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Waste heat recovery from data centers using Organic Rankine Cycle (ORC), and Multi-objective energy and exergy optimization of the system in marine industries

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Abstract

In order to optimize the energy consumption in data centers, it is required to recover the heat generated in them. One of the best methods used for waste heat recovery at low temperatures is an Organic Rankine Cycle. In present study, the method is used for waste heat recovery in a data center and multi-objective optimization in the system. The results showed that after optimization the optimum first- and second-law efficiencies of the above system were 26.49% and 65.98%, respectively, which increased about 21.51% and 17.38%, in that order. In such a situation, the optimal power generation was 97.98 kW. The boiler had the highest exergy destruction of 29.97 kW in base mode and 26.44 kW in optimum mode, followed by the low-pressure turbine with the exergy destruction of 18.4 kW in base mode and 16.83 kW in optimum mode. In addition, the results indicated that the boiler and low-pressure turbine had the highest irreversibility, resulting in an increased contribution of the above components in total irreversibility. Accordingly, the boiler had the highest contribution of 35% (in base mode) and 38% (optimum mode) in the system's irreversibility and was considered as the most effective component in the entire system, followed by the low-pressure turbine with the contribution of 21% in base mode and 25% in optimum mode.

Keywords: Organic Rankine Cycle; Heat Recovery; Data Center; Multi-objective Optimization.

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1. Introduction

Today, most of the electricity needed by communities is supplied using non-renewable fuels. These fuels have destructive effects on the environment, including global warming, ozone depletion and acid rain. On the other hand, the resources of these fuels are limited and as the energy consumption increases, non-renewable resources are declining. So, it is required to optimally use existing energy and save it. Recently, energy saving through waste heat recovery in low-temperature heat sources has become necessary. In many industrial units, the waste heat will negatively affect the environment if it is released before recycling. In this regard, many studies have been carried out and are ongoing in power generation from waste heat in various industries. Organic Rankine Cycle is a very effective way to utilize the heat of renewable resources and the waste heat in various industries (Quoilin and Lemort, 2009). The rapid growth of the IT industry in recent years and increased energy consumption in data centers have resulted in high overall energy consumed by modern societies. The sensible heat flux in a data center usually ranges from 500 to 3,000 watts/m^2, which is much higher than other commercial buildings. The waste heat in a data center can be used to generate power by the organic Rankine cycle. The low boiling point of the organic fluids makes the waste heat in a data center to be a good heat source for the organic Rankine cycle for power generation.

Zare *et al*. (2012) examined different configurations of the Rankine cycle for the recovery of heat from the pre-cooling process in a gas turbine-modular helium reactor with a single-phase condenser. The results showed that the simple organic Rankine cycle outperforms other designs and it economically outperforms other proposed cycles. Soltani *et al*. (2015) thermodynamically analyzed a hybrid heat pump and investigated its performance in order to provide regional heating. They studied the effects of various factors, such as ambient temperature, evaporation pressure, and condensation pressure, on the efficiencies of the system and its components. The energy and exergy efficiencies of the system were equal to 13.87% and 89.8%, respectively.

Suleman *et al*. (2014) designed a new solar energy and geothermal-based multi-generation system. The designed cycle is composed of two organic Rankine cycles for power generation, absorption refrigeration cycle for the provision of refrigeration and a drying system for drying wet products. In order to determine the irreversibility, energy and exergy analyses were performed on all components of the system. According to the calculations, the energy and exergy efficiencies of the system were obtained 54.7% and 76.4%, respectively.

Yu *et al*. (2016) proposed a new hybrid system for the waste heat recovery from heavy-duty diesel engines. Their hybrid system consisted of a high temperature Organic Rankine Cycle and a low temperature Organic Rankine Cycle. The high-temperature Organic Rankine Cycle used the waste heat from the exhaust gas after the turbocharger. As well as the input gas before the turbocharger, and the low temperature Organic Rankine Cycle used the residual waste heat used in the high-temperature Organic Rankine Cycle in addition to the waste heat from the pre-charged air and water chamber. They presented two groups of working fluids sorted based on the thermodynamic performance for each cycle separately.

Song and Gu (2015) coupled two high- and low-temperature Organic Rankine Cycles using a heat exchanger in order to recover the waste heat from engines. This heat exchanger acted as an evaporator for the low-temperature cycle and as a condenser for the high-temperature cycle. The high-temperature organic cycle was used to recover the waste heat from exhaust gas. The residual waste heat and the waste heat from the water chamber were also applied in the low-temperature Organic Rankine Cycle.

Kim *et al*. (2015) presented a new hybrid system for the power generation. The system consisted three Organic Rankine Cycles and the required heat was provided through the waste heat from the natural gas liquefaction. In order to minimize the exergy destruction in the system, three factors were investigated, flow rate, composition of the two working fluids, and working fluid pressure. At the end of the research, the effect of the heat source temperature on the efficiency and performance of the system was accurately analyzed in the temperature range of 25-85 °C.

Karellas and Braimakis (2016) presented thermodynamic and economic modeling of a hybrid multi-objective system on a small scale. The heat required by the system was supplied by biomass and solar energy. The system was composed of an Organic Rankine Cycle and vapor compression refrigeration cycle. This multi-objective system was applied to produce heat and power in winter, and heat, cool, and power in summer. The parameters affecting power generation and exergy efficiency, such as evaporation temperatures and condensation temperature were investigated. The results showed that if the R245fa working fluid was used in the Organic Rankine Cycle at an evaporation temperature of 90 °C and in a state where the fluid is not superheated, the system could produce 53.5 kW heat, 5 kW cooling (in summer) and 42.1 KW power.

Marcinichen *et al*. (2012) investigated and simulated a hybrid cooling system using several micro-evaporators and utilizing the waste heat of a data center. They also explored the feasibility of using a modern data center (with the waste heat of 5-15 kW) to recover the heat from a condenser of a coal-fired power plant. They used the waste heat from a data center for pre-heating of water. They showed reducing trend in using the waste heat from a data center for pre-heating of water consumption, energy consumption, and carbon dioxide released by the hybrid system. There are many studies on the recovery of heat from the low-temperature sources using an Organic Rankine Cycle, but there is no comprehensive research on the waste heat recovery from data centers. In the present research, it is attempted to study the waste heat recovery from data centers using an Organic Rankine Cycle and multi-objective optimization of the cycle.

2. Materials and methods

The waste heat from designed data center is used to generate power. An Organic Rankine Cycle is used for waste heat recovery from data center and power generation. The scheme of the studied hybrid system is presented in Figure 1.

In the present study, multi-objective optimization (energy and exergy) was performed. A genetic algorithm was utilized for optimization process. The most important features of the genetic algorithm are including number of cells and population size. The assumptions were made for optimization as follows (Marcinichen *et al*., 2012; Bao and

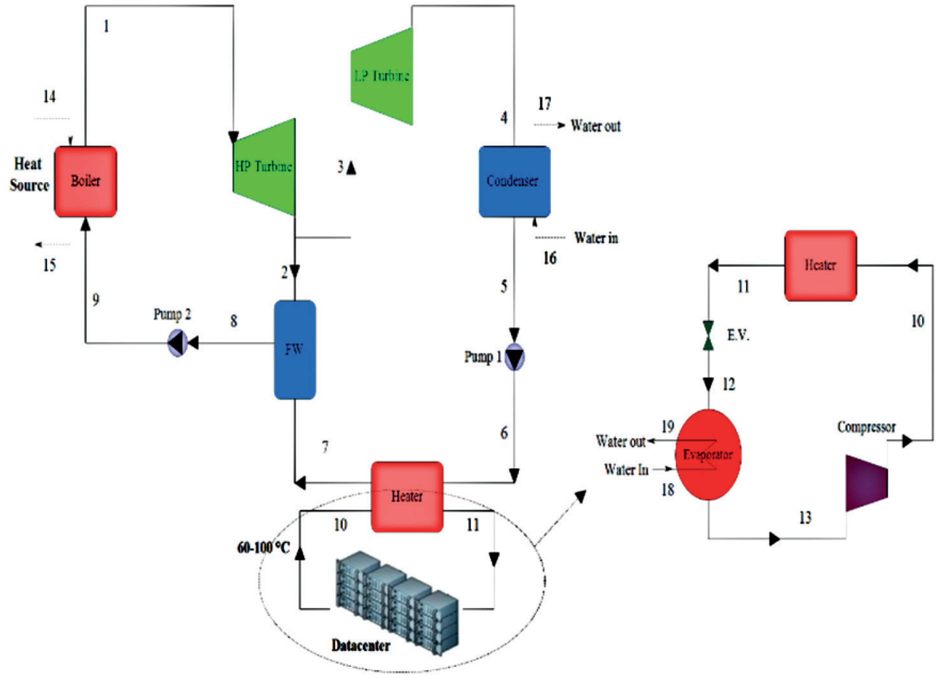


Figure 1. Designed hybrid cycle used for waste heat recovery from the data center

Zhao, 2013; Safarian and Aramoun, 2015):

- Number of generations: 64
- Maximum mutation rate: 0.25
- Minimum mutation rate: 0.0005
- Initial mutation rate: 0.25
- Crossover probability: 0.85

In multivariate optimization, the contribution of each energy and exergy factors is considered equal to 0.5. In the present study, the objective function of multivariable optimization is determined using the following equation:

$$MOF = w_1\eta_{th} + w_2\eta_{ex} \qquad w_1 + w_2 = 1 \tag{1}$$

For the thermodynamic analysis of the system in terms of the mass and energy balance and capability of various elements, Equations (2) to (4) are used.

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{2}$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \tag{3}$$

$$\sum\left(1-\frac{T_0}{T_i}\right)\dot{Q}_i - \dot{W}_{c.v} = \sum \dot{m}_e ex_e - \sum \dot{m}_i ex_i + \dot{E}x_D \tag{4}$$

The subtitle 0 represents the ambient conditions. The second-law efficiency is defined according to Equation (4) (Bejan *et al.*, 1996).

$$\eta_{ex} = \frac{\dot{E}x_P}{\dot{E}x_F} = 1 - \frac{\dot{E}x_D}{\dot{E}x_F} \tag{5}$$

where, $\dot{E}x_P$ and $\dot{E}x_F$ denotes the capability of the product and fuel of each element. To analyze the system in terms of energy and the second law efficiency, the following assumptions are also used (Marcinichen *et al.*, 2012; Bao and Zhao, 2013; Safarian and Aramoun, 2015):

- All processes are stable.
- The effects of kinetic and potential energy are ignored.
- The working fluids of Organic Rankine Cycle and data center are R113 and R134a refrigerants, respectively.

- The output of condenser is saturated liquid and the output of evaporator is saturated vapor.
- Condensing unit components, turbine and pump work under constant entropy efficiency.
- The chemical exergy of the fluids used in different points is ignored.

In addition, the parameters used in the thermodynamic analysis of the system are listed in Table1.

2.1. Validation

Two Organic Rankine Cycle and compression heat pump are investigated as two basic cycles of the main hybrid cycle. In the first step, a simple Organic Rankine Cycle studied by Safarian and Aramoun was selected and the abovementioned system (current research) is simulated under the same conditions. The results are presented in Table 2 that shows consistency in both studies.

In the second part, the compression heat pump used in Sag *et al*. (2015) was selected and the system was simulated under the same conditions. The results are presented in Table 3, which are in consistent with each other.

3. Results and Discussion

The objective function of multivariable optimization determined by Equation (1) presented as decision variables are listed in Table 4.

Table 1. Parameters required for the simulation of the studied system

Parameter	Value	Reference
Reference temperature- $T_0\left(K\right)$	298	(Safarian and Aramoun, 2015)
Reference pressure- $P_0\left(MPa\right)$	0.101	(Safarian and Aramoun, 2015)
Temperature of heat source-$T_{HS}\left(K\right)$	573	(Safarian and Aramoun, 2015)
Boiler outlet pressure- $P_B\left(MPa\right)$	2.5	(Safarian and Aramoun, 2015)
Condenser temperature- $T_{Cond}\left(K\right)$	304	(Bao and Zhao, 2013)
Condenser temperature in data center- $T_{DC,Cond}\left(K\right)$	363	(Marcinichen *et al*., 2012)
Heater final temperature difference- $TTD_H\left(K\right)$	10	(Ghaebi *et al*., 2017)
Evaporator outlet temperature in data center- $T_{DC,Eva}\left(K\right)$	343	(Marcinichen *et al*., 2012)
Evaporator outlet pressure in data center - $P_{DC,Eva}\left(MPa\right)$	1.681	(Marcinichen *et al*., 2012)
Heat source mass flow rate= $\dot{m}_{HS}\left({}^{kg}\!/_{s}\right)$	2	(Safarian and Aramoun, 2015)
Boiler pinch point temperature difference- $PPTD_B\left(K\right)$	5	(Ghaebi *et al*., 2017)
Evaporator final temperature difference- $TTD_{Eva}\left(K\right)$	5	Rostamzadeh *et al*., 2018)
Turbine efficiency- $\eta_{is,Tur}\left(\%\right)$	80	(Safarian and Aramoun, 2015)
Pump efficiency- $\eta_{is,Pump}\left(\%\right)$	85	(Safarian and Aramoun, 2015)

Table 2. Validation of Organic Rankine System; comparison of the results of present study and a research by Safarian and Aramoun (2015)

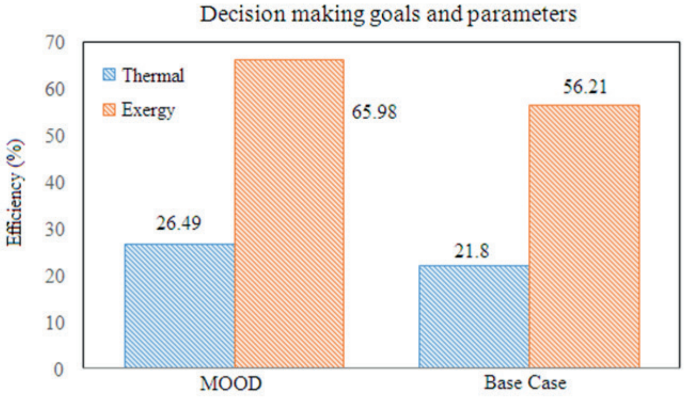
Parameters	Present study	Safarian Aramoun (2015)	Relative difference (%)
Cooling load- $\dot{Q}_{Eva}\,(kW)$	252	252	0
Condenser load $\dot{Q}_{Cond}\,(kW)$	199.2	196	1.63
Pump work- $\dot{W}_{Pump}\,(kW)$	2.25	2.2	2.27
Thermal exchanger load- $\dot{Q}_{IHE}\,(kW)$	31.64	30.5	3.73
Turbine work- $\dot{W}_{Tur}\,(kW)$	55.79	56.5	1.25
Network- $\dot{W}_{net}\,(kW)$	53.54	54.3	1.4
Mass flow rate- $\dot{m}\left(\frac{kg}{s}\right)$	1.164	1.15	1.2
Energy efficiency- $\eta_{th}\,(\%)$	21.2	21.5	1.39
Exergy efficiency- $\eta_{ex}\,(\%)$	33.32	33.24	0.24

Table 3. Validation of compression heat pump; comparison of the results of present study and a study by Sag *et al*. (2015)

Parameters	Present study	Sag *et al*. (2015)	Relative difference (%)
Cooling load- $\dot{Q}_{Eva}\,(kW)$	4.13	4.30	3.9
Compressor work $\dot{W}_{Com}\,(kW)$	1.409	1.52	3.7
Coefficient of performance (COP)	2.805	2.82	0.53

Table 4. Decision variables and their range

Decision variables	Range (unit)
Boiler pinch point temperature difference	2-8 K
Evaporator pressure in data center	1.4-1.9 MPa
Boiler pressure	2.3-2.8 MPa
Heater final temperature difference	6-13 K
Condenser temperature in data center	333-375 K
Evaporator temperature	335-365 K
Condenser temperature	295-310 K



W_1	0.5	-
W_2	0.5	-
Boiler pressure (MPa)	2.8	2.5
Condenser temperature (K)	301.5	304
Condenser temperature in data center (K)	337.1	363
Heater final temperature difference (K)	6.04	10
Evaporator pressure in data center (MPa)	1.632	1.681
Evaporator temperature in data center (K)	365	343
Boiler pinch point temperature difference (K)	5.889	5
First turbine power generation (kW)	29.81	29.4
Second turbine power generation (kW)	80.32	86.56
Condenser power consumption (kW)	2.38	19.34
First pump power consumption (kW)	2.14	2.35
Second pump power consumption (kW)	7.62	6.35
Net power generation (kW)	97.98	82.82

Figure 2. Results obtained in basic and optimum modes

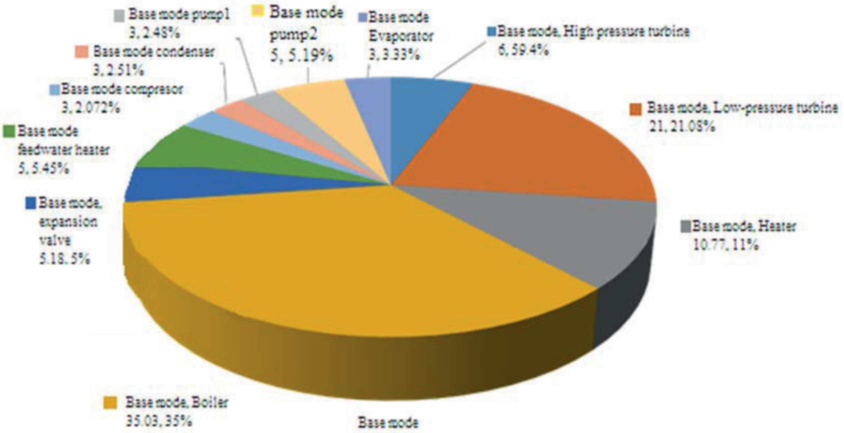


Figure 3. The contribution of various components of the studied system in base mode

Figure 2 shows the results of the thermodynamic simulation of the studied system in the base and optimum modes. According to this figure, after optimization, the energy efficiency and exergy efficiency were calculated to be 26.49% and 65.98%, which shows increasing about 21.51% and 17.38%, respectively, and the optimal power generation was computed 98.98 kW. The optimum mode of the above system was obtained under the following operating conditions: Boiler pinch point temperature difference: 5.88 K, Evaporator pressure in data center: 1.632 MPa, Boiler pressure: 8.8 MPa, Heater final temperature difference: 6.04 K, Evaporator temperature in data center: 365 K, Condenser temperature: 301.5 K.

Figure 3 indicates the contribution of the various components of the system in base mode. As mentioned earlier, boilers and low-pressure turbines have the highest irreversibility, which increases the contribution of the above components in total irreversibility. It can be seen that the boiler had the highest percentage of contribution (35%) in the system's total irreversibility in base mode, followed by the low-pressure turbine with 21% involvement.

Conclusion

To improve the performance of the simulated system, it was optimized to maximize the first- and second- law efficiencies using the genetic algorithm and considering appropriate decision variables. Some of the important results are summarized below:

- The first and second-law efficiencies increased by 21.51% and 17.38% after optimization. The optimum first and second-law efficiencies were calculated to be 26.49% and 65.98%, respectively, and the optimal power generation was estimated 97.98 kW.
- The boiler has the highest exergy destruction of 29.99 kW (in base mode) and 26.54 kW (optimum mode), followed by the low pressure turbine with exergy destruction of 18.04 kW (in base mode) and 16.83 kW (in optimum mode).
- The boiler has the highest contribution (35% in base mode, and 38% in optimum mode) in the system's irreversibility, followed by the low pressure turbine with the contribution of 21% in base mode and 25% in optimum mode.
- Increasing the temperature and mass flow rate of the heat source results in increased power generation, and since the thermal efficiency and exergy efficiency of the system are influenced by the net generated power, as the temperature of heat sources enhances, the thermal efficiency and exergy efficiency increase.
- Increasing the boiler pressure up to $P_B = 2.95$ MPa is caused firstly reducing and then increasing in the net power generation. The minimum net power generation at this point was estimated 50.16 kW. The minimum values of the first- and second-law efficiencies were obtained at $P_B = 2.86$ MPa, with the values of 13.88% and 44.22%, respectively.
- Increasing condenser temperature resulted in reduction in power generation, first-law efficiency and second-law efficiency.
- Increasing the condenser temperature in the data center to $T_{DC,\ Cond} = 370.5$ K firstly increased and then decreased the net power generation. The maximum net power generation at this point was 89.37 kW. Furthermore, the maximum energy

efficiency and exergy efficiency were obtained at $T_{DC, Cond} = 370.5$ K with the values of 21.5% and 53.8%, respectively.

- Heat is one of the inevitable needs of industrial processes, and these processes continuously waste large amounts of energy during their normal operation. In the present study, it was attempted to perform the energy and exergy analyses of the two-phase Organic Rankine Power generation cycle by waste heat recovery of a data center based on the first and second laws of thermodynamics. The proposed hybrid cycle was simulated by applying the first and second laws of thermodynamics on each component of the cycle. The main idea for increasing the thermal efficiency of the power cycle is to increase the average temperature under which the heat is given to the working fluid in the generator, or to reduce the average temperature under which the heat is released from the working fluid in the condenser. Therefore, the average temperature of the working fluid should be as high as possible in the heat absorption process and it should be as low as possible in the heat release process to improve the performance of the simulated system. Optimization of the above system performance was conducted to maximize the first-and second- law efficiencies using the genetic algorithm and considering appropriate decision variables.
- The Organic Rankine Cycle is an appropriate choice for converting low- and moderate temperature heat to electric power. The adaptability of Organic Rankine Cycle as well as its applicability at different temperatures allows connecting these cycles to the existing units to recover waste heat as a secondary cycle or to use it in the simultaneous heat and power generation. Accordingly, the results of the research on the new hybrid cycle showed that this cycle can be used as a secondary cycle in solar thermal collector-based cycles, geothermal cycles, and gas-cooled reactors because it works with low temperature.

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