ХОЛОДИЛЬНА ТЕХНІКА ТА ЕНЕРГОТЕХНОЛОГІЇ

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Using the heat of recirculation gases of the ship main engine by an ejector refrigeration machine for intake air cooling

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One of the promising ways in environmentalizing marine internal combustion engines is the neutralization of harmful substances in exhaust gases through particular gas recirculation (EGR-technology). However, the use of such techniques conflicts with the engine's energy efficiency. In the work presented, the scheme-design solution of the exhaust gas recirculation system with using the heat of recirculation gases by an ejector refrigeration machine for cooling the air at the intake of ship's main engine is proposed. The effect of using the heat of recirculation gases for cooling the air at the intake of the engine is analyzed taking into account the changing climatic conditions for a particular vessel's route line. It is shown that the use of an ejector refrigeration machine reduces the air temperature at the entrance of the main engine by 5-15 ° C, which reduces the specific fuel consumption by 0.5-1.5 g/(kW·h). This reduces emissions of harmful substances when the engine is running with recirculation of gases, in particular, NOx by 30-35%; SOx by 10-12%.

Key Words: *Ejector, Chiller, Recirculation, Exhaust gases, Specific fuel consumption, Ship, Internal combustion engine, Harmful emissions*

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1. Introduction

The rational using of energy resources and prevention of environmental pollution is the most relevant problem for humanity. The internal combustion engines occupy a leading place as an energy source (thermal, mechanical, electrical). It is during the operation of internal combustion engine, due to chemical pollution by toxic substances contained in the exhaust gases, that the greatest harm is caused, and the most sensitive environmental impact comes from ship power plants, in which the main source of energy is internal combustion engines.

The formation of such harmful gases, such as carbon dioxide CO_2, nitrogen oxides NO_x, carbon monoxide CO, sulfur oxides SO_x, etc., depends on the organization of work processes in the internal combustion engine. A very effective way of greening marine internal combustion engines is the artificial neutralization of harmful substances in exhaust gases, for example, exhaust gas recirculation (EGR technology). However, the use of such technologies is in conflict with the energy efficiency of the internal combustion engine, because the measures to reduce emissions require additional costs.

2. Literature Review

Exhaust gas recirculation is a method that significantly reduces the formation of NO_x in marine diesel engines. Using this method fully meet Tier III requirements for NO_x. In the EGR system, after the cooling and cleaning process, a part of the waste gases is recirculated to the air receiver. Thus, part of the oxygen in the air that is used in the combustion process is replaced by CO_2 oxide. This, in turn, reduces the oxygen content of O_2 and the burning rate, thereby reducing the maximum burning temperature, and thus reducing the intensity of NO_x formation [1-5]. NO_x emission reduction is almost linear to exhaust gas recirculation [7-10].

The increased amount of recirculation gases causes under-burning of the fuel and an increase in emissions of CO, CO_2 and soot. Therefore, the quantity (part in the total volume of waste gases) of the recirculation gases must be limited, that is, a compromise must be found between the effect of NO recirculation and combustion efficiency (in the form of low-grade hydrocarbons). This imposes restrictions on the upper limit of the recycle rate [10].

When using EGR, there is an increased fuel consumption due to the slowed rate of heat release. In the upper engine load range, fuel consumption gradually increases with recycle rate. At recirculation ratio K_r = 20 % the fuel consumption increases by 10-20 g/(kWh), in the average engine load range, fuel consumption increases linearly by the K_r, and in the lower load range it slightly affects the fuel consumption.

Using recirculation with a K_r = 10 % can reduce NOx by about 30 % without a significant increase in fuel consumption – although the exhaust gases smoking slightly increases. When K_r = 20 % the reduction in emissions of nitrogen oxides can reach 60 %. However, already at K_r > 10–15 %, the fuel economy deteriorates by 4–7 %. One advantage of the EGR is low cost compared with other methods of reducing NOx. In the case of recycling there is no need to use complex and expensive devices, the manufacture of which for large-sized marine diesel engines causes great technical difficulties.

Since the CO_2 and water molecules have a higher heat capacity, the combustion temperature somewhat decreases. According to the data of [5], an increased mass flow rate gives about 93 % of the effect of reducing the flue gas temperature, while an increase in the specific heat gives about 7 %. The cooling of recirculation gases leads to a decrease in NO_x and particulate emissions with comparable recirculation ratio K_r. This effect is more significant with large recirculation ratio [1].

The work [8] shows the results of using exhaust gas recirculation for the engine of the company MAN 12K90ME9, which is applyid as the main engine on the container vessel. The recycling rate at nominal and partial engine loads was K_r=30–40 %, while NO_x emissions decreased to 80 %, SO_x emissions decreased by 25 %, particulate matter (PM) by 50 %, but this led to an increase in specific fuel oil consumption by 5-6 g/(kWh). The increase in specific fuel oil consumption on low-speed engines up to 5 g/(kWh) is also confirmed in [7]. It is also indicated that it is a technology for EGR at a concentration of fuel sulfur level S <3.5 %.

A typical EGR system for a ship's main low-speed engine includes a scrubber, a cooler, a water mist separator, a fan, and a support system for NaOH solution with a pump and tank. It should be noted that the components of the system are quite dimensional, the pumps of the cleaning system, cooling system and fan (or electric compressor) require a small amount of electrical energy.

Today, it is promising to use technologies that would ensure an increase in the fuel and energy efficiency of the internal combustion engine when working with EGR systems, that is, would combine high environmental efficiency with engine fuel efficiency.

These technologies include, for example, the use of pre-cooling air (before the turbocharger) with the help of ejector waste heat using chillers. The advantage of this solution is the possibility of using the waste heat of recirculation gases (and hence reducing the heat load on the scrubber recycling system).

The aim of the study is assessment of the pre-cooling air efficiency of the ship's main engine by an ejector chiller (ECh) using the heat of exhaust gases of the EGR system.

3. Research Methodology

When analyzing the effectiveness of the application of the proposed comparison solution, it was carried out on the basis scheme with EGR for MAN low-speed two-stroke diesel engines in accordance with the Tier III environmental conditions. Recirculation is provided by bypassing part of the waste gases from the following purification from harmful gases in the scrubber and after cooling in the heat exchanger-gas cooler. The EGR comprise scrubber, chilling unit, condensate trap, the fan and the system is cleaned from the solution of NaOH.

Circuit solution with the use of the heat-using circuit of the ECh is considered for the ship's low-speed two-stroke diesel engine firm MAN B&W specification 6G70ME-C9.5. To analyze the parameters of the recirculation system, as well as the characteristics of the main engine, the CEAS software package of the leading manufacturer MAN was used [11]. The calculation was made for the following initial data: the performance characteristics of the main engine (under ISO conditions) – engine load – NMCR = 90 %; power – N_e = 19656 kW; speed – n_e = 80.1 rpm; specific fuel oil consumption (SFOC) – g_e = 169.8 g/(kWh); exhaust gas recirculation system (EGR) – bypass with scrubber and gas cooler, responsible for Tier III environmental conditions.

The calculation of the characteristics of the engine was carried out on the operating mode during the voyage of the dry-cargo ship from Odessa to Amsterdam. These changes in climatic conditions during the trade route (ambient temperature t_a, temperature of outboard water t_w, humidity rate d_a and and relative humidity $φ_a$ according to the time of the vessel's voyage (fig. 1).

The operating parameters of the heat-recovery contour based on the ECh were calculated using the well known equations and methods, also the software complex developed at the Department of Conditioning and Refrigeration.

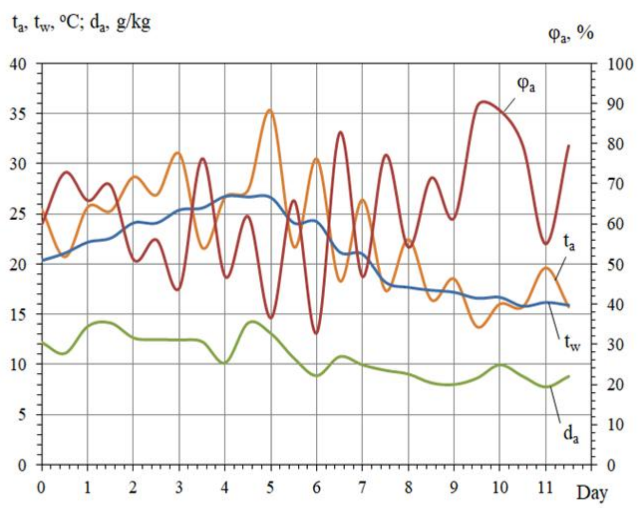


Figure 1 *– The changes in ambient air temperature t_a and temperature of outboard water t_w, humidity rate d_a and relative humidity $φ_a$ of ambient air during the vessel route Odessa-Amsterdam*

The following haracteristics of the ECh for cooling the ship engine intake air were chosen:

1. refrigerant – R142b;

2. refrigerant evaporation temperature in the evaporator-air cooler – t_0 = 5–10 °C;

3. refrigerant condensing temperature in a water cooled condenser by seawater – t_c = 25–45 °C;

4. refrigerant evaporation temperature in the generator – t_g = 80–120 °C.

The following values of coefficient of performance for ECh were chosen: ζ = 0.30; 0.35; 0.40; 0.60.

4. Results

The solution with using the ECh was developed and analyzed (fig. 2). The bypassing recirculation system works as follows: exhaust gases from 10 to 40 % in quantity are fed to the scrubber through the valve, where they are partially cooled and cleaned when water is sprayed with special nozzles. Then the gases are cooled in the heat exchanger - gas cooler (heater of water for refrigerant generator of ECh), condensated water is drained an condensate trap and cooled gases are fed by the fan to the scavenge air receiver, where gases are mixes with the scavenge air coming from the turbocharger.

It is proposed to use the heat of the recirculating gases for high pressure liquid refrigerant evaporation in generator of ECh for generation of high pressure refrigerant vapor as motive fluid for ejector to suct a low pressure refrigerant vapor from refrigerant evaporator - air cooler (AC-RE) at the intake of turcharger. Thus, cooling capacity of ECh is used for cooling air at the intake of the engine turbocharger.

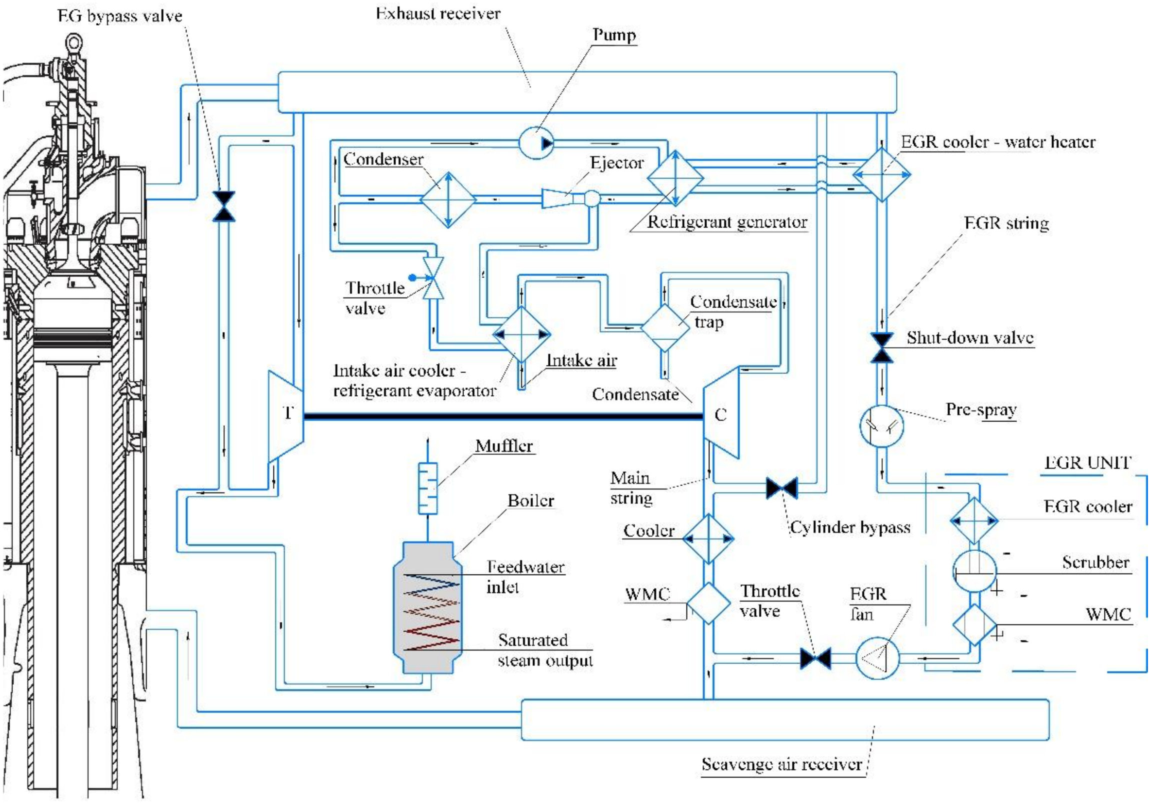


***Figure 2** – Scheme of EGR-technology with bypass matching for the MAN marine diesel engine and ejector chiller: WMC – water mist catcher.*

For MAN B & W 6G70ME-C9.5 engine considered, the specific fuel consumption decreases by about 5 g/(kWh) due to engine inlet air cooling during a voyage (fig 3). With this the degree of recirculation during a voyage is K_p = 15-17 %, the flow of recirculating flue gases is $G_{g.r}$ = 6-7 kg/s and a total exhaust gas flow G_g = 38-39 kg/s. The flow of "fresh" air to the engine turbocharger is $G_{a.egr}$ = 37-38 kg/s with exhaust gas recirculation and G_a = 43-45 kg/s - without recirculation of exhaust gases.

For the 6G70ME-C9.5 engine, according to the data of the MAN company (according to the calculations using the CEAS software package), when cooling intake air for every 10 °C a reduction in specific fuel consumption is 1.09 g/(kWh) or 0.109 g/(kWh·K).

The results of analyzing the operation efficiency of recirculation gas heat-recovery chiller with different coefficients of performance ζ = 0.30; 0.35; 0.40; 0.60 show the following cooling capacities received in chiller (fig. 4): $Q_{0(0,3)}$ = 430–450 kW (ζ = 0.30); $Q_{0(0,35)}$ = 500–530 kW (ζ = = 0,35); $Q_{0(0.4)}$ = 580–610 kW (ζ = 0.40) and $Q_{0(0.3)}$ = = 870-910 kW (ζ = 0,60). The heat load on the ECh generator (heat consumption of chiller) is Q_g = 1450-1520 kW (fig. 4) with appropriate cooling of the recirculation gas in the gas cooler (before the scrubber) from the temperature t_{g1} = 360-410 °C to the temperature t_{g2} = 180 °C (limited taken into account the danger of corrosion) provides decrease in air temperature at the inlet of the engine turbocharger, respectively: $\Delta t_{a(0.3)}$ = 5.1–

8.0 °C (ζ = 0.30); $\Delta t_{a(0.35)}$ = 5.5–9.4 °C (ζ = 0.35); $\Delta t_{a(0.4)}$ = = 6.6–10.8 °C (ζ = 0.40); $\Delta t_{a(0.6)}$ = 8.7–16.0 °C (ζ = 0.60).

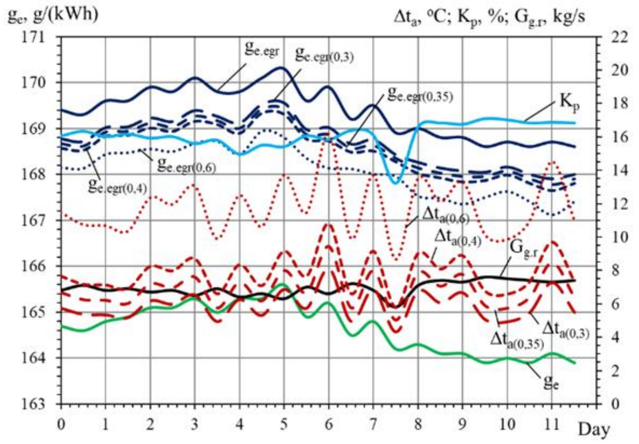


Figure 3 *– Dependences of specific fuel consumption g_e, degree of recirculation K_p, decrease in air temperature at the engine intake Δt_a and recirculation gas flow $G_{g.r}$ during the vessel route Odessa-Amsterdam at different coefficients of performance of chiller ζ = 0.30; 0.35; 0.40; 0.60*

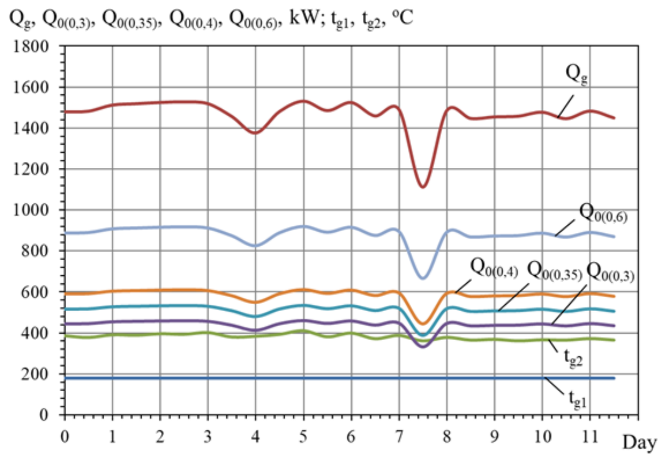
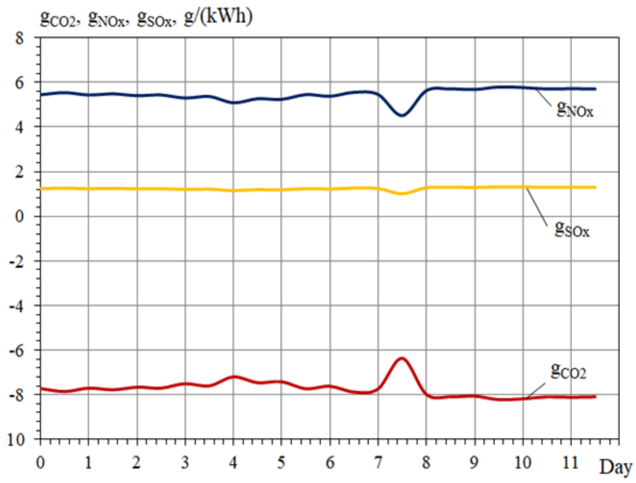


Figure 4 *– The temperature of* recirculation gases cooled by removing the heat for ECh generator (at *the exit from* heat exchanger- gas cooler) *t_{g1}, temperature of the gases at the inlet of heat exchanger - gas cooler t_{g2}, thermal load on the generator of the chiller Q_g, cooling capacity of the chiller at different coefficients of performance $Q_{0(0,3)}$, $Q_{0(0,35)}$, $Q_{0(0,4)}$, $Q_{0(0,6)}$ during the route of the vessel*

A decrease in the engine intake air temperature ensures a reduction in the specific fuel consumption (fig. 3) in accordance with: $\Delta g_{e(0,3)}$ = 0.5–0.7 g/(kWh) (ζ = 0.30); $\Delta g_{e(0.35)}$ = 0.6–0.9 g/(kWh) (ζ = 0.35); $\Delta g_{e\ (0,4)}$ = 0.7–1.2 g/(kWh) (ζ = 0.40); $\Delta g_{e\ (0.6)}$ = 1.1–1.5 g/(kWh) (ζ = 0.60). The maximum efficiency of engine intake air cooling through recirculation exhaust gas heat-recovery corresponds to the coefficient of performance of the chiller ζ = 0.60 and is Δg_e = 0.9-1.1%, while the total specific fuel consumption will be $g_{e(0.6)}$ = 167-168 g/(kWh), and without gas recirculation - g_e = 164-165 g/(kWh).

Reduction of emissions due to lowering the engine intake air temperature when using the heat of recirculation gases is insignificant and amounts to no more than 0.2-0.3% for NO_x and SO_x, but for the system with gas recirculation and ζ = 0.60 (fig. 5) is: $\Delta g_{NOx(0.6)}$ = 29–35 % (5.5–5.8 g/(kWh)); $\Delta g_{SOx(0.6)}$ = 10–12 % (1.2–1.4 g/(kWh)).



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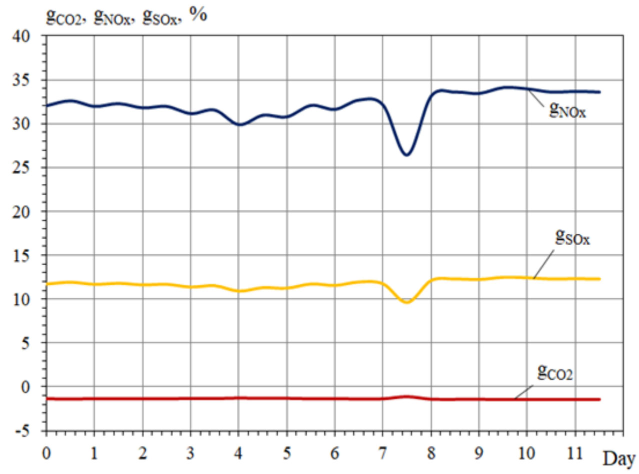

b

Figure 5 *– The values of NO_x, SO_x and CO_2 emissions in absolute units (a) and relative (b) during the route of the vessel*

However, it should be noted that this enhances CO_2 emissions by $\Delta g_{CO2(0.6)}$ = 1.3–1.4 % (6.2–8.0 g/(kWh)).

5. Conclusions

1. A schematic-constructive solution of the exhaust gas recirculation system with the use of its heat by an ejector refrigeration machine for cooling the air at the intake of the ship's main engine is developed.
2. The effect of using the heat of recirculating gases for cooling air at the turbocharger intake was analyzed for the engine MAN 12K90ME9 with the account of changing climatic conditions on the vessel route line Odesa-Amsterdam.
3. It is shown that the use of heat of recirculation gases with an ejector refrigeration machine reduces the air temperature at the intake of the ship's main engine by 5-

15 °C, which ensures a reduction of the specific fuel consumption by 0.5-1.5 g/(kW·h). This reduces emissions of harmful substances when the engine is running with recirculation of gases, in particular, NOx by 30-35%; SOx by 10-12%.

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Використання теплоти рециркуляційних газів суднового головного двигуна ежекторною холодильною машиною для охолодження повітря на вході

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В даний час основу суднової енергетики складають двигуни внутрішнього згоряння із запалюванням від стиснення – дизелі. Дизелі є джерелом інтенсивного забруднення атмосферного повітря. Головні і допоміжні дизелі, в складі суднових енергетичних установок, викидають в навколишнє середовище значну кількість шкідливих речовин, впливаючи тим самим на екологічну обстановку в районах водойм, портів, ремонтних баз, а також здійснює негативний вплив на флору і фауну водних басейнів і на здоров'я людей. Міжнародні конвенції встановлюють жорсткі вимоги до технічного стану суден та процесу експлуатації, при невідповідності яким використання судна може бути в адміністративному порядку обмежено або заборонено. З 2016 року введено в дію нові норми IMO TIER III, згідно з якими зниження шкідливих викидів в регульованих зонах (ECA) має бути скорочено в порівнянні з нормами 2011 р більш ніж в 3 рази. Виконання нових норм в напрямках подальшого вдосконалення робочого процесу, застосування альтернативних палив, присадок до палива і повітря, а також систем селективного каталітичного відновлення не виключає подальшого розвитку наукових досліджень в області очищення відпрацьованих газів. Одним з перспективних напрямів в екологізації суднових двигунів внутрішнього згоряння є нейтралізація шкідливих речовин у випускних газах, зокрема рециркуляцією газів (EGR-технологія). Однак, використання таких технологій вступає в протиріччя з енергетичною ефективністю дви-

гуна. В представленій авторами роботі запропоновано та проаналізовано схемно-конструктивне рішення системи рециркуляції випускних газів суднового головного двигуна з використанням теплоти газів ежекторною холодильною машиною для охолодження повітря на вході. Ефект від використання теплоти рециркуляційних газів для охолодження повітря на вході двигуна проаналізовано з урахуванням змінних кліматичних умов для конкретної рейсової лінії судна. Показано, що застосування ежекторної холодильної машини дозволяє знизити температуру повітря на вході головного двигуна на 5–15°C, що забезпечує зменшення питомої витрати палива на 0,5–1,5 г/(кВт год). При цьому скорочуються викиди шкідливих речовин при роботі двигуна з рециркуляцією газів, зокрема NOx на 30–35 %; SOx на 10–12 %.

Ключові слова: *Ежектор, Холодильна машина, Рециркуляція, Відхідні гази, Питома витрата палива, Двигун внутрішнього згоряння, Шкідливі викиди*

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