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Thermodynamic Investigation of a Trigeneration ORC Based System Driven by Condensing Boiler Hot Water Heat Source Using Different Working Fluids

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ABSTRACT

This study conducts thermodynamic analysis on three trigeneration cycles including Organic Rankine Cycle (ORC), Liquefied Natural Gas (LNG) cold energy, and absorption refrigeration cycle in order to select appropriate working fluids. Different types of ORC cycles including simple ORC, regenerative, and ORC with Internal Heat Exchange (IHE) were investigated. For those types, the operation of six working fluids with different thermodynamic behaviors (R141b, R124, R236fa, R245fa, R600, and R123) was evaluated. In power plants, a low-grade heat source was provided by condensing boiler hot water energy while the thermal sink was prepared by cold energy of LNG. The effect of boiler temperature variation on energy and exergy efficiencies was investigated. According to the derived results, regenerative ORC-based systems possessed maximum energy and exergy efficiencies, while simple ORC and ORC with internal heat exchanger exhibited approximately the same quantities. Also, among these analyzed working fluids, R141b had the maximum energetic and exergetic efficiencies, while R124 and R236fa had minimum performance.

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1. INTRODUCTION

Much effort is required to put a stop to global warming and ozone depletion. To reduce CO_2 emissions, applying effective technologies is necessary. One of the efficient systems to get electricity from low/medium temperature heating is applying Organic Rankine Cycle (ORC). These days, ORC systems have proved to be a perfect technology to turn low-grade heat into applicable electricity or work. In ORC systems, organic fluids are used instead of water in steam power cycles. Modifying the configuration of the cycle and improving the working fluid are some of the methods for enhancing the efficiency of an ORC system. Finding a suitable working fluid that matches the heat source is essential to enhancing the efficiency.

Producing power from low/medium-grade heat sources using ORC systems is one of the appealing subjects that has attracted the attention of the researchers [1-3]. Maizza et al. [4] investigated waste energy recovery using the ORC cycle and studied the properties of some working fluids. Their results demonstrated the role the analytical criteria in selecting the most favorable working fluid in terms of thermodynamics. Wang et al. [5] simulated a modified regenerative ORC cycle using solar energy. According to their results, the cycle performance would increase with increasing inlet temperature and pressure of the turbine. They also proved that R245fa and R123 had better thermodynamic performance. Safarian and Aramoun [6] employed the first and second law of thermodynamics for evaluation of applying R113 as the working fluid in the modified ORC. Among the studied systems, the maximum energy and exergy efficiencies belong to the ORC system with both turbine bleeding and regeneration. Four ORC systems were analyzed by Mosaffa et al. [7] exploiting geothermal energy as the heat source and LNG cold energy as the thermal sink. Among the studied cycles, the regenerative and IHE systems had maximum thermal and exergy efficiencies. Habibzadeh and Jafarmadar [8] investigated applying ten working fluids in an ORC cycle to recover the engine waste heat. They studied the role of various factors in the system efficiency and introduced the most proper working fluid. Results indicated that in the studied ranges, R134a had the best performances. On the other hand, cyclohexane possessed the least appropriate fluid. Behnam et al. [9] studied thermodynamically and economically the performance of a trigeneration system using geothermal. The system included a single-stage absorption refrigeration system, a single-stage evaporation desalination system, and an organic Rankine cycle. The findings showed that a production capacity of 0.662 kg/s freshwater, 161.5 kW power, and 246 kW heat load could be obtained when the geothermal water temperature was set to 100 °C. Akrami et al. [10] investigated a geothermal-based multi-generation energy system in which heating, electricity, hydrogen, and cooling were produced. The system included a domestic water heater to produce heating, an Organic Rankine Cycle to produce electricity, a proton exchange membrane electrolyzer to produce hydrogen, and an absorption refrigeration cycle to

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produce cooling. From the results, 34.98 % and 49.17 % were calculated for the energy and exergy efficiencies, respectively. In a study by Yagli et al. [11], ORC system was used as the downstream cycle of a gas turbine. Various working fluids were investigated and compared. For the turbine inlet pressure between 10-25 bar, benzene had the best performing working fluid. At higher pressures, R123 had the highest performance. Wang et al. [12] analyzed a combined power plant to produce power and cooling in which ORC was applied to generate power. For finding the most appropriate working fluid, zeotropic mixtures were investigated. The results revealed that Isopentane (30 %) and R142b (70 %) zeotropic mixture had the highest efficiency. Mosaffa and Garousi Farshi [13] investigated the effect of using zeotropic mixture in an organic Rankine cycle for a salinity gradient solar pond-based power generation system. For increasing power generation, LNG cold energy is applied as a heat sink. The results showed that R245ca/R236ea mixture possessed an optimal thermal performance. In another study, a combined ORC and LNG regasification was studied by Choi et al. [14]. Results showed that the higher the total conductance for system design, the higher the heat duty should ORC take. Sun et al. [15] studied the selection of suitable configuration including single-stage Rankine Cycles (RC), two-stage RCs, and a regenerative-reheat RC using cold energy of LNG and low-grade heat. According to the optimization of eight working fluids, it was found that the best choice was the modified single-stage RC. Moreover, it was stated that for reheat RC, wet working fluids were better, while dry and isentropic fluids were better for regenerative RC and regenerative-reheat RC. Tian et al [16] investigated the performance of zeotropic and pure fluids in an ORC system. The heat source for the system was the waste heat of the ship engine and the heat sink was LNG. It was concluded that the zeotropic mixtures did not always have better performance than pure fluids. The results indicated that the maximum energy and exergy efficiencies were 22.09 % and 23.28 %.

In this paper, a novel combined cycle was introduced for power and cooling using a condensing boiler. Although in some researches, a combination of ORC and LNG is investigated, but to the knowledge of the authors, there are no studies in which condensing boiler was applied as the heat source. The purpose of the present study is to thermodynamically model and investigate the performances of the simple ORC, the regenerative ORC, and ORC with IHE in different operating conditions in terms of energy and exergy. In this paper, the Organic Rankine Cycle (ORC) and the absorption chiller are considered as upstream and downstream cycles, respectively. In this system, the energy required for the ORC evaporator and absorption chiller generator is prepared by condensing boiler hot water as the heat source while the heat sink is provided by LNG cold energy. Six working fluids with various thermodynamic behaviors have been chosen to analysis and comparison thermodynamically.

2. SYSTEM DESCRIPTION

Figure 1 provides the three different types of ORC systems and absorption refrigeration systems as well as LNG cold energy: (a) simple ORC, (b) ORC with IHE, and (c) regenerative ORC.

In a simple ORC, after absorbing the heat from condensing boiler hot water in the evaporator, the working fluid vaporizes to a saturated vapor at high pressure and temperature and is expended in the turbine to produce electricity. The exhausted working fluid leaving the turbine is condensed in the condenser by applying low-temperature natural gas. The saturated liquid is pumped to the preheater before entering the evaporator to complete the cycle. In the IHE ORC configuration, to enhance the efficiency of the system, part of the energy of the turbine exhaust stream is recovered by an internal heat exchanger. A Feed Organic Heater (FOH) is added for modifying a simple ORC system to a regenerative ORC. The organic fluid exiting the first pump is mixed by a hot turbine extracted stream. The stream leaving the FOH is saturated liquid. The hot ORC turbine leaving stream is applied as the heat source for the natural gas power generation system. In the LNG cycle, the saturated liquid low-temperature LNG is extracted and pumped into the ORC condenser and changes to saturated vapor. Then, in a heat exchanger, it is further heated which enters the turbine. After expansion and power generation, the natural gas is sent to the gas supplying system. For operating the absorption refrigeration system as the cooling subsystem, the hot water of condensing boiler provides a heat source to the generator. In this system, water and LiBr are the refrigerant and absorbent, respectively. The strong concentration of water solution in the absorber is pumped to the generator. In the generator, the solution is boiled out and the water vapor is separated from the solution. The vapor flows through the condenser and rejects heat and then, for providing a cooling effect, expands to the pressure of the evaporator. To complete the cycle, in the absorber, a weak solution stream from the generator and refrigerant stream from the evaporator should solve with each other.

3. WORKING FLUID SELECTION

Organic fluids are capable of operating at a very low temperature and pressure which is one of the advantages of ORC systems over the Rankine cycles. The selection of a suitable working fluid can improve the thermal and exergetic efficiency of ORC. The organic working fluids can be categorized into 3 categories (dry, wet, isentropic) dependant on the saturation vapor curve slope in the T-s diagram. The most suitable working fluid can be selected according to two important factors: possessing the highest efficiency when applying in a cycle and being eco-friendly working fluid, which means near-zero ODP and low GWP characteristics. In this paper, 6 working fluids (R141b, R124, R236fa, R245fa, R600, R123) were elected for thermodynamic analysis of the suggested system. The properties of the six chosen organic fluids are mentioned in Table 1.

4. THERMODYNAMICS APPROACH

4.1. Thermodynamics assumptions

For the thermodynamic investigation of the suggested combined cycles, the following assumptions are considered:

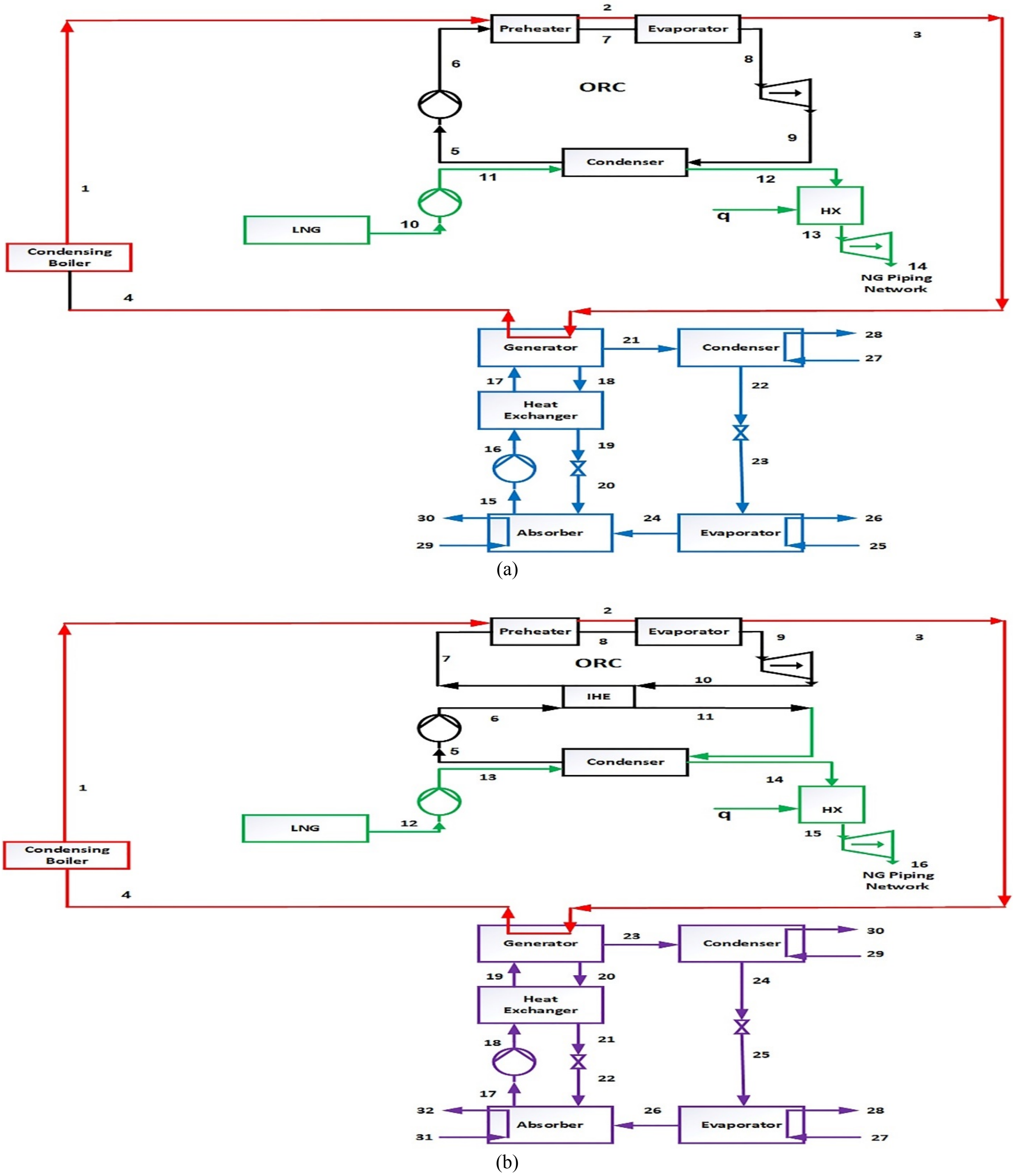
- Pressure and heat losses in all types of equipment are considered zero.
- All processes of components in the cycles are in a steady state.
- The condition of organic fluid is saturated vapor and saturated liquid in the evaporator and condenser, respectively.

- For natural gas simulation, it is assumed to be pure methane. The LNG is saturated liquid in the storage tank under the pressure of P0, while it changes to saturated vapor after passing through the condenser.

For thermodynamics analysis, it is sufficient to apply governing equations (conservation of mass and energy) to each component. These mentioned relations are needed to be applied to each part of the proposed system. Some of the required thermodynamics balance equations in this analysis are presented in Table 2.

Table 1. Properties of the candidate working fluids [17]

Fluid	M (g/mol)	T_{cri} (°C)	P_{cri} (bar)	T_b (°C)	ODP	GWP (100yr)	ASHRAE-SL	TYPE
R141b	116.95	204.35	42.12	32	0.12	7.2	NA	Isentropic
R124	136.48	122.28	36.2	-11.96	0	<1	A1	Isentropic
R236fa	152.04	124.92	32	-0.5	0	98	A1	Dry
R245fa	134	154.1	36.5	15.1	0	10	B1	Dry
R600	58.12	152	38	-1	0	~20	A3	Dry
R123	153	183.7	36.6	27.8	0.02	0.77	B1	Dry



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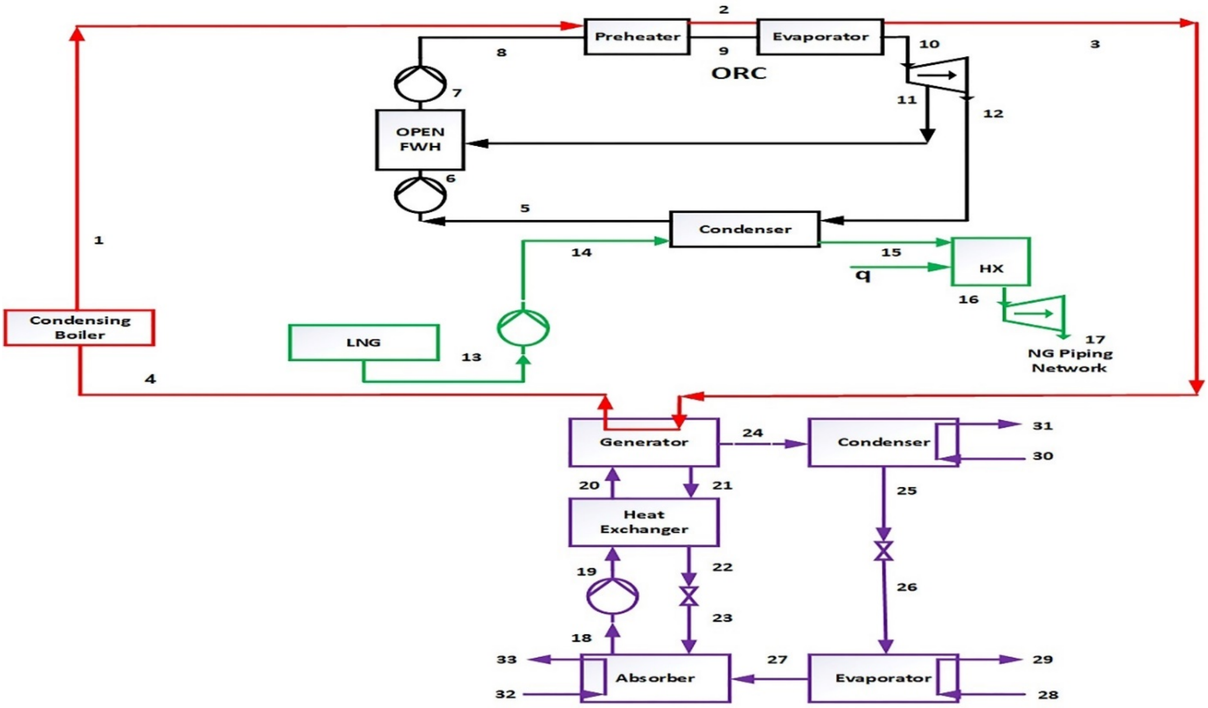

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Figure 1. Cycle configuration: (a) simple, (b) ORC with IHE, and (c) regenerative ORC

Table 2. Some equations used in the thermodynamic analysis of the basic proposed system [18]

Component	Energy	Exergy
ORC		
Pump	$\dot{W}_p = \frac{\dot{m}_5 (h_6 - h_5)}{h_p}$	$\dot{m}_5 (e_5 - e_6) - \dot{W}_p$
Preheater	$\dot{Q}_{preh} = \dot{m}_6 (h_7 - h_6)$	$\dot{m}_2 e_2 + \dot{m}_7 e_7 - \dot{m}_1 e_1 - \dot{m}_6 e_6$
Evaporator	$\dot{Q}_{eva} = \dot{m}_7 (h_8 - h_7)$	$\dot{m}_9 e_9 + \dot{m}_8 e_8 - \dot{m}_2 e_2 - \dot{m}_7 e_7$
Turbine	$\dot{W}_t = \dot{m}_8 (h_8 - h_9) h_t$	$\dot{m}_8 (e_8 - e_9) - \dot{W}_t$
Condenser	$\dot{Q}_{con} = \dot{m}_9 (h_9 - h_5)$	$\dot{m}_9 (e_9 - e_5) - \dot{Q}_{con} (1 - \frac{T_0}{T_{con}})$
LNG		
Pump	$\dot{W}_p = \frac{\dot{m}_{10} (h_{11} - h_{10})}{h_p}$	$\dot{m}_{10} (e_{10} - e_{11}) - \dot{W}_p$
Heat exchanger	$\dot{Q}_{cool} = \dot{m}_{12} (h_{13} - h_{12})$	$\dot{m}_{12} (e_{12} - e_{13}) - \dot{Q}_{cool} (1 - \frac{T_0}{T_{cool}})$
Turbine	$\dot{W}_t = \dot{m}_{12} (h_{12} - h_{13}) h_t$	$\dot{m}_{12} (e_{12} - e_{13}) - \dot{W}_t$
ARC		
Pump	$\dot{W}_p = \frac{\dot{m}_{15} (h_{16} - h_{15})}{h_p}$	$\dot{m}_{15} (e_{15} - e_{16}) - \dot{W}_p$
Expansion valve 1	-----------	$\dot{m}_{19} (e_{20} - e_{19})$
Absorber	$\dot{Q}_{abs} = \dot{m}_{20} h_{20} + \dot{m}_{24} h_{24} - \dot{m}_{15} h_{15}$	$\dot{m}_{24} e_{24} + \dot{m}_{20} e_{20} - \dot{m}_{15} e_{15} + \dot{m}_{29} (e_{29} - e_{30})$
Generator	$\dot{Q}_{gen} = \dot{m}_{21} h_{21} + \dot{m}_{18} h_{18} - \dot{m}_{17} h_{17}$	$\dot{m}_3 (e_3 - e_4) + \dot{m}_{17} e_{17} - \dot{m}_{18} e_{18} - \dot{m}_{21} e_{21}$
Condenser	$\dot{Q}_{con} = \dot{m}_{21} (h_{21} - h_{22})$	$\dot{m}_{21} (e_{21} - e_{22}) - \dot{m}_{27} (e_{27} - e_{28})$
Expansion valve 2	-----------	$\dot{m}_{22} (e_{23} - e_{22})$
Evaporator	$\dot{Q}_{eva} = \dot{m}_{24} (h_{24} - h_{23})$	$\dot{m}_{23} (e_{23} - e_{24}) - \dot{m}_{25} (e_{25} - e_{26})$

For thermodynamic analysis, a thermodynamics code is programmed using Engineering Equation Solver (EES), which is in good agreement with the works of other authors. Table 3 summarizes the basic assumptions and input parameters to simulate and analyze the systems.

Table 3. Thermodynamic parameters conditions considered in this study

Parameter	Value
Hot water inlet temperature	120 °C
Mass flow rate of hot water	255 kg s^{-1}
Hot water return temperature	20 °C
Evaporating temperature of the organic fluid	105 °C
Condensing temperature of the organic fluid	-35 °C
Turbine isentropic efficiency	85 %
Pump isentropic efficiency	90 %
ARC mass flow rate	150 kg s^{-1}
Effectiveness of heat exchanger	60 %
Ambient temperature	25 °C
Ambient pressure	101.3 kPa
LNG turbine inlet pressure	6500 kPa
NG network pressure	3000 kPa
ARC evaporator temperature	7 °C
ARC Generator temperature	80 °C
ARC Condenser temperature	35 °C
ARC Absorber temperature	40 °C

4.2. Model validation

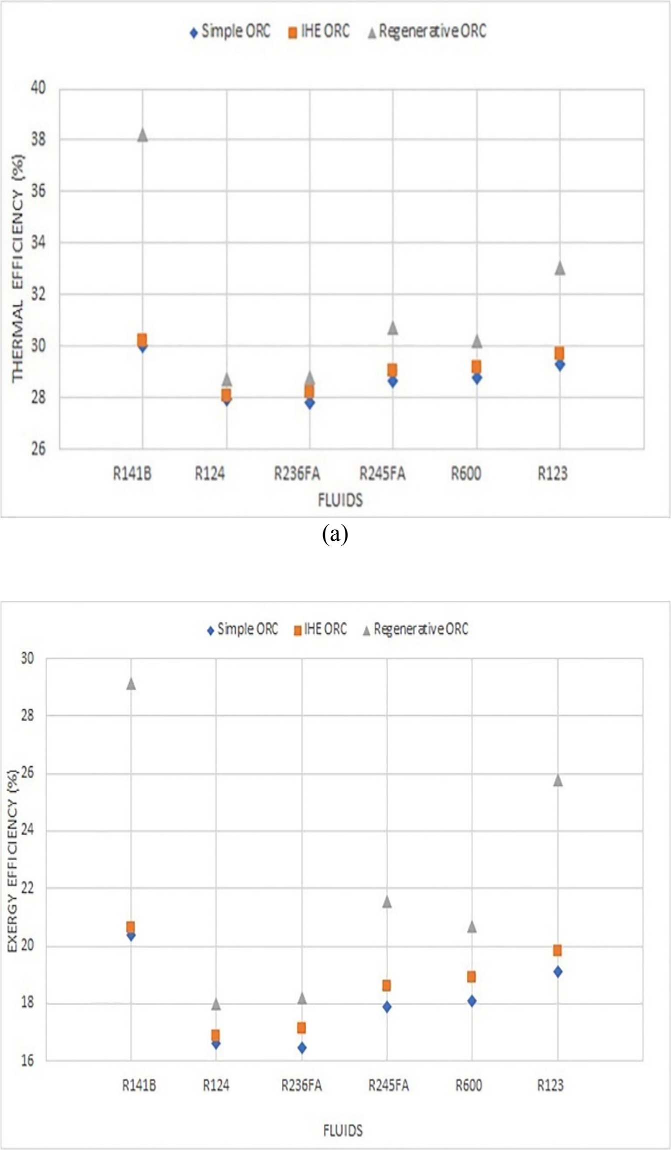
For accurate measurement in the present work, the simple ORC system was validated under the same conditions using three different working fluids with Saleh et al. [19] and Hamdi et al. [20]. Table 4 depicts very good agreement believed to be satisfactory in most engineering problems.

Table 4. System validation of the present study and references [19] and [20]

Fluid	Mass flow rate (Kg s^{-1})	η_{ORC} (%)	Turbine exit temperature (°C)	References
R245fa	33.24	12.54	50.7	[13]
	33.21	13.13	47.79	[14]
	32.46	13.11	47.45	This study
Isopentane	17.44	12.75	58.47	[13]
	17.42	13.21	58.32	[14]
	17.05	13.06	57.55	This study
R600	17.75	12.58	48.43	[13]
	17.60	13.21	45.94	[14]
	16.83	13.22	48.35	This study

5. RESULTS AND DISCUSSION

Figures 2-4 compare the thermodynamic parameters including thermal efficiency, exergy efficiency, and net output power of the cycle obtained for simple, IHE, and regenerative ORC proposed cycles. R141b, R124, R236fa, R245fa, R600, and R123 are the working fluids investigated in the proposed systems. Figure 2 shows thermal efficiency, exergy efficiency, and net power output for the introduced working fluids and for the three different ORC system configurations. The comparison has been done under the same operating conditions for all configurations. It is inferred that for some of the studied fluids, the system efficiencies and net power are the same for the three different configurations. As a result, it can be expressed that a suitable fluid for the system depends on the configuration, and vice versa. According to the results, among the studied working fluids, R141b and R124 had the maximum and minimum thermal efficiencies, respectively. The same trend can be seen for the exergy efficiency and net power. It is concluded that the range of energy efficiencies for the simple ORC, IHE ORC, and regenerative ORC includes (27.83-30.02), (28.07-30.17), and (28.69-38.21) %, respectively. These exergy efficiency values were (16.62-20.37), (16.88-20.63), and (17.99-29.14) %. Finally, (8460-10804), (8722-10962), and (9383-16045) were obtained for net output power. Results depicted that among the three studied systems, the regenerative ORC-based system exhibited the best performance.



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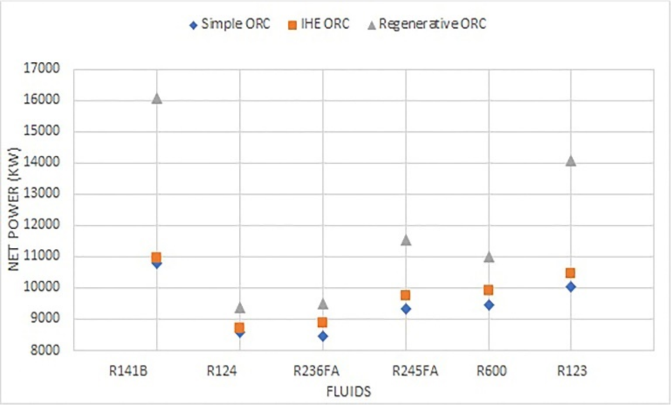

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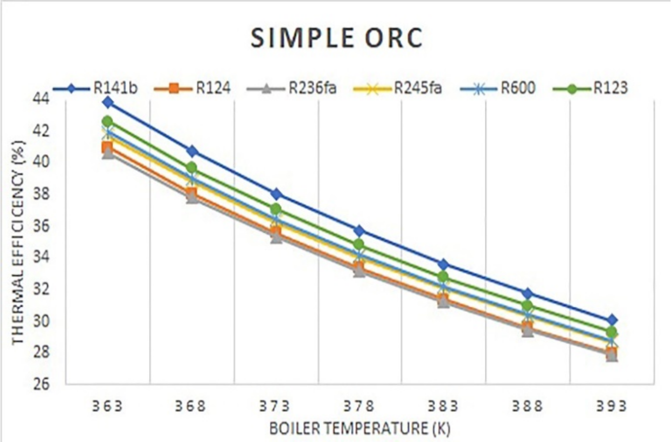
Figure 2. Comparison of thermodynamic parameters: (a) thermal efficiency, (b) exergy efficiency, and (c) net output power

Figure 3 displays the alteration of the thermal efficiency for the simple, IHE, and regenerative ORC-based configurations with the boiler temperature. We notice that for all configurations and working fluids, the energy efficiencies decrease with the increasing boiler temperature. The more energy the boiler produces, the less thermal efficiency the cycle can generate. The reason is that when the temperature of the boiler increases, the boiler produced heat increases and the net power of the system decreases. The rate of the produced heat in the boiler is greater than that of cooling effect and the net power of the system. The figures show that for the studied systems, R141b has the best performance among the set of considered fluids, while R124 and R236fa show the worst performance. Moreover, it is observed that the effect of increasing boiler temperaure is higher in the regenerative ORC than other configurations.



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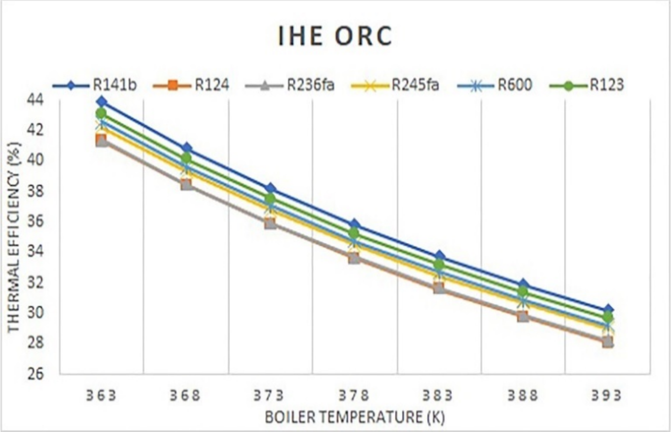

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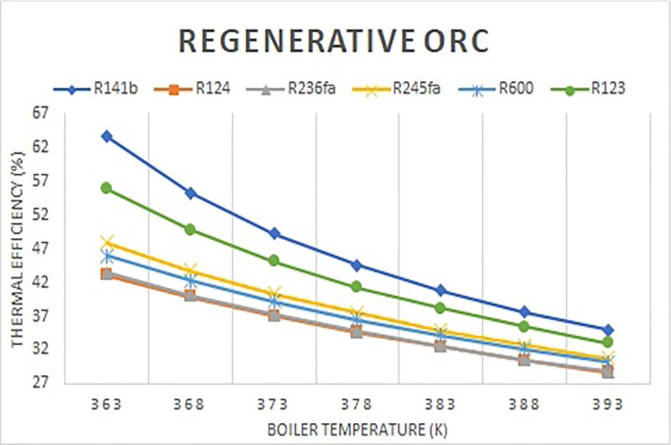

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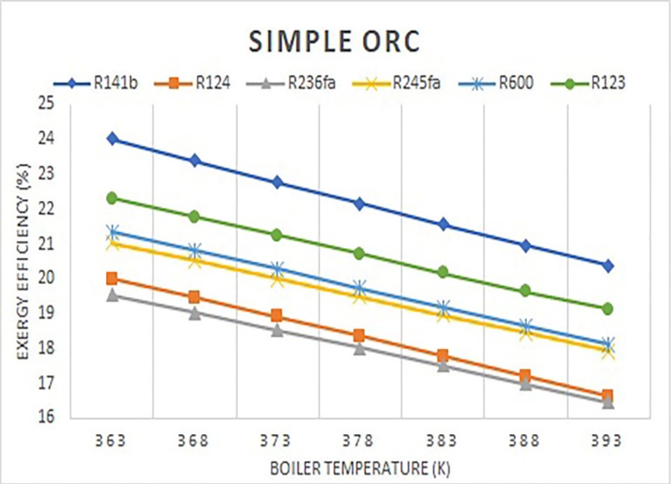
Figure 3. Variation in thermal efficiency versus boiler temperature: (a) simple ORC, (b) IHE ORC, and (c) regenerative ORC

Figure 4 depicts the variation in exergy efficiency versus boiler tempearature. According to the graphs, by increasing boiler temperature from 363 to 393 Kelvin, exergy efficiency of the three studied configurations is reduced. The extent of decrease in the exergy efficiency in the regenerative ORC system is more obvious. The reason for the decrease in the efficiency of the proposed systems is that by increasing the temperature of the boiler, the net power produced by the system is reduced and the boiler exergy increases. The extent of increase in boiler exergy is higher than that of the decrease in the net power output. Therefore, the exergy efficiency of the system decreases.



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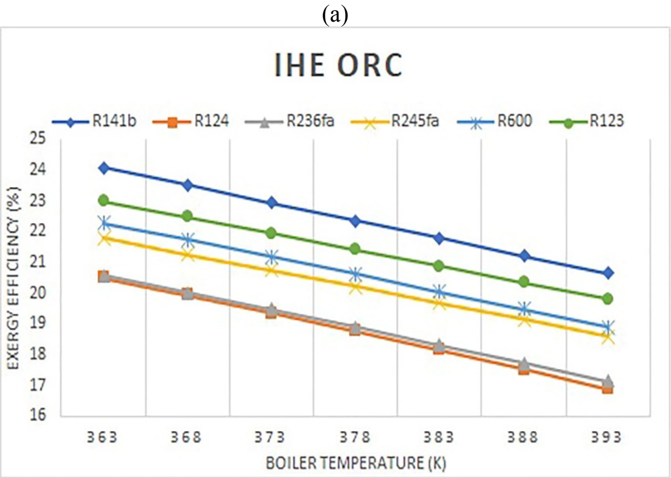

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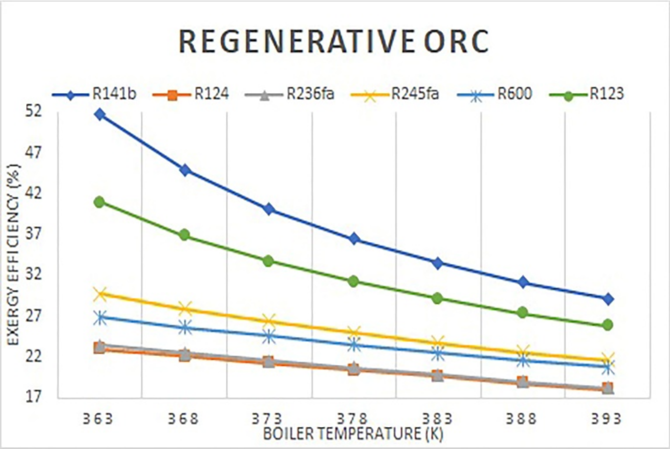

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Figure 4. Variation of exergy efficiency versus boiler temperature: (a) simple ORC, (b) IHE ORC, and (c) regenerative ORC

6. CONCLUSIONS

In this paper, a thermodynamic analysis was conducted for a trigeneration system composed of ORC, LNG cold energy, and absorption refrigeration system which can efficiently recuperate the energy for condensing boiler hot fluid as a low-temperature heat source and entirely utilize LNG cold energy as a heat sink. The efficiency of the three main types of ORC systems, namely simple, internal heat exchanger, and regenerative ORCs are considered. Six working fluids (R141b, R124, R236fa, R245fa, R600, and R123) were analyzed and compared in the studied system from the thermodynamic standpoint.

Some of the obtained results can be summarized as follows:

- Among the presented working fluids, R141b had the highest thermal efficiency, exergy efficiency, and net power, while R124 and R236fa had the lowest amounts and the system with regenerative ORC had the maximum energy and exergy efficiencies.
- Thermal efficiencies for simple, IHE, and regenerative ORC ranged between (27.83-30.02), (28.07-30.17), and (28.69-38.21) %, respectively.
- Thermal efficiencies for simple, IHE, and regenerative ORC ranged between (27.83-30.02), (28.07-30.17), and (28.69-38.21) %, respectively.
- Exergy efficiencies for simple, IHE, and regenerative ORC ranged between (16.62-20.37), (16.88-20.63), and (17.99-29.14) %, respectively.
- Net power output for simple, IHE, and regenerative ORC ranged between (8460-10804), (8722-10962), and (9383-16045), respectively
- Increasing the boiler temperature would decrease the thermal and exergy efficiencies in all systems.

7. ACKNOWLEDGEMENT

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NOMENCLATURE

e	Specific exergy (kJ/kg)
h	Specific enthalpy (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
$\dot{Q}$	Heat transfer rate (kW)
T	Temperature (°C)
$\dot{W}$	Power (kW)
Greek letters	
η	Thermal efficiency (%)
Subscripts	
0	Ambient
1, 2, 3, …	Cycle locations
abs	Absorber
con	Condenser
cool	Cooling
eva	Evaporator
gen	Generator
p	Pump
preh	Preheater
t	Turbine

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