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Exergetic Analysis of Combined Power and Ejector Refrigeration Cycle using Solar Energy as Heat Source

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Abstract—*A combined power and ejector refrigeration cycle is proposed for the production of both power and refrigeration output using duratherm 600 oil as the heat transfer fluid. Exergetic analysis has been done to observe the effect of parameters such as turbine expansion ratio on the performance of the combined cycle. The effect of turbine expansion ratio on the performance of the cycle has significant effects on the net power output, refrigeration output, first law efficiency and second law efficiency using R245fa refrigerant as working fluid.*

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

1. INTRODUCTION

The consumption of fossil fuels continues to satisfy the increasing demand for energy and electricity in the world, leading to environment impacts and potential energy shortages. In order to mitigate energy problems and protect the environment, increasing attention has been paid in recent years to the utilization of renewable energy and low-grade waste heat to generate power.

A combined power and ejector cooling cycle using low grade heat source such as solar energy, geothermal energy, biomass energy, and waste heat from various thermal processes was investigated. This combined power and cooling cycle originally was proposed by Xu et al. (2000), and Tamm et al. (2004) that the cycle could produce both power and cooling simultaneously.

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.

Present study deals with the exergetic analysis of a solar operated combined power and ejector cooling cycle. The effect of most influenced parameter such as turbine expansion ratio has been observed on net power output, refrigeration output, the first law and second law efficiency of the proposed cycle.

2. SYSTEM DESCRIPTION

Fig.1 shows the combined power and ejector refrigeration cycle. 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 receiver results in high temperature of the oil (Duratherm600) which is passing through the central receiver. The oil transfers the thermal energy from central receiver to the refrigerant passing through the HRVG. Superheated refrigerant vapor (4) is expanded in a turbine to generate work. The extracted primary vapor (5) and secondary vapor (13) are mixed in the mixing chamber of the ejector. The stream (6) out of the ejector mixed with turbine exhaust (14) is cooled in the heat exchanger (7-8) and enters the condenser where it condenses and converted into saturated liquid (9). The saturated liquid (9) is divided in two parts (10, 11), one part (11) is passed through throttling valve(TV) where pressure is reduced to evaporator pressure (12) and feed to evaporator, and second part (10) is pumped to heat exchanger (15). The high pressure working fluid heated in the heat exchanger (15-3) before entering the heat recovery vapor generator HRVG. The working fluid at low pressure and temperature from the throttle valve is vaporized in the evaporator (12-13) to produce cooling effect.

For the analysis, the specifications of the combined Rankine and ejector refrigeration cycle are given in Table 1.

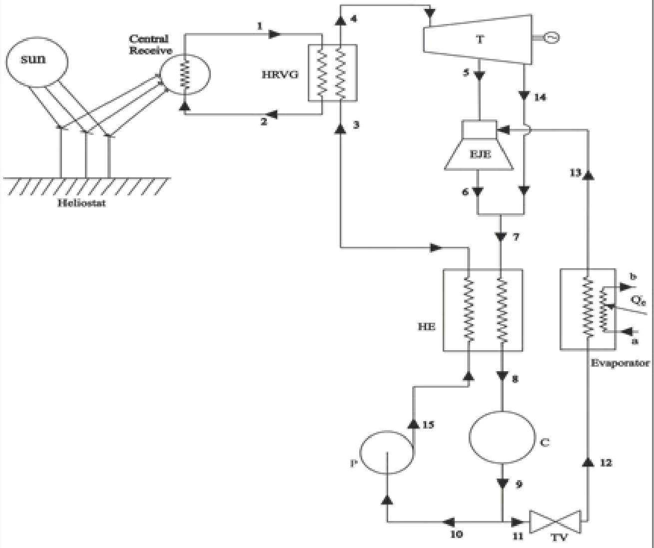

Fig. 1 Schematic diagram of solar operated combined Rankine and ejector refrigeration cycle

Table 1: Main parameters considered for the analysis

Atmospheric Temperature (K)	298
Atmospheric pressure (MPa)	0.10135
Turbine inlet pressure (MPa)	0.650
Turbine inlet Temperature (K)	393-453
Extraction ratio	0.3
Extraction pressure ratio	2.5
Turbine isentropic efficiency (%)	85
Pump isentropic efficiency (%)	80
Condenser temperature (K)	293
Evaporator temperature (K)	268
Solar radiation received per unit area (kWm-2)	0.85
Apparent Sun temperature (K)	4500
Heliostat aperture area (m2)	3000
Oil temperature inlet to CR (oC)	373
Oil temperature inlet to HRVG (oC)	433
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 (%)	30

3. THERMODYNAMIC ANALYSIS

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 formulation and assumption of entrainment ratio is based on mass, momentum and energy equations which is recently developed by Dai et al. (2009) and may be reported as

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

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,

$$\dot{E} = \dot{m}[(h - h_0) - T_0(s - s_0)] \quad (3)$$

According to the Bejan(2000) entropy generation over a control volume is given by

$$\dot{S}_{gen} = \frac{dS}{dt} - \sum_{i=0}^{n} \frac{\dot{Q}_i}{T_i} - \sum_{in} \dot{m}s + \sum_{out} \dot{m}s \geq 0 \quad (3)$$

Turbine expansion ratio is reported as

$$TER = \frac{P_T}{P_C} = \frac{\text{Turbine inlet pressure}}{\text{Condeser pressure}} \quad (4)$$

FIRST LAW EFFICIENCY (η_I)

It can be defined as the ratio of the net power output ($\dot{W}_{net}$) and refrigeration output in the evaporator ($\dot{Q}_E$) to the solar energy input.

The first law efficiency of the combined cycle is given by

$$\eta_I = \frac{\dot{W}_{net} + \dot{Q}_E}{\dot{Q}_{Solar}} \quad (5)$$

$$\dot{W}_T = \dot{m}_f(h_4 - h_5) + \dot{m}_f(1 - E_r)(h_5 - h_{14}) \quad (6)$$

$$\dot{W}_p = \dot{m}_f(h_{15} - h_{10}) \quad (7)$$

$$\dot{W}_{net} = \dot{W}_T - \dot{W}_p \quad (8)$$

$$\dot{Q}_E = \dot{m}_f E_r \mu (h_{13} - h_{12}) = \dot{m}_w (h_a - h_b) \quad (9)$$

SECOND LAW EFFICIENCY (η_{II})

The second law efficiency of combined cycle may be reported as

$$\eta_{II} = \frac{\dot{W}_{net} + \dot{E}_E}{\dot{E}_{Solar}} \quad (10)$$

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,

$$\dot{E}_E = \dot{m}_{sf}[(h_{12} - h_{13}) - T_0(s_{12} - s_{13})] \quad (11)$$

$$\dot{E}_{Solar} = \dot{Q}_{Solar}\left(1 - \frac{T_0}{T_{Solar}}\right) \quad (12)$$

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

4. RESULTS AND DISCUSSION

An exergetic 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.

Fig. 2 and 3 show the effect of variation of turbine expansion ratio (τ) for constant turbine extraction pressure, condenser pressure and evaporator pressure on net power output and refrigeration output, first law efficiency and second law efficiency for R245fa refrigerant as working fluid. As turbine expansion ratio (TER) 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_5) 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.

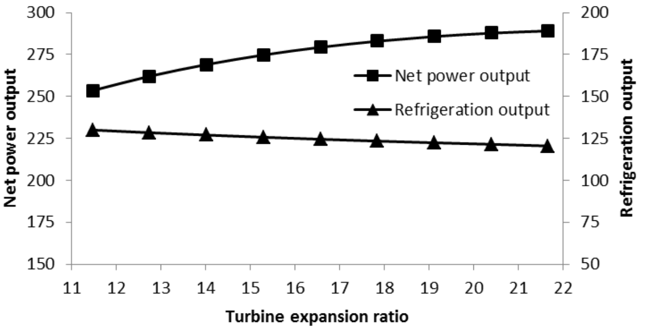

Fig. 2 Effect of turbine expansion ratio on power and refrigeration output of the cycle

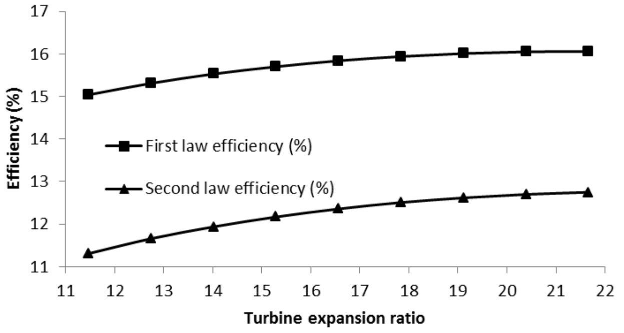

Fig. 3 Effect of turbine expansion ratio on first and second law efficiency

5. CONCLUSION

Present study deals with the solar operated combined power and an ejector refrigeration cycle using R245fa refrigerants as working fluid. The effect of turbine expansion ratio has been observed on the performance (net power output and refrigeration output, first law efficiency and second law efficiency) of the proposed cycle.

From the above discussion, it can be concluded that

- As the turbine expansion ratio (TER) increases, net power output, first and second law efficiency increases while refrigeration output decreases.

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