching for the MAN marine diesel engine: P1, P2, P3, P4 – Circulation Pump; T/C – Turbocharger; EGB – Exhaust Gas Bypass Valve; CB – Cylinder Bypass Valve; ER – Exhaust Receiver; SAR - Scavenge Air Receiver; SDV – EGR Shut-down Valve; WMC - Water Mist Catcher*

The ship low-speed diesel two-stroke engine MAN B & W brand 6G70ME-C9.5 and scheme solutions for it are considered. For analysis, the CEAS software package was used by MAN at [24]. The calculation was made for the following initial data: rated power and engine speed N_n = 21840 kW, n_n = 83 min^{-1}; specific fuel consumption (LVC = 42700 kJ/kg) g_n = 172 g/(kWh) under ISO conditions; turbocharger ABB280L; EGR circuit – bypass with scrubber and gas cooler; operational characteristics: engine load 90%; power N_e = 19656 kW; rotational speed n_e = 80.1 min^{-1}; specific fuel consumption g_e = 169.8 g/(kWh).

The engine characteristics calculation was carried out both at the nominal and at the operating (90% of the engine load) modes and over the entire possible range of partial loads (30-100%), as well as for the following conditions:

1) ISO: air temperature at the turbocharge inlet t_{air1} = 25 °C, cooling water temperature in the charge air cooler t_{w1} = 25 °C, relative air humidity φ_{air1} = 30%;

2) tropical zone: t_{air1} = 45 °C, t_{w1} = 36 °C, φ_{air1} = 60%;

3) cold zone: t_{air1} = 10 °C, t_{w1} = 10 °C, φ_{air1} = 60%.

The exhaust gases parameters and their gasdynamic cooling processes in the aerothermopressor were calculated according to the developed methodology and program using the equations of flow thermodynamics and gasdynamics [21, 23, 25-27].

4. Results

From the point of view of ensuring effective cooling of the exhaust gases in the recirculation system, it is possible to propose a scheme solution with the aerothermopressor installation in front of the scrubber (fig. 2). In this case, the aerothermopressor will provide some increase in gas pressure, which will reduce the backpressure of the engine gas path and, accordingly, will reduce the load on the additional fan (or electro-compressor). Moreover, this apparatus will provide cooling of the exhaust gases to a temperature slightly above the dew point (based on the conditions of danger of low temperature sulphuricacid corrosion). Such a solution will also reduce the heat load on the scrubber and surface gas cooler.

The water injection should be carried out with the amount of water above that necessary for evaporation (at least 10%). Such a solution is necessary to ensure a greater effect of pressure increase as a result of thermogasdynamic compression (by reducing friction losses) and to ensure the conditions for adding water to the scrubber. This will allow reducing the load on the water consumption for injection in the scrubber, as well as partially or fully compensates for pressure loss.

The aerothermopressor using in front of the scrubber of the exhaust gas recirculation system allows increasing the exhaust gases pressure, bypassing the engine through the turbocharger, by 0.2-0.4·10^5 Pa (6-12%) (fig. 3).

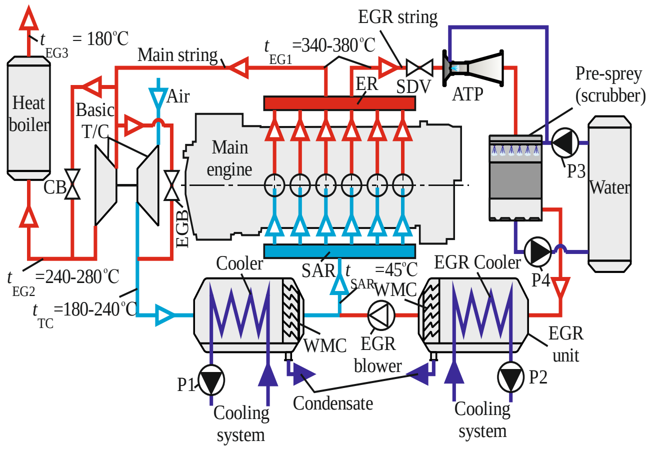

Figure 2 *– Scheme of EGR-technology with bypass matching and aerothermopressor for the marine diesel engine: P1, P2, P3, P4 – Circulation Pump; T/C – Turbocharger; EGB – Exhaust Gas Bypass Valve; CB – Cylinder Bypass Valve; ER – Exhaust Receiver; SAR - Scavenge Air Receiver; SDV – EGR Shut-down Valve; WMC - Water Mist Catcher; ATP - aerothermopressor*

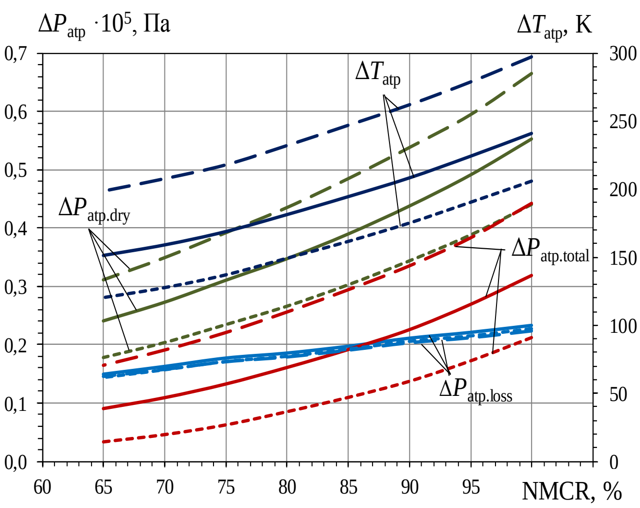

Figure 3 *– Dependences of pressure increase in ATP without friction $\Delta P_{atp.dry}$, pressure increase in ATP taking into account friction $\Delta P_{atp.total}$, friction losses $\Delta P_{atp.loss}$, gas temperature decrease during cooling in ATP ΔT_{atp} from the load on the engine NMCR:*

________ - ISO (t_{air1} = 25 °C; t_{w1} = 25 °C);

__ __ __ - tropical zone (t_{air1} = 45 °C; t_{w1} = 36 °C);

_ _ _ _ _ - cold zone (t_{air1} = 10 °C; t_{w1} = 10 °C)

At the same time, the temperature decrease as a result of the thermogasdynamic compression effect is ΔT_{atp} = 150-300 K (relative temperature is T_{atp1}/T_{atp2} = 1.3-1.7, fig. 4). The amount of water required for evaporation in the aerothermopressor is G_w = 0.35-0.50 kg/s ($g_{w.atp}$ = 0.05-0.08 or 5-8% of the flue gas flow rate, fig. 5), while the coefficient recirculation was K_p = 0.12-0.20 (12-20%) with the consumption of the scrubber $g_{w.egr}$ = 0.02-0.04 (2-4%) (fig. 6).

The pressure increase in the aerothermopressor reduces the backpressure in the gas exhaust system, and thus reduces the load on the exhaust gas recirculation fan. So the fan power is decreased from N_{bl} = 120-160 kW to $N_{bl.atp}$ = 20-110 kW (fig. 7), and in the cold zone with a load on the engine above 75% of the fan's use is not needed at all, since the gas pressure after the aerothermopressor is enough ensure their discharge to the air receiver without additional compensation.

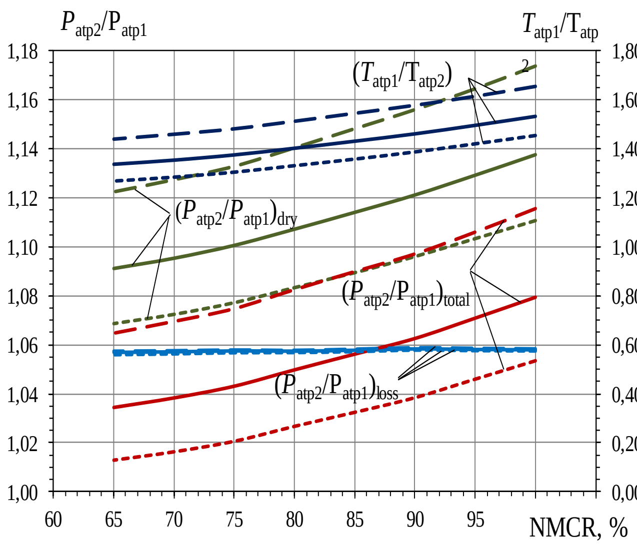

Figure 4 *– Dependences of relative pressure increase in ATP without friction $(P_{atp2}/P_{atp1})_{dry}$, relative pressure increase in ATP taking into account friction $(P_{atp2}/P_{atp1})_{total}$, relative friction losses $(P_{atp2}/P_{atp1})_{loss}$, relative decrease of gas temperature during cooling in ATP (T_{atp1}/T_{atp2}) from the load on the engine NMCR:*

________ - ISO (t_{air1} = 25 °C; t_{w1} = 25 °C);

__ __ __ - tropical zone (t_{air1} = 45 °C; t_{w1} = 36 °C);

_ _ _ _ _ - cold zone (t_{air1} = 10 °C; t_{w1} = 10 °C)

Reducing the load on the recirculation fan, as well as reducing the backpressure in the system, reduces the specific fuel consumption of the engine with $g_{e.egr}$ = 166.5-174.0 g/(kWh) to $g_{e.atp}$ = 164.0-171.0 g/(kWh), i.e. Δg_e = 2.5-3.0 g/(kWh) (1.5-

1.7 %) with total specific fuel consumption without exhaust gas recirculation g_e = 158.0-170.0 g/(kWh) (fig. 7).

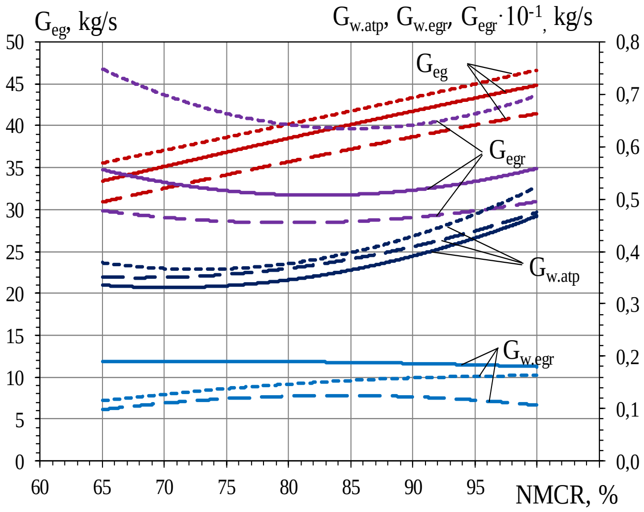

Figure 5 *– Dependences of exhaust gas flow rate change G_{eg}, recirculated gas consumption G_{egr}, water consumption for injection in ATP $G_{w.atp}$, water consumption for injection in the scrubber $G_{w.egr}$ from the load on the engine NMCR:*

_______ - ISO (t_{air1} = 25 ^oC; t_{w1} = 25 ^oC);

__ __ __ - tropical zone (t_{air1} = 45 ^oC; t_{w1} = 36 ^oC);

_ _ _ _ _ - cold zone (t_{air1} = 10 ^oC; t_{w1} = 10 ^oC)

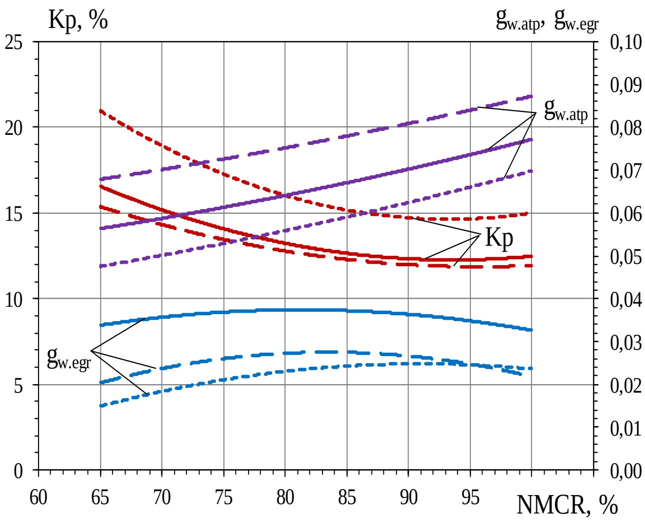

Figure 6 *– Dependences of recirculation coefficient change K_p, relative consumption of water for injection in the ATP $g_{w.atp}$ and in the scrubber $g_{w.egr}$ from the load on the engine NMCR:*

_______ - ISO (t_{air1} = 25 ^oC; t_{w1} = 25 ^oC);

__ __ __ - tropical zone (t_{air1} = 45 ^oC; t_{w1} = 36 ^oC);

_ _ _ _ _ - cold zone (t_{air1} = 10 ^oC; t_{w1} = 10 ^oC)

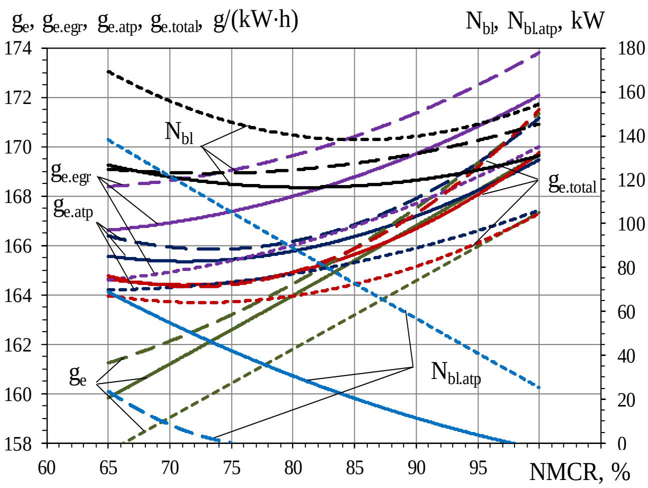

Figure 7 *– Dependences of specific fuel consumption change for an engine without recirculation g_e, specific fuel consumption for an engine with recirculation $g_{e.egr}$, specific fuel consumption for an engine with recirculation and ATP $g_{e.atp}$, specific fuel consumption for an engine with recirculation, ATP and taking into account the reduction in load to the fan (EGR blower) $g_{e.total}$, recirculation fan power N_{bl}, recirculation fan power with ATP $N_{bl.atp}$ from the load on the engine NMCR:*

_______ - ISO (t_{air1} = 25 ^oC; t_{w1} = 25 ^oC);

__ __ __ - tropical zone (t_{air1} = 45 ^oC; t_{w1} = 36 ^oC);

_ _ _ _ _ - cold zone (t_{air1} = 10 ^oC; t_{w1} = 10 ^oC)

From here it can be seen that when loaded on an engine close to operational (90-95 % of engine power) fuel consumption equal to each other, when using a recirculation system with aerothermopressor and without recirculation in general, which makes such a circuit solution rational from the point of view of efficiency. In this case, it is possible to combine high environmental and economic benefits from the use of such a solution.

5. Conclusions

1. The effectiveness of the aerothermopressor application in the exhaust gases recirculation scheme for the ship low-speed two-stroke engine was analyzed. The installation of the aerothermopressor before the scrubber is proposed, which allows reducing its thermal load.

2. The pressure increase in the aerothermopressor by 0.2-0.4·10^5 Pa (6-12 %) allows reducing the backpressure in the gas exhaust system, and thus reducing the load on the exhaust gas recirculation fan, and when the engine load is higher than 75 % in the cold zone, the fan is not needed, which addi-

tionally allows to reduce the specific fuel consumption.

3. The proposed scheme design solution allows for a high environmental friendliness of the existing exhaust gas recirculation system to provide some reduction in specific fuel consumption. It was determined that the decrease in the specific fuel consumption of the engine when using the aerothermopressor is Δg_e = 2.5-3.0 g/(kWh) (1.5-1.7%).

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Спосіб охолодження відхідних рециркуляційних газів аеротермопресором для суднового малообертового двигуна

***Д. В. Коновалов*[1], *М. І. Радченко*[2], *В. І. Максимов*[3]**
[1, 3] Національний університет кораблебудування ім. адм. Макарова (Херсонська філія),
пр. Ушакова, 44, Херсон, Україна
e-mail: dimitriyko79@gmail.com
[2] Національний університет кораблебудування ім. адм. Макарова,
пр. Героїв України, 9, Миколаїв, Україна
e-mail: nirad50@gmail.com

Існує цілий ряд способів і методів зниження викидів шкідливих газів на сучасних суднах. Одним з найбільш ефективних способів зниження викидів оксидів NOx і SOx є використання рециркуляції відхідних газів (EGR-технологія). Недоліком системи рециркуляції відхідних газів є збільшення протитиску через додаткові втрати тиску в скрубері та теплообміннику-охолоджувачі, що впливає на погіршення паливної економічності двигуна. Створення надійного і ефективного теплообмінника для охолодження рециркуляційних газів являє собою складну задачу через відкладення і забруднення, що виділяються цими газами. В представленій роботі проаналізовано ефективність застосування струминного апарату - аеротермопресора в схемі з рециркуляцією відхідних газів для суднового малообертового двотактного двигуна. Аеротермопресор – це двофазний струминний апарат для контактного дисперсного охолодження, в якому за рахунок відведення теплоти від газового потоку відбувається підвищення тиску газу та його охолодження. Розрахунок характеристик двигуна проводився, як на номінальному, так і на експлуатаційному режимах і у всьому можливому діапазоні часткових навантажень. Встановлення аеротермопресора пропонується перед скрубером, що дозволяє зменшити його теплове навантаження. Підвищення тиску в аеротермопресорі на 0,2–0,4 · 10^5 Па (6–12 %) дозволяє зменшити протитиск в системі газовихлопу, а відтак, і зменшити навантаження на вентилятор системи рециркуляції відхідних газів, причому в холодній зоні при навантаженні на двигун вище 75 % застосування вентилятора не потрібно, що додатково дозволяє зменшити питому витрату палива. Параметри відхідних газів, які йдуть на рециркуляцію та процеси їх газодинамічного охолодження в аеротермопресорі розраховували за розробленою методикою та програмою з використанням рівнянь термодинаміки та газодинаміки потоку. Запропоноване схемно-конструктивне рішення дозволяє при високій екологічності застосування існуючої системи рециркуляції відхідних газів забезпечити певне зменшення питомої витрати палива. Визначено, що зменшення питомої витрати палива двигуном при застосуванні аеротермопресора складає 2,5–3,0 г/(кВт·год) (1,5–1,7 %).

Ключові слова: *Аеротермопресор, Термогазодинамічна компресія, Рециркуляція, Відхідні гази, Питома витрата палива, Двигун внутрішнього згоряння*

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