Journal of Material Science and Mechanical Engineering (JMSME)
Print ISSN: 2393-9095; Online ISSN: 2393-9109; Volume 2, Number 7; April-June, 2015 pp. 58-63

http://www.krishisanskriti.org/jmsme.html

Energy and Exergy Analyses of a new Solar Assisted Ejector Cooling and Power Cycle by using Refrigerants R141b, R600, R601 and R601a

Surendra Kumar Agrawal[1], Rajesh Kumar[2]

[1]*Department of Mechanical Engineering,*
Madhav Institute of Technology & Science Gwalior-474005, M.P., India
surendra_srcem@yahoo.com
[2]*Department of Mechanical Engineering, Delhi Technological University,*
Bawana Road, Delhi-110042, India
dr.rajeshmits@gmail.com
** Corresponding author*

Abstract: **In this paper, a solar assisted combined power and ejector refrigeration cycle is proposed and thermodynamically analyzed from the viewpoint of energy and exergy. This cycle combines the Rankine cycle and ejector refrigeration cycle to produce power and refrigeration simultaneously. A simulation is carried out to analyze the cycle performance by using different refrigerants like; R141b, R600, R601 and R601a. The effect of various operating thermodynamic parameters like turbine inlet pressure, turbine back pressure, condenser temperature and evaporator temperature on energy and exergy efficiency of the cycle is observed. It is found that at a common turbine back pressure of 0.4MPa, R141b offers highest energy efficiency (18.37%) and R600 offers highest exergy efficiency (7.65%). At a common evaporator temperature of 270K, R141b offers highest energy efficiency (17.98 %) and R600 offers highest exergy efficiency (6.69%) as compared to other refrigerants is observed. It is clear that, with the increase in turbine inlet pressure from 0.5 MPa to 1.75 MPa of R141b, the energy efficiency increases from 13.8% to 18.69%) and exergy efficiency increases from 3.45% to 8.62%.**

Keywords: **Solar heat, ejector, exergy, refrigerants, power.**

1. INTRODUCTION

Energy is considered as a major agent in the generation of wealth and an important factor in economic developments. With developing technology and the rapid increase in population, the demand for energy and cost of electricity is ever increasing. In view of this, various investigations have been carried out on solar heat and non CFCs operated refrigeration systems like ejector and vapour absorption cooling.

The coefficient of performance of the system increases with an increase in the generator and evaporator temperatures while decreases with an increase in the condenser temperature of the ejector cooling system using the refrigerant R134a [1]. The condenser temperature has more influence than the generator and evaporator temperatures on the area ratio and the entrainment ratio in the ejector refrigeration system by using refrigerants R123 and R141b [2]. The detailed investigation of ejector working characteristics by using R141b, R245fa and R600a as the working fluids shows that different refrigerants perform distinctively different in the ejector refrigeration system [3]. The simulation of solar powered absorption cooling system by using LiBr-H_2O mixture as working fluid is carried out by Atmaca and Yigit [4].

The energy and exergy analyses of single-effect water-lithium bromide absorption cooling system driven by solar heat with cooling capacity of 10 kW is presented by Touaibi [5]. Khaliq et al. [6] presented an industrial waste heat recovery based cogeneration cycle for production of power and refrigeration. They observed the effect of various operating parameters on energy and exergy efficiency. The most of the exergy destruction takes place in the ejector in combined power and ejector refrigeration cycle using R245fa as the working fluid [7]. Dai et al. [8] carried out exergy analysis, parametric analysis and optimization for a novel combined power and ejector refrigeration cycle.

In order to utilize the advantages of the ejector refrigeration cycle and recover solar heat effectively, a new solar assisted combined organic Rankine cycle and ejector refrigeration cycle is proposed and thermodynamically analyzed by using the different refrigerants such as R141b, R 600, R601 and R601a. This combined cycle will produce both power output and refrigeration output simultaneously by using single source of solar heat.

In the present study, exergy method along with energy method is applied to investigate the thermodynamic performance of the proposed cycle. The effect of various operating parameters on energy and exergy efficiency has been observed to find out the optimum operating range.

2. SYSTEM DESCRIPTION

The proposed cogeneration cycle combines the Rankine cycle (RC) and the ejector refrigeration cycle (ERC) as shown in Figure 1. 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). Superheated refrigerant vapour (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 enters in to the central receiver.

For the analysis, the specifications of the combinedRC and ERC are given in Table 1.

TABLE 1: Main parameters considered for the analysis

Parameters	R141b	R600	R601	R601a
Environment temperature (^{0}C)	15	15	15	15
Environment pressure (MPa)	0.10135	0.10135	0.10135	0.10135
Turbine inlet pressure range (MPa)	0.5-1.75	1.0-2.5	0.5-1.5	0.5-1.5
Hot oil outlet temperature from CR (^{0}C)	170	170	170	170
Solar radiation received per unit area (Wm^{-2})	850	850	850	850
Apparent Sun temperature (K)	4500	4500	4500	4500
Heliostat aperture area (m^2)	3000	3000	3000	3000
Turbine back pressure range (MPa)	0.2-0.4	0.35-0.65	0.2-0.4	0.35-0.5
Turbine isentropic efficiency (%)	85	85	85	85
Ejector evaporator temperature range (K)	264-272	264-272	264-272	264-270
Condenser temperature range (^{0}C)	20-30	20-30	20-30	26-32
Pump isentropic efficiency (%)	70	70	70	70
HRVG efficiency (%)	100	100	100	100
Pinch point temperature difference (^{0}C)	10.0	10.0	10.0	10.0
Approach point temperature difference (^{0}C)	5.0	5.0	5.0	5.0
Nozzle efficiency (%)	90	90	90	90
Mixing chamber efficiency (%)	85	85	85	85
Diffuser efficiency (%)	85	85	85	85
Energy efficiency of heliostat field (%)	75	75	75	75
Energy efficiency of central receiver (%)	90	90	90	90
Exergy efficiency of heliostat field (%)	75	75	75	75
Exergy efficiency of central receiver (%)	30	30	30	30

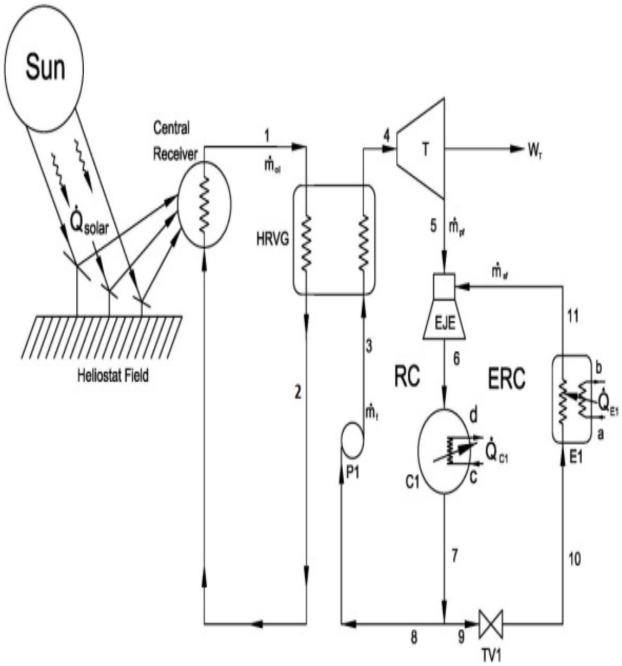

Fig.1. Schematic diagram of solar assisted ejector cooling and power cycle

3. THERMODYNAMIC ANALYSIS

According to the first law of thermodynamics and energy conservation used to determine the overall thermal efficiency, heat and work are equivalent. On the other hand, exergy, based on the second law of thermodynamics, quantifies the difference between heat and work in terms of irreversibility. Exergy is defined as the maximum amount of work which can be produced by a system when it comes to equilibrium with a reference environment, which may be defined mathematically as:

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

The entropy generation over a control volume is given by Bejan [9]

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

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

$$\dot{E}_{X,D} = T_0\, \dot{S}_{gen} \quad (3)$$

3.1. Energy Efficiency (η_{energy})

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

$$\eta_{energy} = \frac{\dot{Q}_{E1} + \dot{W}_{NET}}{\dot{Q}_{Solar}} \quad (4)$$

where, $\dot{Q}_{E1}$, $\dot{W}_{NET}$ and $\dot{Q}_{solar}$ are the refrigeration output of ERC, net power output of Rankine cycle and solar heat input respectively.

The basic equations obtained from the law of conservation of energy in the components of RC and ERC are written as follows:

For HRVG: $\dot{m}_{oil}(h_1 - h_2) = \dot{m}_f(h_4 - h_3)$ (5)

For Turbine (T): $\dot{W}_T = \dot{m}_f(h_4 - h_5)$ (6)

For Pump (P1): $\dot{W}_{P1} = \dot{m}_f(h_3 - h_8)$ (7)

Net Work done: $\dot{W}_{NET} = \dot{W}_T - \dot{W}_{P1}$ (8)

For Ejector (EJE):

$$\dot{m}_{pf}\, h_5 + \dot{m}_{sf}\, h_{11} = h_6(\dot{m}_{pf} + \dot{m}_{sf}) \quad (9)$$

For condenser (C1):

$$\dot{Q}_{C1} = \dot{m}_C(h_d - h_c) = (\dot{m}_{pf} + \dot{m}_{sf})(h_6 - h_7) \quad (10)$$

For Throttle Valve (TV1): $h_9 = h_{10}$ (11)

For Evaporator (E1):

$$\dot{Q}_{E1} = \dot{m}_E(h_a - h_b) = \dot{m}_{sf}(h_{11} - h_{10}) \quad (12)$$

3.2. Exergy Efficiency (η_{exergy})

The exergy efficiency for simultaneous production of cooling and power cycle is given by

$$\eta_{exergy} = \frac{\Delta \dot{E}_{X,E1} + \dot{W}_{NET}}{\dot{E}_{X,Solar}} \quad (13)$$

where, $\dot{E}_{X,Solar}$ is incoming exergy associated with solar radiation falling on heliostat, $\Delta\dot{E}_{E1}$ and $\dot{W}_{NET}$ are the change in exergy at ejector evaporator of ERC and exergy associated with net power output of RC respectively.

$$\dot{E}_{X,Solar} = \dot{Q}_{Solar}\left(1-\frac{T_0}{T_S}\right) \quad (14)$$

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

$$\Delta\dot{E}_{X,E1} = \dot{m}_{sf}[(h_{10}-h_{11}) - T_0(s_{10}-s_{11})] \quad (15)$$

4. RESULTS AND DISCUSSION

In this paper, parametric analysis is carried out to find out the effect of variation of turbine inlet pressure, turbine back pressure, condenser temperature and evaporator temperature on energy and exergy efficiency of the solar assisted cogeneration cycle for simultaneous production of power and cooling. The thermodynamic properties of refrigerant R141b, R600, R601 and R601a used in the ERC cycle were calculated by NIST Standard Reference Database 23 [10].

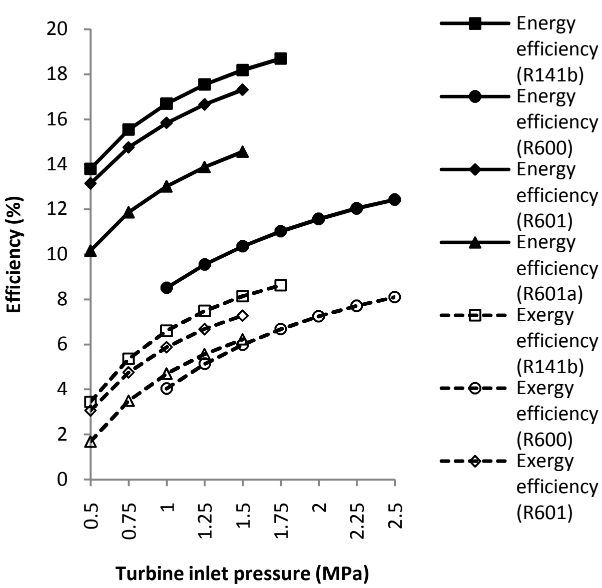

Fig. 2. Effect of turbine inlet pressure on energy and exergy efficiency

Figure 2 shows the effect of turbine inlet pressure on energy and exergy efficiency. With increase in turbine inlet pressure, the enthalpy drop across the turbine increases due to increase in pressure ratio, results in increase in turbine power output. The refrigeration output decreases due to decrease in turbine exhaust temperature which is the primary flow temperature of the ejector. The decreasing primary flow temperature reduces the primary stream velocity leaving the nozzle in the ejector, resulting in the decreasing the entrainment of secondary vapours. Due to combined effect of turbine power and refrigeration output, the energy and exergy efficiency increases with increase in turbine inlet pressure. It is observed that refrigerant R141b offers better energy and exergy efficiency as compared to R600, R601 and R601a. At a common pressure of 1.5 MPa, the refrigerant R141b offers highest energy efficiency (18.18%) and exergy efficiency (8.14%).

Figure 3 shows the effect of turbine back pressure on energy and exergy efficiency. With increase in turbine back pressure, the turbine power decreases because the enthalpy drop across the turbine decreases. It is also clear that the refrigeration output increases with the increase in turbine back pressure because the primary stream velocity leaving the nozzle in the ejector increases. This increase in the nozzle exit velocity contributes to the increasing the entrainment of secondary vapour which leads to the increasing refrigeration output in the evaporator of ERC. Since the rate of increase in refrigeration output is greater than the rate of decrease in turbine power output, the energy efficiency increases with increase in turbine back pressure. It is clear that the exergy output of ERC increases while the exergy of turbine power output decreases with increase in turbine back pressure. Due to combined effect the exergy efficiency decreases with increase in turbine back pressure. At a back pressure of 0.4MPa, R141b offers highest energy efficiency (18.37%) and R600 offers highest exergy efficiency (7.65%).

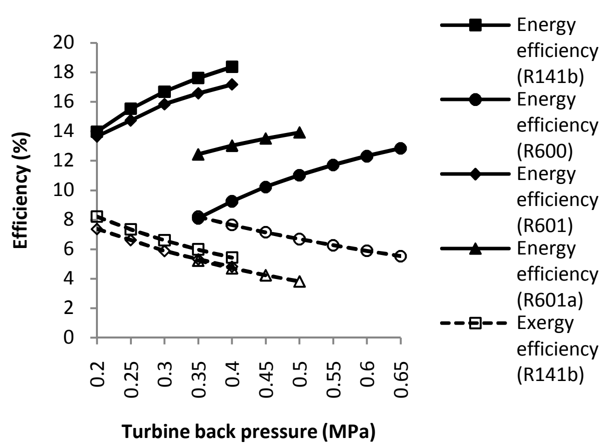

Fig. 3. Effect of turbine back pressure on energy and exergy efficiency

Figure 4 shows the effect of evaporator temperature on energy and exergy efficiency. As the evaporator temperature increases, the refrigeration output increases because the secondary mass flow rate increases in the evaporator. The turbine power output does not vary with the increasing evaporator temperature because the turbine inlet state and outlet state are fixed. The energy and exergy efficiency of combined cycle increases with increase in evaporator temperature. At a common evaporator temperature of 270K, R141b offers highest energy efficiency (17.98 %) and R600 offers highest exergy efficiency (6.69%) compared to other refrigerants.

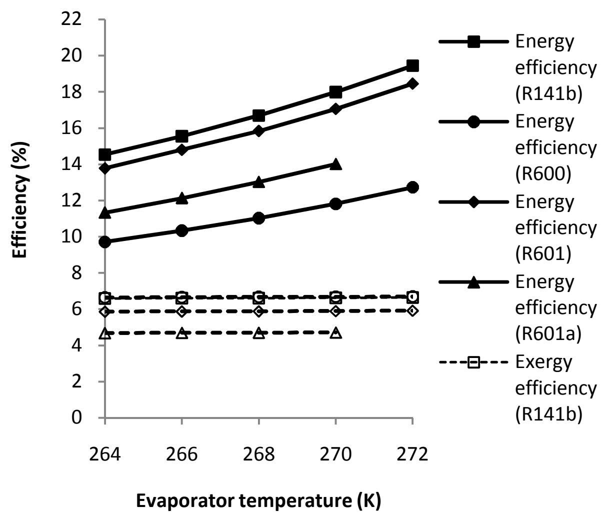

Fig. 4. Effect of evaporator temperature on energy and exergy efficiency

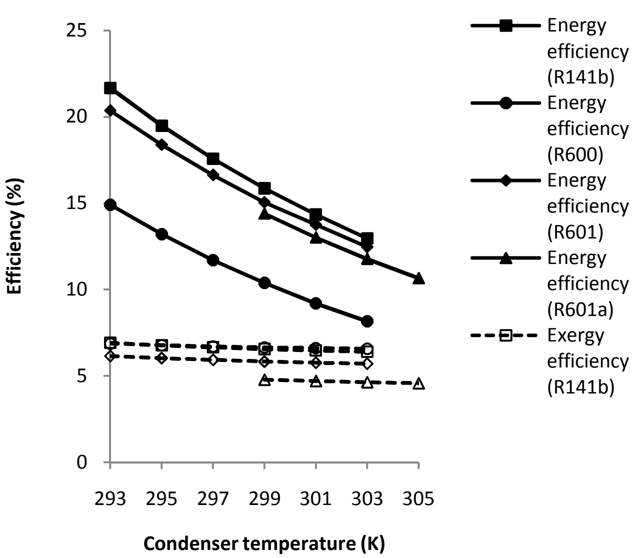

Fig. 5. Effect of condenser temperature on energy and exergy efficiency

The energy and exergy efficiency of combined cycle decreases with increase in condenser temperature as shown in Figure 5. The turbine power output does not vary with the increasing condenser temperature, because the turbine inlet state and outlet state are fixed. As the condenser temperature increases, results in increase in condenser pressure and hence the back pressure on the ejector increases, due to this, refrigeration output and exergy output decreases. At a common condenser temperature of 299K, R141b offers highest energy efficiency (15.86%) and R600 offers highest exergy efficiency (6.65%).

5. CONCLUSION

A combined energy and exergy analyses of a new solar assisted cogeneration cycle for simultaneous production of power and cooling is presented. The effects of key thermodynamic parameters were observed on energy and exergy efficiency of the proposed cycle. The main conclusions of the present study can be summarized as follows:

- with the increase in turbine inlet pressure, the energy efficiency and exergy efficiency increases significantly for all the refrigerants.
- with the increase in turbine inlet pressure from 0.5 MPa to 1.75 MPa of R141b, the energy efficiency increases (13.8% to 18.69%) and exergy efficiency increases (3.45% to 8.62%).
- with the increase in turbine back pressure, the energy efficiency increases and exergy efficiency decreases significantly.
- At a common turbine back pressure of 0.4MPa, R141b offers highest energy efficiency (18.37%) and R600 offers highest exergy efficiency (7.65%).
- with the increase in evaporator temperature, the energy efficiency increases significantly and exergy efficiency increases marginally.
- At a common evaporator temperature of 270K, R141b offers highest energy efficiency (17.98 %) and R600 offers highest exergy efficiency (6.69%) compared to other refrigerants.
- with the increase in condenser temperature, the energy efficiency decreases significantly and exergy efficiency decreases marginally.

REFERENCES

[1] Tirmizi, S.A., Gandhidasan, P. and Zubair, S.M., "Exergetic performance evaluation of ejector cooling system", *International Journal of Exergy,* 9(1), 2011, pp.80-98.

[2] Chen, J., Havtun, H. and Palm, B., "Investgation of Ejectors in Refrigeration System: Optimum Performance Evaluation and Ejector Area Ratio Perspectives", *Applied Thermal Engineering,* 64, 2014a, pp.182-191.

[3] Chen, J., Havtun, H. and Palm, B., "Parametric Analysis of Ejector Working Characteristics in the Refrigeration System", *Applied Thermal Engineering*, 69, 2014b, pp.130-142.

[4] Atmaca, I. and Yigit, A., "Simulation of solar powered absorption cooling system", *Renewable Energy,* 28, 2003, pp. 1277- 1293.

[5] Touaibi, R., Feidt, M., Vasilescu, E.E. and Abbes, M.T., "Parametric study and exergy analysis of solar water-lithium bromide absorption cooling system", *International Journal of Exergy,* 13(3), 2013, pp.409-429.

[6] Khaliq, A., Kumar, R. and Dincer, I., "Exergy analysis of an industrial waste recovery based cogeneration cycle for combined production of power and refrigeration", *Journal of Energy Resources Technology,* 131, 2009, pp.1- 9.

[7] Zheng, B. and Weng, Y.W., "A combined power and ejector refrigeration cycle for low temperature heat sources", *Solar Energy,* 84, 2010, pp.784- 791.

[8] Dai, Y., Wang, J. and Gao, L., "Exergy analysis, parametric analysis and optimization for a novel combined power and ejector refrigeration cycle", *Applied Thermal Engineering,* 29, 2009, pp.1983-1990.

[9] 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.

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