Advances in Computer Science and Information Technology (ACSIT)
p-ISSN: 2393-9907; e-ISSN: 2393-9915; Volume 3, Issue 2; January-March, 2016, pp. 84-89
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http://www.krishisanskriti.org/Publication.html

A Computer Program for Design Optimization and Performance Analysis of Supercritical Organic Rankine Cycle System for Low Grade Exhaust Waste Heat Recovery of I.C Engine

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Abstract—*The power generated inside the cylinder of an IC Engine is not completely transferred to the driving wheels of an automobile. Most of the combustion energy of fuel gets wasted via friction, cooling system and majority through exhaust gas of an I.C Engine. Various bottoming and thermodynamic cycle have been proposed to recover the low grade exhaust waste heat into useful work. Organic rankine cycle system proved to be the best among all the proposed cycle for efficient conversion of low grade waste heat energy. However, the compact design and performance optimization of the ORC system is still a challenge. In present work the Supercritical ORC system is devised as internal heat exchanger (IHE) type. The two supercritical organic dry working fluids are selected namely R245fa and R11 after comparative study carried for the ORC system operation. The system performance through each working fluid is analyzed subsequently. A computer program is developed and the simulation is done in engineering equation solver (EES) for the calculation and analysis of different thermodynamic parameters. The developed computer program also investigates the IHE efficiency, and its overall effectiveness on thermal efficiency of the ORC system. The program also helps in design optimization of ORC system by performance analysis for the selected working fluids and given low temperature heat source.*

Keywords: *I.C Engine, Organic rankine cycle, Supercritical, Internal heat exchanger, working fluid, Computer program, Engineering equation solver*

1. INTRODUCTION

For vehicles with internal combustion engine, approximately 40% of the fuel's chemical energy is wasted as exhaust gas, shown in Figure.1 [1]. If only a part or even a minor amount of this large waste heat could be recovered and converted into electricity, a great sum of heat would be saved and the system efficiency of the vehicle would increase substantially.

Nomenclature

h enthalpy (kJ/kg)
s entropy (kJ/kg K)
$\dot{m}$ mass flow rate (kg/s)
$\dot{I}$ exergy destruction rate (kW)
W power (kW)
T temperature (K)
P pressure (MPa)
t time (s)
$\dot{Q}$ heat absorption rate (kW)
$\dot{V}$ volumetric flow rate (L/s)
L latent heat (kJ/kg)
n exponent of working fluid
R universal gas constant (kJ/(mol K))
A, B, C, D constant coefficients of the vapor pressure correlating equation
ln natural logarithm
D increment in loop
y increment in pressure

Greek letters

π pressure ratio
η efficiency (%)
ρ density (kg/m3)
ε heat exchanger effectiveness (%)

Acronyms

ORC organic rankine cycle
ODP ozone depletion potential
GWP global warming potential
EES engineering equation solver
IHE internal heat exchanger

Subscript

0 reference state
1, 2, 2s, 2a, 3, 4, 4s, 4a state points in cycle
p pump
e evaporator
s single screw expander
c condenser

n	net
th	thermal
tot	total
H	heat source
L	cold source
b	boiling point
cr	critical
m	moderate
r	reduced
vp	vapor pressure
max	maximum
min	minimum

In recent years, there has been active research on exhaust gas waste heat energy recovery for automobiles. Various thermodynamic cycles have been proposed and studied for low-grade waste heat recovery. ORC cycles have demonstrated advantages over conventional steam cycles and are particularly applicable for the recovery of waste heat [2]. The traditional steam cycle does not give a satisfying performance when utilizing low-grade waste heat because of its low thermal efficiency and large volume flows [3]. For low-temperature waste heat recovery in small to medium scale power plants, organic fluids have been proposed because of their several advantages over conventional steam [4]. Working fluid is the main vital component and plays a key role as it is the determining factor of increasing ORC operational efficiency as well as optimizing the size and cost of the cycle operation [5]. Rohit et al. [6] have developed a simulation model using REFPROP and analyzed it in MATLAB for the selection of supercritical organic working fluid of ORC system for exhaust heat recovery. The result shows that R245ca, R11, R123, R245fa are efficient for the ORC system operation and R123, R11and R141b are comparatively better than others. When the safety point and environmental effect is taken into account R245fa, Ethanol and R245ca are found to be the best. The real challenge in designing the ORC system for heat recovery is its compact design and performance optimization. In this paper a computer program is developed and the simulation is done in engineering equation solver (EES) software. The simulation model will calculate the different thermodynamic parameters and analyzes the performance of the ORC system which helps in optimizing its design. After the different comparative study and environmental safety factor taking into account, the two working fluids have been selected namely R245fa and R11 for ORC system operation. The performance of ORC system will be analyzed for each working fluid separately.

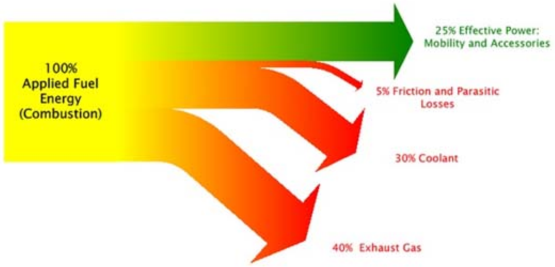


Fig. 1: Typical energy split in gasoline internal combustion engine

2. DESIGN OF ORC SYSTEM AND ITS THERMODYNAMIC ANALYSIS

A typical pictorial representation of ORC for supercritical dry working fluids with internal heat exchanger is shown in Fig. 2. Waste exhaust heat is extracted by the working fluid at the evaporator and heated up to saturated value, then the superheated gas with high enthalpy expanded in the low pressure turbine and the power generated through shaft work is taken through output of generator in form of electricity. After expansion of high enthalpy gas in the turbine the high temperature working fluid enters into the low pressure side of internal heat exchanger (IHE). The working fluid is then condensed and low temperature working fluid is pumped into the evaporator by pump via IHE. Low temperature fluid enters into the high pressure inlet of IHE before conveyed to the evaporator and thus heat flow takes place from low pressure side to high pressure side inside the IHE. Here IHE plays the key role in increasing the efficiency of cycle. Here the supercritical dry fluid does not reaches to the dual-phase stage after expansion and have temperature higher than its condensing temperature. This higher temperature of fluid is being utilized in the preheating of fluid before entering the evaporator and thus requires less power at the heat source and hence enhances the efficiency of cycle. And thus IHE is designed as the counter flow type and installed between the outlet of turbine and inlet of evaporator. In the following model the assumption is made to ignore the pressure and heat loss along the pipe. In the T-s diagram of ORC shown above in Fig. 3, point 1 shows the saturation line of liquid state of working fluid. Point 3 shows the saturation state of vapour line. Work done at pump is from 1-2 and 1-2s is the corresponding state of isentropic process. Outlet of the high pressure side of IHE is denoted by state point 2a whereas process of evaporation take place from 2a-3, 3-4 denotes the process of expansion in turbine, 4-4a represents the process at low pressure side of IHE, 3-4s describes corresponding process of isentropic expansion. The mathematical representation of the process can be stated by the following equations [6]:

Work done by low pressure turbine is calculated as:

$$\dot{W}_s = \dot{m}\,(h_3 - h_4) = \dot{m}\,(h_3 - h_{4s})\,\eta_s \qquad (1)$$

Exergy destruction rate of pump is determined by:

$$\dot{I}_P = T_0\,\dot{m}\,(S_2 - S_1) \qquad (2)$$

Exergy destruction rate of evaporator process is:

$$\dot{I}_S = T_0\,\dot{m}\,(S_4 - S_3) \qquad (3)$$

Net power output is calculation as:

$$\dot{W}_n = \dot{W}_s - \dot{W}_P \qquad (4)$$

The thermal efficiency of the system is:

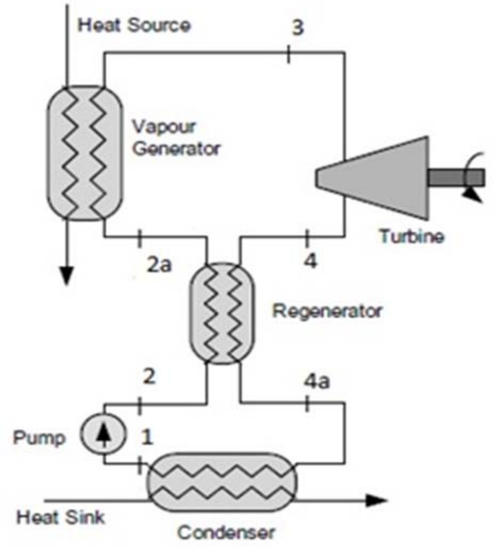


Fig. 2 Typical schematic diagram of ORC for supercritical dry working fluid

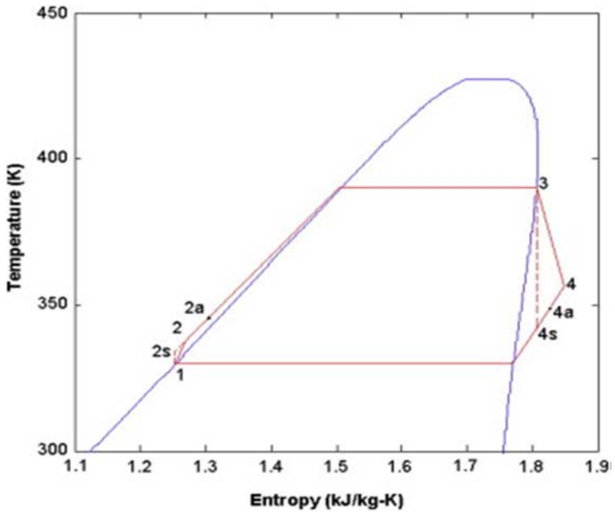


Fig. 3 T-s Plot of ORC

$$\eta_{th} = \frac{\dot{W}_S - \dot{W}_P}{\dot{Q}_e} \qquad (5)$$

The pressure ratio of expander is:

$$\pi = \frac{P_3}{P_4} \qquad (6)$$

Volumetric flow rate at the inlet of expander turbine is determined as:

$$\dot{V}_3 = \frac{\dot{m}}{\rho_3} \qquad (7)$$

The efficiency of IHE is given by:

$$\varepsilon = \frac{T_4 - T_{4a}}{T_4 - T_2} \qquad (8)$$

In the IHE destruction of exergy can be represented as:

$$\dot{I}_{IHE} = T_0\dot{m}[(S_{4a} - S_4) + (S_{2a} - S_2))] \qquad (9)$$

The process at the evaporation is expressed by the equation:

$$\dot{Q}e = \dot{m}(h_3 - h_{2a}) \qquad (10)$$

$$\dot{I}_e = T_0\dot{m}\left[\left(S_3 - S_{2a}\right) - \frac{h_3 - h_{2a}}{T_H}\right] \qquad (11)$$

The process at condensation is represented in the equation:

$$\dot{Q}c = \dot{m}(h_{4a} - h_1) \qquad (12)$$

$$\dot{I}_c = T_0\dot{m}\left[\left(S_1 - S_{4a}\right) - \frac{h_1 - h_{4a}}{T_L}\right] \qquad (13)$$

Total loss in exergy is equated as:

$$\dot{I}_{tot} = T_0\dot{m}\left[-\frac{h_3 - h_{2a}}{T_H} - \frac{h_1 - h_{4a}}{T_L}\right] \qquad (14)$$

3. SIMULATION MODEL AND PERFORMANCE ANALYSIS

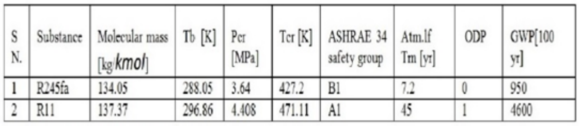
The algorithm of the simulation model developed is shown in Fig. 4. The properties of working fluid as shown in table 1 used for the ORC operation is firstly assigned in the program. Table 2 shows the assumptions made for the design of 10kW ORC system, operating condition of heat source and design parameters fixed, are provided at the input of the computer program [7]. The simulation of developed computer program is done in engineering equation solver (EES) [8]. The overall analysis of ORC system performance, calculation of thermodynamic parameters and result of simulation are shown in table 3. The outcomes for the one of particular supercritical organic dry working fluid R245fa are briefly stated below:

Effect of Pressure Ratio

As shown in Fig. 5 and Fig. 6, the net power output and thermal efficiency is extensively improved across the low pressure expansion turbine. Greater pressure ratio enhances the heat addition and rejection from the cycle thus resulting in greater efficiency and also improves the net power.

Effect of Condenser Temperature

For the selected working fluid efficiency can be enhanced to the maximum value by rising the condenser temperature as shown in Fig. 7. On increasing the condenser temperature the pressure ratio decreases because the net power output is restricted by maximum pressure of the cycle.

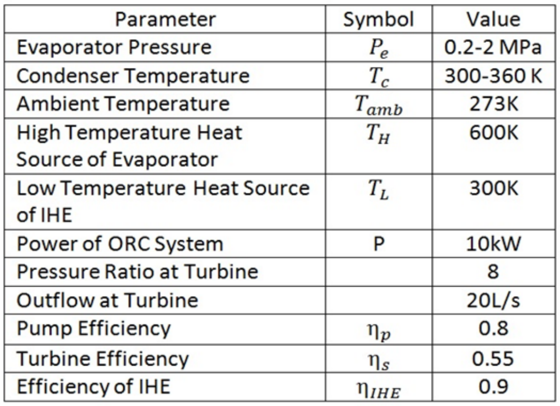


S N.	Substance	Molecular mass [kg/kmol]	Tb [K]	Pcr [MPa]	Tcr [K]	ASHRAE 34 safety group	Atm.lf Tm [yr]	ODP	GWP[100 yr]
1	R245fa	134.05	288.05	3.64	427.2	B1	7.2	0	950
2	R11	137.37	296.86	4.408	471.11	A1	45	1	4600

Table 1 Properties of Selected Supercritical Organic Dry Working Fluid

n.a: non available
T_b : normal boiling point
P_{cr} : critical pressure
T_{cr} : critical temperature

Atm.lf Tm: Atmospheric life time
ODP: ozone depletion potential, relative to R11
GWP: global warming potential, relative to CO_2



Parameter	Symbol	Value
Evaporator Pressure	P_e	0.2-2 MPa
Condenser Temperature	T_c	300-360 K
Ambient Temperature	T_{amb}	273K
High Temperature Heat Source of Evaporator	T_H	600K
Low Temperature Heat Source of IHE	T_L	300K
Power of ORC System	P	10kW
Pressure Ratio at Turbine		8
Outflow at Turbine		20L/s
Pump Efficiency	η_p	0.8
Turbine Efficiency	η_s	0.55
Efficiency of IHE	η_{IHE}	0.9

Table 2. Assumption and Design Parameters of ORC Input to Computer Program

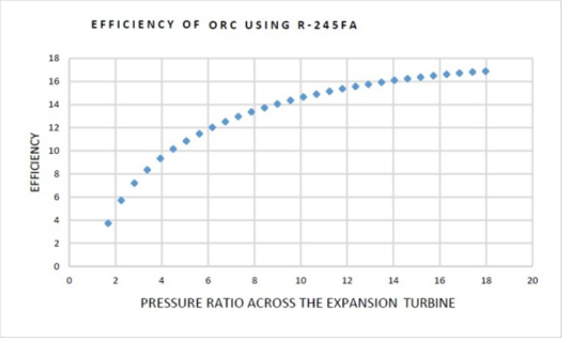


Figure 5. Efficiency of ORC using R245fa

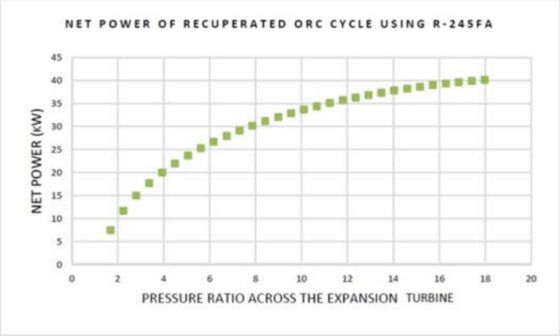


Figure 6. Net Power Output of ORC Using R245fa

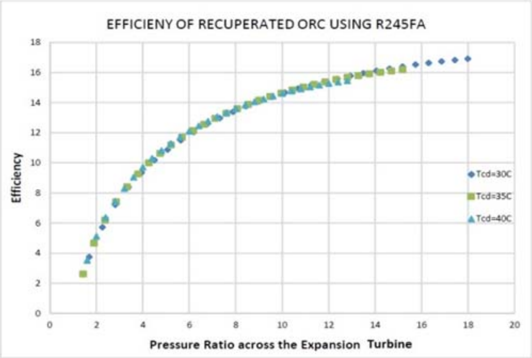


Figure 7. Effect of Condenser Temperature on Efficiency of IHE of ORC

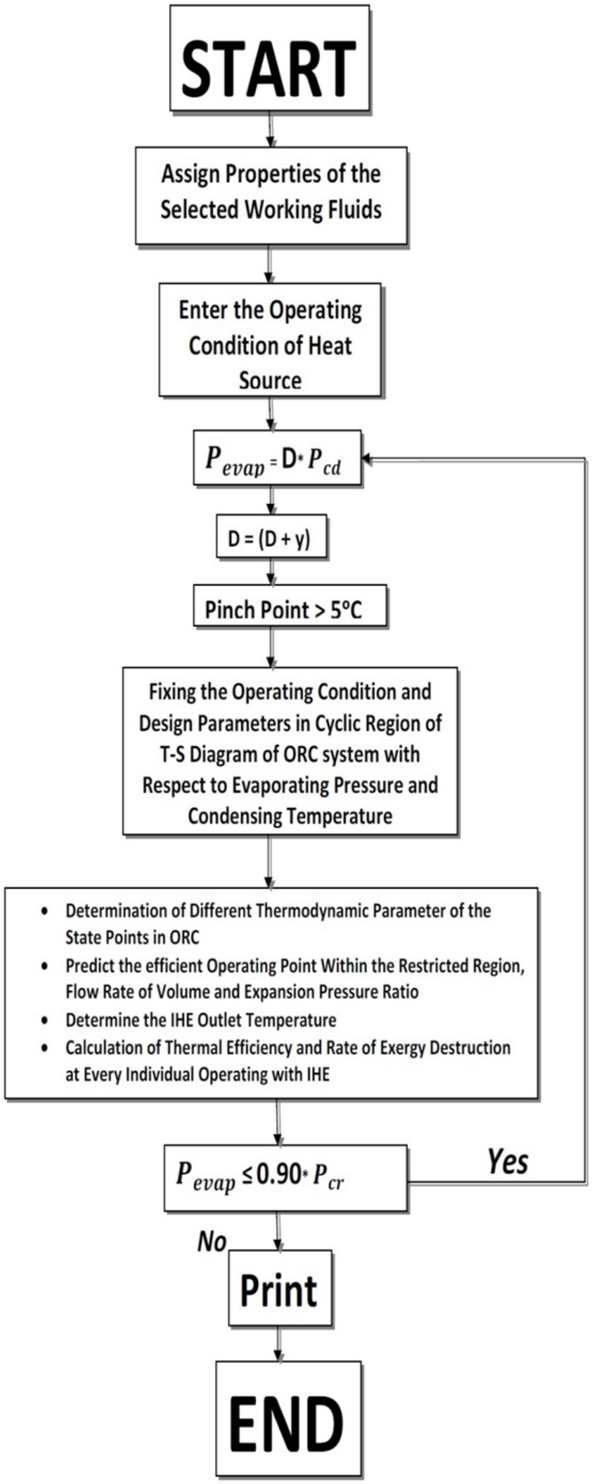


Figure 4. Flow Chart of Computer Program

Table 3. Results of Thermodynamic Properties and Performance Analysis of ORC System of Selected Working Fluid

SN	Substance	$\dot{V}_3$[L/s]	T_e[K]	T_c[K]	P_e[MPa]	P_c[MPa]	$\dot{W}_p$ [kW]	η_{th}	$\dot{I}_{tot}$[kW]	$\dot{m}$[kg/s]	$\dot{I}_c$[kW]	π	$\dot{I}_e$ [kW]	$\dot{Q}_e$ [kW]	$\dot{I}_{IHE}$
1	R245fa	5.740	381.20	304.45	1.4898	0.1869	0.616	9.49	38.764	0.5000	1.281	7.971	29.914	105.18	0.289
2	R11	6.558	400.20	314.14	1.398	0.1760	0.524	10.30	35.121	0.5011	3.379	7.989	24.421	97.201	0.128

4. CONCLUSION

The results obtained in the regions for net power output fixed at 10 kW, were compared. The outcomes indicate that R11 evident minutely greater thermodynamic performances than R245fa. However, R245fa is the most environment-friendly working fluid for engine waste heat-recovery applications. The program analyses IHE performance and compare its effectiveness on the overall thermal efficiency of the ORC. Based on the analysis, the following points are concluded:

- Efficiency of IHE type ORC system is significantly improved by increasing pressure ratios across the expansion turbine.
- The critical temperature of fluid and pinch point based on heat source conditions limits highest attainable efficiency and net power by a given working fluid.
- By using IHE, thermal efficiency and exergetic efficiency of evaporator is improved while the net work done of the cycle is not affected.

5. ACKNOWLEDGEMENTS

This work was supported in part by a grant from the “Department of Mechanical Engineering, National Institute of Technology” Kurukshetra, India.

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