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MAIN ENGINE OF TRANSPORT SHIP INLET AIR COOLING BY EJECTOR CHILLER

Abstract: *The efficiency of cooling the air at the inlet of marine slow speed diesel engine turbocharger by ejector chiller utilizing the heat of exhaust gases and scavenge air were analyzed. The values of air temperature drop at the inlet of engine turbocharger and corresponding decrease in fuel consumption of the engine at varying climatic conditions on the route line Odessa–Yokohama–Odessa were evaluated.*

Keywords: *internal combustion engine, ejector chiller.*

Introduction

Slow speed diesel engines are the most widespread as the main engines of the ships. The fuel efficiency of diesel engines are considerable effected by the variations in ambient air temperatures along the route lines [1, 2]. The increase in marine low speed diesel engines intake air temperature by 10°C causes specific fuel consumption increase by 1.1 g/(kWh) to 1.2 g/(kWh) [3, 4].

In order to enhance the fuel efficiency of the engine it is necessary to cool the cyclic air: at the intake of turbocharger and scavenge air after turbocharger [5, 6]. Waste heat recovery chillers can be applied for engine air cooling [7, 8].

The absorption lithium-bromide chillers (ACh) are the most used for cooling air to about 15°C with a high coefficient of performance COP of 0.7 to 0.8 [9, 10]. But large sizes make mounting the ACh unit in engine room problematical. The ECh consist of heat exchangers [11, 12] suitable for mounting in free spaces. They enables deep cooling air but with a low COP of 0.2 to 0.35 [13, 14] and suitable for transport applications [15, 16].

The heat loss with exhaust gases represents a high part of the total waste heat in combustion engines [17, 18]. The low-temperature economizers [19, 20] use a condensation heat of sulfuric acid and water vapors. The condensed acid vapor glues the ash in exhaust gas, and adheres on heating surface [21], that increases the hydraulic and thermal resistance [22]. The experience of using WFE in boilers and diesel engines indicates the undeniable advantages of this type of fuel: the effective specific fuel consumption decreases by about 8% [23], the concentration of nitrogen oxides in exhaust gases is reduced in 1.4 to 3.1 times [24], CO – in 1.3 to 1.5 times [25], smoke – in 1.3 to 2.4 times [26]. The analysis of literary sources shows, that there is no quantitative data on low-temperature corrosion (LTC) intensity on condensation low-temperature heating surfaces (LTHS) of EGB while WFE combustion.

A double effect is achieved with WFE combustion: enhanced fragmentation of WFE droplets due to their microexplosions intensifies the combustion processes and reduces the particle emission as result, as well as intensifies entrainment of small particles by the exhaust gas flow and decreases their deposits on condensing/heating economizer surfaces and their thermal resistance as result [27, 28].

The purpose of the work is to estimate the efficiency of cooling the intake air of marine slow speed diesel engine by ejector chiller taking into account the variable climatic conditions along the route line.

Methodology

A slow speed diesel engine 6S60MC6.1-TI [2] is considered as an example of the main engine of transport vessel: nominal power N_n = 12.24 MW and continuous service power N_s = 10 MW. For the 6S60MC6.1-TI engine, according to the data of the MAN company (according to the calculations by using "mandieselturbo" software package), cooling inlet air for every 1°C results in reduction of specific fuel consumption within 0.11 g/(kWh) to 0.12 g/(kWh) [2-4].

The efficiency of engine intake air cooling is estimated by decrease in specific fuel consumption Δb_e due to reduce of intake air temperature Δt_a, that depends on the heat Q_h extracted from the exhaust gas and scavenge air and the efficiency of its conversion in refrigeration capacity Q_0 of the chiller, i.e. coefficient of performance COP.

The efficiency of conversion of waste heat into refrigeration capacity is characterized by coefficient of performance $\zeta = Q_0 / Q_h$ as the ratio of the chiller refrigeration capacity Q_0 to the consumed heat Q_h, extracted from the engine exhaust gases, scavenge air and others.

The available refrigeration capacity Q_0 of ECh is calculated as $Q_{0.\mathrm{ECh}} = Q_h \zeta_{\mathrm{ECh}}$, where Q_h is the heat, extracted from the engine exhaust gases and scavenge.

The values of the available air temperature drop in the ECh air cooler $\Delta t_{a.\mathrm{ECh}}$ due to using ECh available refrigeration capacities $Q_{0.\mathrm{ECh}} = Q_h \zeta_{\mathrm{ECh}}$ is calculated proceeding from the heat balance $Q_{0.\mathrm{ECh}} = G_a \xi_a c_a \Delta t_{a.\mathrm{ECh}}$ as $\Delta t_a = Q_{0.\mathrm{ECh}} / G_a \xi_a c_a$, where: G_a – air mass flow rate, kg/s; c_a – specific heat capacity of wet air, kW/(kg·K); ξ_a – specific heat ratio of cooling air process in air cooler.

The available temperatures of cooled air at the outlet of the air cooler $t_{a2} = t_{a1} - \Delta t_a$.

The current values of reduction in specific fuel consumption per 1 hour: $\Delta b_e = \Delta t_a \cdot \Delta b_{e1^\circ\mathrm{C}}$, g/kWh, and the total fuel reduction per 1 hour: $\Delta B_e = N_s \Delta b_e$ or $\Delta B_e = N_s \Delta t_a \Delta b_{e1^\circ\mathrm{C}}$, g/h, where: $\Delta b_{e1^\circ\mathrm{C}}$ – reduction in specific fuel consumption referred to engine intake air temperature drop in 1°C or 1 K, $\Delta b_{e1^\circ\mathrm{C}} = \Delta b_e / \Delta t_a$ = 0.12 g/(kWh·K); N_s = 10000 kW – diesel engine power output.

A refrigeration capacity of ejector chiller Q_0 is defined from available exhaust gas heat Q_G as $Q_0 = \zeta Q_G$, where ζ is coefficient of performance of ejector chiller, ζ = 0.35.

Results

A schema of developed engine intake air cooling system with ejector chiller utilizing the heat of exhaust gas is shown in Figure 1.

The ejector chiller consists of power and refrigeration contours. A generator of power contour uses a heat of exhaust gas to produce a high pressure refrigerant vapour as a motive fluid which energy is used in ejector to compress the low pressure refrigerant vapour, sucked from evaporator-intake air cooler of refrigeration contour, up to the pressure in the condenser.

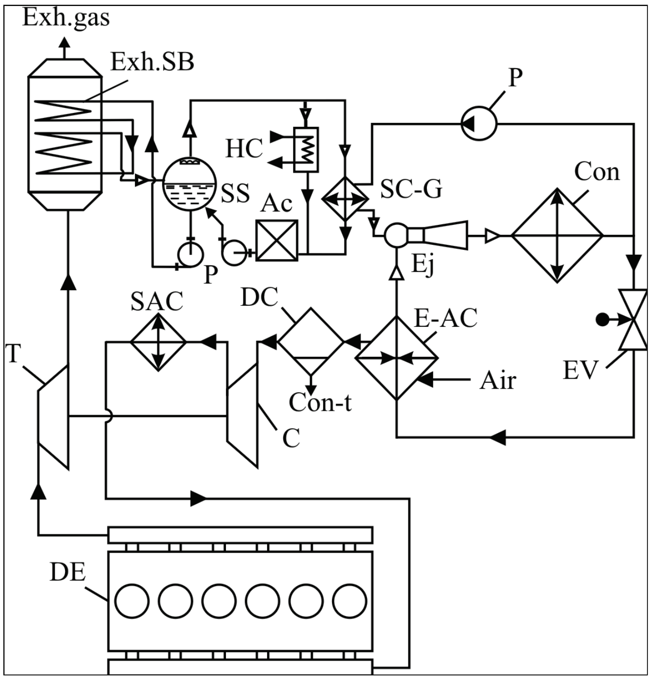


FIGURE 1. *Schema of the engine intake air cooling system with ejector chiller utilizing the heat of exhaust gas: DE – diesel engine, T – turbine and C – compressor of turbocharger, SAC – scavenge air cooler, Exh.SB – exhaust gas steam boiler (economizer), SC-G – steam condenser-generator of refrigerant vapour, E-AC – evaporator-air cooler, Ej – ejector, Con – condenser, EV – expansion valve, P – pump, Con-t – condensate of water steam, DC – droplet catcher, Ac – accumulator of feed water, SS – steam separator, HC – heat consumer*

The efficiency of application of ejector chiller (ECh) for cooling engine intake air is estimated by decrease in specific fuel consumption Δb_e of diesel engine due to reduction of intake air temperature Δt_a, that depends on the heat extracted from the exhaust gas (heat load on the generator of ejector chiller) and the efficiency of its conversion in refrigeration capacity (refrigeration capacity of the ejector chiller (heat removed from intake air in refrigerant evaporator-air cooler), i.e. coefficient of performance COP.

A route line Odessa–Yokohama–Odessa (June-July) 2019 is considered (Fig. 2).

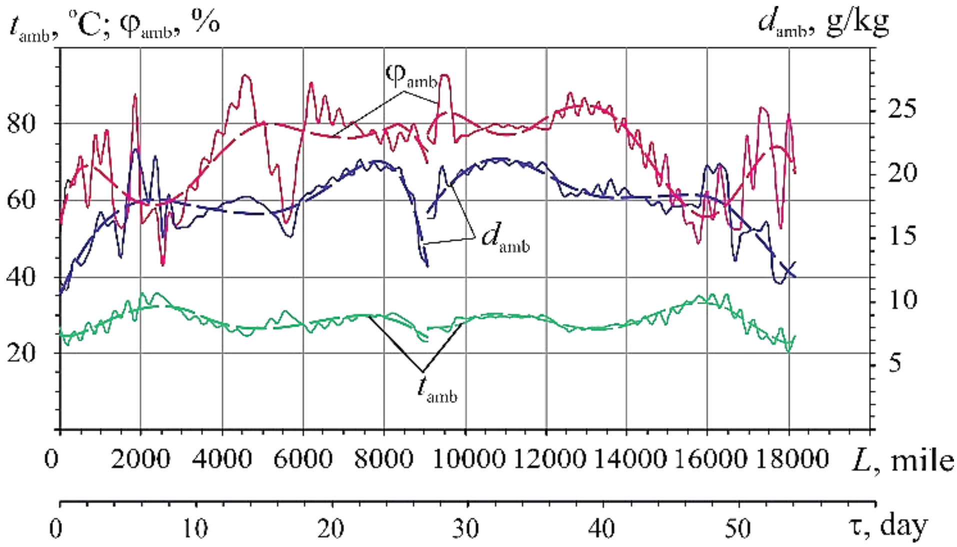


FIGURE 2. *Variation of ambient air temperature t_{amb}, relative humidity φ_{amb} and absolute humidity d_{amb} on the route line Odessa–Yokohama–Odessa*

For each time interval (3 hours) along the route line Odessa–Yokohama–Odessa the values of ambient air temperature t_{amb} and relative humidity φ_{amb} were fixed by applying the well-known program "mundomanz.com" to calculate the processes of cooling intake air in the air cooler at the inlet of turbocharger of diesel engine and define the required temperature drops Δt_a and refrigeration capacities $Q_{0.\mathrm{ECh}}$, as well as the available air temperature drop in the ECh air cooler Δt_a due to using the available refrigeration capacities $Q_{0.\mathrm{ECh}}$ of ECh utilizing the heat of engine exhaust gas and scavenge air.

A decrease in the temperature of air Δt_a at the inlet of engine turbocharger due to its cooling by ejector chiller and, accordingly, the effect of its application depends on the heat of steam produced by exhaust steam boiler (ExhSB), that remains after covering all the ship heat demands. During warm time steam consumption on the bulk carrier is approximately 25% of steam productivity of exhaust boiler, i.e. 75% of steam produced can be used in ejector chiller for cooling the engine turbocharger intake air.

Besides, decrease in temperature of air in the air cooler at the inlet of diesel engine turbocharger $\Delta t_a = t_{a1} - t_{a2}$ depends on temperature t_{a1} and relative humidity φ_a of intake air in the engine room, in turn, depending on parameters of ambient air, i.e. sailing environmental conditions. During sailing in warm time the air temperature in the engine room t_{ER} exceeds ambient temperature by 10°C [1].

The temperature t_{a2}, which limits the depth of engine intake air cooling in the air cooler, in turn, depends on the temperature of boiling refrigerant. A temperature of boiling refrigerant R142b in the evaporator-air cooler is desirable about t_0 = 7°C. The temperature difference between cooled air and boiling refrigerant can be accepted 8°C. Taking into account these values a depth of cooling the air in the evaporator-air cooler is limited to minimum temperature $t_{a2} = t_0 + 8 = 15$°C.

For each time interval (3 hours) and corresponding temperature t_{amb} and relative humidity φ_{amb} of ambient air the processes of cooling of intake air in the air cooler at the inlet of turbocharger of diesel engine, from the air temperature at the cooler inlet (in engine room) $t_{a1} = t_{amb} + 10$°C to air cooler outlet air temperature t_{a2} have been calculated.

Values of air temperature drop in the air cooler of ejector chiller, utilizing a heat of exhaust gas (schema in Fig. 1), Δt_a, are presented in Figure 3.

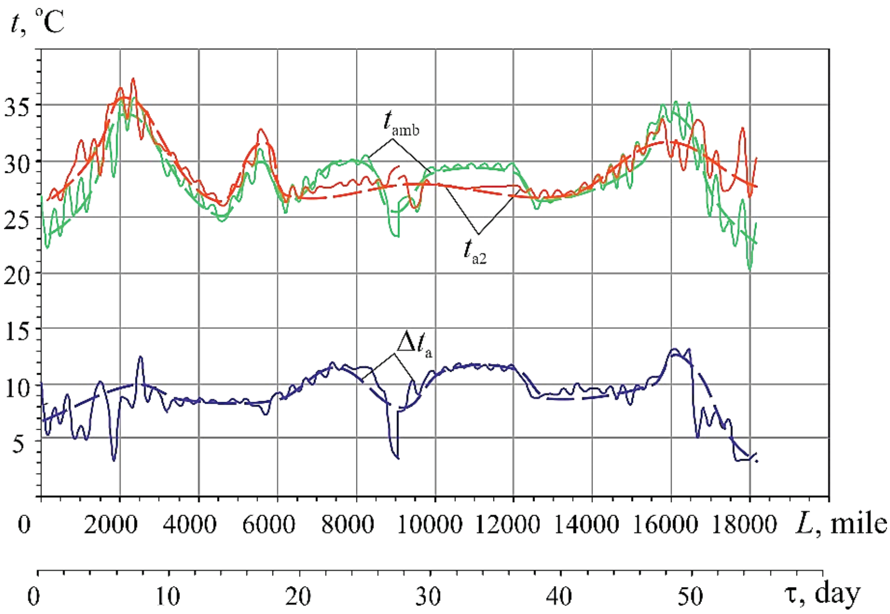


FIGURE 3. *Air temperature drops Δt_a in the air cooler of ECh according to available ECh refrigeration capacities Q_0 due to utilizing a heat of exhaust gas and corresponding temperatures of cooled air at the outlet of air coolers t_{a2} with variation of ambient air temperature t_{amb} on the route line Odessa–Yokohama–Odessa (June-July, 2019)*

As it is shown, decrease in temperature of air in the air cooler of ejector chiller, utilizing a heat of exhaust gas (Fig. 1) Δt_a = 13°C, ..., 18°C. In the case of using only exhaust gas heat a decrease in temperature of air in the air cooler of ejector chiller Δt_a is not enough for lowering air temperature to the minimum value (15°C), which might be possible at refrigerant boiling temperature in the air cooler t_0 = 7°C: temperature t_{a2} at the exit of air cooler is sometimes higher then 15°C (Fig. 3).

Relative values $\Delta Q_0^{''}$ ΔQ_0 of refrigeration capacities required (needed for engine intake air cooling to t_{a2} = 15°C) referred to available ECh refrigeration capacities due to utilizing a heat of exhaust gas are shown in Figure 4.

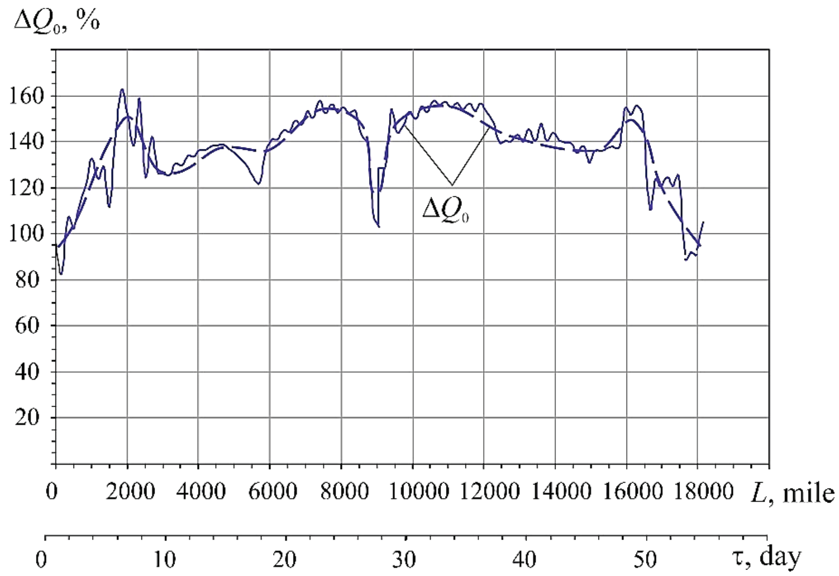
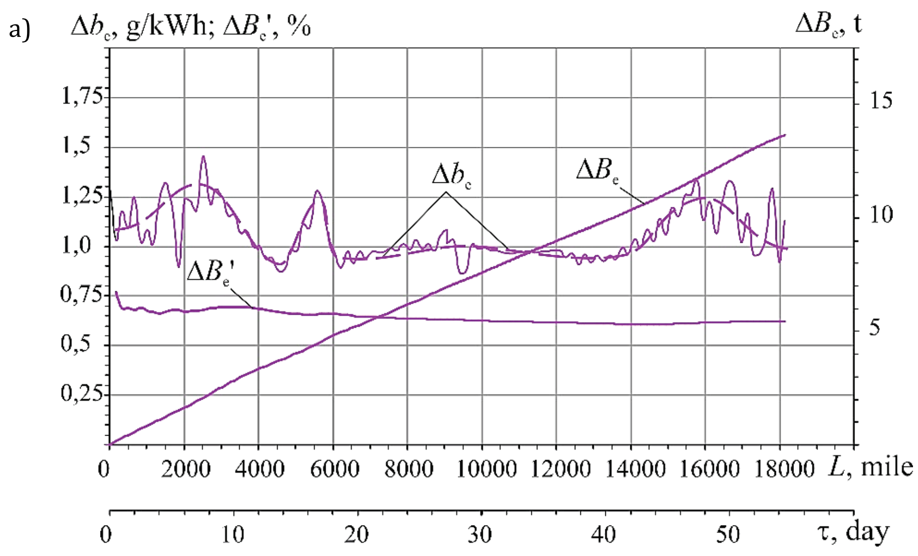


***FIGURE 4.** Relative values ΔQ_0 of refrigeration capacities needed for engine intake air cooling to t_{a2} = 15°C referred to available ECh refrigeration capacities due to utilizing a heat of exhaust gas*

As the relative values $\Delta Q_0 \Delta Q_0^{''}$ of refrigeration capacities needed for engine intake air cooling to t_{a2} = 15°C referred to available ECh refrigeration capacities show, the refrigeration capacities needed for engine intake air cooling to t_{a2} = 15°C considerable exceed the available ECh refrigeration capacities by 40%, ..., 50% when the only exhaust gas heat is used: $\Delta Q_0^{''}$ = 140%, ..., 150% (Fig. 4).

Decrease in specific fuel consumption Δb_e of diesel engine, fuel reduction in absolute B_e, t, and relative $B_e^{'}$, %, values on the route line Odessa–Yokohama–Odessa due to cooling intake air by ejector chiller, using exhaust gas heat (Fig. 1), calculated by program “mandieselturbo” [2], are shown in Figure 5.



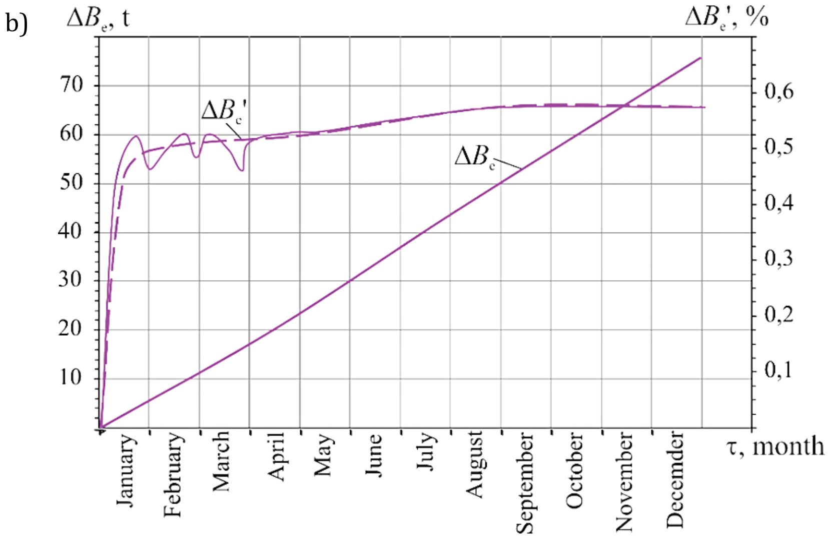


FIGURE 5. *Decrease of specific fuel consumption Δb_e, total fuel consumption for engine power N_s = 10000 kW in absolute ΔB_e, t and relative $\Delta B_e'$, %, values referred to the engine total fuel consumption due to cooling intake air by ejector chiller, using exhaust gas heat on the route line Odessa–Yokohama–Odessa, June-July 2019 (a) and their summarized annual absolute ΔB_e and relative $\Delta B_e'$ values on the route line Odessa–Yokohama–Odessa in 2019 (b)*

As Figure 5 shows, a decrease of specific fuel consumption due to intake air cooling by ejector chiller Δb_e = 1.0 g/(kW·h), ..., 1.2 g/(kW·h), absolute fuel saving during the routes Odessa–Yokohama–Odessa, June-July 2019, is ΔB_e = 13 t (Fig. 5a) and annual fuel saving ΔB_e = 75 t (Fig. 5b) and the relative fuel saving $\Delta B_e^{'}$ is a bit higher than 0.6% for diesel engine 6S60MC6.1-TI (continuous service power N_s = 10 MW).

In order to provide a deeper engine intake air cooling for the operation of engine at the temperature t_{a2} of about 15°C it is necessary to use addition heat, for instance scavenge air heat.

A schema of developed engine intake air cooling system with ejector chiller utilizing the heat of exhaust gas in evaporative section of ECh generator and scavenge air in economizer section is shown in Figure 6.

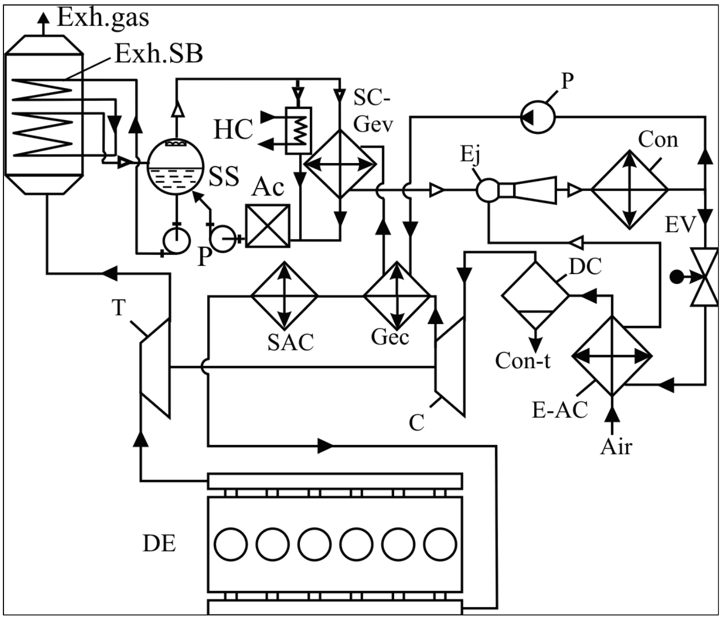


FIGURE 6. *A schema of the engine intake air cooling system with ejector chiller utilizing the heat of exhaust gas and scavenge air: DE – diesel engine, T – turbine, C – compressor of turbocharger, SAC – scavenge air cooler, Exh.SB – exhaust gas steam boiler, SC-Gev – steam condenser-evaporative section of ECh generator, Gec – economizer section of ECh generator, E-AC – evaporator-air cooler, Ej – ejector, Con – condenser, EV – expansion valve, P – pump, Con-t – condensate, DC – droplet catcher, Ac – accumulator of feed water, SS – steam separator, HC – heat consumer*

The ejector chiller consists of power and refrigeration contours. A generator of power contour uses a heat of exhaust gas to produce a high pressure refrigerant vapour as a motive fluid which energy is used in ejector to compress the low pressure refrigerant vapour, sucked from evaporator-intake air cooler of refrigeration contour, up to the pressure in the condenser.

Values of air temperature drop in the air cooler of ejector chiller, utilizing a heat of exhaust gas and scavenge air (Fig. 6), Δt_a, are presented in Figure 7.

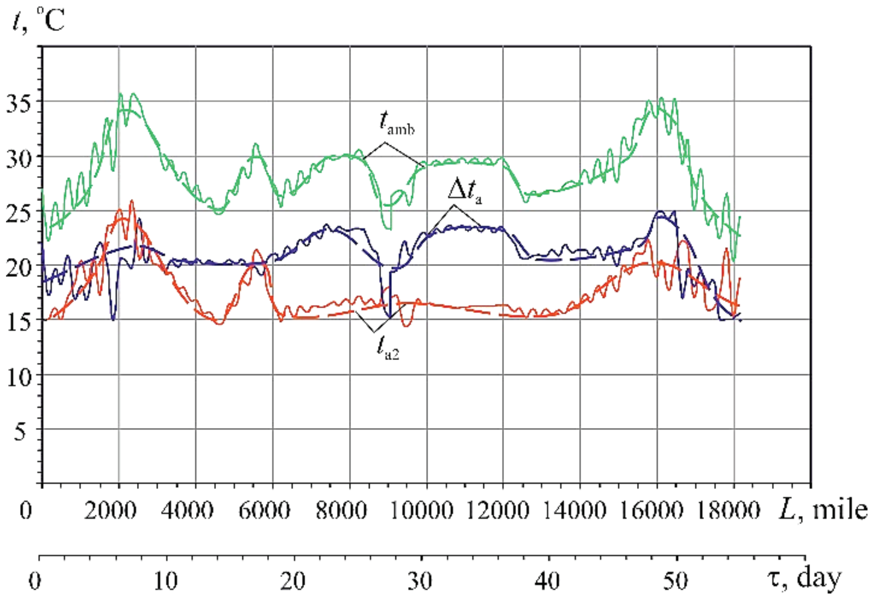


FIGURE 7. *Air temperature drops Δt_a in the air cooler of ECh according to available ECh refrigeration capacities Q_0 due to utilizing a heat of exhaust gas and corresponding temperatures of cooled air at the outlet of air coolers t_{a2} with variation of ambient air temperature t_{amb} on the route line Odessa–Yokohama–Odessa (June-July, 2019)*

As it is shown, decrease in temperature of air in the air cooler of ejector chiller, utilizing a heat of exhaust gas and scavenge air (Fig. 6) Δt_a = 20°C, ..., 23°C (Fig. 7).

Relative values ΔQ_0 of refrigeration capacities needed for engine intake air cooling to t_{a2} = 15°C referred to available ECh refrigeration capacities due to utilizing a heat of exhaust gas and scavenge air are presented in Figure 8.

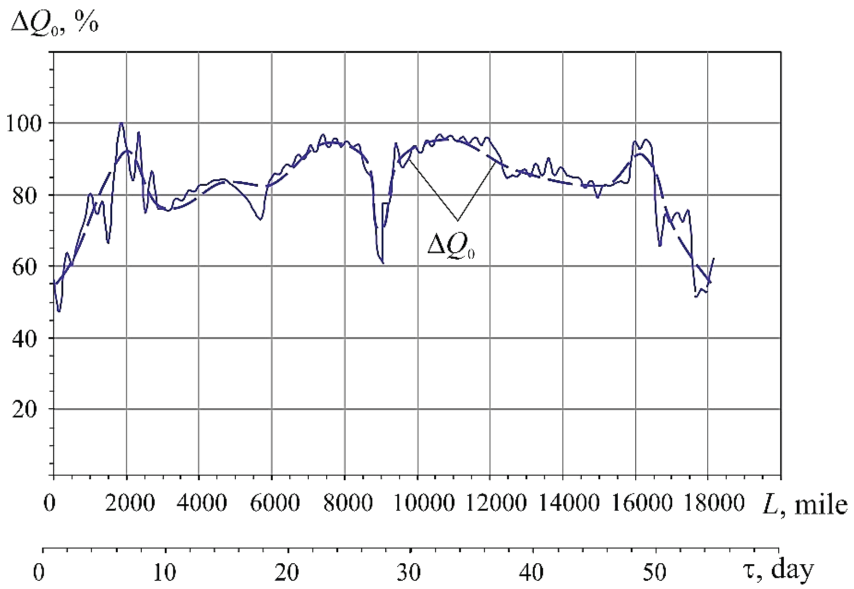


FIGURE 8. *Relative values ΔQ_0 ($\Delta Q_0'$) of refrigeration capacities needed for engine intake air cooling to t_{a2} = 15°C referred to available ECh refrigeration capacities due to utilizing the heat of exhaust gas and scavenge air*

As Figure 8 shows, the relative values ΔQ_0 ($\Delta Q_0'$) of refrigeration capacities needed for engine intake air cooling to t_{a2} = 15°C are generally less than 100%, that means that the available ECh refrigeration capacities while utilizing the heat of exhaust gas and scavenge air are generally enaugh for cooling diesel engine intake air to t_{a2} = 15°C.

The results of calculations of fuel saving due to cooling diesel engine intake air by ejector chiller, using exhaust gas and scavenge air heat on the route line Odessa–Yokohama–Odessa, June-July 2019 and their summarized annual (Fig. 6), calculated by program "mandieselturbo", are shown in Figure 9.

Decrease in specific fuel consumption Δb_e, g/(kW·h), of diesel engine, fuel saving in absolute B_e, t, and relative $B_e^{'}$, %, values on the route line Odessa–Yokohama–Odessa and their summarized annual absolute ΔB_e and relative $\Delta B_e^{'}$ values due to cooling intake air by ejector chiller, using exhaust gas and scavenge air heat are resulted in Figure 9.

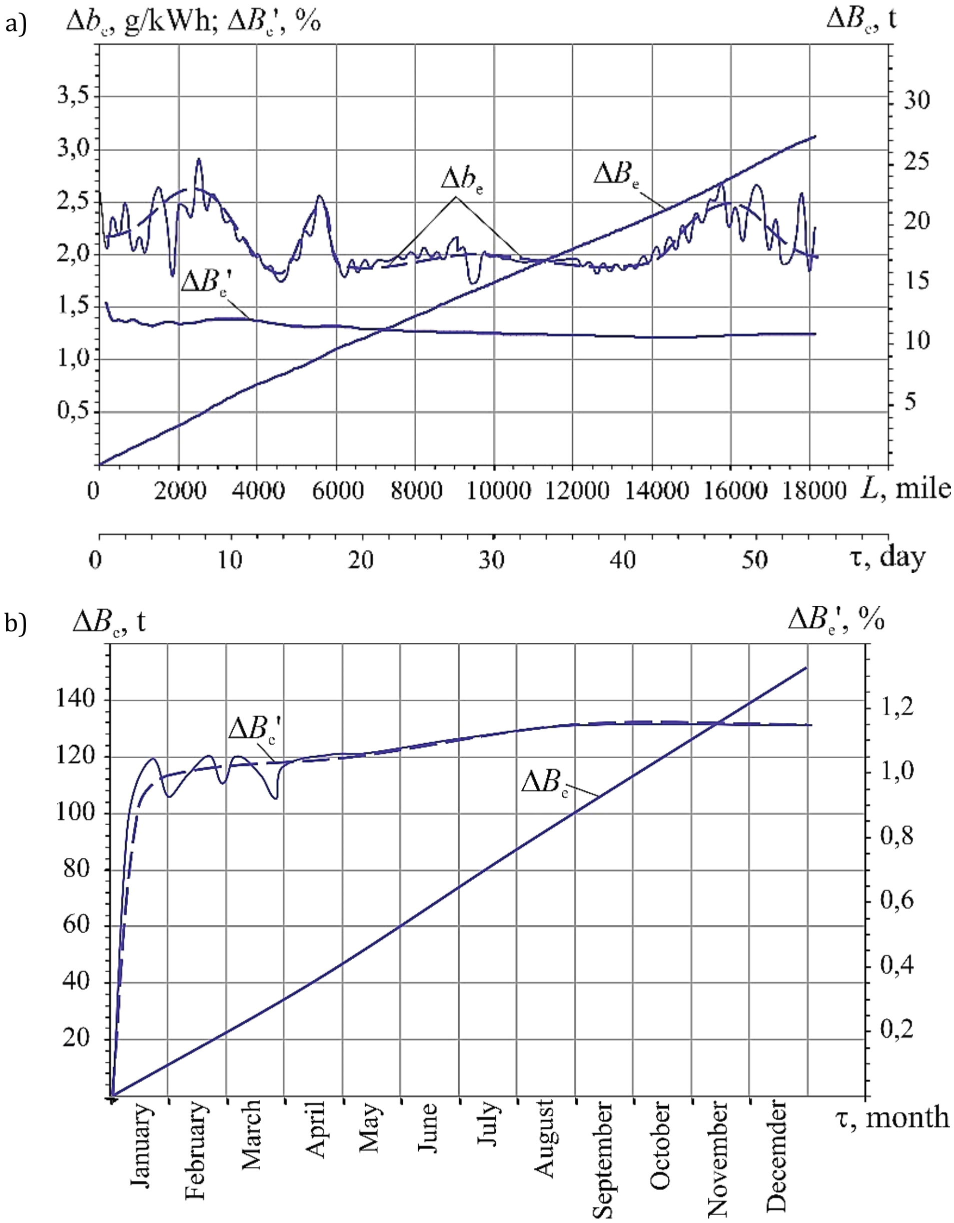


FIGURE 9. *Decrease of specific fuel consumption Δb_e, total fuel consumption for engine power N_s = 10000 kW in absolute ΔB_e, t, and relative $\Delta B_e'$, %, values referred to the engine total fuel consumption on the route line Odessa–Yokohama–Odessa, June-July 2019 (a) and their summarized annual absolute ΔB_e and relative $\Delta B_e'$ values (b)*

As Figure 9 shows, a decrease of specific fuel consumption due to intake air cooling by ejector chiller Δb_e = 2.0 g/(kW·h), ..., 2.5 g/(kW·h), absolute fuel saving during the routes Odessa–Yokohama–Odessa, June-July 2019, is ΔB_e = 26 t (Fig. 9a) and annual fuel saving ΔB_e = 150 t (Fig. 9b) and the relative fuel saving $\Delta B_e^{'}$ is about 1.3% for diesel engine 6S60MC6.1-TI (continuous service power N_s = 10 MW).

In order to provide a deeper engine intake air cooling to the temperature t_{a2} of about 10°C and lower it is necessary to apply two-stage cooling air in hybrid water-refrigerant air cooler by combined absorption-ejector chillers with higher COP.

Conclusions

The efficiency of application of waste heat recovery ejector chiller system for cooling the intake air of marine diesel engine has been analyzed for real changeable climatic conditions on the routes Odessa–Yokohama–Odessa.

The application of ejector chiller provides reducing the engine intake air temperature by 20°C, ..., 23°C with corresponding decrease of specific fuel consumption by 2.0 g/(kWh), ..., 2.5 g/(kWh).

In order to provide a deeper engine intake air cooling to the temperature t_{a2} of about 10°C and lower it is necessary to apply two-stage cooling air in a hybrid water-refrigerant air cooler by combined absorption-ejector chillers with a higher COP.

Conflicts of Interest: The author declares no conflict of interest.

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RESEARCH OF CYCLONE CHARACTERISTICS FOR DRY CLEANING OF GASES FROM DUST

Abstract: *The development and application of new, more efficient dust collection units that will help reduce emissions and conserve some very valuable resources for production is an important area of research. With the growth of innovation in technological enterprises, the number of harmful emissions into the atmosphere is growing. Thus, the ecological condition of the environment deteriorates. The basic analytical dependences which are necessary for construction of a technique of carrying out experiments and calculations of dust catching for concrete working conditions are developed. Methods of calculating cyclones as vortex devices and research of cyclone operation for air purification from dust were investigated. On the basis of the used basic theoretical positions of heat and mass transfer and thermodynamics at carrying out analytical researches the mathematical model was offered. Calculations of new designs of modern cyclones to obtain their geometric dimensions, resistance and dust capture efficiency were presented. Modern cyclones are designed to more effectively remove dust from the air during various types of work.*

Keywords: *modern cyclone, dust collection, mathematical modelling.*

Introduction

In connection with the UN Development Strategy, one of the four main principles is ecology. In the field of thermal energy, the development and application of new, more efficient dust cleaning units, which will help reduce emissions into the atmosphere and save some very valuable resources for production, is of particular interest. Because with the growth of innovation in technological enterprises, the number of harmful emissions into the atmosphere increases. Thus, the ecological condition of the environment deteriorates.

There are several technologies for cleaning the air from dust. Particular attention is paid to cyclone cleaning. The most reliable results from various experiments can be obtained through experiments conducted on physical models. A separate experiment must be performed for each specific design. More general results are obtained using a mathematical model of hydromechanical processes of cyclones. Creating a mathematical model of the movement of dust particles in a swirling flow will assess the impact of various factors on the efficiency of dust control in cyclones.

To determine the nature of the motion of particles transported by the flow in swirling dust air streams, and their deposition on a solid surface requires the calculation of dynamic equations for turbulent flow and particles used the method of calculating gas-dynamic flows, which combines the properties of Euler and Lagrangian approaches, each is a method of “particles in a cell”. An approximation model of the motion of dust particles in the apparatus was created, with the help of which for each type of aerosol the trajectories of its motion in the apparatus are constructed theoretically, having different design parameters of the dust collector. And thus in the future select the most efficient dust collector for each specific type of technological production.