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An investigation of heat recovery of submarine diesel engines for combined cooling, heating and power systems

Roonak Daghigh *, Abdellah Shafieian

Department of Mechanical Engineering, University of Kurdistan, Kurdistan, Iran

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ABSTRACT

High temperature and mass flow rate of the exhaust gases of submarine diesel engines provide an appropriate potential for their thermal recovery. The current study introduces a combined cooling, heating and power system for thermal recovery of submarine diesel engines. The cooling system is composed of a mixed effect absorption chiller with two high and low pressure generators. The exhaust of the diesel engine is used in the high pressure generator, and the low pressure generator was divided into two parts. The required heat for the first and second compartments is supplied by the cooling water of the engine and condensation of the vapor generated in the high pressure generator, respectively. The power generation system is a Rankine cycle with an organic working fluid, which is considered a normal thermal system to supply hot water. The whole system is encoded based on mass stability, condensation and energy equations. The obtained findings showed that the maximum heat recovery for the power cycle occurs in exhaust gas mass ratio of 0.23–0.29 and working fluid mass flow rate of 0.45–0.57 kg/s. Further, for each specific mass ratio of exhaust gas, only a certain range of working fluid mass flow rate is used. In the refrigerant mass flow rate of 0.6 kg/s and exhaust gas mass ratio of 0.27, the power output of the cycle is 53 kW, which can also be achieved by simultaneous increase of refrigerant mass flow rate and exhaust gas mass ratio in a certain range of higher powers. In the next section, the overall distribution diagram of output water temperature of the thermal system is obtained according to the exhaust gas mass ratio in various mass flow rates, which can increase the potential of designing and controlling the thermal system. The effect of parameters of this system on output water temperature was also analyzed. Finally, the performance of mixed effect absorption chiller was examined and the findings indicated that in the exhaust gas mass ratio of 0.375, the system has a coefficient of performance equal to 0.94. The output water temperature of evaporator in this state is 3.64 °C and the cooling system power is 176.87 kW.

1. Introduction

All submarines are equipped with diesel engines, either as a main source of power or for emergency use. They are also possessed of air induction and diesel exhaust systems. Air induction systems take in outside air for combustion within the diesel engines, while exhaust systems discharge the combustion by products overboard. The engines are being cooled by water injection before discharge [1]. Based on the discharge features, exhaust flow rate and cooling water, the injection rates vary for each class of vessel, from about 6116 m^3/h to 14,611 m^3/h and from 0.44 kg/s to 0.95 kg/s, respectively. The exhaust flow temperature can also escalate to 650 °C [2]. Based on the abovementioned figures, merely a small portion of combustion energy turns into output from the crankshaft; most of the energy is, however, wasted in the exhaust and coolant systems. Therefore, there is a tremendous potential for energy recovery from submarine engines.

There is constant production of heat by submarines, which is released into the air by hot engines, storage batteries, galley stove, electric lights, electric heaters, other devices and human occupants. Moreover, there exists continuous production of humidity, discharged into the air by evaporation from four main sources: storage batteries, cooking, human occupants, and the bilges. In addition to the problem of air quality, if the temperature of air reaches the dew point, the interior surfaces start to perspire; i.e. there is always a potential danger from short circuits or grounds in electric systems. Thus, the cooling and air-conditioning systems play a pivotal role in submarines [3]. Hamilton Standard Division conducted a study to determine the type or types of air-conditioning systems, perfectly suited to large submarines. The performance of the systems was examined based on quantitative

* Corresponding author. Tel.: +98 8716664600 8.
E-mail addresses: r.daghigh@uok.ac.ir, daghighm@gmail.com (R. Daghigh).

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and qualitative evaluation of the systems according to five criteria: noise creation, maintenance-free life, volume, refrigerant type and power. The findings of overall rating indicated that the centrally located absorption-cycle, air-conditioning system was the optimum cooling system for a submarine. Absorption-cycle air-conditioning system increases the effectiveness of submarine, decreases it's size and noise. This system requires minimum number of the crews and provides the most comfortable atmosphere for them. Absorption system shows the quietest submerged patrol among all compared systems. Finally it shows the best thermodynamic performance [4].

Haywood et al. investigated the possibility of harvesting data center waste heat to drive an absorption chiller [5]. The initial heat source was waste heat that was produced by CPUs on each server blade. The main challenge of the system was to cool the data center simultaneously and produce sufficient exergy to drive the cooling process, regardless of the thermal output of the data center equipment. Ochoa et al. performed an energetic and exergetic study of an absorption chiller integrated into a microgeneration system [6]. They introduced a thermodynamic cogeneration model that coupled single-effect $LiBr/H_2O$ absorption chiller to a microturbine and analyzed energetic and exergetic behavior of the system. A computational algorithm was developed on the EES-32 platform to assess the impact of the main operating parameters of the cogeneration system. The COP values were reported to be between 0.24 and 0.74. The overall energy and exergy efficiencies of cogeneration were around 50% and 26%, respectively. The concept of automobile waste heat-driven adsorption cooling seems to be quite appealing, on which several studies have already been carried. Zhu et al. used the exhaust gas from a diesel engine of a fishing boat, to drive a zeolite–water adsorption refrigeration system, for preserving aquatic products [7]. Suzuki stated the combination of adsorption cooling system with exhaust heat from engines as a solution to reduce the environmental problems related to current automobiles [8]. Zhang and Wang studied the waste heat-driven adsorption cooling system for automobiles. The effects of some parameters on the performance of the system was also studied [9]. Zhang designed and examined an experimental intermittent adsorption cooling system driven by the exhaust gas of a diesel engine [10]. The experimental findings indicated that the prototype could be successfully utilized for waste heat driven air conditioning. The COP of the system was reported to be 0.38.

Kristiansen and Nielsen studied the potential of applying thermoelectric generators on ships. They intended to develop a thermoelectric generator powered by waste heat recovery from ships. In the study, the potential of system in a bulk carrier was evaluated. It was shown that the exhausts exits the engine and the sludge oil incinerator are the most favorable heat recovery sources [11]. Chen et al. computationally studied the application of thermoelectric generators in marine power plants. Computational Fluid Dynamics modeling is used to evaluate the feasibility of applying thermoelectric generators in the boiler section of marine plants. Finally, the results showed that by supplying 300 kW of the waste heat produced by boiler, thermoelectric generators can produce more than 600 W power [12]. Zhao and Tan reviewed materials, modeling and applications of thermoelectric cooling systems. First, ancient improvements of these systems have been briefly introduced. After that, historical accomplishments in the field of thermoelectric materials have been stated. Finally, different modeling techniques have been summarized in detail [13]. Thermo-electric cooling systems are compact and light in weight. They have no moving parts and are powered by direct current. In spite of mentioned advantages over conventional cooling devices, they have considerable shortcomings for submarines, which omits this system from consideration in studies. Application of large electric generators necessitates using large amounts of highly filtered, high-voltage, d-c power. Also, because of having low efficiency, thermoelectric devices require more sea-water flow in comparison with other systems. This results in considerable noise increase inside submarine. Finally, thermoelectric materials can't afford the required current, used in large-capacity cooling units.

Wang et al. reviewed the studies carried out on thermal exhaust heat recovery with Rankine cycle [14]. Rankine cycle (RC) was viewed the most favorite basic working cycle for thermodynamic exhaust heat recovery systems. It was also reported that designing a systemic structure and selecting both the expander and the working fluid (medium) are critical in order to achieve the highest possible efficiency of the system. Further, Larjola showed that up to 50% of exhaust gas exergy can be recovered by employing a Rankine cycle exhaust heat recovery system [15]. Hung et al. compared different cryogens, that are used as working fluids in Organic Rankine Cycle exhaust heat recovery systems [16].

An organic Rankine cycle (ORC) can be used to recover the waste heat, thereby improving the thermal efficiency of an internal combustion engine. A number of studies have recently been conducted to analyze the ORC performance. Kang studied characteristic performance of Organic Rankine Cycles experimentally [17]. He et al. investigated the optimal evaporation temperature in an organic Rankine cycle [18]. Sun and Li investigated the organic rankine cycle as heat recovery power plant [19]. Wang et al. compared organic Rankine cycle different working fluids for engine waste heat recovery [20]. Generally, the qualities of dry and isentropic fluids do away with the concerns of damage generated by liquid droplets on the turbine blades as a result of wet steam and application of superheated apparatus [21]. Zhang et al. suggested this as one of the major reasons for organic working fluid being adopted as the working fluid of RC [22]. Teng et al. conducted a study and demonstrated that a carefully selected organic fluid can reduce the temperature difference between the waste heat and working fluid. They concluded for diesel engines from which a moderate level of waste heat temperature is generated, the most efficient and highest power output is usually achieved by utilizing an appropriate organic fluid instead of water as the working fluid of RC [23].

As pointed out previously, there is a great potential for energy recovery from submarine engines. So, in this work, a new combined cooling, heating and power system for energy recovery from submarine engines was introduced. A mixed effect absorption chiller was applied to recover the jacket water and exhaust gas waste heat of engines. An organic Rankine cycle (R245fa was selected as the working fluid) and an ordinary heating system were also considered to supply power and hot water demand. The whole system was mathematically modeled and real discharge characteristics of submarine engines were used to investigate the performance of the system.

2. System description

The simple schematic of the proposed system used for heat recovery of a submarine diesel engine is shown in Fig. 1. The system consists of three main sections. First, cooling section is a mixed effect absorption chiller, which is designed to recover the waste heat of both exhaust gas and cooling jacket water. Second, power section is an organic Rankine cycle that utilizes R245fa as working fluid. Finally, a common heating system is considered to provide the hot water requirement of submarine. Based on the demand, the exhaust will be applied to the cooling, power and heating sections in proper ratios. As stated before, the cooling jacket water is only applied to power the low pressure generator of mixed effect absorption chiller. The current and future submarine designs are not limited to weight, but are critically restricted to equipment