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Cooling intake air of marine engine with water-fuel emulsion combustion by ejector chiller

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Abstract. The fuel efficiency of cooling air at the inlet of marine low speed diesel engine with water-fuel emulsion combustion by ejector chiller utilizing the heat of exhaust gas along the route line Mariupol–Amsterdam–Mariupol was estimated. The values of available refrigeration capacity of ejector chiller, engine intake air temperature drop and corresponding decrease in specific fuel consumption of the main diesel engine at varying climatic conditions along the route line were evaluated. Their values for water-fuel emulsion were compared with conventional fuel oil combustion.

1 Introduction

Low speed diesel engines are the most widespread as ship main engines [1]. The variation in ambient air temperatures along the route line influences the fuel efficiency of the engines. Thus, an increase in engine intake air temperature by 10 ºC causes specific fuel consumption increase by 1.1 to 1.2 g/(kWh) [2]. In the most cases at the main engine load above 50% an exhaust gas heat utilized by the exhaust gas boiler exceeds the ship steam demand. It is reasonably to use "surplus" exhaust heat by ejector chiller (ECh) as the most simple in design [3, 4] for engine intake air cooling (EIAC) to improve fuel efficiency [5, 6].

The efficiency of water-fuel emulsion (WFE) combustion is increased compared with fuel oil combustion due to microexplosions of WFE droplets, that intensifies the processes of mixing fuel with air and combustion in the whole. With this the enhanced fragmentation of WFE droplets leads to reduction of the particle emission.

Despite the increased humidifying the surface with an increase of the water content to about 10 %, due to enhanced fragmentation of WFE droplets and entrainment of small particles by the exhaust gas flow, the intensity of their deposition decreases. Thus, the deposits can be easily removed (e.g. by washing).

2 Literature review

A lot of researches are devoted to enhancing the fuel efficiency of combustion engines [7, 8] by cooling cyclic air [9, 10] in waste heat recovery chillers [11]. The absorption lithium-bromide chillers (ACh) are the most widely used and provide cooling air to about 15 ºC with a high coefficient of performance COP of 0.7 to 0.8. But because of large sizes the ACh units mounting in engine room is problematical. The ECh consist of heat exchangers [12] suitable for mounting in free spaces. They enables to deep cool air but with a low COP of 0.2 to 0.3 [13] and quite suitable for railway [14, 15] and marine [16, 17] applications.

The heat loss with exhaust gases represents a high part of the total waste heat in combustion engines [18, 19]. Authors [20] introduced the technique of exhaust gas heat utilization in gas cogeneration unit based on absorption heat exchange. The low-temperature economizers [21] or low-pressure economizers [22] use a condensation heat of vapors of sulfuric acid and water in exhaust gas. The condensed acid vapor glues the ash in exhaust gas, and adheres on heating surface [23], which increases the hydraulic and thermal resistance [24], affecting the reliable and economical operation. 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 % [25], in the exhaust gases the concentration of nitrogen oxides is reduced in 1.4 to 3.1 times [26], the concentration of CO – in 1.3 to 1.5 times [27], smoke – in 1.3 to 2.4 times [28]. The influence of WFE combustion process parameters in low capacity boiler on the level of formation of nitrogen oxides, carbon monoxide and soot was studied [27]. The analysis of literary sources shows, that there is no quantitative data of low-temperature corrosion [29, 30] (LTC intensity of 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

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gas flow and decreases their deposition on condensing/heating economizer surfaces and their thermal resistance as result [31, 32].

The aim of the research is to develop a marine engine intake air cooling (EIAC) system with deep utilization of the exhaust gas heat potential enlarged due to using the heat of low-temperature condensation of vapors of sulfuric acid and water when WFE combustion as a novel trend in ship waste heat recovery.

The research tasks:

• to carry out the experimental research of low-temperature condensation economizer to receive the data on corrosion when WFE combustion;

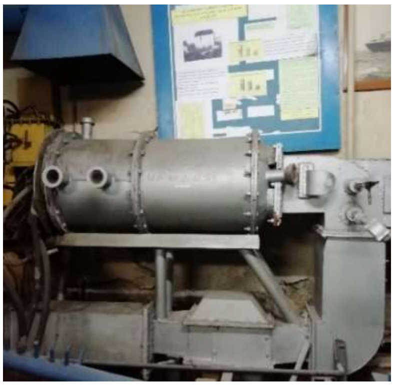
• to develop a marine engine intake air cooling system with deep utilization of the exhaust gas heat when WFE combustion;

• to estimate the fuel efficiency of cooling the intake air of marine low speed diesel engine with WFE combustion by ECh compared with fuel oil combustion on the ship route line.

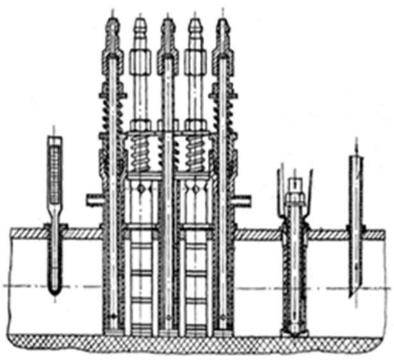
3 Research methodology

3.1 Experimental research

Investigations of corrosion intensity of low-temperature condensation economizer were carried out on an experimental setup (Fig. 1, a) with fuel oil and WFE based on this fuel oil combustion [33, 34] with different water content with an almost constant excess air ratio.



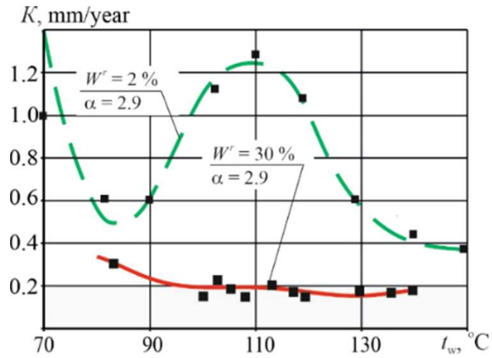
a



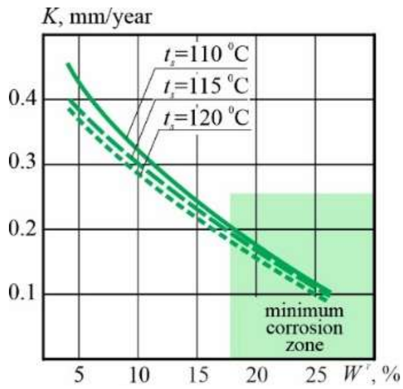
b

Fig.1. General view of the experimental setup (a) and tube-samples of low-temperature condensation economizer (b).

Based on experimental studies the minimum value of wall temperature is defined (Fig. 2, a), at which the permissible speed of low-temperature corrosion at a level of 0.25 mm/year and the minimum value of exhaust gas temperature at exit from EGB are ensured (Fig. 2, b). Fig. 2, b show that the smallest values of corrosion intensity are observed for large values of water content in water-fuel emulsion 30 %.



a



b

Fig. 2. Dependences of corrosion rate of low-temperature condensation economizer on the wall temperature $K = f(t_w)$ (a) and water content W^r in emulsion (b).

The range of wall temperature within 90°C down to 70°C of low-temperature condensation economizer (LTCE) safe operation is determined, which reveals the potential for deep exhaut gas heat utilization as compared with 150°C down to 130°C for conventional fuel oil combustion.

3.2 Theoretical research

A schema of cooling intake ambient air at the suction of turbocharger of diesel engine by utilizing the heat of exhaust gas in evaporative and economizer section of generator is shown in Fig. 3. The ejector refrigeration machine 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.

As an example of transport vessel a bulk carrier with low speed diesel engine 5S60ME-C10.5-TIII as the main engine [2] is considered: nominal power N_n =

12450 kW and continuous service power N_s = 10580 kW. A decrease in temperature of air Δt_a at the engine inlet due to its cooling by ECh and, accordingly, effect from its application depends on the heat of steam produced by exhaust heat utilization steam boiler (Exh.SB), that remains after covering all the heat requirements aboard ship. During warm time steam consumption on the transport ship is approximately 25 % of steam productivity of exhaust boiler, i.e. 75 % of steam produced can be used in ECh for cooling of air at the inlet of diesel engine turbocharger.

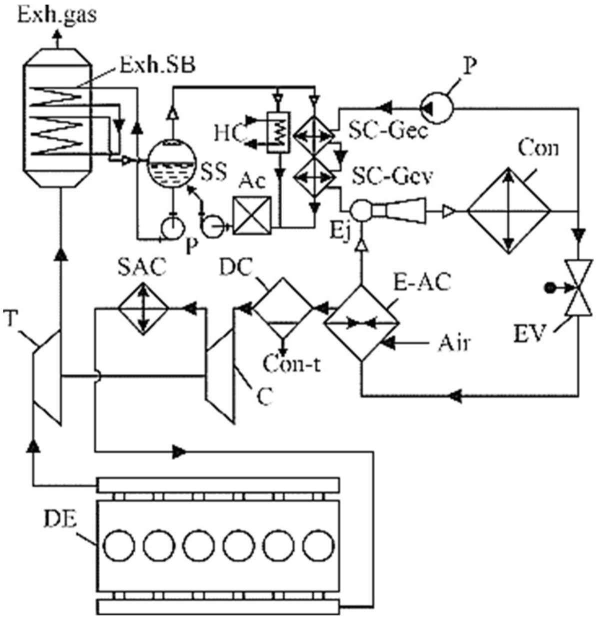


Fig. 3. Schema of system for cooling intake air at the suction of turbocharger by utilizing the heat of exhaust gas: DE – diesel engine; T – turbine, C – compressor of turbocharger; SAC – scavenge air cooler; Exh.SB – exhaust gas steam boiler; SC-Gev – steam condenser-evaporative section of generator; Gec – economizer section of 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. CE – condensation economizer.

Besides, decrease in temperature of air in the air cooler at the inlet of the engine $\Delta t_a = t_{a1} - t_{a2}$ depends on the 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 ºC [2].

The temperature t_{a2} which limits depth of cooling air in the air cooler, in turn, depends on the temperature of boiling refrigerant. In case of application of ECh a refrigerant R142b can be used. A temperature of boiling R142b in the evaporator-air cooler is desirable about t_0 = 7 ºC.

The minimum difference of temperatures between cooled air and boiling refrigerant can be accepted 8 ºC. Taking into account these values a depth of cooling of air in the air cooler is limited to minimum temperature $t_{a2} = t_0 + 8 =$ 15 ºC. A refrigeration capacity of ECh Q_0 is defined from available exhaust gas heat Q_G as $Q_0 = \zeta Q_G$, where ζ – coefficient of performance of ECh ζ = 0.30…0.35.

4 Results

A route line Mariupol-Amsterdam-Mariupol is considered. Values of temperature t and relative humidity φ of ambient air, and also sea water temperature t_w during route were used according to the meteocenter data, fixed each 3 hours. Values of moist content d_a following them were calculated (Fig. 4).

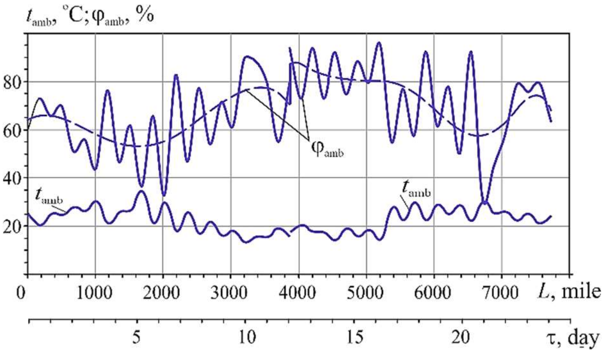


Fig. 4. Variation of ambient air temperature t_{amb} , relative humidity φ_{amb} and absolute humidity d_a , on the route line Mariupol-Amsterdam-Mariupol (22.07.2019…3.08.2019).

As one can see, during summer route the temperature of ambient air t_{amb} changes from 15…20 ºC in middle widths to 25…30 ºC in southern widths (accordingly air temperature in engine room is 10 ºC higher), and relative humidity of air φ_{amb} – from 50…60 % in Mediterranean sea to 80…90 % at Northwest Europe.

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 diesel engine from the air temperature at the cooler inlet (in engine room) $t_{a1} = t_{amb} + 10$ ºC to the outlet air temperature t_{a2} were calculated.

In the case of using the enlarged exhaust gas heat when WFA combustion the values of the available cooling capacity Q_{0WFA} of ECh is higher compared with Q_0 for fuel oil combustion due to deeper exhaust gas heat utilization to lowered temperatures t_{exh2} = 90…110 ºC compared with t_{exh2} = 150…170 ºC (Fig. 5).

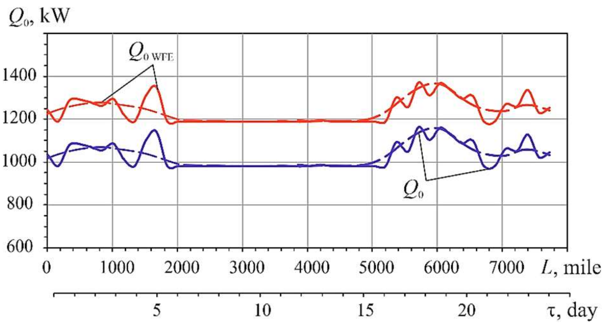


Fig.5. The available cooling capacities of ECh: Q_0 – fuel oil; $Q_{0\,WFE}$ – WFE.

Accordingly the values of air temperature drop at the engine inlet Δt_a when WFE combustion Δt_{aWFE} are higher compared with oil fuel Δt_a (Fig.6).

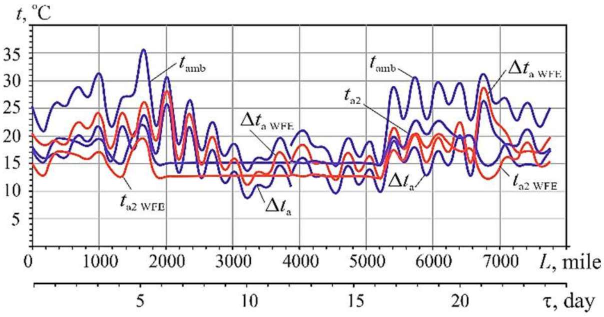


Fig. 6. The values of engine intake air temperature drop: Δt_a – fuel oil; Δt_a – WFE.

As it is shown, decrease in temperature of air in the air cooler of ECh, utilizing a heat of exhaust gas (schema in Fig. 3) Δt_a = 10…20 ºC when oil fuel combustion whereas Δt_a = 15…25 ºC for WFE.

Decrease in specific fuel consumption Δb_e, g/(kW·h), of diesel engine, saving of fuel consumption in absolute B_e, t, and relative B'_e, %, values on the route line Mariupol-Amsterdam-Mariupol due to cooling intake air by ejector refrigeration machine, using exhaust gas heat only (schema in Fig. 1), and by sea water, calculated by program "mandieselturbo" [2], are shown in Fig. 7.

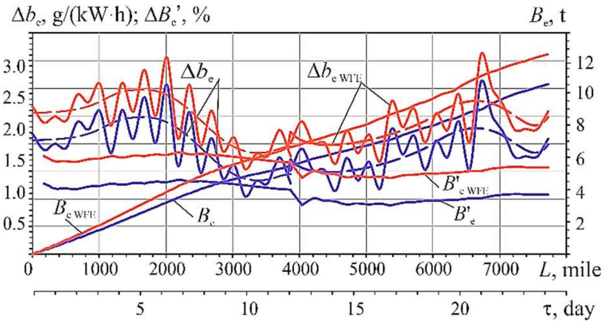


Fig. 7. Decrease of specific fuel consumption Δb_e, g/(kWh), fuel saving in absolute B_e, t, and relative B'_e, %, values on the route line Mariupol-Amsterdam-Mariupol (22.07.2019…3.08.2019): Δb_e, B_e and B'_e – oil fuel; $\Delta b_{e\ WFE}$, $B_{e\ WFE}$ and $B'_{e\ WFE}$ – WFE.

As one can see, a decrease of specific fuel consumption due to intake air cooling by ECh, using exhaust gas heat, Δb_e = 1.2…2.5 g/(kW·h), absolute fuel saving $B_e \approx$ 10 t and relative fuel saving B'_e = 1.2…1.3 % for oil fuel combustion, whereas Δb_e = 1.2…2.5 g/(kW·h), $B_{eWFE} \approx$ 10 t and B'_{eWFE} = 1.2…1.3 % for WFE combustion in diesel engine5S60ME-C10.5-TIII on the route line Mariupol-Amsterdam-Mariupol (22.07.2019…3.08.2019).

The further reserves to increase fuel saving by about 1.5 times consist in complex engine intake and scavenge air cooling with using additional heat of scavenge air in ECh or in combined absorption-ejector chiller wit ACh as a high-temperature stage to cool the air to about 15 ºC and its deep subcooling to 10 ºC and lower in the case of engine intake air.

5 Conclusions

A marine engine intake air cooling system with deep utilization of the exhaust gas heat potential enlarged due to using the heat of low-temperature condensation of vapors of sulfuric acid and water in economizer section of ejector chiller generator when water-fuel emulsion combustion is developed as a novel trend in ship waste heat recovery.

The results of experimental research of low-temperature condensation economizer approved the appropriate corrosion rate when water-fuel emulsion combustion and good perspective for their application in ship waste heat recovery.

The application of developed diesel engine intake air cooling system provides 1.3 to 1.7 % fuel saving on the route line Mariupol-Amsterdam-Mariupol and reveals a good perspectives for increasing the fuel saving by 1.5 times due to complex engine intake and scavenge air cooling through using additional heat of scavenge air in ECh or in combined absorption-ejector chiller.

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