Design and evaluation of a novel bi-evaporator combined power and refrigeration cycle working with various zeotropic mixtures

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ABSTRACT

In present research, a novel bi-evaporator combined cooling and power cycle based on the integration of a double-stage organic Rankine cycle and an ejector refrigeration cycle is devised to recycle heat from exhaust gas of a marine diesel engine. Instead of using conventional pure organic fluids, various appropriate zeotropic mixtures are screened for the proposed system and the results are discussed in terms of the first and second laws of thermodynamics. The results indicated that by recycling 434kW energy from the exhaust gases and using R142/Pentane with 51/49 percent a maximum thermal efficiency of 43.28% and overall cooling load of 166.36 kW can be achieved. In this case, the net electricity and exergy efficiency are obtained 21.83 kW and 20.22% which can be increased by selecting other appropriate mixtures. Additionally, using R142/Pentane with 51/49 percent as working mixture, it is figured out that the auxiliary vapor generator contributes to the highest exergy destruction by 62.3 kW out of overall exergy destruction of 122.15 kW. Also, the energy and exergy efficiencies of the system can be increased simultaneously by increasing the evaporator bubble point temperature.

KEYWORDS

Waste heat, Marine diesel engine, Ejector, Bi-evaporator, Zeotropic mixture

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1. Introduction

Nearly 40% of the overall fuel combusted by an internal combustion engine (ICE) is converted into useful work, while the remaining part of this energy is discarded into environment at high temperature (500-650℃) [1]. Meantime, the International Maritime Organization (IMO) has implemented several preventing regulations in order to hinder pollution of the marine environment and reduce the greenhouse gas (GHG) emissions [2]. Among various devised innovative methods, waste heat recovery (WHR) of marine diesel engines (MDEs) via appropriate technologies is deliberated as the most highly efficient approach by this organization. Among various technologies, organic Rankine cycle (ORC) has shown an exceptional outcome for both low and high temperature WHR of the exhaust gases. A great deal of in depth investigations have spotlighted merits of the ORC for this aim such as its low cost, small volume, high performance, light weight, and simple and routine operation, to name but a few. Since there is a poor thermal matching between the pure working fluids through evaporation process of refrigerant and high-temperature fluid of the marine diesel engine, it is worked diligently to resolve the problem associated with this mis-matching in the MDE-based ORCs. One of the more efficacious method to decrease this mis-matching between marine diesel engine and power sub-system is using zeotropic mixture which is accounted in this study. In zeotropic mixtures, the phase of the mixed fluid does not change isothermally, and hence different temperatures for saturated vapour or liquid state can be attained in a specific pressure [3]. Meantime, combined cooling and power (CCP) systems refer to simultaneous generation of cooling and power from the same source of energy. CCP systems are classified as integrated energy systems and are highly recommended for arid and semi-arid regions. It is worthy to mention that no study has developed a system for waste heat capturing of MDEs to produce cooling at two temperature levels and power for voyage applications, which is considered in the present study. The second novelty of the present study is the design methodology used in devising a new bi-evaporator CCP system which uses the extracted pressure of each turbine at two different scales to provide two primary pressures for ejectors. Thirdly, zeotropic mixture is used instead of pure fluid, where only studies of Yang et al. [4] and Yang and Zhao [5] can be found with this concept. An extensive thermodynamic evaluation of the devised set-up is presented.

2. Methodology

Fig.1 shows the schematic of the new devised bi-evaporator CCP system. Accordingly, the exhaust gases first enter the vapor generator and are used to preheat the mixture, then enter the auxiliary vapor generator and cool it to near the saturation temperature of the gas. The heat transferred from the diesel engine to the cogeneration system and considering some main thermodynamic processes, eventually the process leads to production of the required electricy and cooling in the ships.

3. Governing Equations

A thermodynamic code is developed in MATLAB software coupled with REFPROP to simulate the proposed cogeneration system. For this developed code, some assumptions are made, such as a) Kinetic and potential energies are neglected, b) Zeotropic mixture composition does not vary during the simulation, c) Temperature of the cooled engine exhaust gases from the preheater unit should be set above 375 K to avoid acid corrosion, d) Temperature profile of zeotropic mixture through the heat exchangers is assumed to have a linear distribution. The first and second laws of thermodynamics in terms of mass, energy and exergy balances are used in the present study as follows:

$$\sum_i \dot{m}_{in} = \sum_O \dot{m}_{out} \tag{1}$$

$$\dot{Q}_{c.v} - \dot{W}_{c.v} = \sum (\dot{m}h)_{out} - \sum (\dot{m}h)_{in} \tag{2}$$

$$\dot{Ex}_{D,k} = \sum_{i=1}^{k} \dot{Ex}_{in,i} - \sum_{i=1}^{k} \dot{Ex}_{out,i} \tag{3}$$

Using the above formulations, each component of the proposed system is analyzed and finally the amount of generated electricity and cooling are reported.

Energy and exergy efficiencies of the devised bi-evaporator CCP system are articulated respectively as:

$$\eta_{en,ccp} = \frac{\dot{Q}_{eva1} + \dot{Q}_{eva2} + \dot{W}_{net}}{\dot{Q}_{AVG} + \dot{Q}_{VG}} \tag{4}$$

$$\eta_{ex,ccp} = \frac{\dot{W}_{net} + \left(\dot{Ex}_{28} - \dot{Ex}_{27}\right) + \left(\dot{Ex}_{30} - \dot{Ex}_{29}\right)}{\dot{Ex}_{1} - \dot{Ex}_{3}} \tag{5}$$

4. Results and Discussion

Fig. 2 depicts effect of mass fraction of different zeotropic mixtures on the net electricity and refrigeration load.

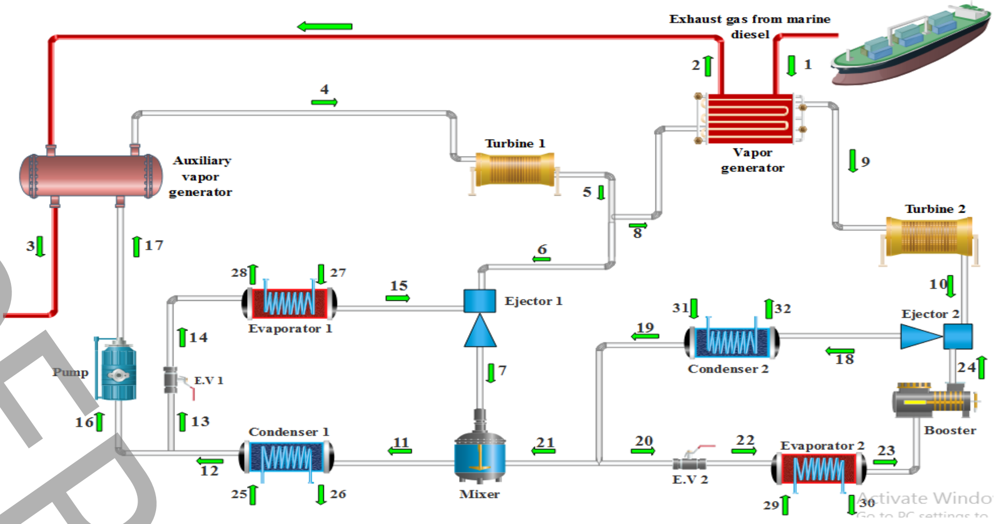


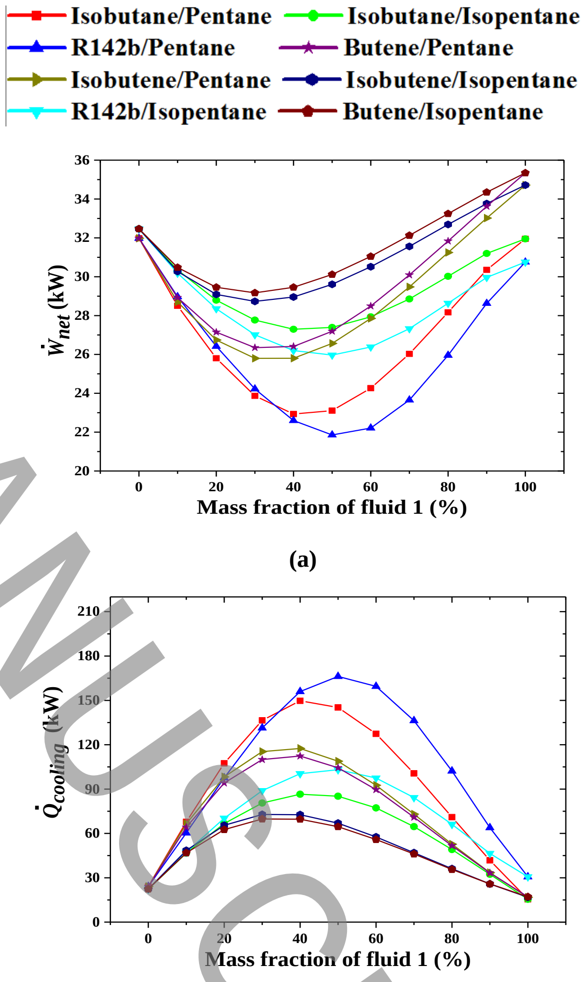
Figure1. Layout of the devised bi-evaporator cogeneration system, operated by waste heat of a marine diesel engine

According to Fig. 2, it can be discerned that the devised cogeneration system produces more refrigeration load than electricity, and hence it is expected to have a pinnacle value for refrigeration load due to its dominant impact rather than for the net electricity. As Fig. 2 indicates, R142b/Pentane is the best selection of mixture to achieve the highest refrigeration load followed by Isobutane/Pentane. The worst zeotropic mixture in terms of refrigeration load is Butene/Isopentane, followed by Isobutene/Isopentane. In terms of net electricity the trend is nearly reverse. The best zeotropic mixture in terms of net electricity is Butene/Isopentane, followed by Isobutene/Isopentane. However, the worst zeotropic mixture in terms of net electricity is R142b/Pentane, followed by Isobutane/Pentane. Also, using pure working fluids (presented in Fig. 2) can lead to higher net electricity. As a conclusion, using zeotropic mixture instead of pure working fluid highly improves refrigeration load and energy efficiency nonetheless decreases net electricity and exergy efficiency.

Table 1 presents the main decisive factors of the proposed system for the two best zeotropic mixtures in terms of energy efficiency.

Table1. Main performance factors for different mixtures

Performance	R142b/ Pentane (0.51/0.49)	Isobutane/Pentane (0.43/0.57)
$\dot{W}_{net}$	21.832	22.879
$\dot{Q}_{cooling}$	166.364	150.203
$\eta_{en,ccp}$	43.282	39.806
$\eta_{ex,ccp}$	20.223	20.107
$\dot{Ex}_{D}^{tot}$	122.154	121.642



(a)

(b)

Figure2. Effect of mass fraction on net electricity and refrigeration load for different mixtures

5. Conclusions

A new integrated bi-evaporator cooling/electricity system working with two cooling temperature levels was devised in this study. Main conclusions of the present study are as follows:

A) The maximum refrigeration load and cogeneration energy efficiency were calculated 166.36 kW and 42.46%, respectively, when R142b/Pentane (0.51/0.49) was used. B) Using Isobutene/Pentane (0.36/0.64) and Isobutane/Pentane (0.43/0.57) led to the lowest cogeneration exergy efficiency of 17.79% and 17.91%, respectively. The highest cogeneration exergy efficiency was associated with Butene/Isopentane (0.35/0.65) by 18.71%, followed by Isobutene/Isopentane (0.34/0.66) by 18.53%. C) The highest net electricity was associated with Butene/Isopentane (0.35/0.65) by 18.02 kW, followed by Isobutene/Isopentane (0.34/0.66) by 17.63 kW.

6. References

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