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A review on efficiency improvement methods in organic Rankine cycle system: an exergy approach

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ABSTRACT

Exergy, one of the handed-down energy conservation techniques, which can obtain from thermodynamic laws (first and second), will disclose the work presented within the system, the amount of irreversibility as well as what are the possible ways to reduce inefficiencies in the system. This discourse mainly highlighted various techniques and possible methods for efficiency improvement in the organic Rankine cycle (ORC). That means mainly concentrated on following key parameters like the selection of working fluid, suitable expander, the different heat sources of an evaporator, and modifications in heat exchanger based on the application of ORC system through an exergy approach for better performance, decrease energy losses, and destruction rate. This review can help to pontificate for better-summarized results that were done before and suggest some ideas for how to select an optimized parameter for better efficiency and to decrease the destruction rate in the ORC system.

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NOMENCLATURE

Nomenclature		Subscript	
ORC	Organic Rankine cycle	d	Destruction
FLT	The first law of thermodynamics	Cr	critical
SLT	The second law of thermodynamics	h_i	Hot stream inlet
I	Irreversibility	h_o	Hot stream outlet
s	Entropy	c_i	Cold stream inlet
T	Temperature in K	c_o	Cold steam outlet
m	Mass in kg/mol	out	out
Ex	Physical Exergy	0	Reference state
e	Specific exergy	Eva	Evaporator
h	Enthalpy	ex	Expander
W	Work done	Cond	Condenser

1. INTRODUCTION

From past decades people are facing a lot of issues to successful utilization of energy and also to recover energy from waste heat. Primarily vapor Rankine cycle with water as a working fluid is a way to convert a large amount of thermal energy into power [1]–[7]. Water has phenomenal properties (thermal/chemical), is easy to pump from one place to another also has some disadvantages like erosion of blades and it is not suitable for low-temperature applications [3], [6], [8].

To fill this gap, the need for a conventional or organic working fluid that has a better property at low-temperature ranges to recover lower heat into work. This ORC was established to produce work output from low-grade waste heat. ORC system can use for power generation in a wide range of applications likely power plants, geothermal plants, solar applications, and waste heat in industries as shown in Figure 1 [9], [10]. Heat driven from geothermal ORC has performed with low-pressure vapor generator will give 38.11% exergy efficiency and 29.98% for high-pressure generator [11]–[14]. Solar ORC coupled with internal feed liquid heater and internal heat exchanger will give better exergy results and also ORC combined with trilateral flash cycle increases up to 15.94% of exergy efficiency [15]–[18]. Introducing an internal heat exchanger, effective usage of turbine bleeding/regeneration in basic ORC helps to get higher efficiency of nearly 38.82% [19]–[21]. The researchers provided a simplified way to select an optimum operating conditions ORC and produced 264.14 kW power at 1300 °C temperature heat source [22]–[24]. New modified ORC suggested that energy, exergy, environmental aspects are considered for better performance [25]–[30] while recovering heat from gas turbine exhaust, the exergy destruction rate of ORC depends on heat source temperature [31] that means if it is increased, the rate of exergy destruction also increases. Energy recovers from medium ORC employed with liquefied natural gas (LNG); transcritical CO_2 cycle raised the exergetic efficiency from 12.3 to 13.08% [5]. Work recovery from LNG cold energy is possible with ORC by using efficient working fluid R22 [32]. The main aim of this review paper is to notify various exergy-based efficiency improvement methods in the ORC system. The paper contains three chapters: first to select the ORC system and its working also equation employed with exergy presented. The second chapter talks about the role of various equipment in ORC, also how to select an optimized one based on the literature. The third chapter with some conclusions and suggestions in calculating exergy destruction and efficiency improvement methods.

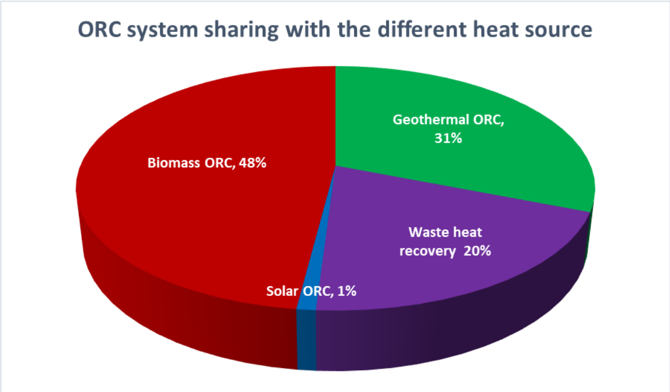

Figure 1. ORC system sharing with the different heat source

2. METHODOLOGY STRUCTURE OF ORGANIC RANKINE CYCLE

The most efficient way to produce power from waste heat (lower grade) is the ORC, it has the structure of a condenser, pump, evaporator, expansion device as shown in Figure 2. An effective working fluid will play a major role to generate power by observing heat from the heat source and converting it into work with the help of an expander.

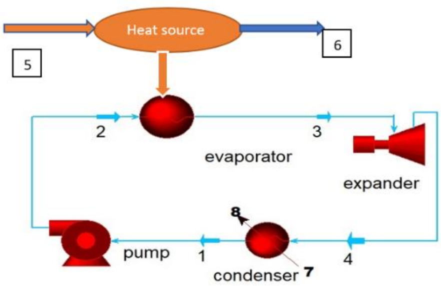

Figure 2. Schematic line diagram of an ORC system

Processes are done on this cycle: i) Isentropic pumping process to raise the pressure of working fluid; ii) Isobaric evaporation to raise the temperature of the fluid (phase change) at constant pressure with the help heat source, fluid will get more potentiality; iii) Isentropic expansion to produce work output with the help of turbine or other expanders, at this stage fluid will lose its internal energy; and iv) Isobaric condensation to get back its original phase for pumping purpose.

3. ENERGY AND EXERGY ANALYSIS

From FLT in the steady-state condition, the mass and energy pass through a system is always constant, also potential and kinetic energy are neglected in the control volume. Mathematically FLT: i) equation for mass balance as (1); and ii) energy balance in the control system as (2) and (3).

$$\sum m_{in} = \sum m_{out} \tag{1}$$

$$e_{in} = e_{out} \tag{2}$$

$$Q + W = \sum m_{out} h_{out} - \sum m_{in} h_{in} \tag{3}$$

SLT always says there is an entropy generation called irreversibility in any process, which means total energy at the inlet doesn't match with the outlet. Based on this there is new technique exergy (availability of work) was introduced to reduce irreversibility within the system. The maximum possible work generated from a system to its reference (temperature 298 K, pressure 1 bar) or atmosphere condition. In ORC there are no chemical changes along with all processes. So chemical exergy is considered as zero. Figure 3 shows the physical exergy module.

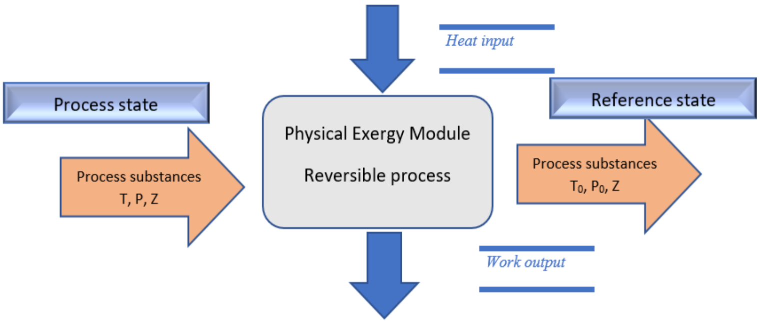

Figure 3. Definition of physical exergy [33]

Mathematical expression: i) Exergy can express as (4); ii) Specific exergy as (5) and (6); and iii) Steady-state condition as (7).

$$E\dot{x} = m_{ex} \tag{4}$$

$$e_x = h - h_0 - T_0(s - s_0) \tag{5}$$

$$\sum E\dot{x}_{in} - \sum E_{out} - E\dot{x}_d = \Delta Ex \tag{6}$$

$$Q + W = \sum Ex_{out} - \sum E\dot{x}_{in} + I \tag{7}$$

Where, Q is total heat input, W is work output from the system, and I is irreversibility in the system rate. Heat and exergy equations for an evaporator and condenser:

$$Q_{Eva} = mh(h_5 - h_6) = mf\,(h_3 - h_2) \tag{8}$$

$$I_{Eva} = (E_5 - E_6) - (E_3 - E_2) \tag{9}$$

$$Q_{cond} = mc(h_8 - h_7) = mf(h_4 - h_1) \tag{10}$$

$$Icond = (E_7 - E_8) - (E_1 - E_4) \tag{11}$$

where, I represent irreversibility in the respective process. The exergetic efficiency of condenser and evaporator can be written as (12) and (13); for expander as (14), (15), and (16); for the pump as (17), (18), and (19).

$$\eta_{Eva} = 1 - (I_{Eva} /(E_5 - E_6)) \quad (12)$$

$$\eta_{cond} = 1 - (I_{cond} /(E_4 - E_1)) \quad (13)$$

$$W_{ex} = m_f (h_3 - h_4) \quad (14)$$

$$I_{ex} = E_3 - (E_4 + W_{ex}) \quad (15)$$

$$\eta_{ex} = W_{ex}/(E_3 - E_4) \quad (16)$$

$$W_{pump} = m_f (h_2 - h_1) \quad (17)$$

$$I_{pump} = (E_1 + W_{pump}) - E2 \quad (18)$$

$$\eta_{pump} = (E_2 - E_1) /W_{pump} \quad (19)$$

Total work done by ORC system given as (20), thermal and exergy efficiency of ORC system as (21) and (22).

$$W_{net} = W_{ex} - W_{pump} \quad (20)$$

$$\eta_{th} = W_{net} / Q_{Eva} \quad (21)$$

$$\eta_{Ex} = W_{net}/ E_{in} \quad (22)$$

Where, E_{in} refers the total exergy input to the system by heat source can be written as (23).

$$E_{in} = (E_5 - E_6) = m_h(h_5 - h_6) - T_0(s_5 - s_6) \quad (23)$$

4. MODIFICATIONS IN THE ORC SYSTEM

4.1. Role of pumps in ORC

Generally, raising the pressure of working fluid in ORC system pumps are plays a vital role without a temperature change. Fluid pumps are devices with a negligible exergy destruction rate in ORC [14]. Some researchers have developed a pumpless ORC system to recover lower grade waste heat. investigated an ORC, control valves are replaced instead of a fluid pump, also two heat exchangers for a pre-expansion process, a generator, and an expender aligned coaxially for the process of power generation [34]. Power output is mainly depending on the inlet temperature of the evaporator, if it increases correspondingly evaporation pressure will increase and it leads to higher power output. Exergy calculated to gravity-type pumpless ORC system with three heat exchangers with a heat source at 90 °C, power fluctuation is mainly due to liquid working fluid has more enthalpy at condensers compared to internal energy inside evaporator [35]. For pumpless ORC have to follow some boundary conditions: heat leakage from heat exchangers to surrounding should be neglected and the rate of flow of hot water insides the evaporator constant through the cycle.

4.2. Heat exchanger/evaporator

Heat exchangers are energy-efficient devices because it delivers a large amount of heat output compared with electrical input [36]. It has a wide range of applications such as water heating, drying, desalination, and space heating [37]. Integration heat exchangers performance is possible with renewable resources like solar and geothermal [38]. During an exchange of heat between hot to cold fluids, according to SLT, there is lots of chance to generate irreversibility, to overcome that an exergetic criterion was proposed by optimum parameter and heat transfer units [39]. The efficiency of an optimum layout of a phase change evaporator for stationary application with DWF (based on exergy) increases from 67 to 72.3% [40]–[44]. Prediction of exergy destruction (around 1.36 kW) for solar-based–direct expansion heat exchangers was done at Calicut (India) climate conditions with R22 as working fluid [45]–[47]. Geometrical changes in the heat exchanger can improve exergy efficiency, which means using a different types of heat exchangers (shell and tube, double tube), using nanofluids to exchange heat [33], [48], [49]. Maddah *et al*. [50] were experimented to prepare modified twisted type tapes for heat exchangers by using turbulent nanofluid (SiO_2-water) [51].

4.3. The heat source for the evaporator

A clear observation is done that the source of heat temperature was varied between 80 to 330 °C, according to temperature the power output from ORC also increases as [22]. The exhaust of the gas turbine has contained a heavier amount of heat, and it was considered as a source of Waste heat to convert as work/power output, this temperature ranged from 375 to 600 °C. The max exergy was found at 600 °C because the mass of the fluid is a larger amount than the required heat load [31]. The maximum generated power is 3.85 MW through the SCO_2-ORC system with a heat source of coal-fired flue gases 200 to 300 °C temperature range at evaporator [32]. By decreasing mass flow rate through a solar pond, the temperature average (47 to 59.78 °C) at the exit of the pond increased for effective utilization as a heat source and got 15.94% of exergetic efficiency [18], [52]. Various heat sources namely geothermal (100-130 °C), solar low heat (100-225 °C), engine exhaust waste heat (150-300 °C), high-temperature energy from solar(250-350 °C) was carried on ORC and calculated 28% of expander efficiency at higher temperatures [53], [54]. An investigation with two heat sources, lubricant oil at 120 °C and engine exhaust at 350 °C was done on the ORC system for effective results [40], [55]. Three kinds of heat sources: saturated steam, hot water, combinations of both in an ORC system with different pinch ranges was performed at a constant condenser temperature of 40 °C and it is found that combined heat source will give lower exergy destruction and higher efficiency [5], [56], [57]. The 63% of exergy efficiency recorded through ORC, which has a heat source of hot water 150-300 °C and delivers 90 °C [58], [59]. Heat recovered from smelting furnace exhaust gas; ORC worked at 38% of efficiency [60]–[62].

4.4. Expansion devices

In ORC system expansion devices are the key equipment, these are helpful to produce electrical energy by using the kinetic energy of fluids. Here can classify as dynamic devices (turbines), positive-displacement devices, and ejectors as shown in Figure 4. In the turbine, the pressurized working fluid is converted as velocity energy (kinetic energy) through a nozzle. After that, it was transferred to turbine blades to convert into electric power with the help of generator equipment [63]. Axial, radial type turbines are available for this operation, generally axial have more than 7 capacities compared with radial turbines. A method was proposed for radial type turbine for mobile ORC [37] with pentane and R245fa as working fluid and found a 7.3% of efficiency difference [64]. Using R123 working fluid in an axial turbine with a thermal efficiency of 10.5% and clinch 6.3 kW power output and 88% of isentropic efficiency [65]. Working of scroll expander follows a similar principle of compressors, for orc the basic way is a better design to improve efficiency. Few researchers explored a general tool for how to design a scroll expander for ORC [66] and achieved 40% of isentropic efficiency. An investigation was done on the performance of ORC through 88 ml/r displacements of scroll expander and its influences on isentropic efficiency decrement from 0.72 to 0.41% [67], [68]. It can be observed that R123, R245fa working fluids have a high frequency to get a power maximum of 3.75 kW [69], [70]. Similarly, a simulated model of screw expander by considering leakage, heat transfer, and friction loss was developed [71]. Rotary type vane expander contains vane, rotor, and stator in a closed volume and expansion process done when the rotor starts rotating. Power output varies from 1-10 kW in an ORC system because of the inlet port location of the working chamber, type of working fluid, and expander dimensions [72], [73]. In the case of piston expander power output varied between 250-1150 W in a micro-ORC system [74]. There is the absence of moving parts in the ejector, and ejector type ORC has more exergetic efficiency compared with traditional ORC [75]. From survey turbines are suggested to large-scale ORCs, screw expanders are better to use in medium-scale, ORCs in small and micro-size are enough with scroll expanders (mainly for laboratories) [63], [76], [77].

4.5. Selection of working fluid

Selecting the best working fluid is a crucial task in ORC because heat duty from the heat source was carried out throughout the cycle operation. So, it should have better performance and thermal props in the expansion and condensation process. Also, withstand a wide range of temperature-pressure changes in between the process.

Recovered heat from gas turbine waste with the help of recuperated ORC, siloxanes as working fluid for effective energy efficiency, and high-temperature ranges (375 to 600 °C) [31], [78]. By using three hydrofluorocarbons (HFC) refrigerants (R245a, R1234yf, R1234ze) with temperature difference 120 to 170 °C, nonetheless higher exergetic efficiency of 38.92% was found with R245a as a working fluid [21], [79]. ORC-CO_2 cycle operated with help of different working fluids, among those all for the optimized process showed that ORC working with R152a as fluid extracted maximum exergetic efficiency of 13.08% [80], [81]. Coal-fired flue gases converted as work by the SCO_2-ORC system, working fluid heptane/R601 yields higher efficiency of 45.54% and 25.65% of destruction rate [32], [78]. R22 shows greater performance among the eight working fluids in ORC to get cold energy in LNG [2], [82]. The R123 working fluid used in the ORC system along with the internal heat exchanger (IHE) and feed liquid heater (FLH), obtained better energy and exergy values of 52.28 and 20.44% respectively [4], [83]. ORC operated using hydrocarbons for cost analysis, cost of cyclohexane is very less among all working fluids (chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), HFCs, and natural fluids) [53], [84]. R245fa working fluid raises exergy efficiency from 67 to 72.3% in ORC for stationary applications and also toluene working fluid 64.5 to 73% for the same application of heat recovery [27]. Achieved 38.11%, 29.98%, and 15.93% exergy destruction in low-pressure vapor generator (LPVG), high-pressure vapor generator (HPVG), and condenser (COND) in ORC system with geothermal dual working fluid [14], [85]. ORC with saturated steam and hot water combination heat source along with R245fa fluid shows better cycle efficiency of 9.4%. and also, the same working fluid was carried on the pumpless ORC system and showed 232 W of power at output [5], [34], [86]. An exergy analysis was done on ORC by using various working fluids and got maximum power generation of 1227 kW with help of R600a fluid [1], [87]. A statement found that mixing of working (70% n-octane+30% n-pentane) results and the highest exergetic records [88]. In the heat recovering process from smelting furnace exhaust among a wide variety of working fluids m-xylene has the most efficient results [50], [89], [90]. Table 1 is showing general parameters while selecting working fluid and Table 2 is showing basic thermodynamic properties of various working fluids.

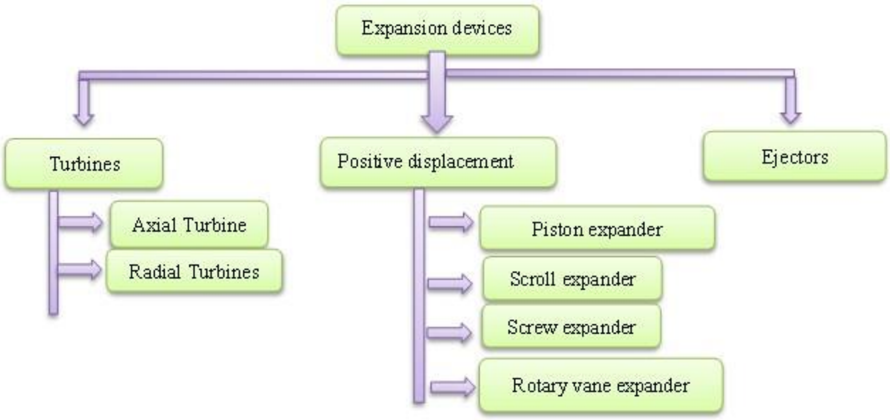

Figure 4. Various types of expansion devices

Table 1. General parameters while selecting working fluid [91], [92]

Parameters	Details
Environmental issues	ODP, GWP, chemical stability, corrosion, flammability
Performance	Good thermal range, heat-carrying for cycle optimization
Features	The critical temperature, density, surface tension, specific heat capacity
Economic	Easy availability and low cost

Table 2. Basic thermodynamic properties of various working fluids [35], [92], [93]

Substance	Mass kg/kmol	T_{cr} (k)	P_{cr} (bar)	ODP
R22	86.46	369.3	49.71	0.05
R134a	102.03	380	36.9	0.055
R152a	66.05	386.6	44.99	0
Propane	44.09	396.82	42.49	-
Isobutane	58.123	408.14	36.48	0
R245fa	134.048	427.2	36.4	0
R123	136.467	456.9	36.74	0.02
Isopentane	72.150	460.43	33.81	0
CO2	44.01	303.98	73.77	0
R227ea	170.03	374.75	29.25	0
R124	136.48	395.28	36.24	0.022
R141b	116.95	477.35	42.12	0.12
R143a	-	345.857	37.6	0
R600	-	425.125	37.96	0
R601	-	469.7	33.7	0
Cyclohexane	84.12	554	40.8	0
Toluene	89.3	592	41.3	0

5. CONCLUSION

Based on the above literature, this paper has an informative collection regarding how to perform an exergy analysis, various methodologies that are available in the present market to improve each process or entire ORC system. Some strong points like heat source temperature, evaporator inlet pressure, and selection of working fluid play major roles for a better-optimized ORC system. It is found that a large amount of exergy destruction at evaporator, expander, condenser, and pump respectively. For further research, this may continue with different hear sources like solar energy, geothermal, industrial waste to recover waste heat towards a better sustainable environment.

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