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APPLICATION OF WASTE HEAT FOR AIR-CONDITIONING IN MOTOR YACHTS

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ABSTRACT

Combustion engine is a primary source for electric energy consumed be all electrical devices in ships and yachts. Conversion of fuel energy into mechanical and electrical energy is related with creation of a significant amount of heat, which is irretrievably removed. Ejection system can be effectively driven by low-grade heat source such as waste heat from the engine. The paper presents analytical analysis of thermal-flow operating parameters of waste heat node used for small yachts air-conditioning systems. The results show that such solution can produce 15 kW of cold consuming 70 kW of heat at temperature 120ºC. Cooling capacity of 15 kW should satisfy cooling demand of small- and mid-size yachts. The approach for steam waste heat recovery system for marine applications was presented.

Keywords: air-conditioning, heat recovery, ejection Refrigeration system, desiccant wheel.

1. INTRODUCTION

Production of cold on ships is used primarily for the needs of air handling units. The demand for it is related with place of sailing of the ship and conditions of climatic zones which it stays. Usually, ships are designed for sailing around the world. Therefore, especially on hot climate the outside weather conditions i.e. the air temperature and relative humidity are high.

To minimize the electricity consumption, the refrigeration system powered by heat can be used. There are known refrigeration devices powered by heat waste. However, these solutions for cooling systems powered by non-electric energy is no available on the market for yachts. This is because absorption systems have more components and as the heat and mass transfer of absorption equipment is poor, large heat transfer areas are required. Ezgi (2014) presented design and thermodynamic analysis of a water-lithium bromide absorption heat pump as an HVAC system for a naval surface ship application are presented. Despite that absorption system can be used in naval ships, they are not suitable for small yachts due to its dimensions and weight.

Production of cold, which consumes significant amounts of electricity, is especially crucial for small vessels due to:

- significant load on the energy system of the vessel through electrically controlled air conditioning systems;
- particular importance of air conditioning systems on small vessels (e.g. yachts) due to the required comfort conditions in different climate zones.

Another aspect that should be taken into consideration is the availability of waste heat, including mainly heat exhausted from the internal combustion engine driving the vessel. Currently, it does not apply to the vessels of low or medium capacity recovery systems of waste heat. One of the key problems of refrigeration technology, especially on vessels, is the fulfillment of strict legal requirements regarding working fluids: currently, typical working fluids are being applied, which will be withdrawn under the EU Directive 517/2014 on fluorinated greenhouse gases from use. The developed proposed solution meets the rigors imposed by legal regulations, which will also facilitate servicing such a system around the world. One of the key problems of technologies specific to small vessels is the requirement of high compactness of devices and reliability of the refrigeration system. The ejector refrigerant system requires the smallest dimensions from

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other refrigeration systems powered by heat, and therefore it seems to be the best solution for use on small yachts.

2. APPLICATION OF THE EJECTOR SYSTEM AND THE DESICCANT WHEEL

Ejector refrigeration system was shown in Fig. 1. it is possible to distinguish the refrigeration circuit and the drive circuit in this system.

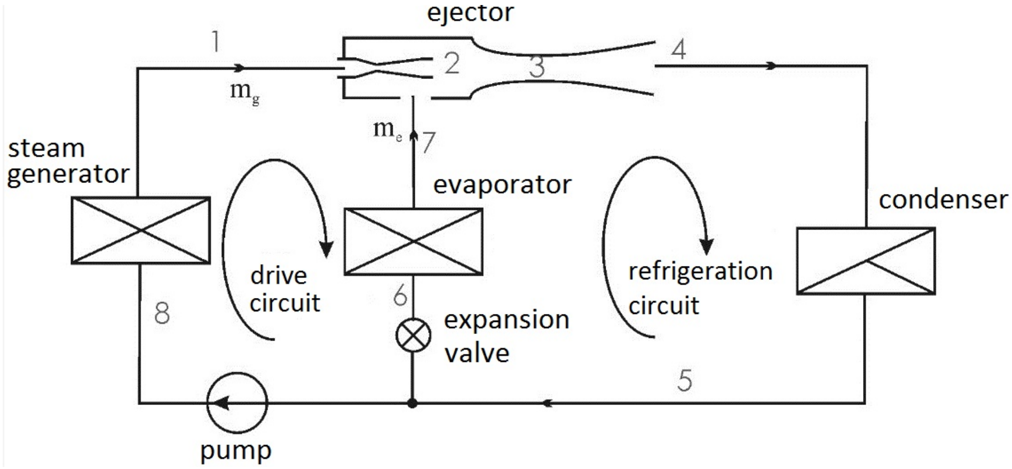

Fig. 1. Schematic diagram of ejector refrigeration system

In an ideal system the motive vapour (state 1) expands isentropically in the motive nozzle to state 2. During this expansion vapour velocity increases as a result of the pressure drop. Usually, the motive vapour reaches the supersonic velocity at the outlet of the nozzle. Vapour of low pressure and high velocity (state 2) entrains vapour from the evaporator at state 7. Inside the ejector both streams are mixed. It is the result of the momentum transfer between both streams. The effect of this process is decrease of the motive vapour velocity and increase of velocity of the entrained vapour. The velocity decrease causes a simultaneous increase in pressure. Despite the velocity decrease, it can be assumed that after complete mixing (state 3) the velocity of the mixed streams is supercritical. The transition from supercritical to subcritical flow takes place in the mixing chamber. This results in a shock wave and a sharp rise in pressure. Depending on the design and operation conditions of the ejector- the shockwave can be created in the mixing chamber or in the diffuser. A further small increase of pressure occurs in the diffuser. The vapour mixture leaving the ejector (state 4) has pressure equal to the pressure in the condenser. After condensation (state 5) the flow is separated. Part of the liquid refrigerant is throttled in the expansion valve to the pressure p_e and then evaporates in the evaporator. The working fluid reaches the state 7 and is entrained again by the ejector. The rest part of liquid is pumped to the vapour generator. During pumping process, pressure of the working fluid rises from p_c (state 5) to p_g (state 8). The boiling in the vapour generator consumes the recovered waste heat and changes parameters of refrigerant from state 8 to state 1.
Authors of this paper have developed a solution for the ejector refrigerant system using a fully ecological working medium R-1234ze indicating a wide range of motive heat temperatures used for production of cold (Gagan et al., 2018a,b, Śmierciew et al., 2017). Authors demonstrated the significant influence of the evaporation temperature on the efficiency of the system. For operation conditions corresponded to high-temperature air-conditioning (16/19°C) in comparison with the standard chilled water parameters (6/12°C) the efficiency of the system was nearly doubled.
The conditions for the air conditioning systems on vessels are defined by:
- the ISO 7547: 2002: Ships and marine technology standard - Design conditions and basis of calculations
- ISO 31-4: 1992, Quantities and units - Part 4: Heat;
- ISO 3258: 1976, Air distribution and air diffusion.

The standards define design parameters for air processing for winter and summer, as well as the conditions of thermal comfort in all of the rooms on vessels. General guidelines for air parameters according to these standards are: outdoor air temperature +35 °C; relative humidity 70%; for indoor air: +27 °C on summer. The standards do not explicitly define conditions for relative humidity for the winter period. However, it is

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good practice to maintain a relative humidity in the room at the level of 40-60%. The amount of fresh air supplied to the room should be at least 40% of the entire supplied air.
Operation of A/C system on a vessel is associated with the need of much higher cooling capacity than is resulted exclusively from the sensible heat gains. Due to the very high relative humidity of the outdoor air - the cooling capacity needed to absorb latent heat gains is significant. This leads to high electric power consumption of the air-condition unit. However, taking into account the possible application of exhaust waste heat, it is possible to use the air conditioning system that ensures operation in the conditions required by the indicated standards with a significantly reduced electric power need to drive the refrigeration system. Usage of the air-conditioning system equipped with a desiccant wheel additionally enhances this opportunity.

Issues related with design and efficiency analysis of the desiccant wheel are the subject of numerous researches. Due to the fact that the heat transfer process takes place in conditions similar to the operation of rotary regenerative heat exchangers (Butrymowicz et al., 2016), it is not so clear how the channel geometry of the wheel influence on the heat and mass transfer efficiency (Camargo et al., 2005, Eicker et a., 2015, Kamar et al., 2016, O'Connor et al., 2016). Guojie et al. (2012) and Zheng et al. (2017) proposed system dedicated directly to the application in air conditioning systems on offshore units. A separate problem is the evaluation of the efficiency of the desiccant wheel operating in the air conditioning units (Bassuoni, 2014, Chung, 2017, Kara et al., 2017). Nevertheless, the proposed system is not yet a sufficiently widespread solution. There is a clear need to assess the possibilities of such a solution applied for A/C systems for vessels. The paper presents an analysis of the possibilities of reduction of cooling capacity by means of usage of the engine exhaust waste heat potential for the exemplary vessel case.

3. ANALYSIS OF AN EXEMPLARY CONVENTIONAL AIR-CONDITION SYSTEM

The paper shows, the application of an air-conditioning system with a desiccant wheel used for the case of the exemplary vessel. For selected vessel, a detailed heat and humidity balance was performed for the summer period. The heating load covers:

- heat gains from people on the vessel: sensible heat 0.70 kW and latent heat 0.50 kW;
- heat gains from the vessel devices located in the wheelhouse 2.50 kW;
- heat gains from solar radiation and the technical equipment in the vessel 11.3 kW;
- latent heat gains associated with infiltration of humid air 7.20 kW.

The total heat gains are 22.2 kW, and the ratio $\Delta i/\Delta x$ was calculated as 7234 kJ/kg. Required air flow is 4475 m^3/h, while the required fresh air is 1790 m^3/h. At first, the classical approach with compression refrigeration device used to remove the moisture for air is considered. The processes of the air-treatment in standard approach are shown in Fig. 2. In standard air-conditioning unit the chilled water is produced by compression refrigeration system. The fresh air (Z) is mixed with the exhaust air removed from the room (W), assuming that the removed air has the same parameters as the internal air (W). The mixed air (M) goes to the evaporator that receives the total heat gain, so the "M" mixture must be cooled down to temperature (O) below the dew point so that the moisture can be condensed. The final moisture content at point O must be equal to the moisture content of the supply air $x_O = x_N$. Due to the fact that the air at the point (O) has a temperature lower than the supply air (N), a heater operating between the points O-N should be used. Usually it is an electric heater.

The calculation procedure of the analysed processes is based on the mass and energy balance formulated for each of the process which may be thought as conventional approach, see Ezgi and Girgin (2015), Zheng et al. (2015), Suono et al. (2011). It is assumed that the system operates in standard conditions of chilled water, i.e. the supply temperature is 6 °C, while the return one is 12 °C. Schematic of air processing in the air conditioning unit with dehumidification of the air by a refrigeration device obtained from calculation results is shown in Fig. 2. In the analysed case the cooling load of the evaporator is 48.8 kW, which is two times higher that total heat gains on the vessel, and the heat load of the air heater is 6.5 kW.

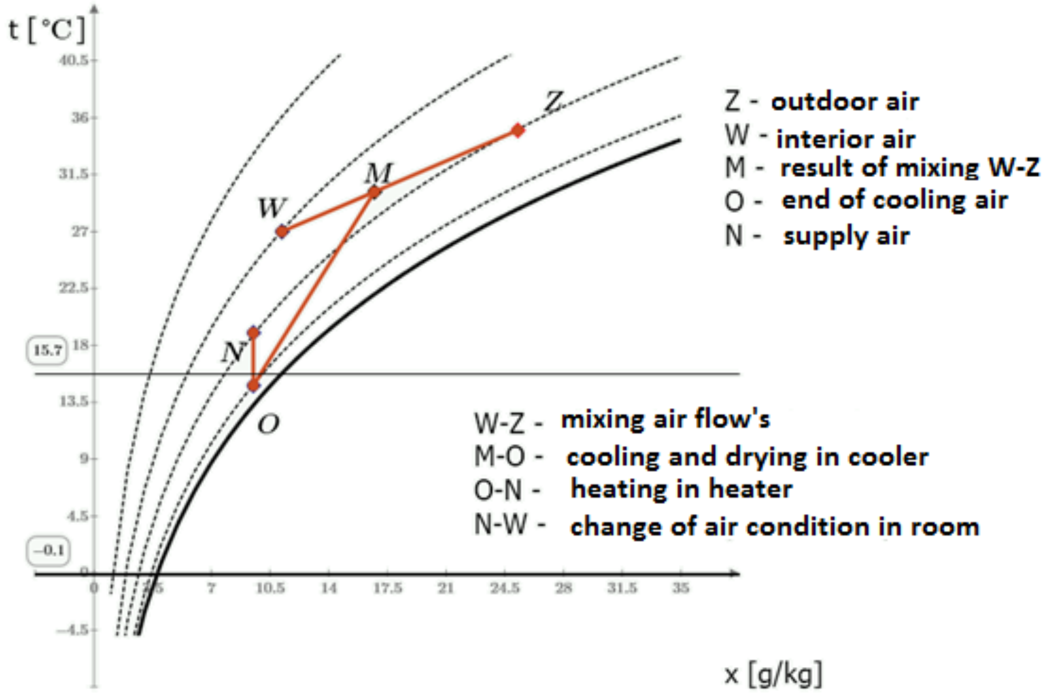

Fig. 2. Schematic of air processing in air conditioning cycle with dehumidification of air by refrigeration system

4. ANALYSIS OF AIR CONDITIONING SYSTEM WITH A DESICCANT WHEEL

As it was indicated above, it is possible to use the ejector refrigeration system that is powered by the waste heat generated by the engine on the vessel. An alternative solution to the air-conditioning system that also uses the waste heat potential to dry the air is the desiccant wheel. The air conditioning system equipped with the desiccant wheel is schematically shown in Fig. 3. The expected temperature of the fluids at characteristic points are shown in the figure.

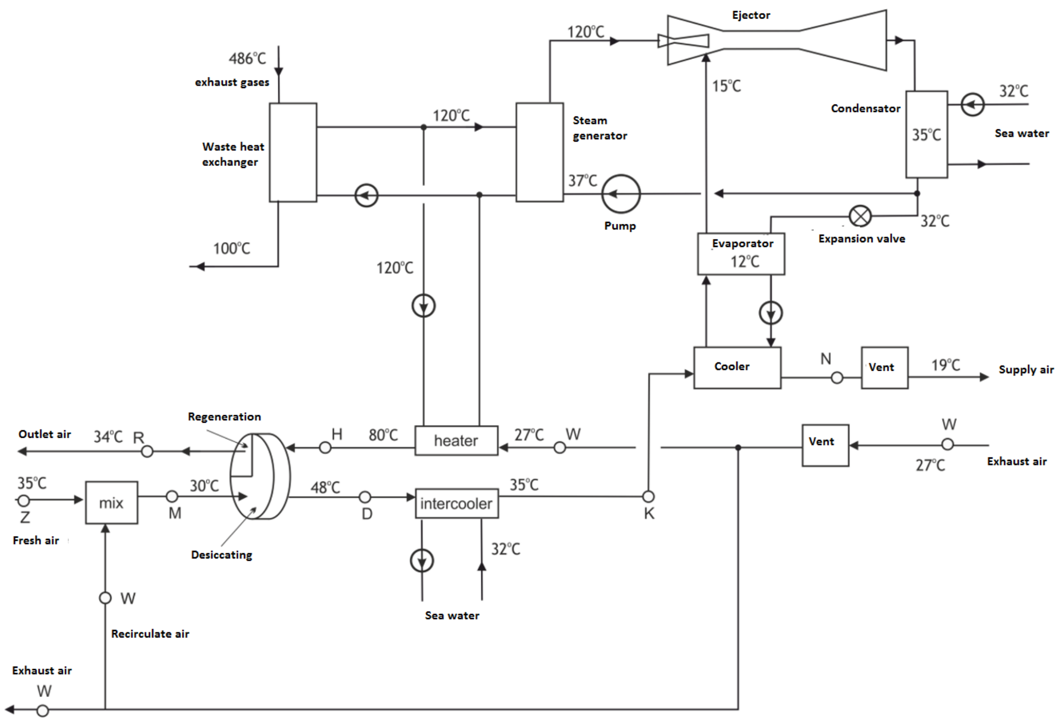

Fig. 3. Air conditioning cycle with latent heat absorption in desiccant wheel

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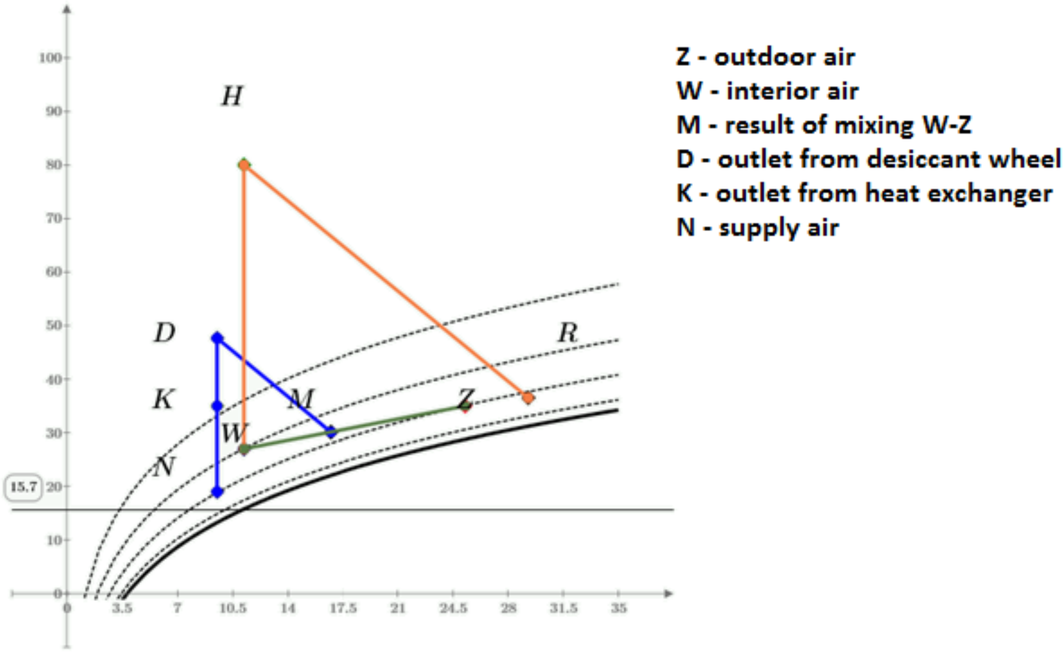

Fig. 4. Air conditioning cycle with latent heat absorption in desiccant wheel for assumed operating parameters

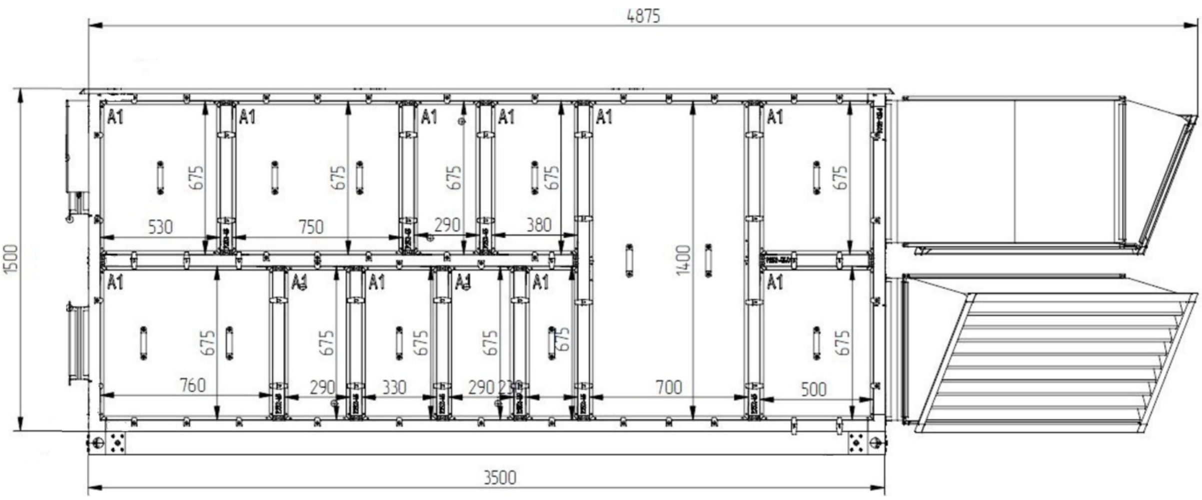

Fig. 5. View of the air-conditioning unit prepared for motor yacht.

The air processes in the air-conditioning system using the desiccant wheel is shown in Fig. 4. This system is additionally equipped with intercooler allowing for pre-cooling of the air with sea water, which additionally reduces the demand for cooling power in the considered case. In the proposed system, fresh air (Z) is mixed with the exhaust air removed from the room (W), assuming that the exhaust air has the same parameters as the internal air (W). The mixed air (M) is drying and heating in the desiccation wheel, obtaining the parameters of point (D). Pre-cooling takes place in the additional heat exchanger cooled by sea water (K). The evaporator in this case only receives the sensible heat gains cooling the air from point (K) to the point (N). Schematic of the air processing in the air conditioning unit with application of the desiccant wheel obtained from calculation results is presented in Fig. 4. In the analysed case, the heat load of the evaporator is 23.6 kW which is almost the same as heat load of the vessel, heat load of the heater for the regeneration process is 29.1 kW, the heat power of the pre-cooling is 17.8 kW. The ejector refrigeration system requires 49.2 kW motive heat. The air-conditioning unit prepared for the application of the4 discussed motor yacht is presented in Fig. 5.

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5. WASTE HEAT RECOVERY SYSTEM DEDICATED FOR MARINE APPLICATIONS

The steam heat recovery system was proposed for the engine of the type TD 232 V 12 of the maximum power of 225 kW for 1500 rpm; this engine is dedicated for application in small and medium sized vessels such motor yachts or special vessels. The schematic of the proposed heat recovery system is presented in Fig 6. The system operates as follows: steam is generated in the flue gas heat exchanger 1. Then steam passes through the liquid phase separator 2 and flows to the reduction station 3, where the pressure is reduced do desired level corresponding to the required temperature in the heat exchanger 4. In the heat exchanger 4 steam condenses and released heat of condensation is transferred to drive the refrigeration system or it is used for heating purposes. Condensate flows to the liquid receiver 5 and circulating pump 6 is used to transfer liquid water to the flue gas heat exchanger 1. The heating capacity of the flue gas heat exchanger is controlled by the control valve 9. The cycle is equipped with the two-stage security system preventing uncontrolled pressure increase. The first stage is the bleed valve 7 through which refrigerant flows to the condensate collector, the second stage is the auxiliary security valve 8 (not showed in the schematic).

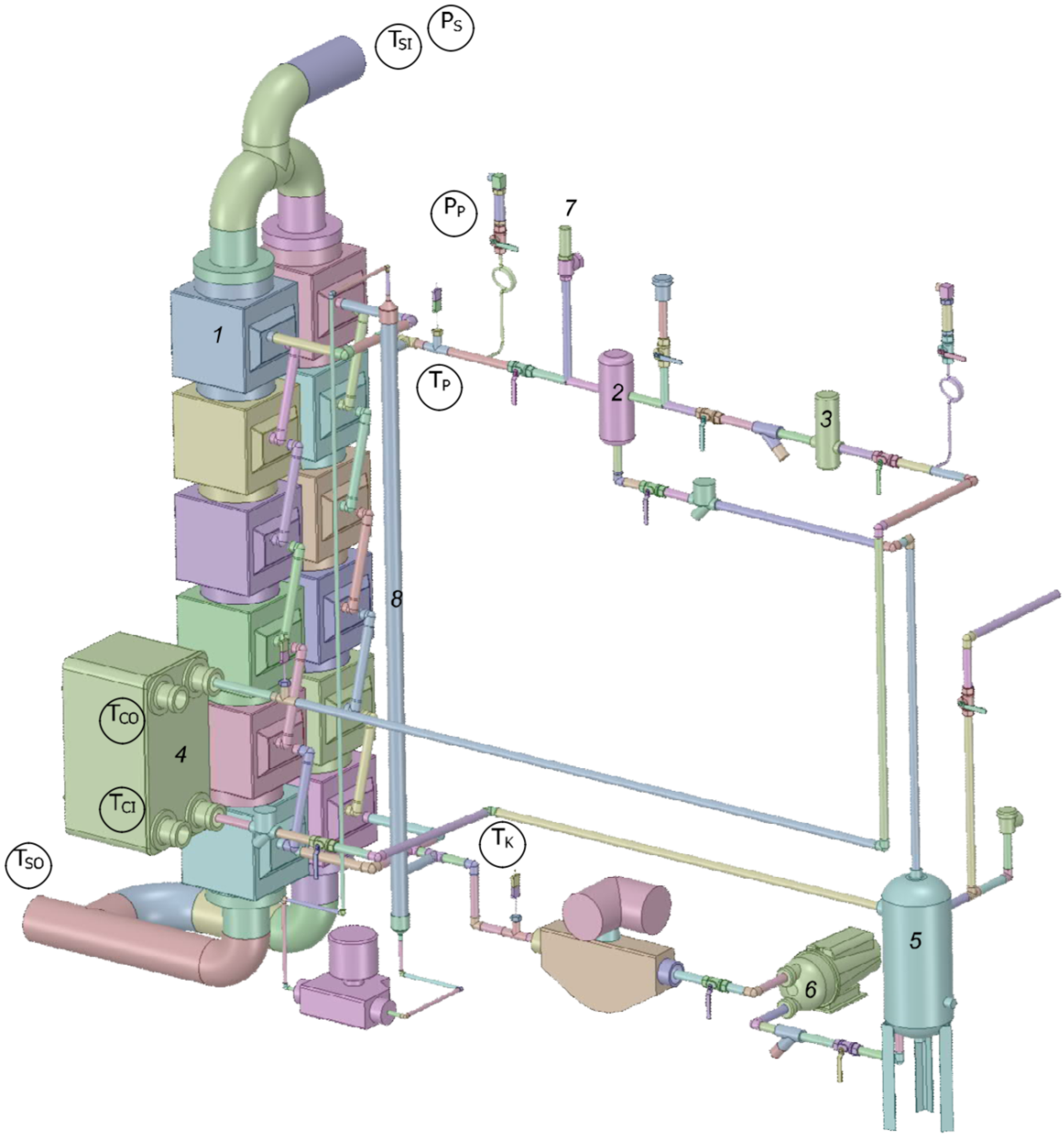

Fig. 6. Spatial schematic of the prototype steam heat recovery system: 1- section of the flue gases heat exchangers; 2 – liquid-vapour separator; 3 – pressure reduction station; 4 – steam condenser; 5 – condensate collector; 6 – pump; 7 – security valve.

The proposed configuration of the steam heat recovery system may be thought as an innovative solution for marine applications. The system was validated experimentally to confirm of the ability to transfer the required waste hate rate form the engine to the refrigeration and air-conditioning systems. Confirmation of acceptance of the discussed system was obtained from two independent marine classification societies. It was confirmed that the proposed solution meets the safety requirements, compactness, and technical criteria relevant for the heat recovery from flue gas ducts in marine applications.

6. CONCLUSIONS

The air-conditioning system for vessels equipped with a desiccant wheel and ejection refrigeration system was presented and briefly discussed. Both devices, i.e. desiccant wheel and ejection system use waste heat gained from exhaust gases from combustion engines.

Exemplary results of calculation have been presented. Results show that in the proposed air-conditioning system equipped with the desiccant wheel the cooling power is almost the same as total heat load of the vessel, while for conventional system with compression refrigeration system the cooling power is over two times higher than total heat load of the vessel. The use of the waste heat to drive the ejector refrigeration system allows for a significant reduction of an electric power consumption in the vessel.

The indicated solution is implemented by present shipyard in application to vessel of small and medium capacities. Due to the major innovative potential of the developed solution, further work is planned towards developing a configuration of the system ensuring high compactness and energy efficiency. The own approach for steam waste heat recovery system to drive the refrigeration and air-conditioning system was presented.

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