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Energy and Exergy Analyses of a new Solar Assisted Cogeneration Cycle for Simultaneous Production of Power and Double Effect Cooling

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Abstract: **In this paper, a solar operated combined power and ejector-absorption refrigeration cycle is proposed and thermodynamically analyzed for simultaneous production of cooling at two different evaporators at different temperatures along with power. The thermodynamic analysis is carried out from view point of energy and exergy. The effect of key thermodynamic parameters like; hot oil outlet temperature, refrigerant turbine inlet pressure and ejector evaporator temperature on energy and exergy efficiency along with exergy destructions in various components of the proposed cycle is observed. It is observed that out of 100% solar heat energy supplied to the system around 7.68% is produced as refrigeration output in ERC and ARC cycle, 5.49% is produced as power output in RC cycle and 102.19% is lost to the environment. The irreversibility in central receiver 52.5%, heliostat field 25%, condenser of ERC 3.98%, HRVG 3.79% and ejector 3.72% is observed. The exergy efficiency of around 6% is obtained which is much lower than energy efficiency 13% of solar assisted cogeneration cycle for simultaneous production of power and double effect cooling. With the increase in hot oil outlet temperature from central receiver (160°C-180°C), the energy efficiency decreases (15.22% -11.74%) significantly and exergy efficiency increases (5.06%-7.37%) marginally. With increase is turbine inlet pressure from 0.9 MPa to 1.7 MPa., the energy efficiency increases significantly (13.17% to 36.86%) while exergy efficiency decreases marginally (6.22% to 4.4%).**

Keywords: ***ejector, absorption, energy, exergy, double effect cooling, power.***

1. INTRODUCTION

In order to meet out the increasing demand of power and cooling simultaneously, the combined power and refrigerating cycle have been explored. Xu et al. [1] proposed a combined power and refrigeration cycle and some further researches on the cycle were carried out by Hasan et al. [2]; Yidal et al. [3]; Sadrameli and Goswami [4]). Zhang and Lior [5] proposed a new combined refrigeration and power system. They investigated the effects of the key thermodynamic parameters on both energy and exergy efficiencies. Wang et al. [6] also proposed a combined power and refrigeration system which combined Rankine cycle and absorption refrigeration cycle. These systems are relatively complicated, resulting in a higher capital investment. Although much research has been carried out on the combined power and refrigeration cycle, most of them have combined the Rankine cycle or Kalina cycle with the absorption refrigeration cycle, and a very little attention has been paid to the combination of Rankine cycle and ejector refrigeration cycle. The ejector refrigeration cycle has the possibility of using a wide range of refrigerants with the system.

Recently, in refrigeration industry the use of efficient dual-evaporator refrigeration systems has been paid a lot of attention. These systems sound even more interesting when they are a combination of different kinds of conventional refrigeration systems for simultaneously production of power and producing cooling effects at two different temperatures in the cycle by using low grade heat source. In this context, a new solar powered ejector-absorption refrigeration cycle is proposed and analyzed in this paper. This cycle will produce power and cooling effect at two evaporators at different temperatures in the cycle by using the single source of solar heat.

2. SYSTEM DESCRIPTION

The proposed cogeneration cycle consists of Rankine cycle (RC), ejector refrigeration cycle (ERC) and absorption refrigeration cycle (ARC) by using only single source of solar heat for simultaneous production of power and double effect cooling as shown in Figure1. Solar energy falls on the heliostat field and reflected on the aperture area of central receiver which is located at the top of the tower. The concentrated rays which falls on to the central receiver results in higher temperature of the central receiver, is used to heat the oil (Duratherm600). The oil flows through the pipes which transfer the thermal energy from central receiver to the HRVG (1-2) and generator (2-12). Superheated refrigerant vapour of R141b (4) is expanded in a turbine to generate power. The turbine exhaust (5) passes through converging diverging supersonic nozzle of ejector. The very high velocity refrigerant vapour at the exit of the nozzle creates a very high vacuum at the inlet of the mixing chamber and extract secondary vapour (11) from the evaporator of ERC into the mixing chamber and this causes cooling effect at evaporator-1(E1) of ERC. The primary vapour (5) and secondary vapour (11) are mixed in the mixing chamber. The mixed stream (6) is condensed in the condenser-1(C1). The saturated liquid (7) is divided in to two parts (8, 9), one part (9) is passed through throttling valve-1 (TV1) where pressure is reduced to evaporator (E-1) pressure (10) and feed to evaporator-1 (E1), and second part (8) is pumped by pump-1(P1) to the HRVG of RC cycle. The stream (2) coming out from HRVG passes through the generator of ARC and finally enters to the central receiver (12). The superheated pure water vapour (13) coming from generator is condensed in condenser-2 (C2). Saturated liquid (14) at condenser pressure passes through throttle valve-2 (TV2) to generate saturated liquid (15) at reduced pressure i.e. pressure in the evaporator-2(E2). Saturated vapour (16) after receiving heat from evaporator-2 (E2) enters into the absorber. Solution (20) which is a mixture of LiBr-H_2O passes through heat exchanger and cooled to (21) and then passes through throttle valve-3 (TV3) to reduce its pressure i.e. absorber pressure. Absorption temperature is maintained at 35^0C at evaporator-2(E2) pressure. Two streams (16, 22) mixed at absorber and form a new mixture (17), which passes through pump-2 (P2) and solution heat exchanger (SHX) and then finally enters to the generator (19).

For the analysis, the specifications of the combined RC, ERC and ARC are given in Table 1.

TABLE 1: Main parameters considered for the analysis

Environment Temperature (^{0}C)	15
Environment pressure (MPa)	0.10135
Turbine inlet pressure range (MPa)	0.9 - 1.7
Hot oil outlet temperature from central receiver (^{0}C)	160 – 180
Hot oil inlet temperature to central receiver (^{0}C)	85
Generator temperature (^{0}C)	80
Solar radiation received per unit area (Wm^{-2})	850
Apparent Sun temperature (K)	4500
Heliostat aperture area (m^2)	3000
Turbine back pressure range (MPa)	0.22-0.3
Turbine isentropic efficiency (%)	85
Ejector evaporator temperature range (K)	264 – 272
Evaporator temperature of ARC (^{0}C)	5
Condenser-2 temperature (^{0}C)	35
Absorber temperature (^{0}C)	35
Hot oil mass flow rate (kg s^{-1})	8.0
Pump isentropic efficiency (%)	70
HRVG efficiency (%)	100
Pinch point temperature difference (^{0}C)	10.0
Nozzle efficiency (%)	90
Mixing chamber efficiency (%)	85
Diffuser efficiency (%)	85
Energy efficiency of heliostat field (%)	75
Energy efficiency of central receiver (%)	90
Exergy efficiency of heliostat field (%)	75
Exergy efficiency of central receiver (%)	30
Effectiveness of SHX (%)	100

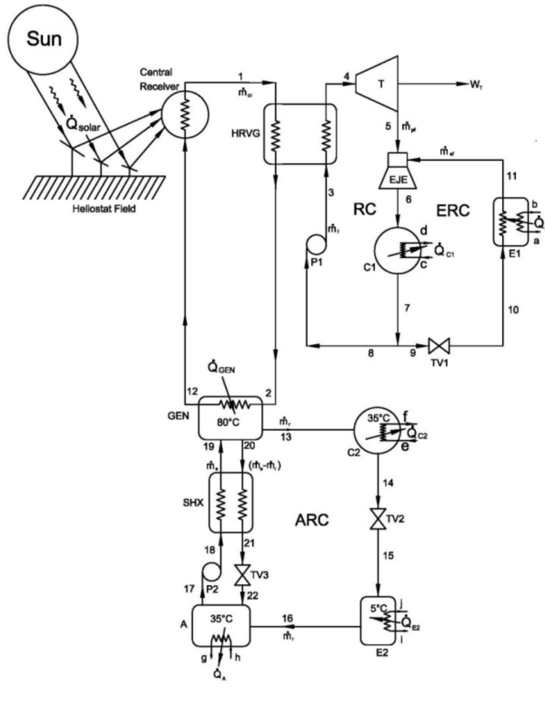

Fig. 1. Schematic diagram of solar assisted cogeneration cycle for simultaneous production of power and double effect cooling

3. THERMODYNAMIC ANALYSIS

A method of exergy analysis which combines basic principles of conservation of mass and conservation of energy along with the second law of thermodynamics is applied for the analysis of thermodynamic cycles of power and refrigeration. This methodology is expected to provide a complete thermodynamic view of the given refrigeration system with a view to provide a guidance for performance improvement.

Exergy analysis, calculates 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, which may be defined mathematically as:

$$\dot{E} = \dot{m}[(h - h_0) - T_0(s - s_0)] \tag{1}$$

The entropy generation over a control volume is given by Bejan [7]

$$\dot{S}_{gen} = \frac{dS}{dt} - \sum_{i=o}^{n} \frac{\dot{Q}_i}{T_i} - \sum_{in} \dot{m}s + \sum_{out} \dot{m}s \geq 0 \tag{2}$$

According to Gouy-Stodola theorem, the exergy destruction and entropy generation are related as

$$\dot{E}_D = T_0 \dot{S}_{gen} \tag{3}$$

3.1. Energy Efficiency (η_{energy})

Energy efficiency is defined as the ratio of the desired effect ($\dot{Q}_{E1}$, $\dot{Q}_{E2}$, $\dot{W}_T$) to the thermal energy of solar heat input ($\dot{Q}_{solar}$).

The energy efficiency of the proposed cycle for simultaneous production of power and double effect cooling is given by

$$\eta_{energy} = \frac{\dot{Q}_{E1} + \dot{Q}_{E2} + \dot{W}_T}{\dot{Q}_{Solar}} \tag{4}$$

where, $\dot{Q}_{E1}$ and $\dot{Q}_{E2}$ are the refrigeration output of ERC and ARC and $\dot{W}_T$ is the turbine work output.

3.2. Exergy Efficiency (η_{exergy})

The exergy efficiency of simultaneous production of power and double effect cooling cycle may be reported as

$$\eta_{exergy} = \frac{\Delta \dot{E}_{E1} + \Delta \dot{E}_{E2} + \dot{W}_T}{\dot{E}_{Solar}} \tag{5}$$

Where, $\dot{E}_{Solar}$ is incoming exergy associated with solar radiation falling on heliostat, $\Delta\dot{E}_{E1}$, $\Delta\dot{E}_{E2}$ and $\dot{W}_T$ are the change in exergy at ejector evaporator of ERC, evaporator of ARC and power output from turbine of RC respectively.

$$\Delta\dot{E}_{E1} = \dot{m}_{sf}[(h_{10} - h_{11}) - T_0(s_{10} - s_{11})] \tag{6}$$

$$\Delta\dot{E}_{E2} = \dot{m}_r[(h_{15} - h_{16}) - T_0(s_{15} - s_{16})] \tag{7}$$

$$\dot{E}_{Solar} = \dot{Q}_{Solar}\left(1 - \frac{T_0}{T_S}\right) \tag{8}$$

where, T_s = Apparent Sun temperature (K)=4500K

4. RESULTS AND DISCUSSION

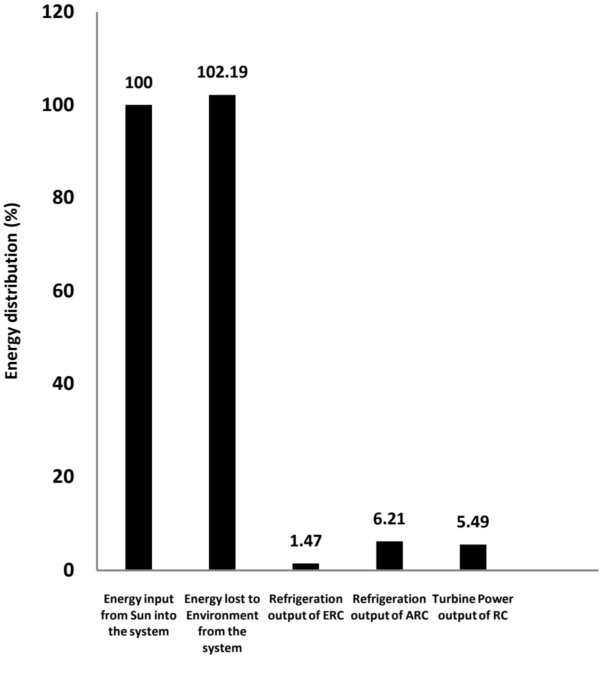

Fig. 2 Percentage (%) of Suns energy distribution in the cycle for simultaneous production of power and double effect cooling

In this paper, parametric analysis is carried out to find out the effect of variation of hot oil (Duratherm600 oil) outlet temperature fro central receiver, turbine inlet pressure and ejector evaporator temperature on energy and exergy efficiency of the solar assisted cogeneration cycle for simultaneous production of power and double effect cooling. The thermodynamic properties of refrigerant R141b used in the ERC cycle were calculated by NIST Standard Reference Database 23 [8] and thermodynamic properties; enthalpy and entropy of LiBr- H_2O mixture for the operation of ARC are taken from chua et al. [9].

Figure 2 shows that out of 100% solar heat energy supplied to the system, around 7.68% is available as useful refrigeration output in ERC and ARC, 5.49% as turbine power output in RC cycle and the rest of the energy which includes the heat rejected at the condenser and absorber of ARC and heat rejected at the condenser of ERC is lost to the environment.

Figure 3 indicates that out of 100% exergy associated with solar heat, around 0.35% is produced as exergy output of refrigeration (exergy associated with cooling produced in ERC and ARC cycle), around 5.87% is produced as exergy output (exergy associated with turbine power output) of RC cycle for production of power. The rest of the exergy is destroyed due to irreversibilities in various components of the cogeneration cycle. In this context, it is indicated that majority of the irreversibility occurred in central receiver (52.5%), Heliostat field (25%), condenser of ERC (3.98%), HRVG (3.79%) and ejector (3.72%). The component like central receiver, heliostat field, condenser of ERC, HRVG and ejector where maximum exergy destroyed needs special attention from second law point of view. A reduction in the irreversibility in these components will improve the overall performance of the cycle.

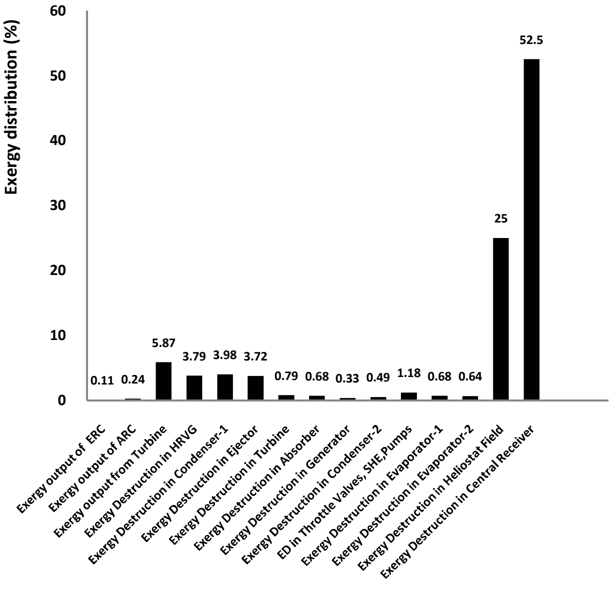

Fig. 3. Percentage (%) of Suns exergy distribution in refrigeration, power output and exergy destructions in the cycle

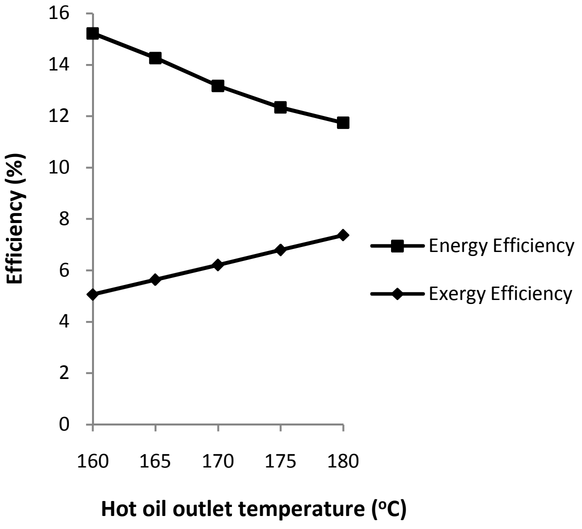

Fig. 4. Effect of hot oil outlet temperature on energy and exergy efficiency

Figure 4 indicates the effect of variation of hot oil outlet temperature on energy and exergy efficiency of proposed cogeneration cycle. It is found that refrigeration output of ERC and power output of RC increases while refrigeration output of ARC and total energy output decreases with the increase in hot oil outlet temperature. Since the rate of decrease of refrigeration output of ARC is greater than the rate of increase of refrigeration output of ERC and power output of RC cycle, the total energy output decreases with increase in hot oil outlet temperature. It is observed that exergy output of ERC and RC cycle increases while exergy output of ARC decreases with increase in hot oil outlet temperature. The total exergy output increases due to the fact that the rate of increase of exergy output of ERC and RC cycle is higher than rate of decrease in exergy output of ARC. Hence, the energy efficiency decreases while exergy efficiency of the cycle increases with increase in hot oil outlet temperature.

Figure 5 shows the variation of energy and exergy efficiency with increase in turbine inlet pressure of proposed cogeneration cycle for simultaneous production of power and double effect cooling. It is clearly observed that the energy efficiency increases significantly with increase in turbine inlet pressure of combined cycle. This is due to the fact that increase in turbine inlet pressure causes a significant increase in refrigeration output of ARC and reduction in refrigeration output of ERC and power output from turbine of RC cycle. Since the rate of increase in the refrigeration output of ARC is much greater than the rate of decrease is refrigeration output of ERC and power output from turbine of RC cycle, therefore, the overall energy efficiency of proposed cogeneration cycle increases with increase in turbine inlet pressure. The exergy efficiency of the proposed cycle shows the trend of decreasing with increase in turbine inlet pressure. This is only because of increase in turbine inlet pressure the total exergy output of proposed cogeneration cycle for power and double effect cooling decreases.

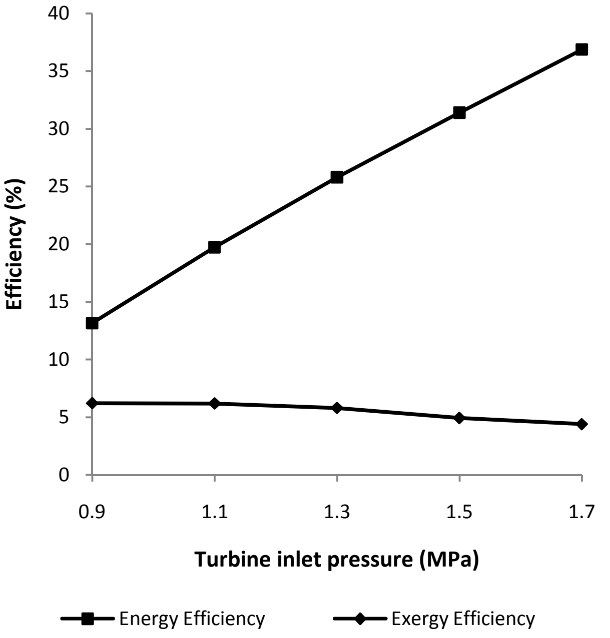

Fig. 5. Effect of turbine inlet pressure on energy and exergy efficiency

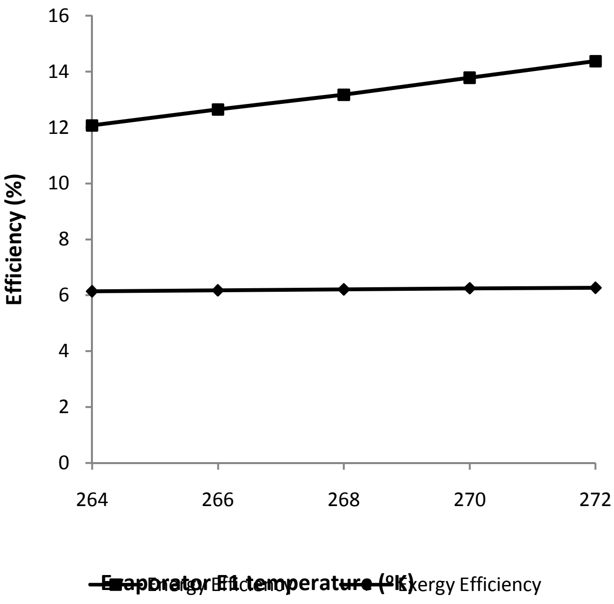

Fig. 6. Effect of evaporator E1 temperature on energy and exergy efficiency

Figure 6 shows the effect of variation of ejector evaporator (E1) temperature on energy and exergy efficiency of proposed cogeneration cycle. It is observed that an increase in the ejector evaporator temperature the energy efficiency increases significantly and exergy efficiency increases marginally.

5. CONCLUSION

A combined energy and exergy analysis of a new solar assisted cogeneration cycle for simultaneous production of power and double effect cooling is presented. The effect of various operating parameters was observed on energy and exergy efficiency of the proposed cycle. The main conclusions from present study can be summarized as follows:

- out of 100% solar heat energy supplied to the system around 7.68% is produced as refrigeration output in ERC and ARC cycle, 5.49% is produced as power output in RC cycle and 102.19% is lost to the environment.
- out of 100% solar exergy input to the system, around 0.35% is available as exergetic refrigeration output in ERC and ARC cycle, 5.87% is available as exergetic power output from turbine of RC and remaining is lost due to irreversibilities in the components and via thermal lost to the environment.
- the irreversibility in central receiver 52.5%, heliostat field 25%, condenser of ERC 3.98%, HRVG 3.79% and ejector 3.72% is observed.
- the exergy efficiency of around 6.218% is obtained which is much lower than energy efficiency 13.17% of solar assisted cogeneration cycle for simultaneous production of power and double effect cooling.
- with the increase in hot oil outlet temperature from central receiver (160^{o}C-180^{o}C), the energy efficiency decreases (15.22% -11.74%) significantly and exergy efficiency increases (5.06%-7.37%) marginally.
- with increase is turbine inlet pressure from 0.9 MPa to 1.7 MPa., the energy efficiency increases (13.17% to 36.86%) while exergy efficiency decreases (6.22% to 4.4%).
- with increase in ejector evaporator temperature from 264K to 272K, the increase in energy efficiency from 12.07% to 14.37% and increase in exergy efficiency from 6.14% to 6.22% is observed.

Presented cogeneration cycle is expected to meet out the demand of simultaneous production of power and double effect cooling by using only single source of solar heat in an effective and sustainable manner.

REFERENCES

[1] Xu, F., Goswami, D.Y. and Bhagwat, S.S., “A combined power/cooling cycle”, *Energy*, 25, 2000, pp. 233-246.

[2] Hasan, A.A., Goswami, G.Y. and Vijayaraghavan, S., "First and second law analysis of a new power and refrigeration thermodynamic cycle using a solar heat source", *Solar Energy,* 73, 2002, pp. 385-393.

[3] Yidal, A., Best, R., Rivero, R. and Cervantes, J., "Analysis of a combined power and refrigeration cycle by the exergy method", Energy, 31, 2006, pp. 3401-3414.

[4] Sadrameli, S.M. and Goswami, D.Y., "Optimum operating conditions for a combined power and cooling thermodynamic cycle", *Applied Energy*, 84, 2007, pp. 254-265.

[5] Zhang, N. and Lior, N., "Development of a novel combined absorption cycle for power generation and refrigeration", ASME *Journal of Energy Resources Technology*, 129, 2007, pp. 254-265.

[6] Wang, J.F., Dai, Y.P. and Lin, G., "Parametric analysis and optimization for a combined power and refrigeration cycle", *Applied Energy*, 85, 2008, pp. 1071-1085.

[7] Bejan, A., "Fundamentals of exergy analysis, entropy generation minimization and the generation of flow architecture", *International Journal of Energy Research,* 26, 2002, pp. 545-565.

[8] NIST Standard Reference Database 23, NIST Thermodynamic and Transport Properties of Refrigerants and Refrigerants Mixtures', *REFPROP*, Version 6.01., 1998, USA.

[9] Chua, H.T., Toh, H.K., Malek, A., Ng, K.C. and Srinivasan, K., "Improved thermodynamic property fields of LiBr-H_2O solutions", *International Journal of Refrigeration,* 23, 2000, pp.412-429.