Marine Diesel Engine Inlet Air Cooling by Ejector Chiller on the Vessel Route Line

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Abstract. The fuel efficiency of marine slow-speed diesel engines with cooling the air at the turbocharger suction by ejector chiller that recovers the waste heat of exhaust gas and scavenge air was analyzed. The application of ejector chiller is caused due to its the simplest design that enables easy it's assembling in free space of engine room and reliable operation in a marine application. An assessment was made of air temperature drops in the air cooler at the inlet to the turbocharger of a marine diesel engine and a reduction in fuel consumption under variable climatic parameters along the Odesa-Yokohama-Odesa route. The application of an ejector chiller provides reducing the engine intake air temperature by about 10 °C with a corresponding decrease of specific fuel consumption by 1.0…1.2 g/(kWh) when using only the heat of exhaust gas. The fuel reduction of the marine diesel engine is increased practically twice when additional heat of scavenging air is used by an ejector chiller (ECh). The corresponding schemes of the systems for cooling the air at the turbocharger suction by ejector chiller are proposed.

Keywords: Internal combustion engine · Ejector chiller · Energy efficiency · Fuel consumption · Exhaust gas · Scavenge air

1 Introduction

The fuel efficiency of combustion engines: gas turbines [1, 2] and gas engines [3, 4], internal combustion engines including diesel engines [5, 6] considerably depends on the temperature of sucked air, falling with its raising. Low-speed diesel engines gained the widest applications as the main ship engines [7, 8]. The specific fuel consumption of the main marine engine increases by 0.11 to 0.12 g/(kWh) for a 1 °C increase in the air temperature at the inlet to the turbocompressor unit.

To improve the engine's fuel economy, the sucked air at the turbocharger intake could be used. Heat losses accompanied by exhaust gases and scavenge air consist of a main part of the total waste heat in combustion engines [9, 10]. Therefore, the waste heat recovery chillers can be applied for engine air cooling [11, 12].

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2 Literature Review

The most used for air cooling down to 15 °C are The absorption lithium-bromide chillers (ACh). They have a high coefficient of performance (COP) of 0.7 to 0.8 [13]. But it should be noted that their placement in the engine room is problematic due to their large dimensions. At the same time, the ECh consists of heat exchangers [14], which are rationally installed in free space. The use of the ECh allows for deep air cooling but at the same time has a low COP of 0.2 to 0.35 [15, 16] and is suitable for transport applications [17, 18].

The heat of water vapor condensation with subsequent condensation of sulfuric acid vapor is used in low-temperature economizers [19]. This method makes it possible to increase thermal and hydraulic resistance [20, 21]. This is achieved because the condensed acid vapors emit ash in the exhaust gases [22], and subsequently, they settle on the heating surface [23].

The purpose of the study is to evaluate the efficiency of cooling the sucked air of marine low-speed diesel engine [24, 25] by waste heat recovery [26] in ejector chiller with account the changeable climatic conditions [27] during the voyage line.

3 Research Methodology

A low-speed MAN diesel engine 6S60MC6.1-TI (rated power 12.24 MW and continuous operating power 10 MW) [28] is chosen as an example of the main drive engine of the transport ship. The engine turbocharger sucked air cooling efficiency is estimated by specific fuel consumption reduction Δb_e gained due to the sucked air temperature drop Δt_{a}.

For air cooling in ECh, the following parameters were chosen in the research: refrigerant – R142b; refrigerant condensing temperature in the condenser to = 25–45 °C; refrigerant evaporation temperature in the evaporator-air cooler $t_0 = 5$ °C.

According to the calculations using the "mandieselturbo" software package [29], cooling turbocharger inlet air for every 1 °C of temperature drop results in a reduction of specific fuel consumption within 0.11 to 0.12 g/(kWh) for low-speed diesel engine 6S60MC6.1-TI.

The sucked air temperature drop Δt_{a} depends on the waste heat Q_{h} extracted from the engine (heat of exhaust gas, scavenge air) and the efficiency of its converting to refrigeration capacity Q_0 by the chiller, characterized by a coefficient of performance. The coefficient of performance $\zeta = Q_0/Q_{\mathrm{h}}$ is the ratio of the refrigeration capacity Q_0 received to the heat Q_{h} consumed through its extracted from the engine exhaust gas, scavenge air, and other heat sources.

The available refrigeration capacity is calculated as

$$Q_0 = Q_{\mathrm{h}}\zeta, \tag{1}$$

where Q_{h} – the heat extracted from the engine exhaust gases and scavenge air.

The available sucked air temperature drop in the air cooler Δt_{a} due to using available refrigeration capacities Q_0 is calculated following the heat balance

$$Q_0 = G_{\mathrm{a}}\xi_{\mathrm{a}}c_{\mathrm{a}}\Delta t_{\mathrm{a}}, \tag{2}$$

where G_a – air mass flow rate, kg/s; c_a – air specific heat capacity, kW/(kg·K); ξ_a – specific heat ratio.

The temperature of cooled air at the air cooler outlet:

$$t_{a2} = t_{a1} - \Delta t_a. \tag{3}$$

The current values of specific fuel consumption reduction per 1 h:

$$\Delta b_e = \Delta t_a \cdot \Delta b_{e1^\circ C}, g/\text{kWh}; \tag{4}$$

the total fuel reduction per 1 h:

$$\Delta B_e = N_s \Delta b_e, \text{ g/h}. \tag{5}$$

where $\Delta b_{e1\,^\circ C}$ – specific fuel consumption reduction referred to engine sucked air temperature drop in 1 °C, $\Delta b_{e1\,^\circ C} = \Delta b_e / \Delta t_a = 0.12$ g/(kWh·K); N_s, kW– diesel engine power.

4 Results

A circuit of the ship diesel sucking air cooling system by ECh recovering exhaust gas heat was developed (Fig. 1).

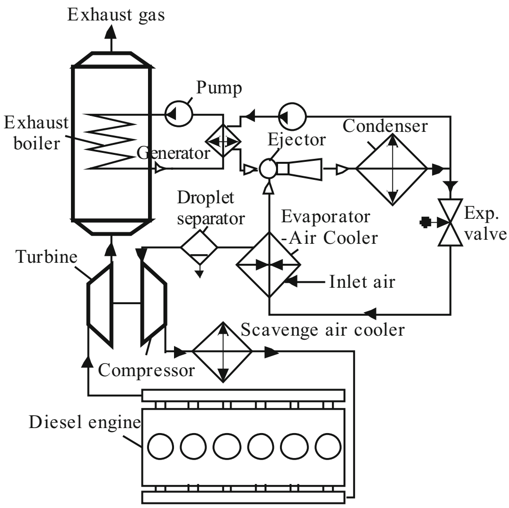


Fig. 1. A circuit of diesel engine sucking air cooling system by ECh recovering exhaust gas heat.

The generator of ECh consumes the heat of engine exhaust gas to generate the refrigerant vapor of a high pressure as a induce fluid for the ejector to compress the refrigerant vapor of low pressure, sucked from the evaporator-air cooler at the ship engine turbocharger, up to the condensing pressure of refrigerant in the condenser.

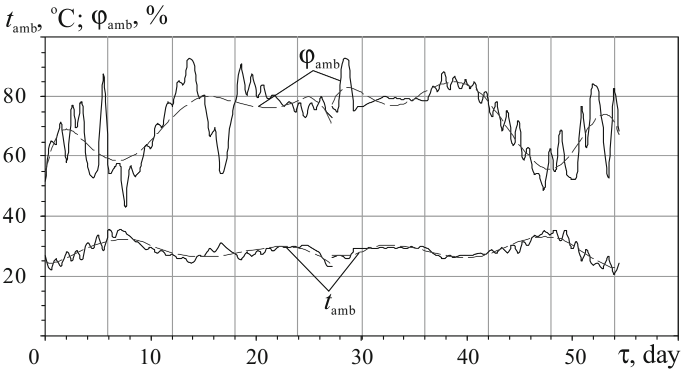


Fig. 2. Ambient relative humidity φ_{amb} and air temperature t_{amb} changes along Odesa-Yokohama and Yokohama-Odesa's voyage routes.

The changes in climatic conditions along the voyage route Odesa-Yokohama and Yokohama-Odesa (June–July) 2019 are considered (Fig. 2).

The values of ambient relative humidity φ_{amb} and air temperature t_{amb} were taken each 3 h along the voyage routes Odesa-Yokohama and Yokohama-Odesa by applying for the program "meteomanz.com" [30].

As mentioned above, the efficiency of application of engine turbocharger sucked air cooling by ECh is estimated by specific fuel consumption reduction Δb_e due to sucked air temperature drop Δt_a.

A reduction in the temperature Δt_a of air at the engine turbocharger suction and, accordingly, the effect of its cooling depends on the available heat of exhaust gas boiler (ExhB), according to Fig. 1, and the efficiency of its converting to refrigeration capacity by ECh, id est. on the coefficient of performance (COP) of ECh.

In addition, a reduction in temperature Δt_a of air in the air cooler at the ship diesel engine turbocharger suction $\Delta t_a = t_{a1} - t_{a2}$ depends on the temperature t_{a1} of the air at the inlet of the air cooler that, which in turn, depends on the way of the air suction by engine turbocharger. If the engine turbocharger sucks the air from the engine room, the temperature t_{a1} at the inlet of air cooler, id est. in the engine room the air temperature t_{ER}, surpass environing temperature by 10 °C: $t_{a1} = t_{amb} + 10$ °C. But when the engine turbocharger sucks the ambient air passing through the suction duct, the temperature t_{a1} at the inlet of an air cooler is higher than ambient temperature by 5 °C due to heat influx from engine room surroundings to suction duct: $t_{a1} = t_{amb} + 5$ °C.

A target temperature t_{a2}, which limits the depth of engine turbocharger sucked air cooling, relies on the temperature of refrigerant boiling in the evaporator-air cooler at the intake. Issuing from a desirable value of refrigerant boiling temperature about $t_0 = 7$ °C to keep a coefficient of performance (COP) of ECh about 0.3 and temperature distinction among boiling refrigerant and cooled air of about 8 °C the minimum temperature of refrigerated sucked air is accepted as $t_{a2} = 15$ °C.

The cooling of the air that enters the turbocharger from the engine room was calculated. Changes in the air temperature drop $\Delta t_a = t_{a1} - t_{a2}$ and the temperatures of cooled air t_{a2} available due to recovering exhaust gas heat by ECh for each time interval of 3 h on the voyage routes Odesa-Yokohama and Yokohama-Odesa (June–July, 2019) are presented in Fig. 3. With this, the temperature of the air sucked from the engine room was calculated as $t_{a1} = t_{amb} + 10$ °C.

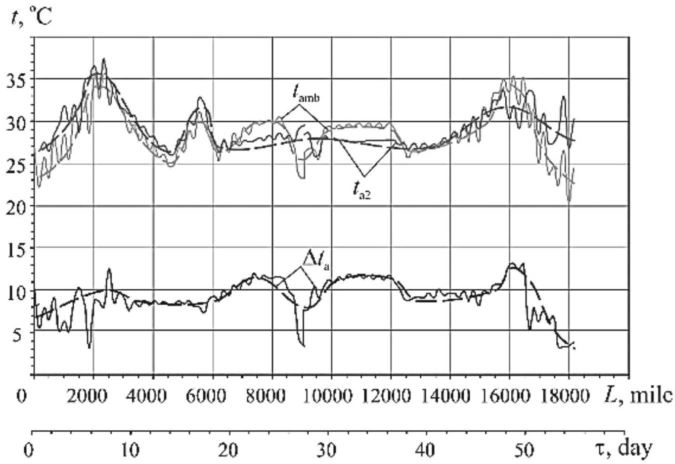


Fig. 3. Changes in air temperature drop Δt_a and temperatures of cooled air t_{a2} available due to recovering exhaust gas heat by ECh on the routes Odesa-Yokohama and Yokohama-Odesa (June–July, 2019).

As Fig. 3 shows, temperature reduction of turbocharger sucked air in the air cooler Δt_a is about 10 °C, id est. just enough to compensate the temperature increment of about 10 °C for ambient air incoming the engine room caused by heat influx from the engine room environment. The values approve of cooled air temperature t_{a2} at the air cooler outlet closed to t_{amb} (Fig. 3). Thus, when using in ECh only the heat of exhaust gas, the temperature reduction of sucked air Δt_a in the air cooler is not enough for its reducing to the minimum value of about 15 °C, which might be achieved at boiling refrigerant temperature $t_0 = 7$ °C.

The results of calculation of fuel efficiency enhancement for marine diesel engine 6S60MC6.1-TI due to its turbocharger sucked air cooling by ECh, recovering the heat of exhaust gas, on the routes Odesa-Yokohama and Yokohama-Odesa are presented in Fig. 4. A reduction of diesel engine specific fuel consumption Δb_e due to turbocharger sucked air cooling was calculated by applying the program "mandieselturbo" [29].

As Fig. 4 shows, due to the cooling of the intake air by ECh while using the heat of the exhaust gases, the reduction in specific consumption will be $\Delta b_e = 1.0 \ldots 1.2$ g/(kW · h) , and absolute fuel-saving ΔB_e during the voyage routes Odesa-Yokohama and Yokohama-Odesa, June–July 2019, is about 15 t and relative fuel saving $\Delta \overline{B}_e$ is about 0.7%, id est. comparatively small. To enhance further fuel efficiency due to deeper engine sucked air cooling down to the temperature t_{a2} of about 15 °C, the additional heat, for instance of scavenging air, is to be used.

A developed scheme for cooling the charge air of a marine engine in the ECh with heat recovery from the charge air and exhaust gases is shown in Fig. 5.

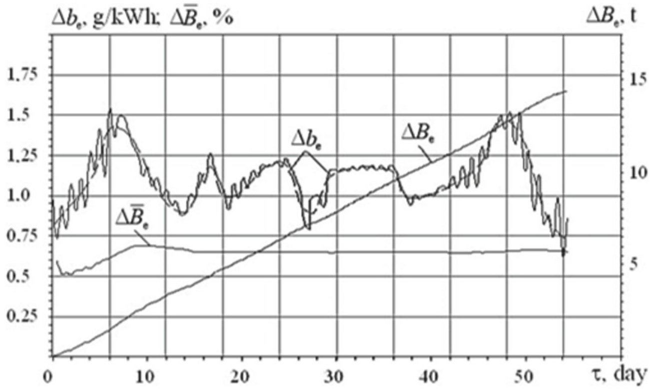


Fig. 4. Current values of specific fuel consumption reduction Δb_{e} and summarized fuel-saving ΔB_e, t, for two routs Odesa-Yokohama and Yokohama-Odesa and its relative value $\Delta \overline{B}_{\mathrm{e}}$, %, as related to the total engine fuel consumption due to cooling air sucked by turbocharger from the engine room and recovering the heat of exhaust gas.

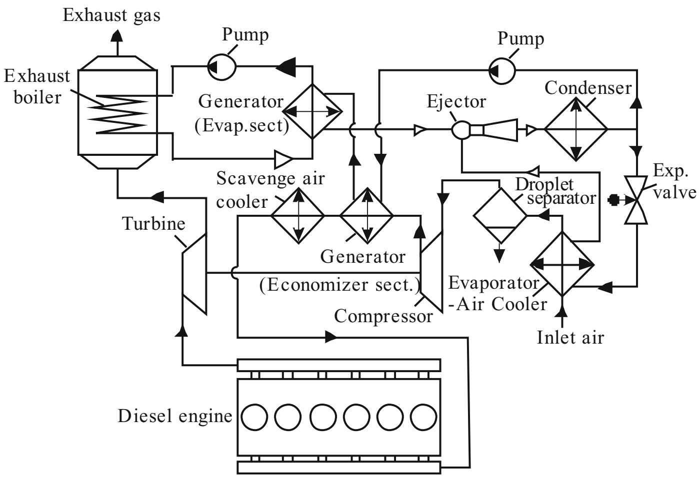


Fig. 5. A circuit of engine turbocharger sucked air cooling system with ECh recovering the exhaust gas and scavenging air heat.

With this, a scavenge air heat is used in the economizer section of the refrigerant generator to increase the temperature of liquid refrigerant from condenser to the temperature of its boiling in the evaporative section of the generator by using the heat of exhaust gas.

Values of temperature reduction $\Delta t_{\mathrm{a}}'$ and $\Delta t_{\mathrm{a}}''$ in the air cooler for the air sucked from the engine room when the temperature t_{a1} at the inlet of air cooler $t_{\mathrm{a1}} = t_{\mathrm{amb}} + 10$ °C and for the ambient air passing through a suction duct with the temperature $t_{\mathrm{a1}} = t_{\mathrm{amb}} + 5$ are presented in Fig. 6.

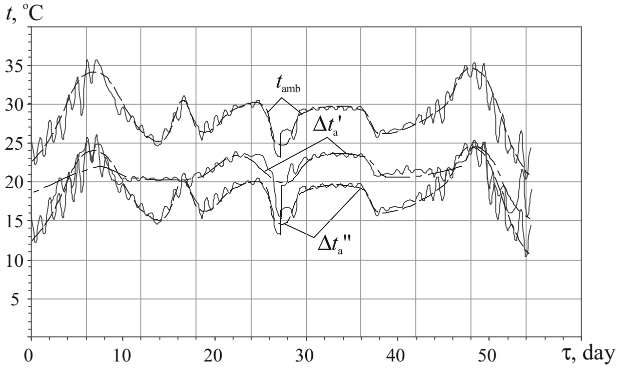
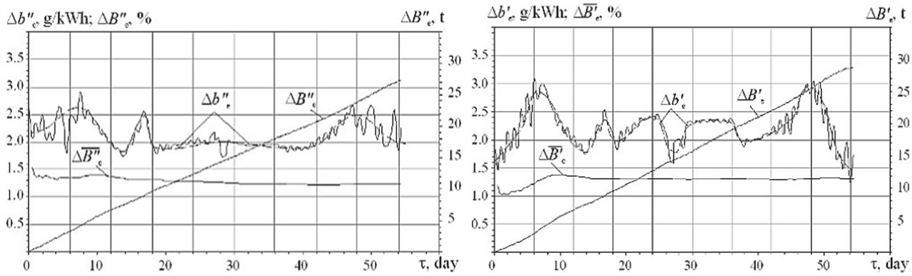


Fig. 6. Air temperature reduction Δt_a in the engine sucked air cooler due to recovering the heat of exhaust gas and scavenge air on the routes Odesa-Yokohama and Yokohama-Odesa (June–July, 2019): $\Delta t_a = t_{a1} - \Delta t_a$; Δt_a–for $t_{a1} = t_{amb} + 10$ C; $\Delta t_a''$–for $t_{a1} = t_{amb} + 5$ C.

The results of calculations of fuel efficiency enhancement of marine diesel engine 6S60MC6.1-TI due to its turbocharger sucked air cooling by ejector chiller, recovering the heat of exhaust gas and scavenge air, on the routes Odesa-Yokohama and Yokohama-Odesa are presented in Fig. 7.



(a) (b)

Fig. 7. Current values of specific fuel consumption reduction Δb_e and summarized fuel-saving ΔB_e, t, for two routs Odesa-Yokohama and Yokohama-Odesa and its relative value $\Delta \overline{B}_e$, %, as related to the total engine fuel consumption: $a - \Delta b_e''$, $\Delta B_e''$,$\Delta \overline{B}_e''$; $t_{a1} = t_{amb} + 5$ °C; $b - \Delta b_e'$, $\Delta B_e'$, $\Delta \overline{B}_e'$; $t_{a1} = t_{amb} + 10$ °C; diesel engine power $N_s = 10$ MW.

As one can see, heat recovery of charge air and exhaust gases in the ejector chiller by cooling the intake air of the turbocharger makes it possible to reduce the specific fuel consumption on the routes Odesa-Yokohama and Yokohama-Odesa is $\Delta b_e = 2.0\ldots2.5$ g/(kW · h). With this summarized, total fuel saving is $\Delta B_e = 26\ldots28$ t, and its relative value $\Delta \overline{B}_e$ is about 1.3% for marine diesel engine 6S60MC6.1-TI.

To gain engine more fuel-saving through deeper turbocharger sucked air cooling to the temperature 10 °C and lower the two-stage cooling in water-refrigerant air cooler by applying absorption-ejector chillers with higher COP might be realized.

5 Conclusions

The efficiency of the waste heat recovery ejector chiller application for cooling the intake air of marine diesel engine has been analyzed for actual changeable climatic conditions on the trip line Odesa-Yokohama-Odesa.

The efficiency of cooling the sucked air of marine diesel engine by waste heat recovery in ejector chiller with account the changeable climatic conditions during the voyage line Odesa-Yokohama-Odesa was analyzed.

The ejector chiller was chosen due to the simplest design that enables its accessible location aboard the ship. But its coefficient of performance COP is not high: of 0.2 to 0.3, which requires enlarged heat consumption.

The application of an ejector chiller provides reducing the engine intake air temperature by about 10 °C with a corresponding decrease of specific fuel consumption by 1.0…1.2 g/(kWh) when using only the heat of exhaust gas. The fuel reduction of the marine diesel engine is increased practically twice when the ejector chiller uses additional heat of scavenging air. The corresponding schemes of the systems for cooling the air at the turbocharger suction by ejector chiller are proposed.

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

To provide a more profound 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.

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