THERMODYNAMIC AND THERMO ECONOMIC ANALYSIS OF ORGANIC RANKINE CYCLE WITH MULTI-OBJECTIVE OPTIMIZATION FOR WORKING FLUID SELECTION WITH LOW- TEMPERATURE WASTE SOURCES IN THE INDIAN INDUSTRY

Bipul Krishna Saha [1], Basab Chakraborty[1]*, Prashant Pundeer[2]
[1]Rajendra Mishra School of Engineering Entrepreneurship,
[2]Department of Mechanical Engineering,
Indian Institute of Technology, Kharagpur, India
*basab@see.iitkgp.ac.in

ABSTRACT

Sustainability and environmental protection have become an important issue in the energy-intensive industry. Driven by this, targets have been set to reduce the dependency on fossil fuels for lowering the carbon dioxide emission and sustainable energy use. In India, low-grade waste heat (less than 400 °C) is an extensive opportunity in increasing the energy efficiency for the industry. The Organic Rankine cycle (ORC) and Regenerative-ORC are considered as promising technologies to recover the low-grade industrial waste heat. In this work, fifty-two potential working fluids were screened for ORC and RORC system. A multi-objective optimization was performed for thermodynamic (exergy efficiency) and thermo-economic performance (levelised energy cost) using Non-dominated Sorting Genetic algorithm (NSGA-II). Optimal compromise solutions were obtained from Pareto frontiers (as obtained from NSGA-II) by assigning normalized weighted score to every point and selecting the minimum value point for each of the fifty-two potential working fluids. Based on the selected optimal solution, the efficiency of the cycle and total plant set-up cost was determined. Following this methodology, results show that Benzene and Toluene performed best among the fifty-two selected working fluids for the pre-selected cycle's thermodynamic parameters. The result also includes the calculated static investment payback period for the fluids.

1. INTRODUCTION

In the past few years, the use of low-grade waste heat from different industrial sources has received growing attention in India. The reason behind, low-grade waste heat has huge potential in decreasing the consumption of fossil fuels [1]. In recent years, ample research has been conducted for the development of technologies that can recover industrial low-grade waste heat and convert to electricity through an organic Rankine cycle (ORC) technology. Among different cycles like Kalina cycle, Goswami cycle, supercritical CO_2 cycle, and trilateral flash cycle, ORC is most commonly used for its component availability and cycle simplicity. A developing country like India has been facing a shortage of fossil fuel that is presently the biggest problem in India's energy sector. Due to the deficiency of fossil fuels and significant environmental pollutions produced by the increasing industrialization, consumption of low-grade waste heat energy has been drawing significant attention from both academia and government organizations. Unlike the traditional Rankine cycle, the ORC system is using organic substances as a working fluid, which can be better adapted for different heat sources temperature.

In India, the estimated electricity consumption increased from 5,01,977 GWh during 2007- 08 to 10,66,268 GWh during 2016-17. The proportion growth in electricity utilization from 2015-16 (10,01,191 GWh) to 2016-17 (10,66,268 GWh) is 6.50%. Of the total utilization of electricity in 2016-17, Indian industry consumed for the largest share (40.01%), followed by domestic (24.32%), agriculture (18.33%) and commercial sectors (9.22%)[2]. The potential for waste heat from the Indian industry is huge. The main energy consuming industry like iron and steel, cement and glass have multiple sources of low-grade waste heat which can be easily converted to the electricity. The waste heat from industry is commonly categorized into low-temperature (< 230 °C), high-temperature (> 650 °C) and medium-temperature (230–650 °C) waste heat. The medium and high temperature waste heat recovery techniques are well established. Though very few technologies are available to extract low-grade waste heat. The conversion efficiency for recovering low-grade waste heat is less than 25% of the total waste heat due to low exergy. Due to the negligible cost of low-grade waste heat, it should not be affected by its low efficiency. The appropriate cost-effective technology is determined through a reasonable payback period, investment and profit. ORC technology is accepted as a promising technology for low-grade waste heat recovery and it is broadly accepted to transform low-grade heat to power.

Based on the previous literature review, there are plenty of literature available on the fluid selection, but there is a lack of comprehensive modeling work from the economic aspects of the ORC system and operating performance with different low-grade waste heat sources. However, there is a particular relationship between the cost of investment and working fluid selection while recovering the low- grade waste heat by the ORC system. There is a direct relation between the physical properties of working fluid and the capital cost of the primary equipment like turbine, evaporator, condenser, and pump. Hence, this should be accepted as an evaluation factor for low-grade waste heat recovery and working fluid selection. Earlier work was expressively focused on the selection of the working fluids for the ORC system. Hung (2001) indicated that the working fluids R113 and R123 showed a better performance for recovering low-grade waste heat[3]. Pang et al (2017) compared an experimental ORC system operating with R245fa and R123 as working fluids for the waste heat source temperature set at 110°C [4]. They changed the mass flow rate in a system and observed the maximum power output. R245fa generated the maximum net power output with an efficiency of 3.9% and in another case, the waste heat temperature was fixed at 120°C, wherein the system achieved a maximum efficiency of 4.4%. Shao et al (2017) developed a new micro radial inflow turbine for an ORC system using working fluid R123 [5]. They investigated the turbine’s operational characteristics and performance. The maximum speed of the radial inflow turbine was reported around 53,564 rpm for the turbine output power of 3.386 kW and electric power of 1.884 kW. However, the above-mentioned works only focused on the thermodynamic evaluation instead of the economic viability. Therefore, ORC system required a novel evaluation criterion, which can be integrated with the economic and thermodynamic performances of different working fluids. In this work, the static investment payback period (SIPP), thermodynamic performance (exergy efficiency, EXE) and economic performance (levelised energy cost, LEC) were introduced. This key index helps to find the optimal working fluid based on their evaporation temperature. The NSGA-II optimization technique was used for calculating the effect of EXE and LEC.

The flow of the work is organized as follows. First, the work methodology is defined and 52 working fluids are considered for this case study. Based on their thermodynamic performances, five potential working fluids are selected for the ORC and RORC system. In the succeeding section, NSGA-II is used for obtaining a series of Pareto optimal solutions of each working fluid. Therefore, the optimal solution of EXE and LEC is determined. This is followed by the introduction of SIPP for evaluating the effectiveness of investment by simultaneously considering the optimal EXE and LEC to identify the most cost-effective working fluid for low-grade waste heat recovery for Indian industry.

2. METHODOLOGY

2.1 Process simulator

The ORC system utilizes of low-grade energy sources. This system uses high molecular mass organic fluid for low- grade waste heat recovery system [6]. As shown in Fig. 1, ORC system primarily consist of four different processes: Process 1–2 (expansion in Turbo-expander), Process 2–3 (heat rejection in Condenser), Process 3–4 (pumping process) and Process 4–1 (constant-pressure heat addition in Evaporator). The RORC system has five different processes: Process 1–2 (expansion process), Process 2–2* (regenerator), Process 3–4 (pumping process), Process 4–4* (constant-pressure heat addition) and Process 4*–1 (heat addition). Energy balance equations are listed in Table 1. The simulation was programmed using Matlab programming coupled with Coolprop library that returns characteristic fluid properties like entropy, enthalpy etc.

2.2 Thermodynamic analysis

The Eq. (1) shows the external irreversibility occurring inside the ORC and RORC system [7]:

$$\dot{I} = \dot{m}T_0[\sum s_{outlet} - \sum s_{inlet} + \sum_k \frac{q_k}{T_k}] \tag{1}$$

Where, q_k is the heat transferred from all heat source to the working fluid and T_k refers to the temperature of all heat sources. For steady-state, steady flow system, assuming there are only one inlet and one outlet for each equipment, the Eq. (1) reduces to:

$$\dot{I} = \dot{m}T_0[(S_{outlet} - S_{inlet}) + \frac{q_k}{T_k}] \tag{2}$$

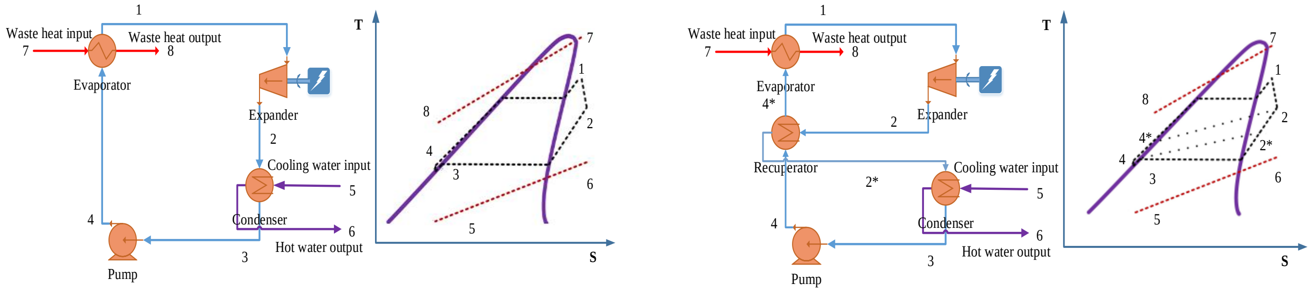

Figure 1: A layout of the ORC and RORC system. The numbers in this diagram indicate the fluid flow direction.

Table 1. Energy balance equation for ORC and RORC system.

Process	ORC and RORC cycle component	Energy balance equations (ORC)	Equation Number	Energy balance equations (RORC)	Equation Number
Process, 4-1	Evaporator	$\dot{Q}_E = \dot{m}(h_1 - h_4)$	(3)	$\dot{Q}_E = \dot{m}(h_1 - h_4)$	(7)
Process, 1-2	Turbo expander	$\dot{W}_T = \dot{m}(h_1 - h_2)\eta_{tur}\eta_{mech}$	(4)	$\dot{W}_T = \dot{m}(h_1 - h_2)\eta_{tur}\eta_{mech}$	(8)
Process, 2-3	Condenser	$\dot{Q}_C = \dot{m}(h_2 - h_3)$	(5)	$\dot{Q}_C = \dot{m}(h_4 - h_3)$	(9)
Process, 3-4	Pump	$\dot{W}_p = \dot{m}(h_3 - h_4)/\eta_{pum}$	(6)	$\dot{W}_p = m(h_3 - h_4)/\eta_{pum}$	(10)
Process, (4-4* & 2-2*),	Regenerator (RORC)			$(h_2 - h_{2^*}) = -(h_4 - h_{4^*})$	(11)

The 1st law efficiency is stated as:

$$\eta_{Thermal} = (\frac{W_T - W_P}{Q_E})*100 \tag{12}$$

Exergy of a stream is calculated using the following equation:

$$Ex_{mass} = m\left[(h - h_0) - T_0(s - s_0)\right] \tag{13}$$

The exergy efficiency (EXE) of the ORC and RORC cycle is defined as

$$\eta_{ex} = (\frac{W_{net}}{\dot{m}[(h_{WH-in} - h_0) - T_0(s_{WH-in} - s_0)]})*100 \tag{14}$$

2.3 Economic analysis

An economic model (involving capital investment, operations and maintenance cost) for ORC and RORC system construction in an industrial plant is discussed in this section. The equipment module costing technique is adopted from Ref. [8] to estimate the capital cost of component materials that are assumed to be: Carbon steel and copper for shell and tubes of evaporator, condenser and regenerator; Carbon steel for centrifugal pump and turbine.

The bare module cost of primary equipment is given as follows:

$$C_{bm,X} = C_{PC,X}.F_{m,X} \tag{15}$$

where $F_{m,X}$ denotes the bare module cost factor of equipment materials as listed in Table 2. $C_{PC,X}$ denotes the purchase equipment cost (PEC) and is expressed as follows:

$$\log_{10} C_{PC,X} = K_{1,X} + K_{2,X}\log_{10} Y + K_{3,X}(\log_{10} Y)^2 \tag{16}$$

where X= Type of equipment, Y= Heat transfer area of the evaporator, Condenser and regenerator or power capacity of turbine and pump. In Table 2, the value cost coefficients $K_{1,X}$, $K_{2,X}$ and $K_{3,X}$ are given. Thus, the total summation of capital cost is as follows:

$$C_{total} = \sum C_{bm,X} \tag{17}$$

The Chemical Engineering Plant Cost Index (I_{CEPC}) is used to account for issues caused by inflation [9]. The I_{CEPC} values as obtained from equipment manufacturers for the year 2001 and 2017 are 397 and 632.5 respectively. The final capital cost of all the equipment is obtained as:

$$C_{total,2017} = \frac{C_{total}.I_{CEPC,2017}}{I_{CEPC,2001}} \tag{18}$$

Table 2. The capital cost estimation model with the coefficient.

X	Y	$K_{1.X}$	$K_{2.X}$	$K_{3.X}$	$F_{m.X}$
Evaporator	$A_{eva}(m)^2$	4.3247	-0.3030	0.1634	2.9
Condenser	$A_{con}(m)^2$	4.3247	-0.3030	0.1634	2.9
Turbine	$W_{Turbine}(kW)$	2.7052	1.4398	-0.1776	3.5
Pump	$W_{pump}(kW)$	3.3892	0.0536	0.1538	2.8
Regenerator	$A_{reg}(m)^2$	4.3247	-0.3030	0.1634	2.9

The Capital Recovery Factor (CRF) is calculated as:

$$\text{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{19}$$

where i = interest rate (5%) and n = Lifetime (25 years) of the entire ORC and RORC system. The Levelised Energy Cost (LEC) is obtained as:

$$\text{LEC} = \frac{CRF.C_{total,2017} + C_{om}}{T_{om}.W_{net}} \tag{20}$$

where C_{om} = Cost of operation and maintenance that is taken as 1.5% of $C_{total,2017}$, T_{om} = Operation hours in one year, taken to be 8000 h. The Static investment payback period (SIPP) is defined as:

$$\text{SIPP} = \frac{C_{total,2017} + C_{om}}{D_{hr}} \tag{21}$$

where D_{hr} = income per hour by recovering the waste heat for power generation and stated as:

$$D_{hr} = \eta_{System}.m(h_{WH-in} - h_{WH-out}).C_{elec} \tag{22}$$

In the above equation, C_{elec} denotes the price of electricity taken to be 0.0688 USD/kWh that refers to the industrial pricing as published by U.S. Energy Information Administration for the year 2017.

2.4 Multi-objective optimization

In this work, the non-dominated sorting genetic algorithm (NSGA-II that was proposed by Prof. Deb K in 2001) has been applied for multi-objective optimization of thermodynamic performance and economic analyses of the selected working fluids. NSGA-II have been applied as: (1) A fast non-dominating sorting algorithm to simplify the computation while preserving the elite members in the parent population. (2) Crowding distance based comparison to ensure evenly distributed solution points on Pareto frontier. The general form of the objective function is expressed as follows:

$$\begin{Bmatrix} V-\min f(x)=\left[f_1(x), f_2(x),......., f_n(x)\right]^T \\ \text{s.t.} \qquad x\in X \\ \qquad X\subseteq R \end{Bmatrix} \tag{23}$$

where x represents the decision variables vector, R represents the constraints, and V-min denotes to obtaining the minimum of the multi-objective function vector $f(x)$. If the solution $x_1 \in X$ is more optimal than all the other solutions in X, then, x_1 is reflected as the Pareto optimal solution.
In the study, the minimum LEC and maximum EXE are obtained by the objective function as follows:

$$\psi=\begin{Bmatrix} \text{minimum LEC }(\mathrm{T_{Eva}},\Delta \mathrm{T_{Superheat}},\dot{m}_{wf},\mathrm{T_{HS\ Out}},\mathrm{T_{CS\ Out}}) \\ \text{maximum EXE}(\mathrm{T_{Eva}},\Delta \mathrm{T_{Superheat}},\dot{m}_{wf},\mathrm{T_{HS\ Out}},\mathrm{T_{CS\ Out}}) \end{Bmatrix} \tag{24}$$

Therefore, five different decision-making variables are selected (T_{Eva}) denotes evaporation temperature, ($\Delta T_{\text{Superheat}}$) superheating degree, ($\dot{m}_{wf}$) working fluid mass flow rate, (T_{HS_Out}) heating source outlet temperature, and (T_{CS_Out}) cooling source outlet temperature. The pinch point temperature differences at the inlet of evaporator and condenser are both taken to be 4°C. In order to determine the optimal compromise solutions on Pareto frontier, a normalized weighted score is evaluated for every point and selection is weighted on preferably lower LEC values.

2.5 Analysis and Calculation model

Peng – Robinson equation was used for the thermodynamics property calculation of working fluid [11]. In this study, all expander and pumps are working with 75% efficiency. Table 3 shows the parameters used in preparing the simulation model. The simulation was performed for the industrial average waste heat source at 328°C. In the simulation, we took care that only vapor superheated stream should enter in the expander and liquid stream should enter in the pump.

Table 3. The parameter used in making the simulation model.

Parameter	Value	Parameter	Value
Hot fluid	Dry air	Property package	Peng – Robinson
Cold fluid	Water	Condenser pressure drop	25 kPa
Cold source inlet temperature	15 °C	Pump isentropic efficiency	75%
Cold source outlet temperature	Dependent	Exhaust gas mass flow rate	10 kg/s
Exhaust gas inlet pressure	150 kPa	Exhaust gas inlet temperature	328ºC
The average temperature in Kharagpur	26.7 °C	Heat exchanger pressure drop	25 kPa

3. RESULT AND DISCUSSION

3.1 The net power output and exergy efficiency

The objective of this work is to parametrically analyze, compare and optimize the power output and exergy efficiency of the system. It was observed that the power output depends on the critical pressure of the working fluid. As a result, the power output was better for fluids with high critical pressure. It was found that optimal results were obtained for the working fluids with critical temperature slightly lower than the input waste gas temperature. It was also observed that the exergy efficiency of regenerative ORC was generally found to be higher than that of simple ORC system. Fifty-two potential working fluids were studied here, which were categorized into four different groups: hydrocarbon (HC), hydrofluorocarbon (HFC), chlorofluorocarbon (CFC) and others (alcohols, siloxanes, etc.). Fig. 2 and 3 display the results for best cycle configuration and optimum exergy efficiency for the given 52 working fluids. It is observed in the figures that the alcoholic fluids methanol and ethanol provide maximum power output (419.97 kW and 412.43 kW) and exergy efficiency (27.03 and 26.55) in both systems. Alcohols are wet fluids and they would need superheating. So, alcohol is generally avoided in the ORC system. As the CFCs will be phased out by 2030 in the developing countries, they are not suitable for the case study. HCs are the best choice for developing countries like India. In ORC and RORC, Benzene and Toluene are found to be the most suitable working fluid respectively with the corresponding values of maximum power output and exergy efficiency as (397.98 kW, 25.62) and (444.59 kW, 28.62) respectively. These findings are obtained using Eqn(s) (4), (8) and (14).

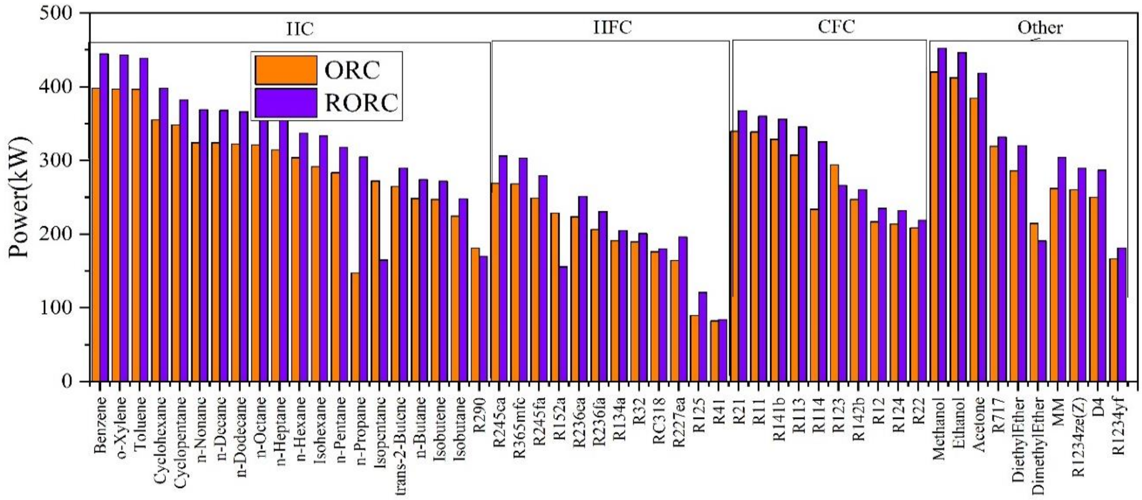

Figure 2: Comparison of ORC and RORC with different working fluids of optimal net power output.

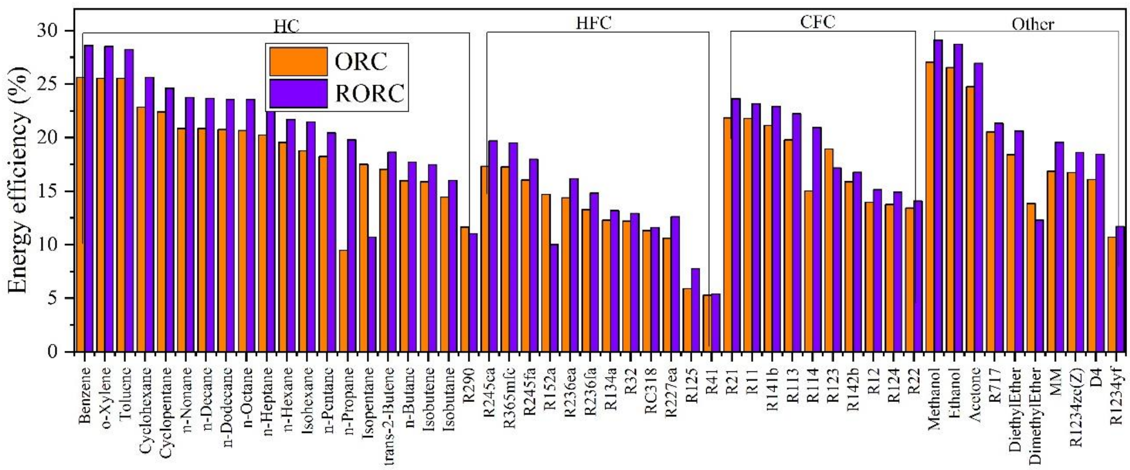

Figure 3: Comparison of ORC and RORC with different working fluids of optimal exergy efficiency.

3.2 Optimisation result and optimal compromise solution

Using NSGA-II, the Pareto frontiers were obtained for LEC and EXE optimization results among 52 working fluids as shown in Fig. 4. For each working fluid, 25 optimal solutions were considered simultaneously with an optimal balance between the maximum EXE and minimum LEC for the compromise solution. Best two or three fluids of each group have been displayed in Fig.4 for both the ORC and RORC system. The optimal compromise solutions was selected using normalized weighted score and have been compared for the best five working fluids from each group in Fig. 5. As shown in the figure, among the 20 optimal compromise solutions, the best two fluids for the ORC system are Benzene and Xylene whose EXE and LEC values are (29.97% and 29.88%) and (0.071 and 0.076) respectively. Similarly, Toluene and Xylene are the best working fluids for the RORC system where the corresponding EXE and LEC values are (33.32% and 33.21%) and (0.172 and 0.444). These findings are obtained from Eqn.(s) (14) and (20).

3.3 Economic investment and payback period analysis

In the SIPP calculation, Benzene and Toluene are found to show the highest power generation efficiency and a moderate total cost respectively with the SIPP values of 14360.9 h and 24039.46 h among the 52 candidates. With the shortest SIPP among the 52 working fluids, Benzene and Toluene appears as the most cost-effective working fluid. In comparison with the RORC, the ORC system consumes higher duration to cover the primary invested value. Here, the SIPP acts as a hypothetical index to analysis the performance ranking of the 52 working fluids in an ideal and identical situation with corresponding economic and thermodynamic models. These findings are obtained from Eqn. (21).

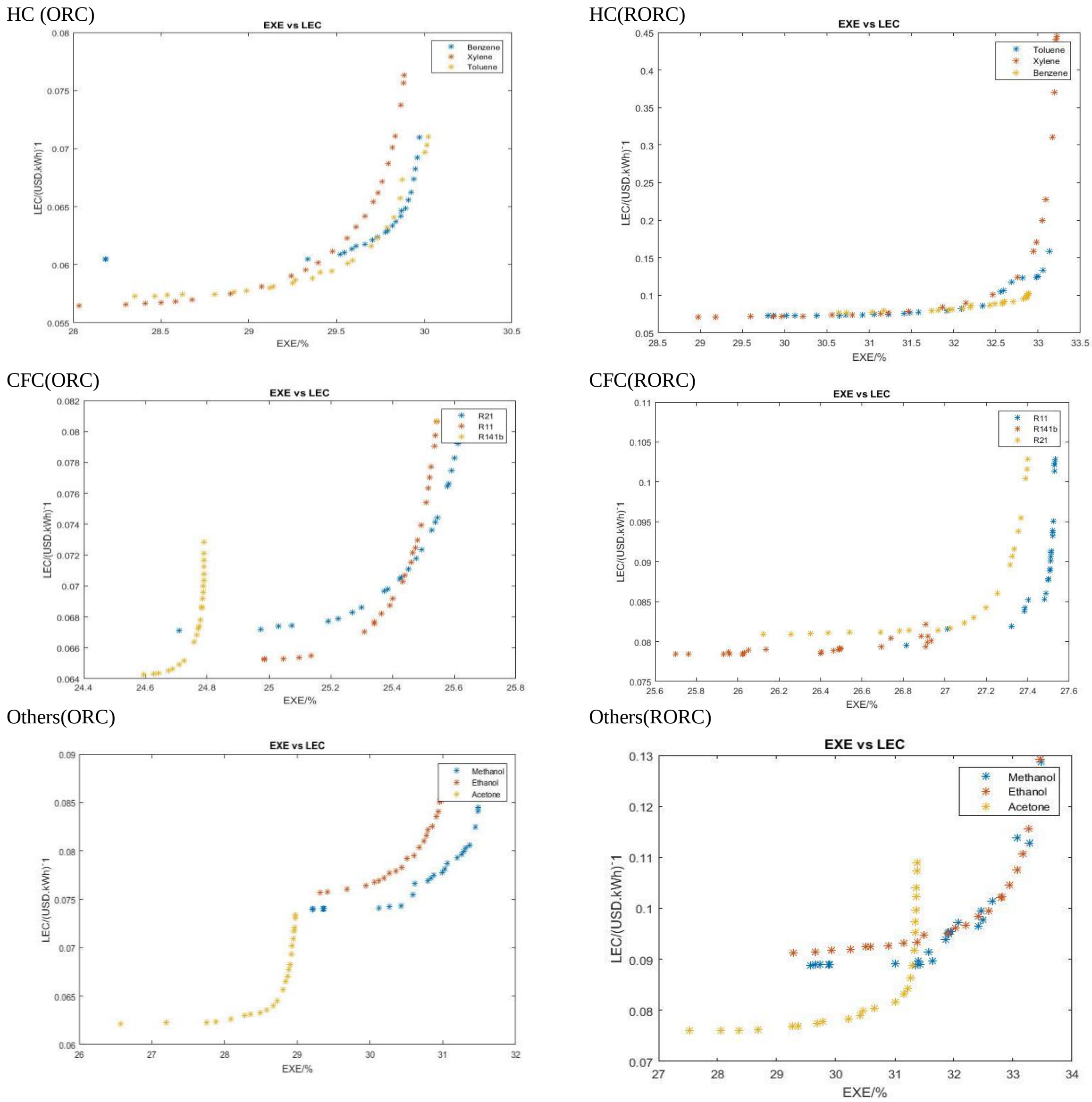

Figure 4: Optimal compromise solution on the Pareto frontiers of top performances fluids in all section.

4. CONCLUSION

In this work, 52 working fluids have been studied for the ORC and RORC system with a 328°C waste-heat in the Indian industry by setting an evaluation criterion for the most optimal solution. Considering EXE and LEC as the objective performances, the Pareto frontiers was obtained using NSGA-II to determine the optimal compromise solutions. With respect to net power output and exergy efficiency, the RORC appears to be the best system for the low-grade waste-heat recovery in Indian industry. Out of four different categories as-hydrocarbon (HC), hydrofluorocarbon (HFC), chlorofluorocarbon (CFC) and others (alcohol) working fluid it is observed that Benzene and Toluene are found to be the most suitable working fluid with the corresponding values of maximum power output and exergy efficiency as (397.98 kW, 25.62) and (444.59 kW, 28.62) respectively. The optimal compromise solutions are given as ordered pairs (EXE, LEC) for best 20 working fluids. Toluene and Xylene are the best working fluids for the RORC system, where the corresponding EXE and LEC values are (33.32% and 33.21%) and (0.172 and 0.444) respectively. The most cost-effective working fluid has been determined based on a reasonable evaluation criterion of the SIPP. Benzene and Toluene are found to be best working fluid based on SIPP for the ORC and RORC systems, respectively with the SIPP values of 14360.9 h and 24039.46 h among the 52 candidates.

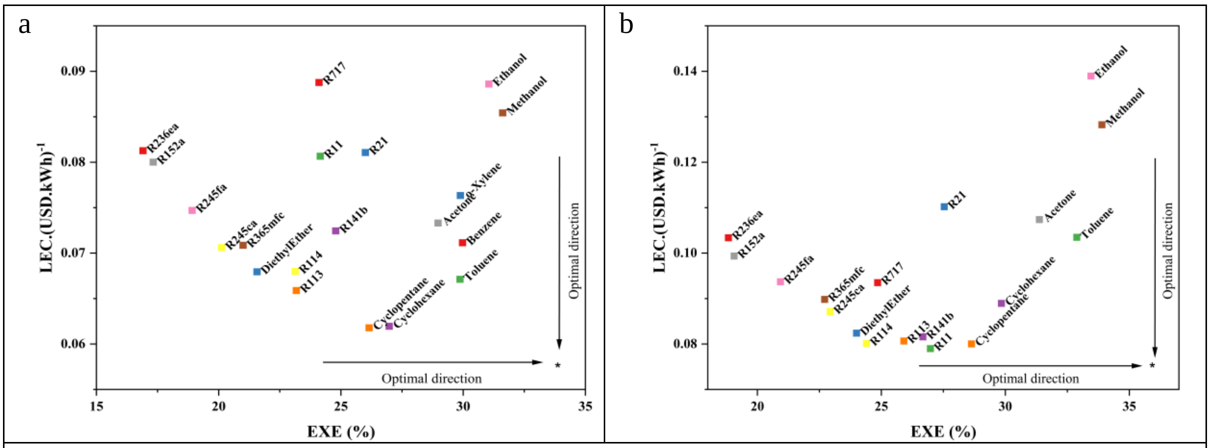

Figure 5: Comparison of ORC and RORC with different working fluids of optimal compromise solutions. (a) ORC and (b) RORC

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