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Analysis of GSER as a Combined Power and Refrigeration System for a Demand during a Day

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Abstract- Development of innovative thermodynamic cycles is important for the efficient utilization of low temperature heat sources such as solar, geothermal and waste heat sources. In this paper, three combined power and ejector refrigeration cycles for low temperature heat sources is investigated. The combined cycles are included: SER, GER and GSER. Exergetic and thermodynamic analysis of these systems are defined based on demanding during the day. It provides a complete analysis about the possibility of using of the systems to meet the good decision. The results show that the GSER system is the best choice of these systems due to its high produced power and high cogeneration efficiency.

Keywords- *GSER, Combined Power, Refrigeration*

I. INTRODUCTION

The importance on energy conservation has resulted in new efforts to develop more efficient refrigeration systems for achieving low temperature [1]. Combined cycles have been proposed in recent years as alternative power cycles in order to solve the problem of primary energy consumption in the energy systems and to reduce environmental pollution. Therefore, it is very important to focus on utilizing these waste heats and renewable energy for their potential in reducing fossil fuel consumption and alleviating environmental problems. Many works have been done to explore the combined power and refrigeration cycle to utilize the low temperature heat sources, such as solar energy, geothermal energy and low temperature waste heat.

Much research has been done on the combined power and refrigeration cycle and most of them are combined the Rankine cycle with the absorption refrigeration cycle, and little attention has been paid to the combination of Rankine cycle and the ejector refrigeration cycle. The ejector refrigeration system produces enough advantages such as less moving parts and low operating, installation and maintenance cost except for the relatively low performance [2-6]. The other advantage of ejector refrigeration cycle is the possibility of using wide range of refrigerants in the system [7].

Alexis [8] studied a combined power and refrigeration cycle with ejector refrigeration cycle. This cycle used extraction steam from steam turbine in conventional Rankine cycle to heat the working fluid in an independent steam ejector refrigeration cycle. They concluded that, this system can be as alternative solution instead of absorption, in the summer. Pridasawas and Lundqvist [9] used exergy analysis as a tool to analyze the performance of an ejector refrigeration cycle driven by solar energy. The results showed that the most significant losses in the system are in the solar collector and the ejector. Wang et al. [10] proposed a new combined power and refrigeration cycle for the cogeneration, which combines the Rankine cycle and the ejector refrigeration cycle by adding an extraction turbine between heat recovery vapor generator (HRVG) and ejector. Their results indicated that the significant exergy destruction occurs in the heat recovery vapor generator, followed by the ejector and turbine. Khaliq et al. [11] proposed the combined power and ejector refrigeration system which uses R141b as a working fluid and employed LiBr–H_2O absorption refrigeration system. They concluded that the proposed cogeneration cycle yields much better thermal and exergy efficiencies than the previously investigated combined power and ejector cooling cycle. Agrawal et al. [12] studied the solar operated thermodynamic cycle using duratherm 600 oil as heat transfer fluid. They observed the effects of some parameters such as hot oil outlet temperature, refrigerant turbine inlet pressure on the first and second law performances.

Dai et al. [13] proposed a novel combined power and refrigeration cycle, which combines the Rankine cycle and the ejector refrigeration cycle. An exergy analysis and a parametric analysis of the combined cycle using R123 as working fluid were conducted to evaluate the effects of the key parameters on the cycle performance. Zhen and Weng [14] studied a combined power and ejector refrigeration cycle for low temperature heat sources using R245fa as the working fluid. Their results indicated that the proposed cycle has a big potential to produce refrigeration and most exergy losses take place in the ejector.

This combined cycle was also investigated by Ko and Kim [15] for the working fluid of R245fa without considering the exergy loss of the heat addition process.

Li et al. [16] proposed an Organic Rankine Cycle with Ejector (EORC). In the EORC, an ejector and a second-stage evaporator were added to the ORC. They also introduced a Double Organic Rankine Cycle (DORC) in order to analyze and compare the EORC with the ORC and DORC in the thermal performance.

II. SYSTEM ANALYSIS

A combined power and ejector refrigeration cycle for low temperature heat sources is investigated in this paper. The proposed cycle combines the organic Rankine cycle and the ejector refrigeration cycle. The ejector is driven by the exhausts from the turbine to produce power and refrigeration simultaneously. The system consists of a pump, boiler, turbine, ejector, condenser, expansion valve, and evaporator as shown in Fig. 1. The working fluid considered in this study is R141.

In this study the following assumptions are used for the convenience of analysis [10]:

1) The flow inside the ejector is in steady state and one dimensional.

2) The working fluid enters the turbine as superheated vapor, and leaves the condenser and evaporator as saturated liquid and saturated vapor, respectively.

3) Velocities of streams at the inlet and outlet of the ejector could be negligible.

4) The temperature difference between the hot and cold streams in the boiler and condenser is higher than the pinch point temperature difference.

5) Pressure drop and heat loss in the system are negligible.

6) The pump and turbine have constant isentropic efficiency.

7) The effects of irreversibility at the nozzle, mixing, and diffuser sections can be taken into account by using their efficiencies.

8) Kinetic, potential and chemical exergies of the substances are neglected.

The basic equations obtained from the conservation law for energy in the components are written as follows:

$$\dot{w}_{comp} = \dot{m}_{g1}(h_{g2} - h_{g1}) \tag{1}$$

$$\dot{Q}_{cc} = \dot{m}_{cc} LHV_{CH_4} \eta_{cc} \tag{2}$$

$$\dot{W}_g = \dot{m}_{g4}(h_{g4} - h_{g5}) - W_{comp} \tag{3}$$

$$\dot{Q}_g = \dot{m}_{g6}(h_{g6} - h_{g7}) \tag{4}$$

The key component of this combined cycle is ejector and its performance is dependent upon entrainment ratio which determines the magnitude of mass flow rate of secondary refrigerant in terms of mass flow rate of primary refrigerant coming out from the turbine. The basic principle of the model was introduced based on gas dynamics and formulated as: [17,18]

$$(m_2 + m_{10})h_4 = m_{10}h_{10} + m_2 h_2 \tag{5}$$

$$\dot{w}_{comp} = \dot{m}_{g1}(h_{g2} - h_{g1}) \tag{6}$$

The formulation and assumption of entrainment ratio is based on mass, momentum and energy equations which is recently developed by in [13] and may be reported as:

$$\omega = \frac{m_{10}}{m_2} = \sqrt{\eta_n \eta_m \eta_d \frac{h_2 - h_{n,s}}{h_{d,s} - h_m}} - 1 \tag{7}$$

The basic equations obtained from the conservation law for energy in the components are written as follows: For Evaporator:

$$Q_e = m_{10}(h_{10} - h_9) \tag{8}$$

For steam turbine:

$$W_{st} = m_1(h_1 - h_2) + (m_1 - m_2)(h_2 - h_3) \tag{9}$$

For pump:

$$W_p = m_p(h_{12} - h_{11}) \tag{10}$$

where W_{net} is the power output from the turbine, reduced by the power input to the pump, and Q_{in} is the total heat added to the cycle from the heat source:

$$W_{net} = W_{st} - W_p \tag{11}$$

$$Q_{in} = m_1(h_1 - h_{13}) \tag{12}$$

First law efficiency (η_{th}) can be defined as the ratio of the net power output (W_{net}) and refrigeration output in the evaporator to the energy input. The first law efficiency of the combined cycle is given by:

$$\eta_{th} = \frac{w_{net} + Q_e}{Q_{in}} \tag{13}$$

Exergy analysis determines the system performance based on exergy, which is defined as the maximum possible reversible work obtainable in bringing the state of the system to equilibrium with that of the environment. Mathematically

$$E = m((h_i - h_0) - T_0(s_i - s_g)) \tag{14}$$

Exergy efficiency is defined as the exergy output divided by the exergy input to the cycle. The exergy input is taken as the available energy change of the heat source. The exergy output is the exergy of the network and the exergy of the refrigeration.

$$\eta_{ex} = \frac{W_{net} + E_e}{E_{in}} \tag{15}$$

$$E_e = m_e((h_9 - h_{10} - T_0(s_9 - s_{10}))) \tag{16}$$

$$E_{in} = m_{13}((h_{14} - h_{13}) - T_0(s_{14} - s_{13})) \tag{17}$$

III. RESULTS AND DISCUSSION

The thermodynamic performance of three combined power and ejector refrigeration cycles driven by the sensible heat of low-temperature heat source is investigated. The combined power and ejector refrigeration cycles investigated in this paper are included: Gas turbine and Ejector Refrigeration cycle (GER), Steam turbine and Ejector Refrigeration cycle (SER) and Gas and Steam turbine and Ejector Refrigeration cycle (GSER).

Fig. 2 shows the fuel consumption of the cycles. The results show that the fuel consumption of the GER system is constant while the fuel consumption of the SER and GSER will vary during the day according to the ratio of the extraction. When the systems produce more power due to the low temperature working fluid in the steam turbine output, fuel consumption will be higher.

Fig. 3 shows the produced cooling of the combined cycles. The produced cooling of the SER and GSER cycles is according to the demanding for cooling during the day but for the GER cycle, it is not flexible and the capacity is based on the greatest cooling during the day.

The produced power of three combined power and refrigeration cycles is shown through fig. 4. It is shown that the produced power of the GSER cycle is the highest due to the similar fuel consumption while GER ranks second in power generation and SER is ranked third. In fact, the produced cooling is inversely proportional to the produce power of cycles. So that while the cooling production is high, the power production will be low due to higher levels of fluid out of the middle of steam turbine.

Fig. 5 shows the cogeneration efficiency of the cycles. It is demonstrated that that maximum efficiency is achieved when the produced cooling is high due to the middle hours of the day (noon). This reality shows the importance of using of cogeneration systems for optimal utilization of energy. The cogeneration efficiency of the GER and GSER systems is more than the SER system. The cogeneration efficiency of SER combine cycle is low due to its low produced power.

Exergy efficiency of the combined power and refrigeration systems are depicted through Fig. 6. The results show that the Exergy efficiency of the SER system is the highest. The high exergy efficiency of ESR is due to its limited operating temperature. While the system produces more power generation, the exergy efficiency increases. Exergy efficiency is slightly lower during the hottest hours of the day due to the higher exergy loss of the refrigeration cycle.

Table 1 shows the performance of the combined power and ejector refrigeration cycles at typical working conditions.

Table 2 shows the thermodynamic properties of three combined power and refrigeration systems during the day. In this table the values of the extraction ratio, cooling and power production, fuel consumption, cogeneration and Exergy efficiency are shown based on the cooling demand at different times of the day.

The results show that the best choice of these three combined systems is GSER system due to our need. The GSER system has the flexibility to produce high- cogeneration efficiency and Exergy efficiency. The SER system does not have a good performance despite of its high exergy efficiency. GER system is the second selection of these combined power and refrigeration cycle. Also, the GSER system can produce 284 Mwhr power more than GER that can justify its high cost of investment.

IV. CONCLUSION

For the utilization of low-temperature waste heat, the performance of three combined power and ejector refrigeration cycle is thermodynamically investigated. Power and cooling production, cogeneration efficiency and Exergy efficiency of the systems are studied at any desired period of time and they were utilized as the tools to evaluate the performance of the systems.

The results show that the GSER system has the most power generation and cogeneration efficiency among the others. The GER system is the second choice of these systems. The SER system does not have a good performance despite of its high exergy efficiency.

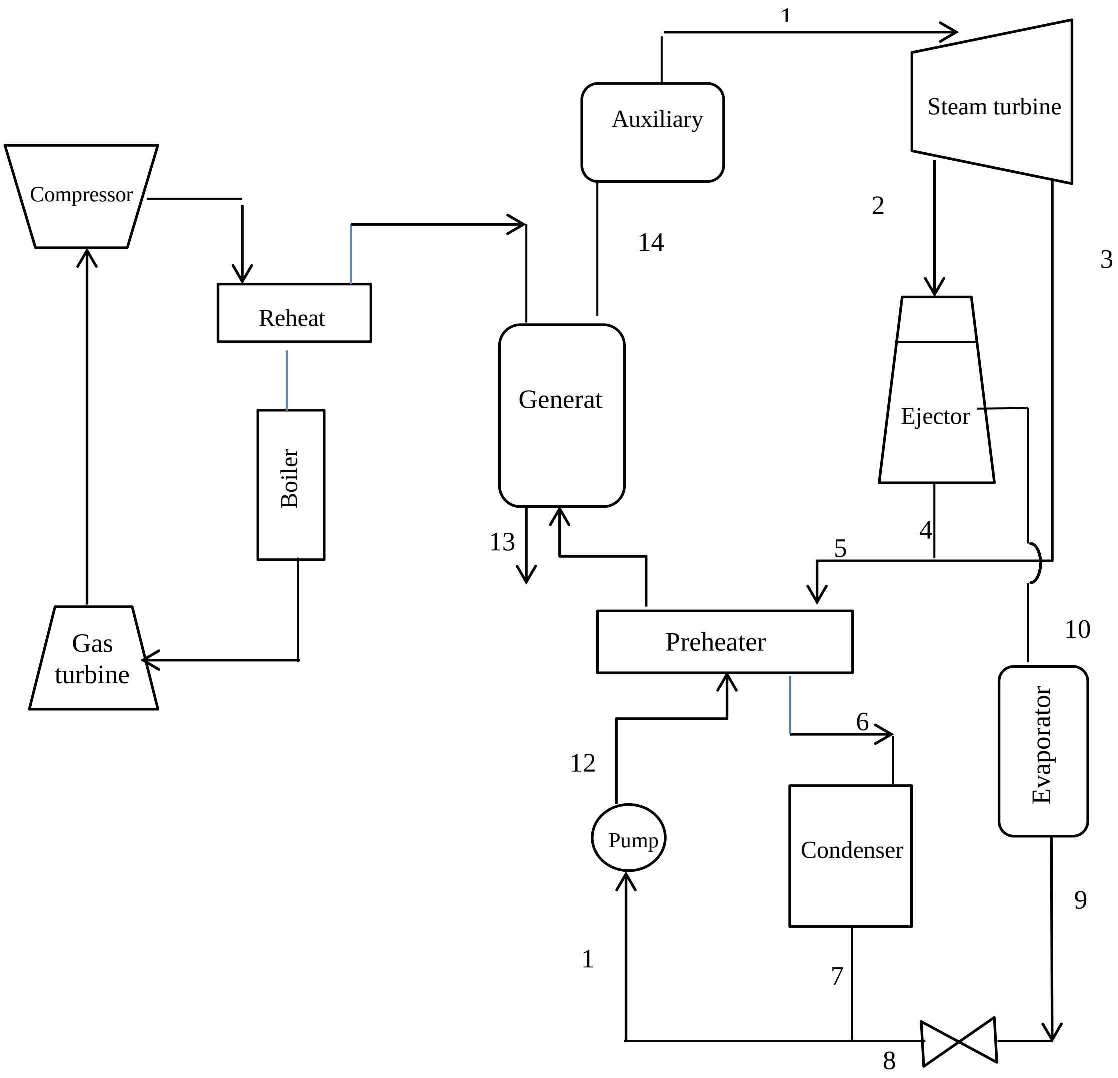

Figure 1. Schematic of the combined power and refrigeration cycle (GSER)

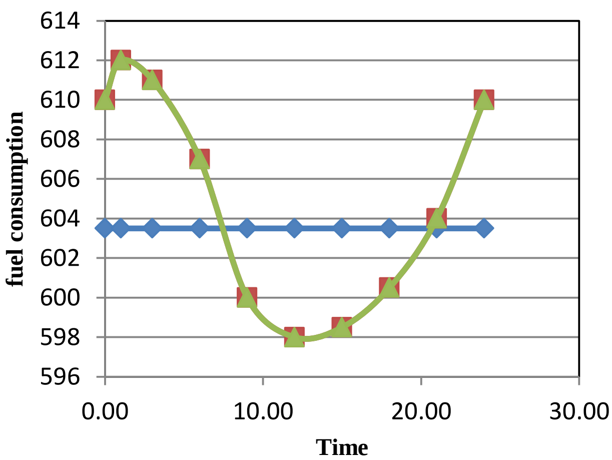

Figure 2. fuel consumption during period of time

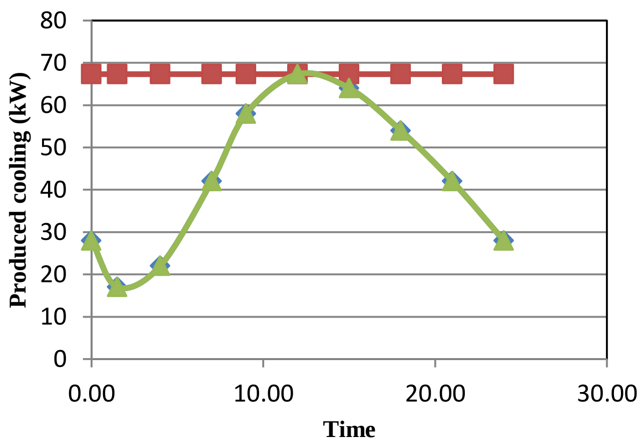

Figure 3. Produced cooling during period of time

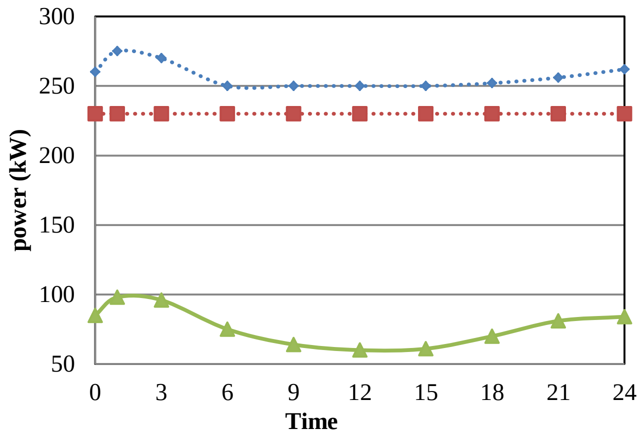

Figure 4. produced power during period of time

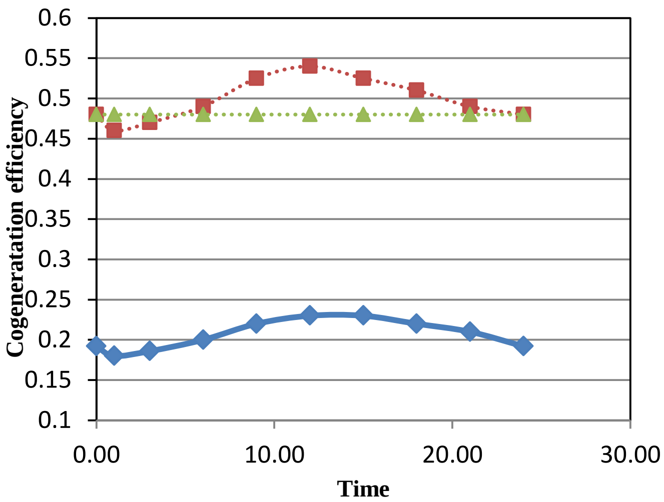

Figure 5. Cogeneration efficiency of different combined power and refrigeration cycles

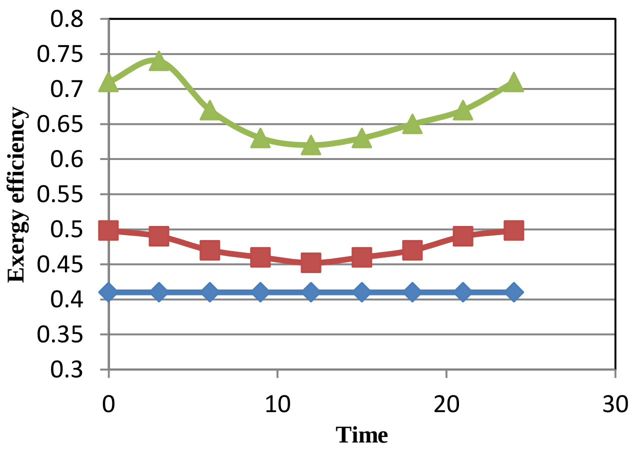

Figure 6. Exergy efficiency of different combined power and refrigeration cycles

TABLE I. THE PERFORMANCE OF THE COMBINED POWER AND REFRIGERATION CYCLE (GSER) AT TYPICAL WORKING CONDITIONS

state	s (Kj/kg.K)	h (Kj/kg)	P (kPa)	T (˚C)	$\dot{E}$ (Kj)
g1	5.715	304.6	101.4	31	0
g2	5.808	644.7	101.4	362.5	276.5
g3	6.225	958.3	978.8	649.4	442.2
g4	6.791	1603	912.1	1200	876.7
g5	6.904	1014	112.6	698.4	314.0
g6	6.544	705.5	107.6	419.6	134.3
g7	5.852	349.9	102	76	3.278
s1	1.033	362	1251	130	70.05
s2	1.076	343.4	283.1	90	17.99
s3	1.061	317.3	116.1	55.1	2.318
s4	1.095	328.7	116.1	69	5.024
s5	1.083	324.5	116.1	64	7.105
s6	1.024	305.9	116.1	41	5.29
s7	0.296	80.3	116.1	36	0.08725
s8	0.296	80.3	116.1	36	0.01346
s9	0.302	80.3	39.9	8	-0.3573
s10	1.021	282.6	39.9	8	-4.011
s11	0.296	80.3	116.1	36	0.07379
s12	0.296	80.7	251	36	0.5476
s13	0.367	102.8	251	54	1.420
s14	1.020	356.6	251	130	68.29

TABLE II. THERMODYNAMIC PROPERTIES OF COMBINED POWER AND REFRIGERATION SYSTEMS (GSER, SER, GER) DURING THE DAY

Time		24	18	12	6
Cooling demand (kW)		26	57	67	42
Extraction ratio	GSER	0.33	0.72	0.86	0.53
	SER	0.18	0.38	0.45	0.28
	GER	×	×	×	×
Produced cooling	GSER	26	57	67.33	42
	SER	26	57	67.33	42
	GER	67.33	67.33	67.33	67.33
Power (kW)	GSER	262.2	249.7	245.6	255.8
	SER	91.8	79.3	75.1	85.3
	GER	221.2	221.2	221.2	221.2
Fuel consumption (kW)	GSER	610	601	598	605
	SER	610	601	598	605
	GER	604	604	604	604
Cogeneration efficiency (kW)	GSER	0.47	0.51	0.52	0.49
	SER	0.19	0.23	0.24	0.21
	GER	0.48	0.48	0.48	0.48
Exergy efficiency	GSER	0.49	0.47	0.46	0.48
	SER	0.72	0.65	0.62	0.68
	GER	0.41	0.41	0.41	0.41

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