Ministry of Education and Science of Ukraine
Black Sea Universities Network

ODESA NATIONAL UNIVERSITY OF TECHNOLOGY

International Competition of Student Scientific Works

BLACK SEA SCIENCE 2022

PROCEEDINGS

Black Sea Science International Competition of Student Scientific Works by Odesa National University of Technology

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ODESA, ONUT 2022

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The author of the work is responsible for the accuracy of the information.

Odesa National University of Technology, 2022.

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INTRODUCTION

International Competition of Student Scientific Works “Black Sea Science” has been held annually since 2018 at the initiative of Odesa National University of Technology (formerly Odesa National Academy of Food Technologies) with the support of the Ministry of Education and Science of Ukraine. It has been supported by Black Sea Universities Network (the Association of 110 higher education institutions from 12 countries of the Black Sea Region) since 2019, and by Iseki-FOOD Association (European Integrating Food Science and Engineering Knowledge into the Food Chain Association) since 2020.

The goal of the competition is to expand international relations and attract students to research activities. It is held in the following fields:

- Food science and technologies
- Economics and administration
- Information technologies, automation and robotics
- Power engineering and energy efficiency
- Ecology and environmental protection

The jury includes both Ukrainian and foreign scientists. In the 4 years that the competition has been held, the jury included scientists from universities of 24 countries: Angola, Azerbaijan, Benin, Bulgaria, China, Czech Republic, France, Georgia, Germany, Greece, Israel, Italy, Kazakhstan, Latvia, Lithuania, Moldova, Pakistan, Poland, Romania, Serbia, Slovakia, Switzerland, Turkey, USA.

At the same time, every year the geography has expanded and the number of foreign jury members has increased: from 46 jury members representing 25 universities from 12 countries in 2018, to 73 jury members of the 46 universities from 19 countries in 2022.

More than a thousand student research papers have been submitted to the competition from both Ukrainian and foreign institutions from 25 countries: China, Poland, Mexico, USA, France, Greece, Germany, Canada, Costa Rica, Brazil, India, Pakistan, Israel, Macedonia, Lithuania, Latvia, Slovakia, Romania, Kyrgyzstan, Kazakhstan, Bulgaria, Moldova, Georgia, Turkey, Serbia.

The interest of foreign students in the competition grew every year. In 2018, the students representing 15 institutions from 7 countries have submitted 33 works. In 2021 the number of submitted works increased to 73, authored by the students of 40 institutions from 18 countries.

The competition is held in two stages. In the first stage, student research papers are reviewed by members of the jury who are experts in the relevant fields. In the second stage of the competition, the winners of the first stage have the opportunity to present their work to a wide audience in person or online.

All participants of the competition and their scientific supervisors are awarded appropriate certificates, and the scientific works of the winners are included in the electronic proceedings of the competition. Every year the competition receives a large number of positive responses from Ukrainian and foreign colleagues with the desire to participate in the coming years.

4. POWER ENGINEERING AND ENERGY EFFICIENCY

EFFICIENCY IMPROVING OF MARINE ENGINES BY USING A CONTACT COOLING SYSTEM WITH A THERMOPRESSOR

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Abstract. *Ensuring the optimal initial parameters of the working cycle by improving the turbocharging system is one of the reserves for increasing the efficiencyof marine internal combustion engines. Reducing the power consumed by the charge air turbocharger provides a power reserve for the turbocharger turbine, which can be transferred to the engine shaft or used to drive an electric generator. There are several approaches to charge air cooling, one of them is to use thermopressor technologies in the ICE turbocharging system which allows two processes to be combined: contact cooling of the charge air and pressure increase, which reduces the compressor power consumption. A thermopressor can be used to carry out these processes. The authors of the research analyzed water spray systems and developed a scheme for improving the air-cooling systems of ship engines, which consists in the use of water injection into a thermopressor. This scheme allows to reduce the charge air temperature to 50...67 degrees, increase the relative increase in air pressure at the thermopressor outlet by 2...10%, and, accordingly, reduce the power of the engine turbocharger.*

Keywords: *turbocharger, pressure increase, water injection, charge air cooler.*

I. INTRODUCTION

There are many areas for further improvement of internal combustion engines in order to increase their efficiency, despite the high economic parameters, which are the result of a fairly high organization of the working processes of modern engines. In this case, a rational reserve for increasing efficiency is to improve systems serving the internal combustion engine, for example, the charge air cooling system improving. Today, there are several approaches to charge air cooling, on the one hand it is the use of surface air coolers. The heat exchange surface of such air coolers is a tubular-lamellar or tubular-finned structure. On the other hand, it can be applying of the contact cooling method: the forced air enters the humidification tower, in which water is injected by several nozzles to lower the air temperature and humidify it.

The authors propose to use thermopressor systems for charge air cooling. The effect of thermo-gas-dynamic compression occurs when the air is cooled in the thermopressor. This effect consists in increasing the gas pressure in the process of instantaneous evaporation of water injected into the air flow, which is accelerated to aspeed close to sonic. At the same time, heat from the charge air is removed for water evaporation, as a result of which the air temperature decreases. The thermopressor is a compact jet device, which in terms of dimensions significantly outperforms othersurface and contact type coolers, in addition, provides a certain pressure increase.

II. LITERATURE ANALYSIS

2.1. Analysis of modern methods of spraying water for air cooling systems

It is appropriate to conduct a literature review of liquid spraying methods when analyzing the contact cooling method. In many contact cooling systems, water injection will be effective if the liquid is properly atomized. This directly depends on the quality and the correct choice of nozzles (sprayers) for water, based on specific operating conditions. First of all, it is necessary to determine the type of spray and choose the type of spray torch that is most suitable for this case [1].

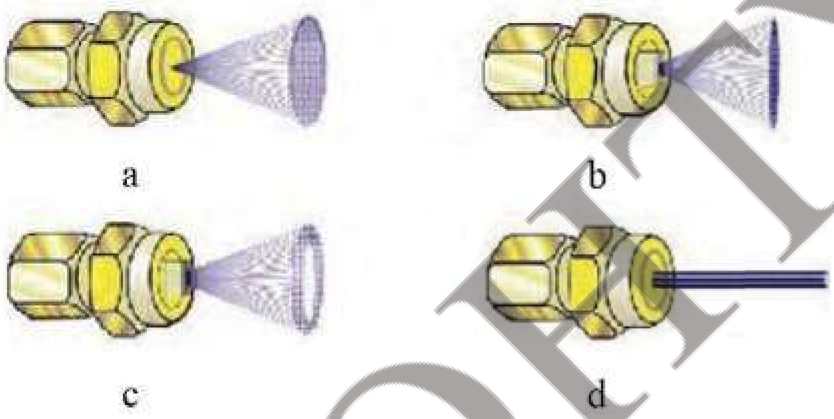


Fig. 1. Fluid spray types: full cone (a), flat spray (b), hollow cone (c), narrow spray (d)

Spraying water with hydraulic nozzles occurs under the action of pressure [1], which is pumped by the pump, which leads to the disintegration of the liquid into droplets (Fig. 2).

Fig. 2. Hydraulic water spray

In other words, passing through the spray device (nozzle), the liquid flow acquires a sufficiently high speed, turning into a form that promotes rapid dispersion (jet, film, large particles, depending on the ratio of the spray to a particular class). Thenarrowing of the nozzle cross section contributes to an increase in the flow rate, sincepotential energy is converted into kinetic energy. At the outlet of the nozzle, when thepressure drops sharply, the laminar fluid flow breaks into drops of different sizes and creates a certain spray type.

Spraying water with pneumatic nozzles (Fig. 3) occurs as a result of the dynamic interaction of the liquid with the gas flow, that is, due to the simultaneous supply of compressed air and liquid under pressure to the mixing chamber of a two-phase nozzle [1]. In pneumatic atomization, the determining factor in the destruction of liquid continuity is the influence of a high-speed gas flow intended for additional splitting of water jets into small drops.

Fig. 3. Pneumatic water spray

Regardless of the chosen spraying method, a decrease in the droplet sizeinevitably leads to an increase in specific energy consumption, that is, a decrease in thespraying efficiency. Thus, in hydraulic spraying, in order to reduce the droplet size, it is necessary to increase the liquid pressure drop across the nozzle. For example, when spraying 1 m^3 of water at P = 0.2…0.4 MPa, the droplet size is on average 250…300 µm, and the efficiency is 0.05…0.07%. To obtain drops with a diameter of 100 µm, the pressure drop has to be increased to 1.0...1.5 MPa, while the efficiency drops to 0.02. 0.03%. If the desired particle size is 50 microns, the pressure increases to 3.0. 4.0 MPa, and the efficiency decreases to thousandths of a percent.

Obtaining the required droplet size is not an easy task. Thus, traditional mechanical and hydraulic nozzles with a working pressure even up to 30 MPa do not provide the required spray quality [2].

The original solution to the water spray problem was applied by Mee IndustriesInc [3, 4]. To supply water to the air flow, nozzles of a special design were developed,in which atomization is realized due to impact action (Fig. 4). Water under high pressure (15…20 MPa) is supplied to the nozzle head, as a result of the impact, drops with a diameter of no more than 50 microns are obtained.

Despite the relatively wide distribution of such systems, they require rather complex water supply pumping equipment and create known difficulties when operating the system under high pressure.

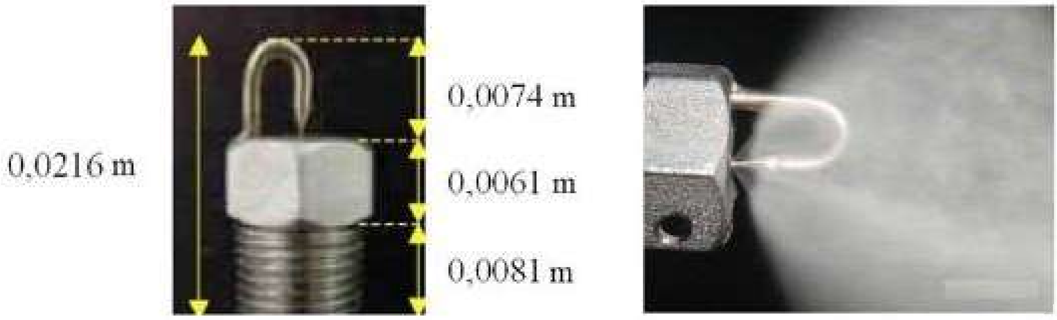


Fig. 4. The appearance of the nozzle and water spray (MeeFog)

Among the latest approaches, a particularly attractive way to improve the qualityof atomization is the use of the thermophysical properties of "explosive boiling" of water when it is overheated relative to the saturation temperature. At the end of the 90s,it was proposed to supply the nozzle with water superheated relative to the saturation temperature at a given pressure at the injection point (swirl-flash technology), when the “hydrodynamic” grinding of the swirling liquid film at the outlet of the nozzle intensifies with a sharp boiling up in its volume [5].

2.2. Analysis of modern methods of cooling the charge air of internalcombustion engines

Internal combustion engines are used as the main engines in diesel marine power plants. The charge air of the internal combustion engine is cooled in order to ensure normal operating conditions for the turbocharger and increase the mass charge of air in the cylinders. The air is cooled in heat exchangers of various designs: round-tubular, flat-tubular with corrugated common plates, with a surface made of profiled sheets, etc. Cooling of charge air for every 10 K increases the mass of air entering the working cylinder by 2.0–2.5% and leads to a decrease in the average temperature of the working cycle and the heat stress of engine parts at increased boost pressure [6].

The increase in air temperature or charge in the compressor depends on the degree of pressure increase, compressor efficiency and heat exchange with the walls, that is, on the design of the compressor. At high pressure ratios, the engine intake temperature can become high (unless charge air cooling is applied), which adversely affects the engine.

On supercharged engines, charge air cooling is the most important and simple means of increasing power, which is the more effective, the higher the pressure ratio in the compressor π_c. Along with reducing heat losses and improving mechanical efficiency (higher power without increasing the pressure level), charge air cooling also contributes to a decrease in specific fuel consumption [7, 8].

To cool the charge air in modern diesel engines, different cooling methods can be used: surface, evaporative, water contact, turbo-expander, cooling with the use of a vortex effect. With surface cooling, depending on the design, there can be plate and tubular heat exchangers (which have become more common), and by the type of coolant, coolers can be water-air and air-air [8].

The decrease in charge air temperature is typically 40–70°C. The value of pressure losses in the exhaust gas system, according to the requirements of manufacturers for modern supercharged internal combustion engines, should be no more than 4.9 kPa. Thus, the use of charge air coolers in modern engines improves their fuel-economic and environmental performance. In this case, it is especially important to develop heat exchange systems in charge air coolers with minimal energylosses in heat and mass transfer processes.

To increase the efficiency of the piston ICE cycle, different schemes of direct water injection are used [9, 10]. In the working cycle of a piston engine, starting from the moment of ignition of the fuel-air mixture, the pressure and temperature that make it possible to organize the injection of water can be at any stage of the cycle after the start of the combustion process. There are known schemes for supplying water to the inlet pipe in order to cool the fresh air charge [9, 10].

Wârtsilâ's early designs used a Combustion Air Saturation System (CASS) to saturate the combustion air. An aqueous aerosol (dispersed stream) was injected through nozzles directly into the charge air stream immediately after the turbocharger. After heating, the mixture was saturated again by introducing an additional amount of water (Fig. 5). This solution provided a reduction in NOx to 3 g/(kW·h) [11], which is more efficient than the use of a water-fuel emulsion.

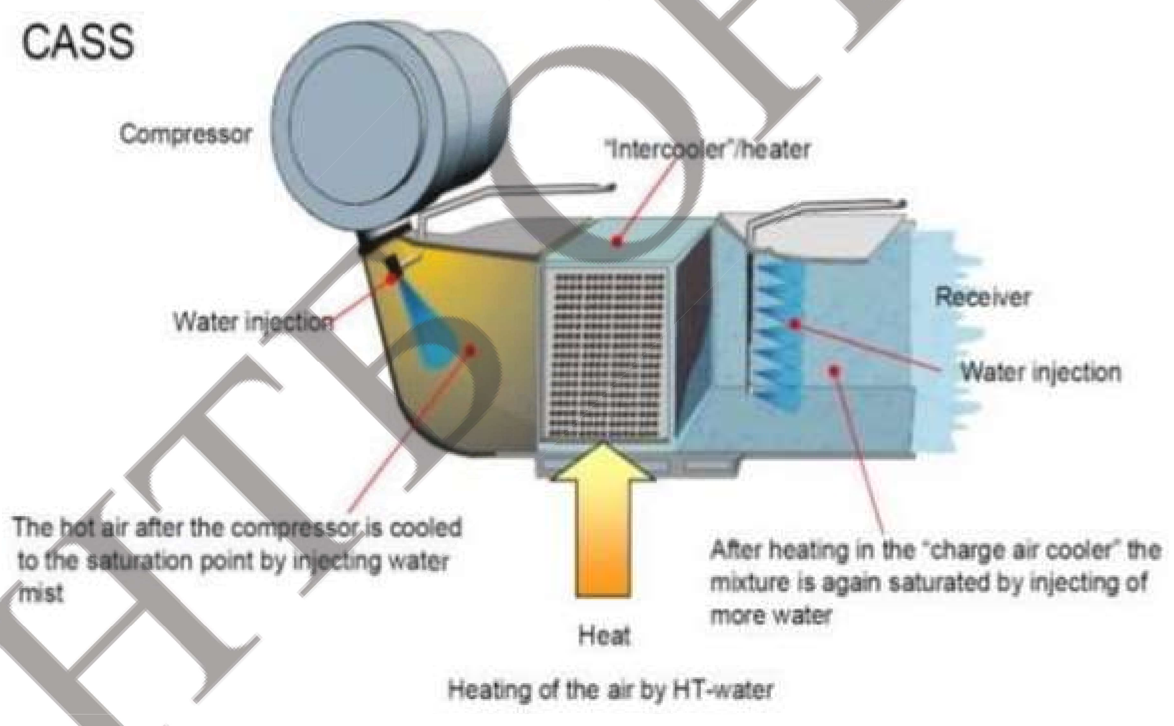


Fig. 5. Wârtsilâ charge air cooling system [101, 102]

In order to reduce NOx emissions, MAN has investigated the possibility of humidifying the charge air. To do this, the German company Munters Euroform developed a system called Humid Air Motor (HAM), which allows increasing air humidity up to 99% [12]. System testing showed that NOx was reduced by 70-80% in operational mode. The authors explain this by the fact that the increased content of steam in the charge air reduces the temperature peaks in the combustion chamber.

The disadvantage of all the considered methods is that the water injection reduces the average cycle temperature in the combustion zone and, as a result, the efficiency of the working process. This disadvantage can be eliminated by choosing the optimal method of water supply. Water injection at the beginning of the compression process not only reduces the maximum temperature of the working process, but also reduces the cost of compression work in the compressor, thereby increasing the total work per cycle [13].

III. OBJECT, SUBJECT AND RESEARCH METHODS

3.1. Goals and tasks of the research

The scientific and applied problem that is being solved in the research is the improvement of the internal combustion engine charge air system using evaporative cooling of the charge air in the thermopressor.

The object of research is ICE charge air cooling processes.

The subject of research is processes of contact (evaporative) cooling of charge air of internal combustion engines and their parameters.

Methods of research. The parameters of the charge air and the processes of its cooling in the thermopressor were calculated according to the method and program software using the equations of thermodynamics and gas dynamics of the flow, taking into account air humidity.

The goal of the research is to determine the directions of improving the fuel efficiency of the internal combustion engine by using the thermopressor systems for cooling the charge air.

Realization of the set purpose demands the solution of the following tasks.

- to analyze modern water spray systems in order to improve the cooling of the internal combustion air;
- to develop a special software based on known methods for calculating thermopressor devices, taking into account the features of the process of contact cooling of charge air;
- to develop a scheme of ICE charge air cooling systems using a thermopressor.

3.2. Methods for studying the operation of a thermopressor apparatus

In technology, processes are widely used in which the movement of gas through channels occurs under various external actions. These include a change in the cross-sectional area of the channel, the exchange of energy with the environment in the form of mechanical energy or heat transfer, the friction of the channel wall, the change in gas flow due to the supply of liquid to the flow, the process of mechanical and thermal interaction of liquid drops with a gas flow, etc.

Intensive heat supply causes an increase in aerodynamic resistance, and removal – its decrease. With intensive heat removal and appropriate organization of the working process, it is possible not only to significantly reduce the resistance, but also to increasethe total pressure in the gas flow. In this case, due to the predominant thermal action (heat removal), the gas flow is compressed. The apparatus is called a thermopressor, inwhich the total gas pressure increases at the outlet due to the removal of heat from thegas flow.

Heat can be removed by contact heat exchange through the channel walls and by evaporative cooling of the cooling water injected into the gas flow. The possibility of the process proceeding with an increase in the total pressure of the flow during evaporative cooling was theoretically shown for the first time by L.A. Vulis [14] in 1946. The issues of the working process theory, design and testing of a thermopressor received some coverage in the literature [15, 16].

During contact cooling of the air flow with water, a number of processes occur that mutually influence each other. The processes of heat and moisture exchange between air and water are decisive. Depending on the ratio between the vapor content of saturated air near a water droplet and the vapor content in the volume of air, either evaporation or condensation occurs [13]. In the process of contact of air with droplets of injected water, a layer of saturated air with water temperature is formed near the surface of the droplet. As a result, if the air is unsaturated, the driving force of mass exchange appears, in which the vapor formed around the surface of the droplet passes into the nearby layers of air and then, under the action of diffusion, spreads in the total volume.

The total heat flux was determined by the following equation [17, 18]:

$$dQ = dQ_c + dQ_{lat} \; . \qquad (1)$$

The wet bulb temperature of the air is the temperature of a water droplet at which the total heat exchange between air and the droplet is zero ($dQ_c = dQ_{lat}$). However, in an unsaturated air flow, heat removal does not stop and continues at a constant droplet temperature. This process is accompanied by humidification of the air, that is, the evaporation of water. The heat necessary for this evaporation is removed from the cooled air, as a result of which its temperature decreases [19].

The amount of sensible heat transferred from air to a drop was determined by the following equation [17]:

$$dQ_c = \alpha \cdot \left(T_a - T_d\right) dA_d \; , \qquad (2)$$

where α – heat transfer coefficient, W/(m^2·K);

A_d – surface area of a water droplet, m^2;

T_a, T_d – air temperature and water droplets temperature, K.

Since water droplets are assumed to be spherical when evaporated, the droplet surface area is given by:

$$A_d = \pi \delta_d^2 \qquad (3)$$

Accordingly, the mass of the droplet is:

$$m_d = \rho_w \pi \frac{\delta_d^3}{6} \qquad (4)$$

The amount of latent heat of evaporation of a droplet is [18]:

$$dQ_{\text{lat}} = j_{\text{m}} \cdot r \cdot (d_{\text{a}} - d_{\text{s}}) dA_{\text{d}} \tag{5}$$

where j_{m} – mass flow density, kg/(m^2·s);

r – latent heat of vaporization, J/kg.

(d_{a}-d_{s}) – the difference between the moisture content of air in the main volume and unsaturated air around the droplet.

When a two-phase mixture moves in the thermopressor evaporation section, three characteristic modes can be distinguished (Fig. 6) [20, 21]:

- mode I: the influence of the drag of liquid droplets prevails over all other actions and determines the behavior of the flow;
- mode II: the determining process is the evaporation of the liquid;
- mode III: the surface friction of the air on the dry walls of the thermopressor predominates.

The diameter of a liquid droplet greatly affects the length of the evaporation section and the speed regime: with a decrease in the primary droplet size, the length of the evaporation section and friction losses are significantly reduced.

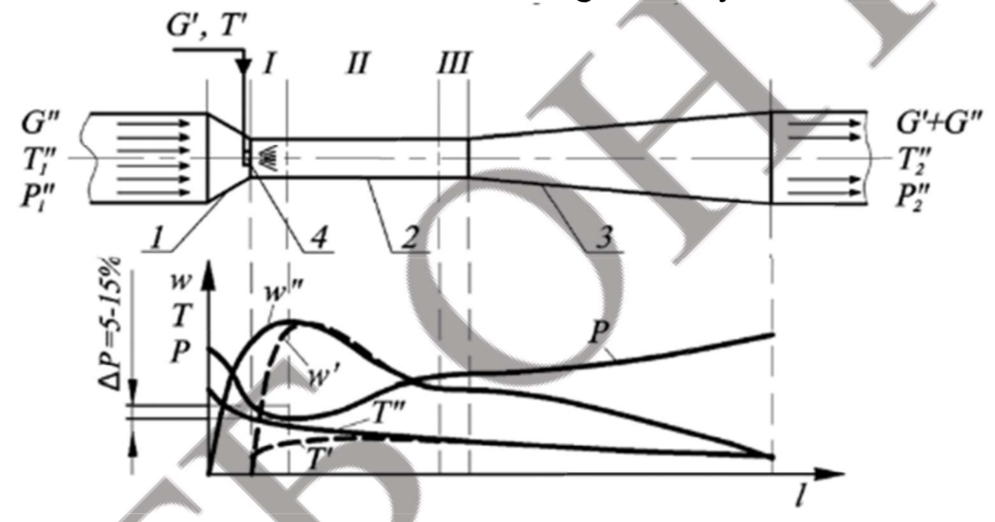


Fig. 6. The main structural elements of the thermopressor:
1 – confuser; 2 – evaporation chamber; 3 – diffuser; 4 – nozzle

Water injection increases the friction coefficient by 10...20%, so in order to avoid a further increase in losses, it is necessary to reduce the aerodynamic drag of the structural elements of the system. For this purpose, it is desirable to place injection devices in a flow with a low gas velocity (in front of the nozzle) and make them more streamlined [21].

3.3. Features of the cooling scheme application of internal combustion engines using a thermopressor

For modern marine medium-speed engines, as a rule, a three-circuit cooling system is used. At the same time, two cooling sections are used in the charge air cooler: high-temperature, in which heat is removed from the air to the water of the engine cooling system, and low-temperature, with heat removed to the fresh water circuit of the central cooler.

A diagram using a thermopressor as a charge air cooler for the main turbocharger is illustrated in Fig. 7. Air is sucked in by a single-stage turbocharger and compressed to a pressure less than the pressure at the inlet to the internal combustion engine cylinders. After that, the air with high temperature and pressure enters for evaporative cooling in the thermopressor. At the same time, due to the effect of thermo-gas-dynamic compression, the air temperature is significantly reduced, and the pressure rises to the required value corresponding to the engine inlet. The final temperature reduction is carried out in the charge air cooler.

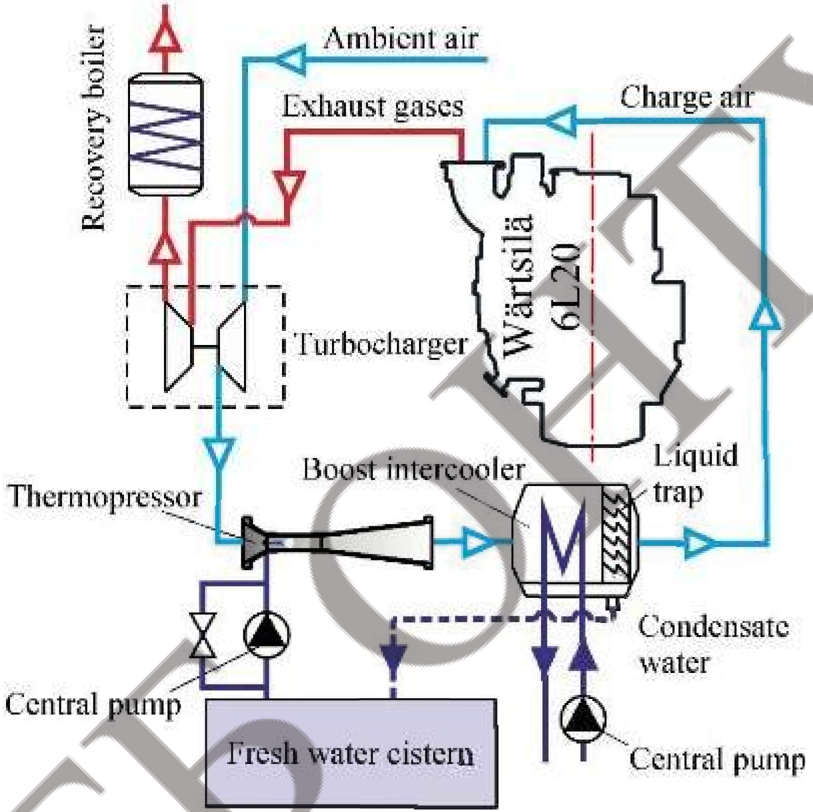


Fig. 7. Cooling system of a medium-speed main marine engine using a thermopressor

To determine the operating characteristics of the thermopressor and the main parameters of engine operation, a software package was developed based on known methods for calculating thermopressor devices [18, 21, 22], as well as taking into account the features of the process of contact cooling of the engine charge air.

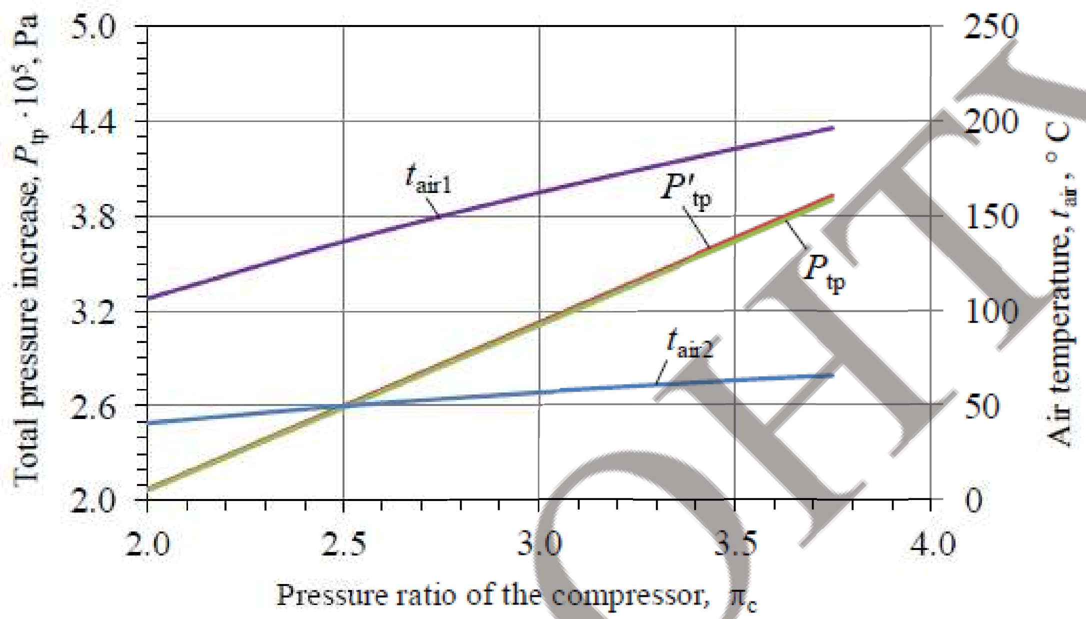
IV. RESULTS

Results of research into the use of thermopressor systems for charge air cooling.

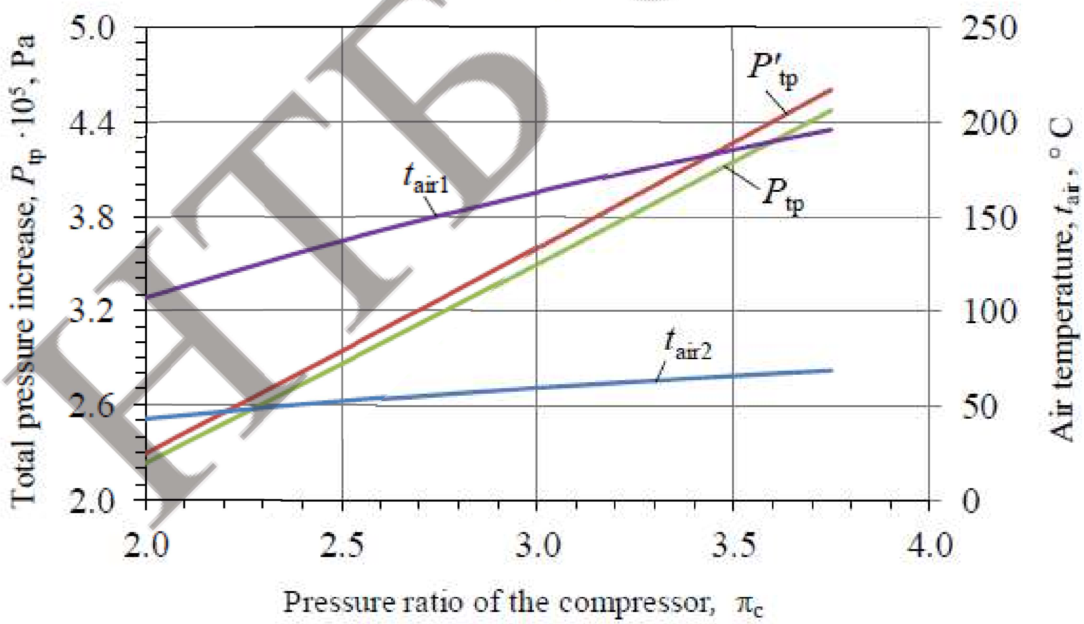
The calculation of the thermopressor system was made for the main ship's marine engine of Wârtsilâ (Finland) brand 6L20 (N_e = 1200 kW, n = 1000 min^{-1}).

An analysis of the study results of the use of a thermopressor in charge air cooling systems (Fig. 8a, 9a) shows that the total air pressure at the "real" thermopressor outlet is P_{tp} = 2.0…3.8·10^5 Pa (up to 2.0%), and the total air pressure without friction losses is P'_{tp} = 2.0…3.9·10^5 Pa at a water temperature for injection at the inlet of the thermopressor t_{w1} = 25 °C, at the air velocity at the inlet to the evaporation chamber M = 0.35. The air temperature at the thermopressor inlet is t_{air1} =106…196 °C, the air temperature at the thermopressor outlet is t_{air2} = 48...62 °C.

For the air velocity at the inlet to the evaporation chamber M = 0.85: the total air pressure at the "real" thermopressor outlet is P_{tp} = 2.2…4.4·10^5 Pa and the total air pressure without friction losses P'_{tp} = 2.3 …4.6·10^5 Pa. The air temperature at the thermopressor inlet is t_{air1} = 106…196 °C, the air temperature at the thermopressor outlet is t_{air2} = 50…65 °C (Fig. 8b, 9b).



(a)



(b)

Fig. 8. Dependences of the total air pressure at the thermopressor outlet without friction losses P'_{tp}, the total air pressure at the "real" thermopressor outlet P_{tp}, air temperature t_{air} on the pressure ratio in the turbocharger π_c:
M = 0.35 (a); M = 0.85 (b)

The research results show (Fig. 9a) that for the air velocity at the inlet to the evaporation chamber M = 0.35, the consumption of water injected into the thermopressor is G_w = 2.50...5.78 10^{-2} kg/s. And for the air velocity at the inlet to the evaporation chamber M = 0.85, the consumption of water injected into the thermopressor is G_w = 3.32...6.96 10^{-2} kg/s (Fig. 9b).

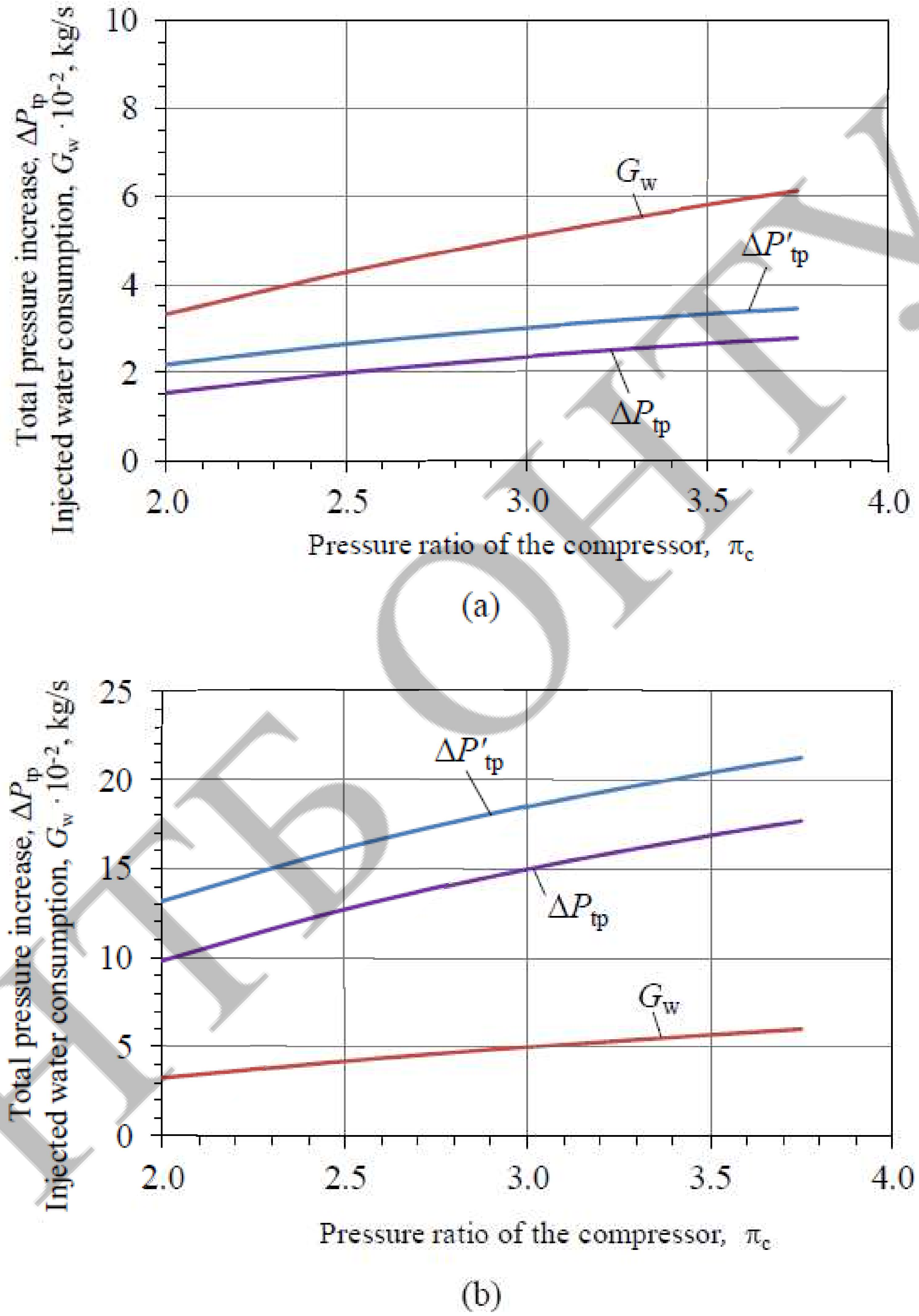
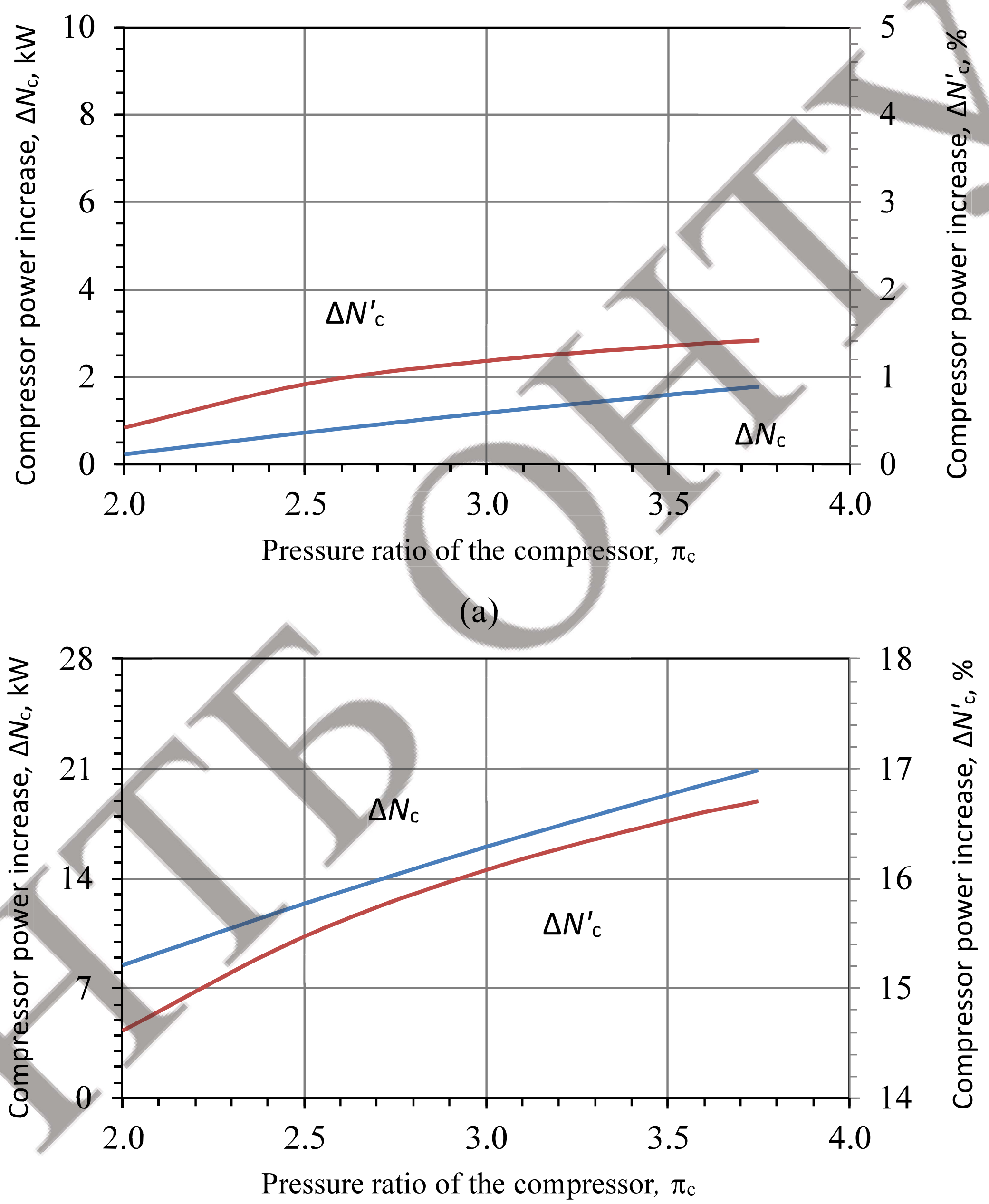


Fig. 9. Dependences of the air pressure increase at the thermopressor outletwithout friction losses $\Delta P'_{tp}$, the air pressure increase at the "real" thermopressor outlet ΔP_{tp}, injected water consumption G_w on the pressure ratioin the turbocharger π_c: M = 0.35 (a); M = 0.85 (b)

The obtained air parameters at the outlet of the thermopressor correspond to those recommended by the manufacturer for this type of engine, according to which the charge air temperature after the charge air cooler should not exceed 50 ... 70 °C.

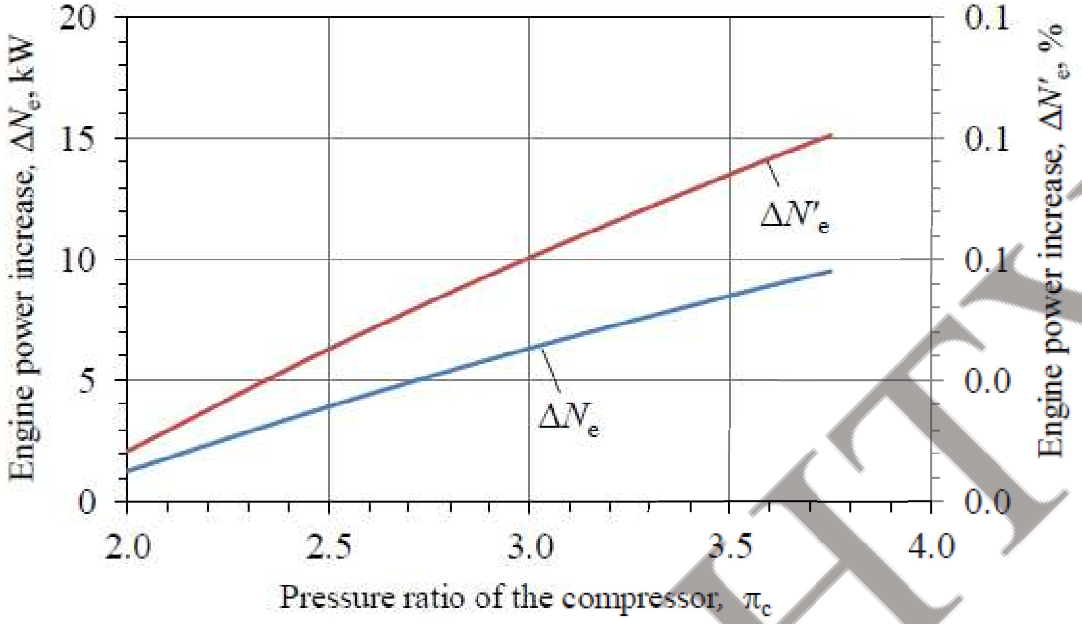
Thus, the use of a thermopressor for cooling the charge air makes it possible to reduce the compressor drive power (Fig. 10a) by ΔN_c = 1…2 kW (0.5…1, 5 %) for the air velocity at the inlet to the evaporation chamber M = 0.35. And for the air velocity at the inlet to the evaporation chamber M = 0.85, the reduction in the compressor drive power is ΔN_c = 7…21 kW (13.0…17.5%).



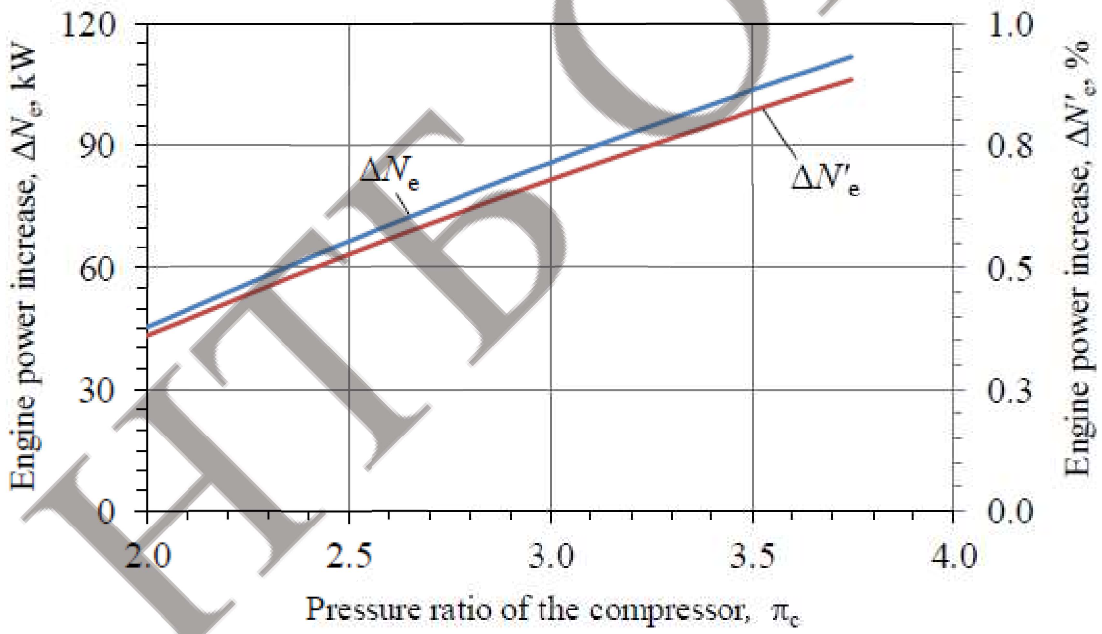
(b)

Fig. 10. Dependence of the change in compressor power ΔN_c, $\Delta N'_c$ at the injected water temperature t_{w1} = 25 °C on the pressure ratio in the turbocharger π_c: M = 0.35 (a); M = 0.85 (b)

Cooling of the charge air with a thermopressor reduces the power consumed by the supercharged compressor and, accordingly, the power of the internal combustion engine increases. Thus, the engine power increased by ΔN_e = 2…10 kW (up to 0.1%) for the air velocity at the inlet to the evaporation chamber M = 0.35 (Fig. 11a). And for the air velocity at the inlet to the evaporation chamber M = 0.85, engine power increased by ΔN_e = 38…109 kW (0.4…1.0%).



(a)



(b)

Fig. 11. Dependence of the engine power increase ΔN_e, $\Delta N'_e$ at the injectedwater temperature t_{w1} = 25 °C on the pressure ratio in the turbocharger π_c: M = 0.35 (a); M = 0.85 (b)

Thus, the use of a thermopressor in charge air cooling systems makes it possibleto reduce the power consumed by compressors by 1–17%, thereby increasing the powerof the internal combustion engine up to 1%.

V. CONCLUSIONS

1. The principle of cooling the charge air of the internal combustion engine with a simultaneous increase in pressure is proposed, which makes it possible to reduce the power consumption of the standard turbocharger while maintaining the total compression ratio πk.

2. The use of a thermopressor in charge air cooling systems makes it possible to reduce the power consumed by compressors by 1–17%, thereby increasing the power of the internal combustion engine up to 1%.

3. For the purpose of contact cooling of the charge air as well as environmental humidification of the charge air at the inlet to the ICE cylinders (in order to reduce the emission of nitrogen oxides NOx), a method of fine water spraying in the charge air by a thermopressor is proposed. This technology makes it possible to eliminate the need for complex water spray systems with nozzles located throughout the entire flow section.

4. Due to the higher intensity of heat exchange during contact cooling in the thermopressor (compared to surface cooling in traditional charge air coolers), the dimensions of the thermopressor are smaller compared to other types of heat exchangers.

5. It is proposed to use the water discharged during the cooling of moist air in the surface charge air cooler for injection into the thermopressor, which makes this system self-sufficient – autonomous.

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