Research of the Aerothermopressor Cooling System of Charge Air of a Marine Internal Combustion Engine Under Variable Climatic Conditions of Operation

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Abstract. Principle of charge air cooling of the internal combustion engine with an aerothermopressor is proposed. It is implemented on the transport ship regular line. Arising thermogasdynamic compression allows increasing the air pressure. The aerothermopressor application in the charge air cooling systems makes it possible to reduce the power consumed by compressors, Nc by 3–10%, thereby the engine power is increased by 1–3% and the specific fuel consumption is decreased by 2–4%. It is established that in case of increasing the ambient air temperature tamb at the turbocharger input the effect from the aerothermopressor used for cooling of the charge air is increased: the turbocharger power reduction ΔN_C is increased with a corresponding increase in engine power and a decrease in specific fuel consumption. The relative (related to air flow) water mass flow is determined, which has to be injected at completely evaporated in a thermal overpressure: 0.02–0.05 (2–5%).

Keywords: Thermogasdynamic compression · Cooling system · Charge air · Specific fuel consumption

1 Introduction

The marine diesel engines are applied as the main engine in the modern ship power plants compound. On transport, industrial, support and other types of ships, small, medium and high-speed diesel engines with supercharging are used. The turbocharger (TC) efficiency is significantly influenced by the input air parameters, what in turn leads to a fuel efficiency deterioration of the internal combustion engine (ICE).

For modern power plants based on ICE, the power increase is carried out by increasing the work output of expanding the combustion products with decreasing, in turn, the power consumption for compression of the working medium. This is achieved by cooling the charge air, which leads to a decrease in the ICE specific fuel consumption.

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2 Literature Review

Using the charge air cooling allows increasing1 the ICE power by 2.5–3.0% for every 10 °C of the air temperature reducing [1, 2]. Turbochargers of modern ship's ICE have relatively high compression ratio π_c = 2–4 [2–5]. In this case, the turbocharger turbine uses almost the whole heat drop of ICE exhaust gases, that is, the turbine and compressor power are equal to each other $N_c = N_t$. It is possible to get additional work by reducing the compression operation and to unload the turbine [6]. This technology with jet pump technology has been used in plants for the combined production of energy and has made it possible to increase the efficiency of a power plant to 2% [7–14]. One of the modern ways of power increase and ICE fuel consumption reduce is using of contact charge air cooling by water injection. However, there is a significant length of the evaporation zone with this, which is constructively difficult to implement, and, moreover, may lead to water drops hitting into the ICE turbocharger.

Using of water to improve engine performance has been applied almost since their creation. Water injection using allows [1, 2, 5, 15]: reducing the combustion knock probability in the engines with spark firing; reducing heat loss in the cooling system, by reducing the cycle integral temperature; maximally realizing the exhaust gases thermal potential, due to the increase of the working medium mass; reducing emissions of NOx.

The MAN company investigated the possibility of charge air humidifying to reduce NOx emissions. For this purpose, the German company Munters Euroform developed a system called Humid Air Motor (HAM), which allowed increasing the air humidity to 99% [1, 16]. The system test showed that the NOx was reduced by 70–80% on the operating mode. This is explained by the fact that the high steam content in the charge air reduces the maximum temperature in the combustion chamber.

At an early stage of developments of the Wärtsilä company, air saturation device in the combustion space was introduced – Combustion Air Saturation System (CASS). The water mist sprayed through the nozzles directly into the charge airflow immediately after the turbocharger. As follows from Wärtsilä reports, this provided a NOx reduction to 3 g/(kWh) [17, 18].

In the next developments Wärtsilä went on the way of instant water injection into the combustion chamber. The water mass injection (15–70%) of cyclic fuel supply allowrf obtaining a NOx content reduction by 50%, while the efficiency loss did not overgrow 2–3 g/(kWh). An injector with two nozzle tips with separate fuel injection and water was developed for the direct injection, as well as a water supply system to the nozzle.

Mitsubishi Heavy Industries has investigated split fuel and water injection (SFWI) through a single sprayer equipped with a special dispensing valve allowing to fill the inner cage seated to the nozzle needle in the periods between water injections. During injection, fuel, water and fuel are displaced consequently, forming clearly defined layers in the spray swatch [19, 20].

The disadvantage of all the considered methods is that the water injection reduces the integral temperature of the cycle in the combustion space and, as a consequence, the working process efficiency is decreased. Another effective method of water use for increasing the fuel efficiency, reducing NOx emissions and the pollution specific weight in heat exchangers utilizers is the water-oil emulsions using [21].

One of the promising ways of contact air cooling is to use of thermogasdynamic compression. This process consists of the gas pressure increase which occurs in the process of instantaneous evaporation of water injected into the air flow, accelerated to a speed close to sound. For water evaporation the heat is taken from the charge air away, as a result air temperature is decreased [22–24]. The device, in which thermogasdynamic compression is applied, is called an aerothermopressor.

The aerothermopressor is a jet device, which in size greatly wins compared with other coolers of surficial and contact type. Due to the joint action of turbulization accelerated air flow and instantaneous evaporation there is an effective atomization of injected water [25]. Using of the aerothermopressor in the turbocharging system of the internal combustion engine is a promising direction. It allows increasing the heat engine efficiency as it is expected to achieve a triple effect: charge air cooling; increase of charge air pressure; reduction of nitrogen oxides emissions NO_x (environmental humidification) [26].

Climatic conditions changing of the ship power plants operation based on the ICE requires the rational organization of thermogasdynamic compression processes in the aerothermopressor and the rational heat load magnitude determination of the device, which will ensure maximum fuel economy.

The charge air cooling with an aerothermopressor will increase the fuel and energy efficiency of the marine internal combustion engine in a wide range of climatic conditions during the regular ship line. This can be achieved by effectively charge air cooling in front of the engine receiver and reducing the compression work in the compressor. In addition, the maximum temperature can be decreased in the engine cycle, and, as a result, NOx emissions can be reduced.

3 Research Methodology

Hydrometeorological parameters changing significantly affects the indicators change of the main engine operation. In order to take into account these changes, the ship regular line was determined and a method for obtaining climatic (hydrometeorological) data was developed for it. For passenger cruise yacht “Hanse Explorer” with the chosen main engine 8L20 the main task is cruises and expeditions to different corners of the World. The variant cruise line from the port of Odesa (Ukraine) to the port of Fortaleza (Brazil) is considered.

To obtain the necessary climatic data, a search and processing method on climatic and hydrometeorological data was developed. The study considered the ship power plant of the passenger yacht with the main engine of Wärtsilä, model 8L20 (Ne = 1360 kW, n = 1000 min^{-1}) on the route Odesa (Ukraine) – Fortaleza (Brazil) (L = 5250 miles, from 02.01.2018 to 17.01.2018 – 376 h, average speed of the vessel is 14.0 knots (25.9 km/h)).

The main climatic data were obtained: relative humidity (φ_{oa}), outside air temperature (t_{oa}), pressure (p_{oa}) and seawater temperature (t_{sw}). For receiving this data it was necessary to obtain the geographical coordinates of the ship at the measure time.

Based on the received data, corresponding schedules of climatic indicators changes were constructed during the Odesa-Fortaleza ship line (Fig. 1). The parameters of the operation of medium-speed marine diesel engines were calculated under varying climatic conditions during the voyage using the Diesel RK program [27].

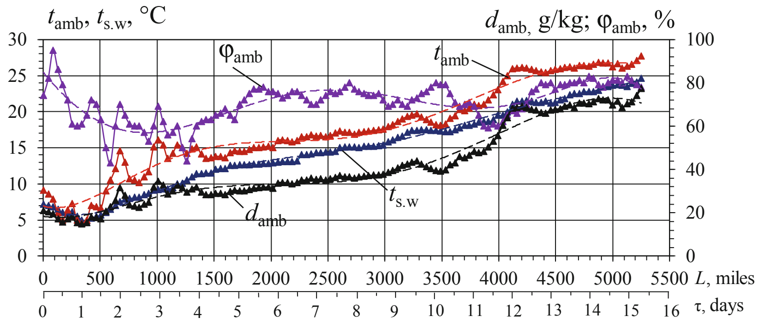

Fig. 1. Chart of the dependence of changes in climatic indicators on the Odesa-Fortaleza route from 02.01.2018 to 17.01.2018: t_{amb} – air temperature; $t_{s.w}$ – seawater temperature; φ_{amb} – air relative humidity; d_{amb} – moisture content of air; L – length of the route; τ – route time.

The calculation of the characteristics of the aerothermopressor (air pressure P_a, air temperature T_a, air speed w_{air}, water velocity w_w, etc.) and its main geometrical parameters of the flow part under the climatic conditions of navigation of the ship, as well as operational features of the main marine engine were carried out according to the methods [22, 24, 26, 28]. In the calculation considered the pressure loss in the nozzle (confuser), the working chamber, the diffuser, as well as the frontal resistance of drops of injected water. The hydraulic nozzle characteristics for water injection were also taken into account: the nozzle torch angle was 60–80°; nozzle torch length – 100 mm; droplets diameter at the confuser outlet – 20–35 μm. Calculation of aerothermopressor parameters was carried out taking into account calculation of contact cooling processes for moist air [29].

According to the above equations, a software package has been developed for calculating the aerothermopressor cooling system of ship ICE charge air.

4 Results

The basis for the parameters calculation of thermogasdynamic compression is the mathematical model included the description of the processes taking place in the aerothermopressor (device, the principle of which is the effect of thermogasdynamic compression), compression processes in the turbocharger and processes of heat transfer in the air cooler. The models of these processes are based on the laws of energy conservation, mass and heat balances, based on the equations of heat transfer and the state of working mediums.

An intense heat supply causes the aerodynamic resistance increase, and heat dissipation leads to the aerodynamic resistance reduction. With intensive heat removal and the corresponding work process organization, it is possible not only a significant resistance reduction, but also an increase of gas flow total pressure. In this case, due to the prevailing thermal action (heat removal), the gas flow is pressed. Device, in which the total gas pressure increases by the removing heat from the gas flow, is called the aerothermopressor (thermopressor) (Fig. 2) [24, 28, 30].

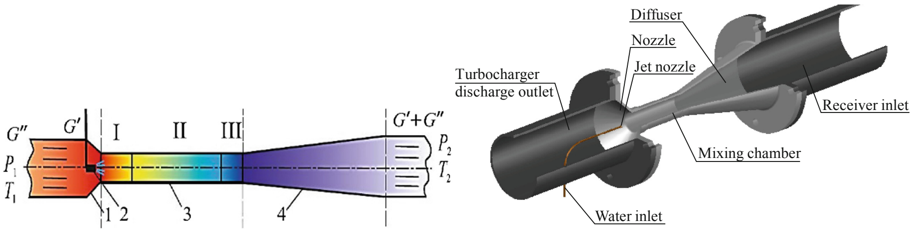

Fig. 2. Basic elements and modes of the aerothermopressor operation (a) and 3-D model of the aerothermopressor for the engine cooling system (b): G′, G″ – water and air mass rates; P_1, P_2 – inlet and outlet air pressure; T_1, T_2 – inlet and outlet air temperature; 1 – nozzle (confuser); 2 – water spray nozzle; 3 – mixing chamber (evaporator); 4 – diffuser.

The Mach number M determines the energy value of gas and vapor-gas flows. At low numbers M, the rate of evaporation is small, which leads to increase the evaporation section length, in accordance with the rise of energy losses on friction. At higher numbers M, the more intense evaporation occurs on a smaller section along the evaporation section length with relatively less frictional losses. The mean diameter of the drop is decreased and there is more intense water evaporation on the smaller pipeline length, with relatively less frictional losses.

There are the following modes of working processes in the flow part of the aerothermopressor. Modes: I – the influence of the frontal resistance of liquid droplets is dominant; II – evaporation process (thermogasdynamic compression); III – superficial friction prevails (pressure is additionally increased, velocity is decreased).

A three-circuit cooling system for the main engine is usually used on the modern ships. Such a scheme, as well as the calculated data for the cooling system of the main engine 8L20 of Wärtsilä for made under standard conditions according to ISO.

It is advisable to install the aerothermopressor in the circuit of the three-circuit cooling system immediately after the charge air compressor (Fig. 3).

Since the temperature of the charge air behind the aerothermopressor is 55–70 °C (Fig. 3), it is proposed to install an air cooler after the aerothermopressor. A drip trap installation will ensure safety against the ingress of water droplets into engine cylinders. The parameters of air, exhaust gases, etc. at the characteristic points of the engine cooling system also are shown in Fig. 3.

The aerothermopressor pressure increase ΔP_{tp} greatly depends on the cooling temperature decrease Δt_{tp}, and therefore the inlet air temperature t_{tp1}. The temperature in front of the aerothermopressor corresponds to the air temperature at the turbocharger

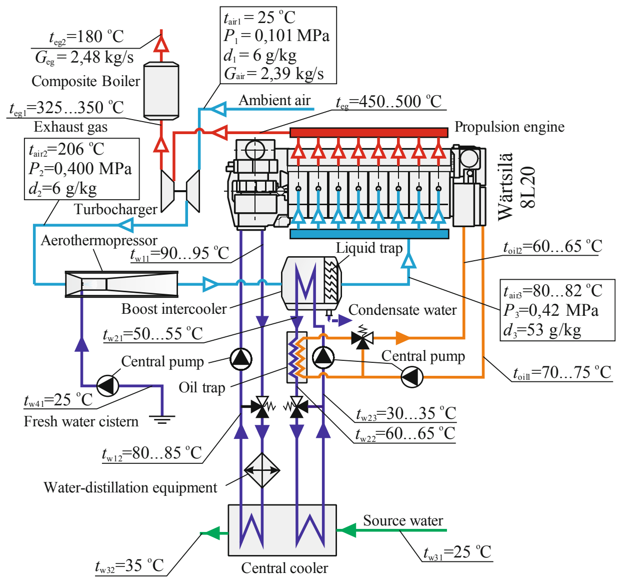

Fig. 3. The three-circuit cooling system of the 8L20 medium-speed marine engine from "Wärtsilä" by using the aerothermopressor.

injection (t_{tp1} = 150–240 °C). The temperature at TC is higher, the higher the suction temperature and the pressure ratio increase in TC π_c. At the minimum temperature at the aerothermopressor outlet t_{tp2} was taken at the temperature 2–3 °C above the temperature of the condensing point, hence the high air temperature is t_{tp2} = 60–92 °C.

Simulation of the charge air cooling system operation is shown that applied aerothermopressor provides (Fig. 4, 5) air cooling from the temperature behind the compressor t_{tp1} = 180–210 °C (π_c = 4.2) to the temperature t_{tp2} = 65–75 °C depending on the hydrometeorological conditions during the voyage. The smaller temperatures correspond to a lower value of the ambient air at the compressor inlet and a higher value of the relative air humidity φ. That is, air is cooled by the amount Δt_{tp} = 115–135 °C. The air temperature decrease in the aerothermopressor is accompanied by pressure increase as a result of thermogasdynamic compression. At the same time, the pressure increase is ΔP_{tp} = 4–9% or 17–38 kPa (taking into account the losses on aerodynamic drag in the flow parts of the aerothermopressor). Air cooling occurs until the air is completely saturated with water vapor, i.e., φ_{tp} = 100%, while the moisture content of air at the outlet from the aerothermopressor is quite large and amounts to d_{tp} = 20–80 g/kg. The thermal load on the aerothermopressor corresponds to the thermal load of the regular air cooler and is Q_{tp} = 380–480 kW. The amount of liquid (water) that is injected into the air is G_w = 0.15–0.18 kg/s (2–5% of the air flow compressed in the compressor).

When the pressure is increased in the aerothermopressor while simultaneously lowering the temperature, the compressive work in the compressor is reduced, and accordingly the compressor capacity is decreased by ΔN_c = 10–40 kW (Fig. 6).

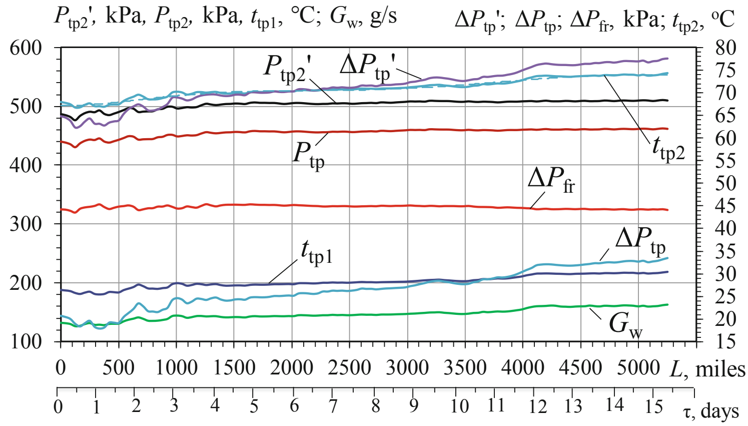

Fig. 4. Dependences of input and output air temperatures from the aerothermopressor t_{tp1}, t_{tp2}, water consumption G_w, pressures at the dry aerothermopressor outlet P_{tp2}' and aerothermopressor outlet P_{tp2}, pressure increase in the dry aerothermopressor $\Delta P_{tp}'$, pressure increase in the aerothermopressor ΔP_{tp}, frictional losses ΔP_{fr} on the length of Odesa-Fortaleza.

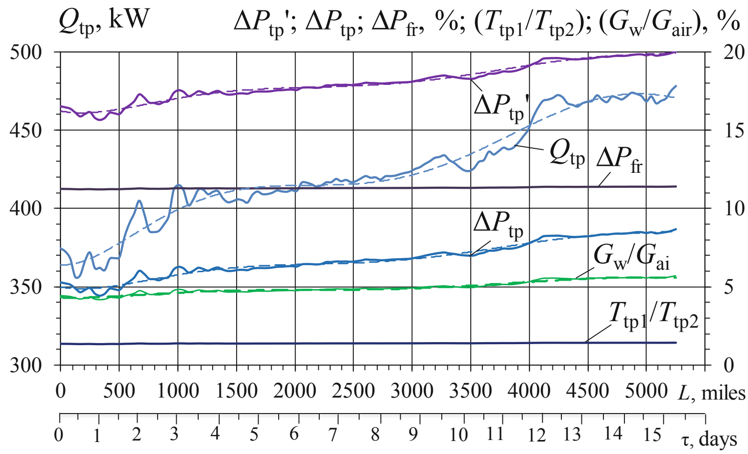

Fig. 5. Dependences of aerothermopressor heat load Q_{tp}, relative water consumption (G_w/G_{air}), pressure increases in the dry aerothermopressor $\Delta P_{tp}'$ and in the aerothermopressor ΔP_{tp}, frictional losses ΔP_{fr}, temperature rate (T_{tp1}/T_{tp2}) on the length of Odesa-Fortaleza.

Calculation of main engine parameters was carried out with Diesel-RK program complex, taking into account the change in the corresponding air parameters at the entrance to engine cylinders, which in turn affected the performance of engine units (Fig. 7). Calculation of engine parameters shows that using aerothermopressor cooling allows reducing the specific fuel consumption during the voyage by Δg_e = 4–8 g/(kW h) (2–4%) with the corresponding increase in engine power by ΔN_e = 1–3%.

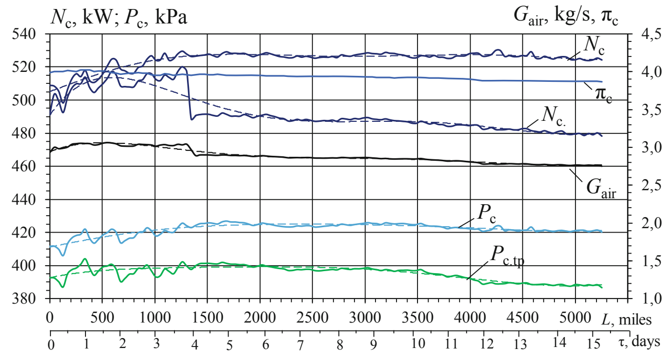

Fig. 6. Dependences of compressor power N_c and compressor power of aerothermopressor system $N_{c.tp}$, air consumption G_{air}, total pressure on the compressor P_c and total pressure on the compressor of the aerothermopressor system $P_{c.tp}$, compression ratio π_c for a case with the aerothermopressor on the length of Odesa-Fortaleza.

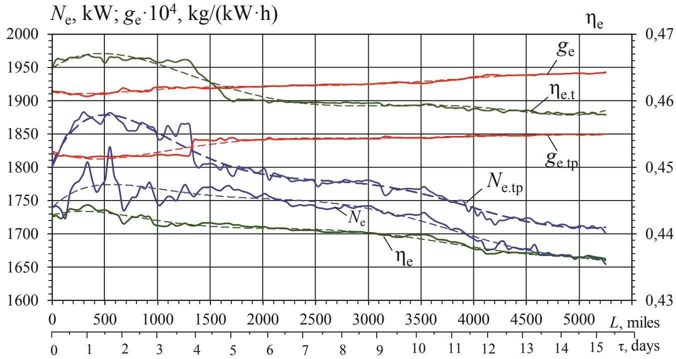

Fig. 7. Dependences of the main engine power N_e, specific fuel consumption g_e, effective efficiency η_e for the base version and the main engine power $N_{e.tp}$, specific fuel consumption $g_{e.tp}$, effective efficiency $\eta_{e.tp}$ for a case with the aerothermopressor on the length of Odesa-Fortaleza.

An analysis of change in parameters of the compressor operation during the voyage shows that using aerothermopressor makes it possible to increase the efficiency of the main engine and, accordingly, the ship's power plant as a whole (Fig. 7).

Results analysis of the modeling the main marine engine operation 8L20 and the aerothermopressor at various velocities in the working chamber (0.40–0.95) M (the velocity interval corresponds to the aerothermopressor operational modes during the ship line) at fixed parameters of the external air at the engine inlet (the parameters correspond to the ISO standard) makes able to conclude that the fuel consumption reduction by the main engine is Δg_e = 1.0–2.9 g/(kW h) (0.5–1.5%).

5 Conclusions

The aerothermopressor application in the charge air system of the Wärtsilä 8L20 marine engine of a passenger yacht on the route Odesa (Ukraine) - Fortaleza (Brazil) was considered.

The contact cooling of the charge air by the aerothermopressor ensures efficient water spraying in the air flow, that is, due to flow turbalization at high flow rates (Mach number M = 0.80–0.95) the droplets size is decreased.

The aerothermopressor application in the cooling system of the ship ICE charge air allows reducing capacity of the charge-air compressor, and accordingly, the power is increased by 1–3% with a corresponding reduction in the specific fuel consumption by 2–4%. The thermal load on the aerothermopressor is Q_{tp} = 380–480 kW. The amount of liquid (water) that is injected into the air is G_w = 0.15–0.18 kg/s (2–5% of the air flow compressed in the compressor). The pressure increase is ΔPtp = 4–9% or 17–38 kPa (taking into account the losses on aerodynamic drag in the flow parts of the aerothermopressor).

The aerothermopressor as a multifunctional device combines following functions: pressure increase (compressor function) and temperature decrease (cooler function). Also the aerothermopressor can be used in power plants for ecological humidification of charge air, in order to reduce emissions of nitrogen oxides NOx.

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