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Energy and Exergy Analyses of Solar Operated Organic Rankine Cycle by using R245fa

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Abstract

In this paper, energy and exergy analyses of a solar assisted Organic Rankine Cycle using R245fa as working fluid is carried out for production of power. The proposed cycle is an integration of solar-sub system using heliostat and central receiver and Organic Rankine Cycle. Energy destruction rate in each component of the cycle is determined to identify the realistic performance of the cycle along with causes and locations of thermodynamic imperfection. Duratherm 600 oil is used as a heat transfer fluid in solar-sub system. After analysis it is observed that the highest exergy destruction takes place in central receiver 52.5%, heliostat field 25%, HRVG 5.5%, and condenser 2.55%. The energy efficiency is 9.95% and exergy efficiency is 10.66% are observed.

Keywords: Solar heat, R245fa, Energy, Exergy, Organic Rankine Cycle, Exergy destruction

I. INTRODUCTION

Solar energy is an inexhaustible, clean and safe source of energy, it has received much attention as one of the most promising candidate to substitute the conventional sources (fuels) for energy supply [1, 2]. He et al. [3] reviewed about the utilization of solar energy as a primary source for power production and its integration with ORC. Kumar and Agrawal [4] work on a solar assisted with combined power and ejector refrigeration cycle and thermodynamically analyzed from the view point of energy and exergy. This cycle combines the Rankine cycle and ejector refrigeration cycle to produce power and refrigeration simultaneously.

ORC is promising energy conversion technology has been the focus of many researches is recent year due to its typical advantages of using law grade heat source, such as industrial waste heat, solar energy and geothermal energy. Organic Rankine Cycle owing to usage of the organic fluid as working fluid instead of water and high pressure steam. Quoilin et al. [5] reviewed an Organic Rankine Cycle (ORC) which is as identical as Steam Rankine Cycle, except that it employs organic fluids with a low boiling point as working fluids to generate power from low-temperature heat sources. Lecompte et al. [6] reviewed that Organic Rankine Cycle (ORC) is being accepted as a viable technology which is capable to convert low-temperature heat into electrical power due to unmanned operation. Morin et al. [7] studied various aspects of energy and exergy analysis which has to be used to show the exergetic performances for an Organic Rankine Cycle (ORC). In this system supply of electrical energy in an existing building with a known configuration is considered.

Darvish et al. [8] studied thermodynamic performance of a regenerative organic Rankine cycle that utilizes low temperature heat sources to facilitate the selection of proper organic working fluids is simulated. Tchanche et al. [9] studied theoretical performances as well as thermodynamic and environmental properties of few fluids which have been comparatively assessed for use in low-temperature solar organic Rankine cycle systems. Efficiencies, volume flow rate, mass flow rate, pressure ratio, toxicity, flammability, ODP and GWP were used for comparison. Of 20 fluids investigated, R245fa appears as the most suitable for small scale solar applications. Xu et al. [10] suggested that thermal efficiencies are well correlated with critical temperature and R245fa can be used over a wide heat source temperature.

II. SYSTEM DESCRIPTION

The solar assisted Organic Rankine Cycle consists of solar energy collecting sub-system and Organic Rankine Cycle sub-system. Figure 1 illustrates the schematic diagram of the entire system. The Organic Rankine Cycle sub-system consists of four main components, namely: a heat recovery vapour generator (HRVG), a turbine, a condenser and a pump. Solar radiation falls on the heliostat field and it is reflected on the aperture area of central receiver, aperture area 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, which is used to heat the oil (Duratherm oil 600). The heated oil flows through the pipes which transfers thermal energy from central receiver to the R245fa flowing in the HRVG. The superheated refrigerant vapour of R245fa expanded in the turbine to produce power, the turbine exhaust is condensed in the condenser. The saturated liquid is pumped by pump to the HRVG (Boiler) of Organic Rankine Cycle.

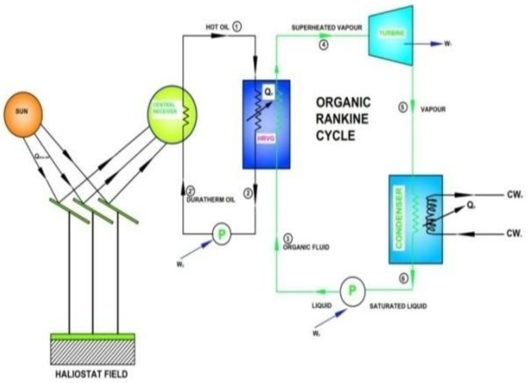

Fig: 1 Schematic Diagram of Solar ORC.

III. ASSUMPTIONS

The solar driven ORC for power generation is mathematically modeled using mass, energy and exergy balanced on each component as well as on the whole system. To simplify the theoretical analysis, some assumptions are made as follows:

1. The system runs at steady state process.

2 .Pressure drop and heat loss in pipelines are all neglected.

3. The working fluid at the condenser outlet is saturated liquid.

4. Kinetic and potential energy and exergy are ignored.

5. Chemical exergy of materials is neglected.

6. The dead state properties are taken as T_o=25°C and P_o=1.01325 bar.

IV. ENERGY EQUATIONS

A. *Energy Equations for Solar-Sub System:*

Energy efficiency of heliostat field

$$\eta_{\text{en, heliostat}} = \frac{Q_{cr}}{Q_{solar}}$$

Energy efficiency of central receiver

$$\eta_{\text{en, cr}} = \frac{Q_{durathermoil}}{Q_{cr}}$$

B. *Energy equations for Organic Rankine Cycle sub- System:*

The Organic Rankine Cycle sub-system is modeled based on the laws of mass and energy conservation.

In the HRVG, the heat addition into the power cycle is

$$Q_{HRVG} = m_f\,(h_4\text{-}h_3) \qquad (1)$$

In the condenser, heat rejected is expressed

$$Q_{cond.} = m_f\,(h_5\text{-}h_6) \qquad (2)$$

For the turbine, the isentropic efficiency is expressed

$$\eta_T = \frac{h_4 - h_5}{h_4 - h_{5S}}$$

The power output of the turbine is given by:

$$W_T = m_f\,(h_4 - h_5) \qquad (3)$$

For the pump, the isentropic efficiency can be expressed

$$\eta_P = \frac{h_{3S} - h_6}{h_3 - h_6}$$

The ORC pump power consumption is defined as:

$$W_P = m_f\,(h_3 - h_6) \qquad (4)$$

$$W_{\text{ net}} = (W_T) - (W_P) \qquad (5)$$

$$\eta_{en} = \frac{W_{net}}{Q_{solar}}$$

V. EXERGY EQUATIONS

A. *Exergy Equations for Solar-sub System:*

$$\eta_{\text{ex, heliostat}} = \frac{E_{x,cr}}{E_{x,solar}}$$

$$\eta_{\text{ex, cr}} = \frac{E_{x,durathermoil}}{E_{x,cr}}$$

$$E_{\text{x, solar}} = Q_{solar}\,(1\text{-}\frac{T_0}{T_s})$$

Where, T_0 = Environmental temperature = 298K

T_s = Sun temperature = 4500K

B. *Exergy equations for Organic Rankine Cycle sub System:*

Exergy destruction in HRVG

$$E_{xd\,HRVG} = \text{moil} * (h_1 - h_2) - T0 * (T1 + 273)/T2 + 273) + \text{mf} * (h_3 - h_4) - T0 * (S_3 - S_4)$$

Exergy destruction in Turbine

$$E_{xd\,Turbine} = (h_4 - T_o * S_4) - (h_5 - T_o * S_5) - (h_4 - h_5)$$

Exergy destruction in condenser

$$E_{xd,cond.} = (h_5 - T_o * S_5) - (h_6 - T_o * S_6)$$

Exergy destruction in pump

$$E_{xd,pump} = (h_6 - T_o * S_6) - (h_3 - T_o * S_3) + (h_3 - h_6)$$

$$E_{x,input} = Q_s^*[1 - T_0/(T_4 + 273)] + W$$

$$E_{xd\ total} = E_{xd\ HRVG} + E_{xd\ turbine} + E_{xd\ cond.} + E_{xd\ pump} + E_{xd\ helio} + E_{xd\ CR}$$

VI. RESULT AND DISCUSSION

A program was developed to analyze the cycle performance. R245fa was selected as working fluid in the cycle. The properties of R245fa were estimated by EES software version 9.224-3D. Table 1 Input data used in the system analysis. Table 2 shows the main properties of R245fa.Table 3 shows the simulation results of the state point at working condition. Table 4 shows the percentage (%) of Sun's energy distribution in ORC. Results of energy analysis shows that useful energy output 9.95 % and remaining 90.05 % is lost to environment. Table 5 shows the percentage (%) of Sun's exergy distribution in ORC. Results clearly indicate that exergy efficiency is 10.66 %. The exergy destruction in central receiver 52.5 %, heliostat field 25 %, are obtained. The analysis clearly indicate that main focus areas for thermodynamics performance improvement are central receiver (CR) and heliostat field in which largest exergy destruction (Irreversibility) takes place.

Table-2 Main Parameters Consider For The Analysis

Mass flow rate of R245fa	0.5235 kg/sec
Mass flow rate of oil	1.222 kg/sec
Turbine inlet pressure	2000 KPa
Turbine back pressure	177 KPa
Condenser temperature	30^{o}C
Duratherm Oil temperature entering to HRVG	170^{o}C
DNI (Direct normal intensity)	770 W/m^2
Environment temperature	25^{o}C
Environment pressure	1.01325 bar
Sun temperature	4500 K
Heliostat aparture area	300 m^2
Turbine isentropic efficiency	85%
Pump isentropic efficiency	70%
HRVG	100%
Pinch point temperature difference	10^{o}C
Approach point temperature difference	5^{o}C
Energy efficiency of Heliostat	75%
Energy efficiency of central receiver	90%
Exergy efficiency of Heliostat	75%
Exergy efficiency of central receiver	30%

Table-2 Main Properties of R245fa

S.NO	Substance	Molecular mass (kg/k mol)	T_{bp} (^0C)	T_{crit} (^0C)	P_{crit} (MPa)	Safety data ASHRAE 34 Safety Group	Atmospheric life time (yr)	ODP	GWP (100 Yr)
1	R245fa	134.05	15.14	154	3.651	A3	7.2	0	1020

Table- 3 Properties of the Working Fluid at a Different State Points

State Point	Pressure [Kpa]	Temperature [^{0}c]	Enthalpy [Kj/Kg]	Entropy [Kj/Kg-K]
3	2000	31.09	41.1	1.137
4	2000	160	538.9	1.93
5	177	97.8	493	1.952
6	177	30	239.1	1.135

Table- 4 Percentage (%) of Sun's Energy Distribution in Organic Rankine Cycle

Energy input/output	**Sun's energy distribution**	
	R245fa	
	KW	%
Energy input from Sun into system	231	100 %
Turbine work	24.02	10.39 %
Pump work	1.027	0.44 %
Net power output	22.99	9.95 %
Energy efficiency		9.95 %
Energy on the heliostat	173.3	75.02%

Table -5 Percentage of Sun's Exergy Distribution in Organic Rankine Cycle

Exergy Input/Output & Destructions	**Sun's exergy distribution**	
	R245fa	
	KW	%
Exergy associated with solar heat input	215.7	100 %
Exergy of net power output	22.99	10.66
Exergy efficiency		10.66 %
Exergy destruction in HRVG	11.87	5.50 %
Exergy destruction in condenser	5.52	2.55 %
Exergy destruction in turbine	3.444	1.59 %
Exergy destruction in pump	0.302	0.14 %
Exergy destruction in Heliostat field	53.92	25 %
Exergy destruction in central receiver	113.19	52.5 %
Miscellaneous losses	4.46	2.06%

VII. CONCLUSION

A solar operated Organic Rankine Cycle for production of power is discussed in this paper using R245fa as a working fluid. A simulation was carried out to analyze the cycle performance. The energy efficiency of 9.95 % and an exergy efficiency of 10.66 % is obtained at the typical working condition. The exergy analysis shows that most exergy losses takes place in the heliostat field, central receiver, HRVG, and condenser.

ABBREVIATIONS

E_{xd} → Exergy destruction rate (KW)
$E_{x.in}$ → Inlet exergy into the system (KW)
ORC → Organic Rankine Cycle
Q_{HRVG} → Heat added to the (HRVG) (KW)
$Q_{cond.}$ → Heat rejected by the condenser (KW)
Q_{solar} → Solar heat input (KW)
T → Temperature (K)
W_{net} → Net power output (KW)
$E_{x,solar}$ → Incoming exergy associated with solar radiation
$\eta_{en,\ heliostat}$ → Energy efficiency of heliostat field

$\eta_{en,\ cr}$ → Energy efficiency of central receiver
η_T → Isentropic efficiency of the turbine
η_P → Isentropic efficiency of the pump
$\eta_{ex,\ heliostat}$ → Exergy efficiency of heliostat
η_{ex}, cr → Exergy efficiency of central receiver.

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