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Thermodynamics Analysis of a Solar Operated Combined Power and Ejector Cooling Cycle with Environmentally Benign Fluids

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Abstract—*Thermodynamic analysis is carried out to investigate the performance of a solar operated combined power and ejector cooling cycle using various ecofriendly refrigerants (R290, R152a, R134a, and R717). The effect of most influenced parameter such as turbine expansion ratio on the entrainment ratio, net power output; refrigeration output, first law and second law efficiency of the proposed cycle have been studied. The performance comparison of the cycle using various environmentally benign fluids is also studied.*

Keywords: *Solar energy, ejector, turbine expansion ratio, ecofriendly refrigerants, entrainment ratio.*

1. INTRODUCTION

Most of the Refrigeration and air conditioning systems are driven by electrical power. In order to reduce electricity consumption and environmental degradation, Scientist and Engineers have to switch over to the solar thermal driven refrigeration / air conditioning systems. For efficient utilization of solar energy, a combined power and refrigeration cycle has been analysed to improve the overall efficiency of the system.

A low temperature heat source driven combined power and cooling cycle which combines the Rankine power cycle and absorption cooling cycle using ammonia–water mixture as the working substance was proposed by Xu et al. (2000). Vidal et al. (2006) have done the exergy analysis of a combined power and refrigeration cycle using ammonia–water mixture as the working substance. The second law efficiency of the combined cycle was found to be 53%.

Most of the researchers have been concentrate their efforts on combined Rankine with absorption refrigeration cycle. The use of the ejector refrigeration cycle with the combination of power is given a little attention. Alexis (2007) developed a computer programme and studied the effect of performance parameters on combined power and cooling cycle. It is shown that ejector refrigeration system is more economical than absorption refrigeration system.

Recently, an energy and exergy analyses of combined power and ejector refrigeration cycles was reported by (Wang et al., 2008; Yapici and Yetisen, 2007; Dai et al., 2009; Wang et al., 2009; Gupta et al., 2014) which shows that the maximum irreversibility/exergy loss occurs in heat addition process followed by the ejector and turbine.

Much effort has been done to study the performance of combined power and ejector cooling cycle using single ecofriendly refrigerant only. The study of the performance of combined power and ejector cooling cycle using various ecofriendly refrigerants is missing in the literature. Present study shows the thermodynamic analysis of a solar operated combined power and ejector cooling cycle with ecofriendly refrigerants as working substance. The effect of most influenced parameter such as turbine expansion ratio (τ) has been observed on the performance (entrainment ratio, net power output, refrigeration output, first law and second law efficiency) of the proposed cycle.

2. SYSTEM DESCRIPTION

Fig.1 shows the solar operated combined power and ejector cooling system. It consists of an extraction turbine (ET) and an ejector (EJE) which produces power and cooling respectively. Heat transfer fluid (duratherm fluid 600) is used to superheat the high pressure refrigerant in the heat recovery vapor generator (HRVG). Superheated refrigerant vapor (1) expands in the extraction turbine. Extracted vapor (2) flows into the ejector nozzle and entrains secondary vapor (13) from the evaporator mixes in mixing chamber of the ejector. The ejector exit stream (4) mixes with the extraction turbine exhaust (3) and is cooled in the heat exchanger (5-6), and then enters into the condenser (C). Saturated liquid (7) from condenser then enters into throttle valve (11) and pump (8).

The high pressure liquid flows into the heat exchanger (9-10) and then converted into superheated vapor (1) in the HRVG. The saturated liquid (11) expands to the evaporator pressure (11-12) in the throttle valve and vaporized in the evaporator (12-13) to produce refrigeration effect.

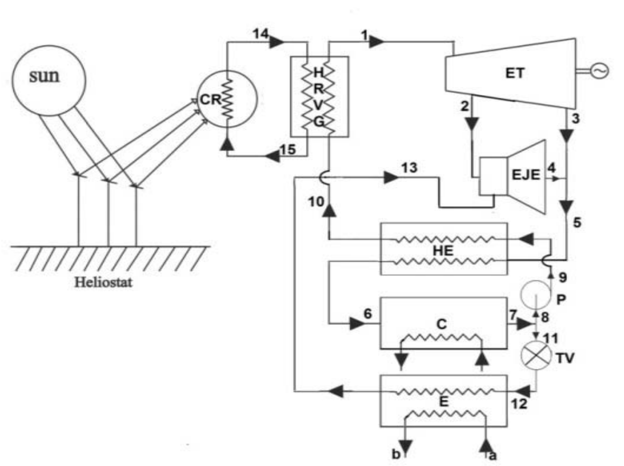

Fig. 1 Solar operated combined power and ejector cooling cycle

For the analysis, the parameters used of the combined power and ejector refrigeration cycle are given in Table 1

Table 1: Main parameters considered for the analysis

Environment Temperature (K)	**298**
Environment pressure (MPa)	0.10135
Turbine inlet Temperature (K)	393
Extraction ratio	0.5
Turbine isentropic efficiency (%)	85
Pump isentropic efficiency (%)	70
Condenser temperature (K)	303
Evaporator temperature (K)	273
Water temperature inlet to evaporator (K)	299
Water temperature outlet to evaporator (K)	283
Apparent Sun temperature (K)	4500
Heliostat aperture area (m2)	3000
Solar radiation received per unit area (kWm-2)	0.85
Oil temperature inlet to CR (oC)	363
Oil temperature inlet to HRVG (oC)	403
HRVG efficiency (%)	100
Pinch point temperature difference (oC)	10.0
Nozzle efficiency (%)	90
Mixing chamber efficiency (%)	85
Diffuser efficiency (%)	85
First law efficiency of heliostat field (%)	75
First law efficiency of central receiver (%)	90
Second law efficiency of heliostat field (%)	75
Second law efficiency of central receiver (%)	varied

3. THERMODYNAMIC ANALYSIS

The entrainment ratio is determined on the bases of mass, momentum and energy equations that is recently developed by Dai et al. (2009) and may be written as

$$\mu = \sqrt{\eta_n \eta_m \eta_d \left(h_{pf,n1} - h_{pf,2s}\right)/\left(h_{mf,ds} - h_{mf,m}\right)} - 1 \qquad (1)$$

The efficiencies of ejector components such as nozzle, mixing chamber, and diffuser are given in Table 1.

A thermodynamic analysis provides an opportunity to evaluate the theoretical performance of the combined power and ejector cooling cycle. It determines the system performance based on exergy, which may be defined as the maximum possible reversible work obtainable in bringing the state of the system to equilibrium with that of the surroundings Bejan, A., (2002). Mathematically,

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

3.1. First law efficiency (η_i)

First law efficiency is defined as the ratio of the sum of the net power output ($\dot{W}_{net}$) and refrigeration output in the evaporator ($\dot{Q}_E$) to the solar energy input ($\dot{Q}_{Solar}$).

The first law efficiency of the combined cycle is given by

$$\eta_I = \frac{\dot{W}_{net} + \dot{Q}_E}{\dot{Q}_{Solar}} = \frac{(\dot{W}_T - \dot{W}_p) + \dot{Q}_E}{AI} \qquad (3)$$

Where

$$\dot{Q}_E = \dot{m}_f E_r \mu (h_{13} - h_{12}) = \dot{m}_w (h_a - h_b) \qquad (4)$$

$$\dot{W}_T = \dot{m}_f (h_1 - h_2) + \dot{m}_f (1 - E_r)(h_2 - h_3) \qquad (5)$$

$$\dot{m}_f = \dot{m}_{pf} + (1 - E_r) \qquad (6)$$

$$\dot{W}_p = \dot{m}_f (h_9 - h_8) \qquad (7)$$

A and I are the aperture area and direct normal radiation per unit area respectively.

3.2. Second law efficiency (η_{ii})

The second law efficiency of combined cycle may be reported as

$$\eta_{II} = \frac{\dot{W}_{net} + \dot{E}_E}{\dot{E}_{Solar}} \qquad (8)$$

Where, $\dot{E}_{Solar}$ is incoming exergy associate with solar radiation falling on heliostat, $\dot{E}_E$ is the exergy of refrigeration output in the evaporator,

$$\dot{E}_E = \dot{m}_{sf}[(h_{12} - h_{13}) - T_0(s_{12} - s_{13})] \qquad (9)$$

$$\dot{E}_{Solar} = \dot{Q}_{Solar}\left(1 - \frac{T_0}{T_{Solar}}\right) \qquad (10)$$

Where T_{Solar} the apparent sun temperature = 4500K

4. RESULTS AND DISCUSSION

A thermodynamic analysis has been carried out to observe the effect of turbine expansion ratio on the performance of the solar driven combined power and ejector cooling cycle.

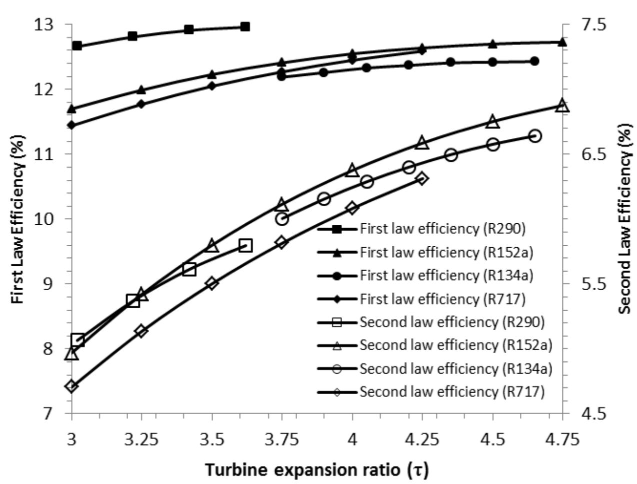

Figure 2 Effect of turbine expansion ratio on First and Second law efficiency of the cycle

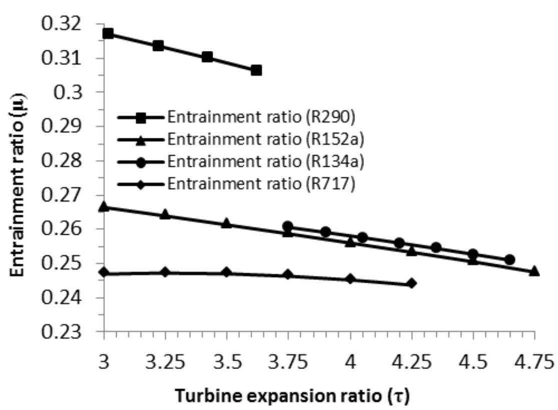

Figure 3 Effect of turbine expansion ratio on entrainment ratio

Fig. 2, 3 and 4 show the effect of variation of turbine expansion ratio (τ) for constant turbine extraction pressure, condenser pressure and evaporator pressure on first law efficiency and second law efficiency , entrainment ratio, net power output and refrigeration output for various eco-friendly refrigerants (R290, R152a, R134a, and R717). As turbine expansion ratio (τ) increases keeping the condenser pressure constant, enthalpy change across the turbine increases which results in increase in net power output. At the same time, refrigeration output decreases because at high turbine expansion ratio the turbine extraction temperature (T_2) decreases. The increase in turbine power output is greater than the decrease in refrigeration output results in increase in first law efficiency. A similar trend is also observed for the second law efficiency because the turbine power output increases and exergy of refrigeration output decreases with the increase in turbine expansion ratio. With the increase in turbine expansion ratio (τ), there is decrease in turbine extraction temperature (T_2). This decrease in turbine extraction temperature results in decrease in enthalpy drop in the nozzle of the ejector which causes the reduction of the velocity of primary flow at the exit of the nozzle in the ejector i.e. the entrainment ratio decreases. As stated earlier when turbine expansion ratio increases, the enthalpy change across the turbine increases which results in increase in net power output. At the same time refrigeration output decreases because at high turbine expansion ratio the turbine extraction temperature decreases.

It is also observed that among the various ecofriendly refrigerant, R290 gives better first law efficiency and refrigeration output while R152a gives better net power output and second law efficiency at high turbine expansion ratio.

The effect of turbine expansion ratio (τ) on the performance of the system for various ecofriendly refrigerants is summarized in table 2.

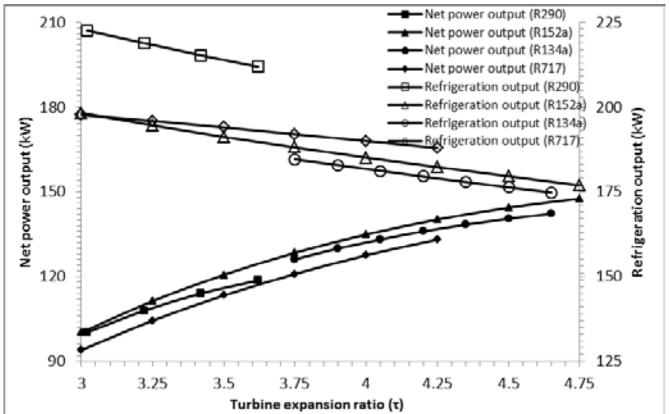

Figure 4 Effect of turbine expansion ratio on net power output and refrigeration output of the cycle

Table 2: The performance of the system for various ecofriendly refrigerants

	R290	R152a	R134a	R717
(ηI)	High ηI for high τ		Low ηI for high τ	
(ηII)		High ηII for high τ		Low ηII for high τ
Wnet		High Wnet for high τ		Low Wnet for high τ
QE	High QE for high τ		Low QE for high τ	

5. CONCLUSION

Present study deals with the solar operated combined power and an ejector refrigeration cycle with ecofriendly refrigerants as working fluid. The effect of turbine expansion ratio has been observed on the performance (first law efficiency and second law efficiency, entrainment ratio, net power output and refrigeration output) of the proposed cycle.

From the above discussion, it can be concluded that

- As the turbine expansion ratio (τ) increases, net power output, first and second law efficiency increases while the entrainment ratio and refrigeration output decreases.
- At high turbine expansion ratio (τ) the performance of R290 and R152a is better other than that of other refrigerants.

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