A Review on the Performance of Organic Rankine Cycle with Different Heat Sources and Absorption Chillers

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ABSTRACT

This article reviews the performance of organic Rankine cycle with different heat sources. Plenty of waste heat is widely available in low to medium temperature range from various sources such as engines, machines and processes. The conversion of these low-grade waste heat into electricity is a feasible solution to provide clean energy. The Organic Rankine Cycle (ORC) is a suitable thermal cycle for the waste heat recovery application. The thermodynamic performance of ORC with different operational parameters and several working fluids is discussed. Further, the feasibility of integration of various absorption chillers in ORC, which is run by low-grade waste heat available at the outlet of the evaporator of ORC is evaluated.

Keywords: Organic Rankine Cycle, Diffusion Absorption Chiller, Condenser, Thermal efficiency, Waste Heat Recovery

INTRODUCTION

Conventional energy resources are limited and fossil fuels are depleted day by day, also their environmental effects are unpleasant or undesirable. Due to the inefficiency of use and equipment around 50% of World's energy is wasted as heat [1]. The sources of such waste heat include internal combustion engines [3-6], gas turbine exhaust gas [7,8], solar energy [9,10], geothermal energy [11,12], biomass energy [13,14], and industrial processes [15-16]. These waste heat sources can be efficiently utilized by different thermodynamic cycles like organic Rankine cycle, Kalina cycle, supercritical Rankine cycle, trilateral flash

Nomenclature

Variables and Parameters

$h_{p,i}$	Enthalpy of refrigerant at pump inlet (kJ/kg)
$h_{p.o}$	Enthalpy of refrigerant at pump outlet (kJ/kg)
$h_{p,o,isen}$	Isentropic enthalpy of refrigerant at pump outlet (kJ/kg)
$h_{t,i}$	Enthalpy of refrigerant at turbine inlet (kJ/kg)
$h_{t,o}$	Enthalpy of refrigerant at turbine outlet (kJ/kg)
$h_{t,o,isen}$	Isentropic enthalpy of refrigerant at turbine outlet (kJ/kg)
h_1	Enthalpy of refrigerant at the inlet of expander (kJ/kg)
h_2	Enthalpy of refrigerant at the outlet of expander (kJ/kg)
h_4	Enthalpy of refrigerant at the inlet of pump (kJ/kg)
h_5	Enthalpy of refrigerant at the outlet of pump (kJ/kg)
m_w	Mass flow rate of working fluid (kg/sec)
Q_{in}	Heat input to the cycle (kW)
T_h	Heat source high temperature (°C)
T_l	Heat sink low temperature (°C)
W_{net}	Net power produced by the system (kW)
W_p	Power produced by pump (kW)
W_t	Power produced by turbine (kW)

Symbols

η_p	Isentropic efficiency of pump
η_t	Isentropic efficiency of turbine (%)
η_{th}	Thermal efficiency (%)

cycle [17]. Among all the cycle Organic Rankine Cycle (ORC) is the most suited cycle for waste heat recovery. India has the potential to generate power through ORC from all the waste heat resources is around 4.4 GW till 2017. For the higher source temperature (> 370) Steam Rankine Cycle is best suited. For lower temperature waste heat (<370) it is not cost effective cycle due to following reason: (1) Low pressures steam requires cumbersome and costlier equipment and (2) superheating the steam from low-temperature waste heat is not possible due to its earlier condensation occurs (sudden implosion) which erodes turbine blades and other parts [25].

Abbreviations and Acronyms

AC	Absorption chillers
ALT	Atmospheric life time
ARC	Absorption refrigeration cycle
ARS	Absorption refrigeration system
CHP	Combined heat and power
COP	Coefficient of performance
CPC	Compound parabolic concentrator
DAR	Diffusion absorption refrigeration
ERC	Ejector refrigeration cycle
GWP	Global warming potential
IC	Internal Combustion
LFR	Linear Fresnel Reflector
MM	Hexamethyl disiloxane
ODP	Ozone depletion potential
ORC	Organic Rankine cycle
OTEC	Ocean thermal energy conversion
PTC	Parabolic trough concentrator
PTORC	Parallel two stage organic Rankine cycle
SRC	Steam Rankine cycle
STORC	Series two stage organic Rankine cycle
XCRC	External compound parabolic concentrator

Subscripts

h	high
in	input
l	low
p	pump
p,i	pump inlet
$p.o$	pump outlet
$p,o,isen$	pump outlet isentropic
t	turbine
th	thermal
t,i	turbine inlet
t,o	turbine outlet
$t,o,isen$	turbine outlet isentropic
w	working
1,2,4,5	thermodynamic state

This review article is organized as follows: First, the basic configuration and working fluid for organic Rankine cycle are discussed. Next, the theoretical and experimental performance of ORC with various heat sources is reported. Then, the integration of different types of absorption chillers with ORC is described. Finally, the last part consists of knowledge gap, future development, and conclusion.

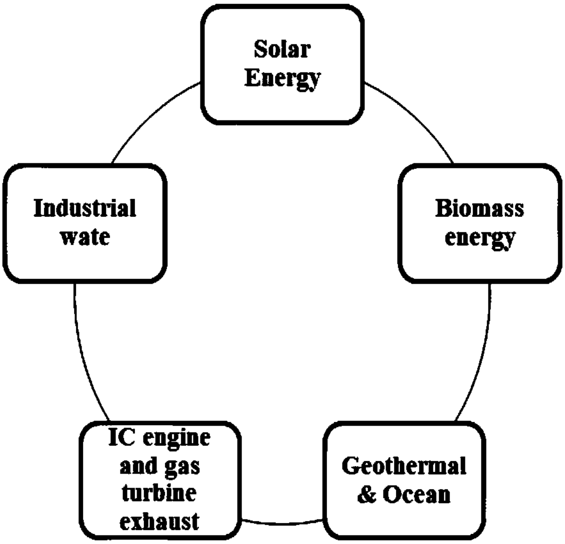

Figure 1. Various heat sources for organic Rankine cycle

BASIC CONFIGURATION OF ORGANIC RANKINE CYCLE

Figures 2 and 3 depict the ORC T-S diagram and schematic diagram, respectively. Available waste heat is used to heat the heat transfer fluid (HTF). In the evaporator, the HTF fluid gives heat to the organic fluid (OF) to convert it into vapor. The OF vapor is expanded in the turbine to produce power. Next, the OF is condensed in the condenser. The liquid OF is pumped by a pump to the evaporator and the cycle repeats. The following are some advantages of ORC: (1) Available from few kW to several MW (2), long system-working life, (3) less maintenance required, and (4) reliable and simple structure.

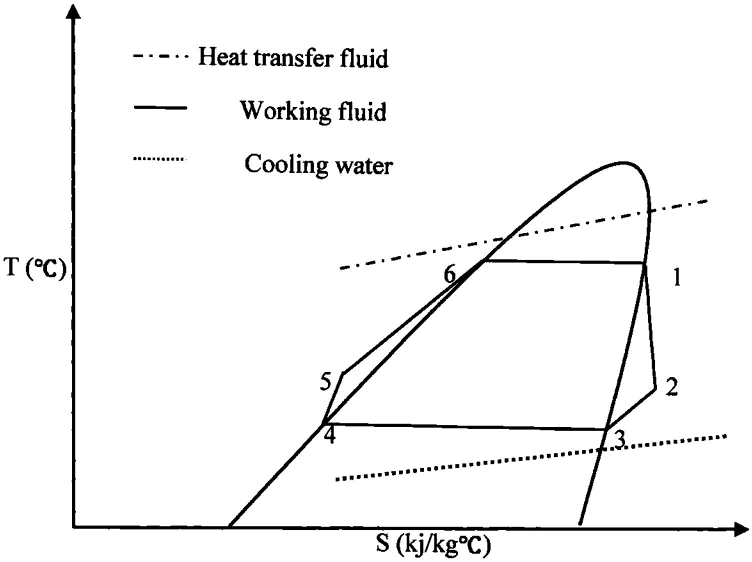

Figure 2. T-S diagram of Organic Rankine cycle. Numbers on diagram refer to steps in Figure 3.

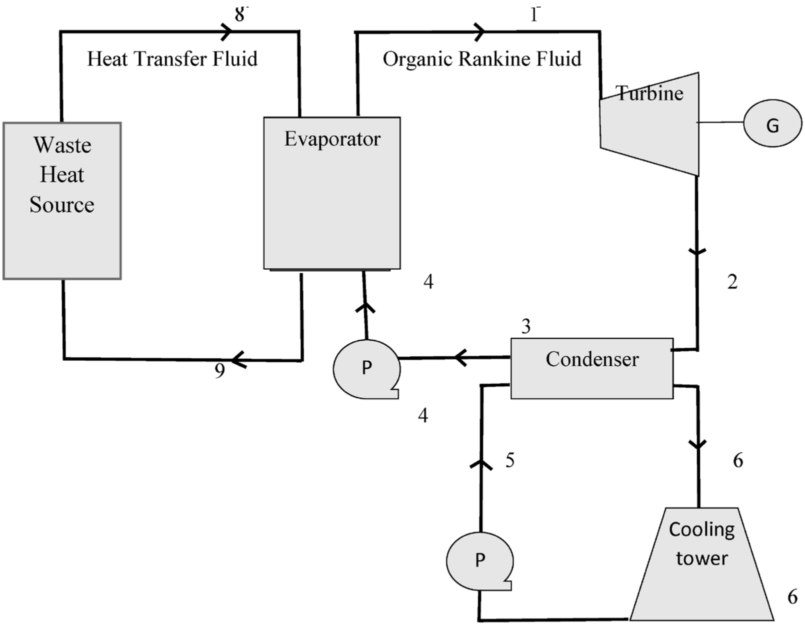

Figure 3. Layout of Organic Rankine Cycle. See Figure 2.

Ideal Thermodynamic cycle

The thermal efficiency is defined as [18].

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{W_t - W_p}{Q_{in}}$$

Ideal isentropic pump and turbine efficiency is given by

$$\eta_p = \frac{h_{p,o,isen} - h_{p,i}}{h_{p,o} - h_{p,i}}$$

$$\eta_t = \frac{h_{t,i} - h_{t,o}}{h_{t,i} - h_{t,o,isen}}$$

$$W_p = m_w(h_5 - h_4)$$

$$W_t = m_w(h_1 - h_2)$$

$$Q_{in} = m_w(h_1 - h_5)$$

With W_{net} is the net power produced by system, W_t is the expander power output, W_p is the pump power consumption, Q_{in} is heat input to ORC cycle and m_w is the mass flow rate of working fluid. For a source temperature T_h and sink temperature T_l the Carnot thermal efficiency is given by,

$$\eta_{th} = 1 - \frac{T_l}{T_h}$$

The source temperature and sink temperature are two important parameters which affect the performance of the organic Rankine cycle. A small increment in the source temperature increases the system generating and thermal efficiency of the cycle slightly. An increase in the sink or condenser temperature leads to a decrease in the turbine expander power and performance of system [74]. The condensing temperature varies under the different climatic condition as the condensing temperature depends upon the ambient temperature. The operation performance of condenser is also difficult under such circumstances [77].

Working Fluid for ORC

The essential characteristics of working fluid in the ORC are shown through saturation vapor curves. The cycle efficiency and arrangement of equipment are affected by such curves. In Figure 4, three types in Temperature-Entropy (T-S) diagrams and saturation vapor curves are considered:

(a) a wet fluid with negative slope $\frac{dT}{dS} < 0$,

(b) isentropic fluid with infinitely large slopes $\frac{dT}{dS} = 0$,

(c) dry fluid with positive slope $\frac{dT}{dS} > 0$ [19].

As the wet fluids have a negative slope so at the exit of the turbine outlet stream contains a lot of moisture. This moisture may corrode the blades of the turbine and reduces the isentropic efficiency of the expander [20]. Due to high heat transfer requirement and need of a superheater increases the cost of a system for wet fluid. Heat transfer coefficient in the vapor phase is low for this fluid.

There is no requirement of superheater for "dry" and "isentropic" fluids. Therefore, the "dry" or "isentropic" type working fluid are most suitable for the ORC system [20, 21]. Apart from these properties, the working fluid should also have many thermo-physical properties which should be taken into account for the ORC.

PERFORMANCE OF ORC WITH DIFFERENT HEAT SOURCES

The performance of ORC is varied with the various heat source and different organic working fluid. For a different heat source, biomass, solar, industrial waste, etc., the physical condition and temperature are different.

Performance with Solar energy

The sun is a great source of heat on Earth. It is a sphere of hot gases produced by nuclear fusion reactions with a diameter of 1.39 x 10^9m. The radiation coming from the sun is divided into beam radiation and diffuse radiation. Beam radiation directly reaches the earth surface, and scattered radiation reaches the surface after scattering from the sky. The value of yearly average solar radiation reaching the earth surface varies around 250 W/m^2 in desert areas, and 60 W/m^2 at higher altitudes [25].

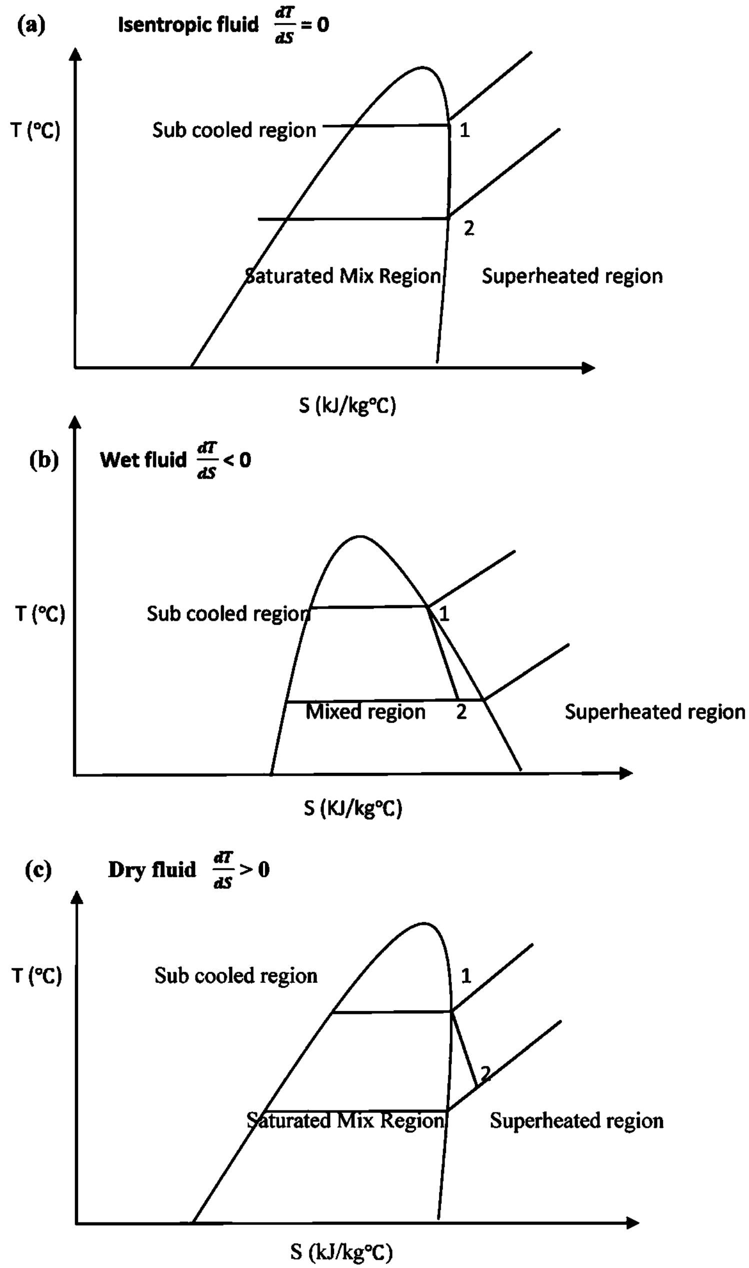

Figure 4. Different working fluids for ORC (a) Isentropic fluid (b) Wet fluid (c) Dry fluid

Table 1. Thermo-physical Properties of Organic Working Fluid

Specific Volume	Organic fluids should have low specific volume (larger vapor density). A small size expander and heat exchanger are required as low specific volume possess smaller mass flow rate of working fluid resulting in low cost of system.
atent heat of vaporization	Lower heat of vaporization is preferable for the organic Rankine cycle. This characteristic allows the heat transfer process at a variable temperature in the evaporator [22]. Therefore there is a better match of the temperature profile in the heat source and the evaporator, so it reduces the irreversibility of the system [23].
Thermal stability	At higher temperatures, there may be chances of decomposition of organic fluids. This leads to ignition and corrosion in the system. The organic fluid should maintain its thermal stability through the expected operating temperature range.
Critical Temperature	The critical temperature of organic fluid should be close to the maximum temperature of the cycle to achieve the optimal efficiency [24].
Molecular weight	Enthalpy drop across the expander is inversely proportional to the molecular weight. So less enthalpy drop across the expander for the larger molecular weight fluids reduces the number of stages needed for expander and decreases the complexity and cost.
Environmental impacts	Organic fluid with minimal Global Warming Potential (GWP), low Atmospheric Lifetime (ALT) and zero Ozone Depletion Potential (ODP) are preferable.
Viscosity	To reduce the friction losses in pipes and heat exchangers, less viscous fluid in liquid and vapor phase is required.
Safety	A non-flammable and non-toxic organic fluid is used for safety and health issues of the operator.

Solar radiation around 1.7 x10^{17} W reaches Earth surface, which is ten thousand times greater than the current world energy consumption [26]. Concentrated solar power and solar ponds are used to generate power. See Table 2.

Parabolic trough collector and linear Fresnel reflector (line focusing concentrating solar collectors) are well suited for the ORC system. Compared with SRC, ORC exhibits higher part load efficiencies with dry organic fluids for temperature range up to 400°C. Optical efficiency and the cost of PTC are greater than LFR [27]. A small-scale prototype of

Table 2. Key Features of Solar Thermal Technologies [25].

Technology	Annual solar to electricity efficiency	Practical operating temperature	Power cycles considered	Commercial maturity
Linear Fresnel Reflector, LFR	8-10%	150-400°C	SRC, ORC	medium
Parabolic Trough Collector, PTC	12-15%	150-400°C	SRC,ORC	high
Central Receiver tower	20-30%	300-1200°C	SRC, Brayton	medium
Parabolic dishes	20-30%	300-1200°C	Stirling, SRC, Brayton	low

SRC: Steam Rankine Cycle.

ORC cycle with power capacity less than 10 kW is connected with parabolic trough collectors. The Source temperature was less than 130°C, and condensing temperature was about 32.2°C. Gross electrical efficiency was around 8% with this system [28]. Jing et al. [29] developed a model to predict the performance of ORC coupled with Compound Parabolic Collector or CPC using R123 as a working fluid. The evaporator temperature was 147°C, and the overall efficiency was 7.9% achieved. Quoilin S. et al. [30] describe a model which predict the performance of ORC with a different fluid, single stage, and double stage expansion machine. Organic fluid SES36 gives maximum overall efficiency around 7.9% with evaporator temperature 189°C. R134a gives the least efficiency of 3.6% and a source temperature of 85°C.

Table 3. Solar collector outlet temperature [32, 33, 34]

Collector type	Description	Conversion technology	Temperature(°C)
Concentrated solar collectors	Parabolic trough collector Fresnel reflector technology	ORC or steam cycle	200-450 100-400
	Parabolic discs Solar tower	ORC or steam cycle steam cycle steam cycle	750 1000
Simple solar collectors	Flat plate collector Evacuated tube collector	Heat or ORC Heat or ORC	<150 90-200
Solar pond	Heat exchanger	ORC	80-90

(a) (b)

Figure 5. The solar powered ORC, (a) solar collectors (b) ORC prototype [28]

Performance with Biomass energy

Biomass energy resources can play a vital role in the power generation in those countries whose economy is dependent on agricultural activities. It is carbon neutral, widely available and clean energy resource. The biomass is derived from the waste of plant and animals. It includes various waste like animal wastes, waste from the food industry, wood wastes and wood, algae, aquatic plants, crops and municipal solid waste [35]. Gasification is most suited technology for the power generation from biomass. Many authors studied about the power generation for small to medium scale through gasification technology [36-40]. Mena B De et. al [41] has done a modeling and simulation of CHP system which consists of an external combustion chamber, Organic Rankine Cycle generator and updraft gasifiers. Olive trees used for the gasification which is the by-product of olive industry. ORC simulation results show that efficiency achieved around 18.7% with source condition at 25 bars and 300 and sink condition around 100°C. For high-temperature heat source (>900), Toluene has been selected as organic working fluid. The family of alkyl benzenes is best suited for the biomass application with source temperature 573K, sink temperature 363K and pressure between 0.9 to 1.5 Mpa [42]. Liu H. et al. [43] studied a thermodynamic model of 2 kW Organic Rankine Cycle with biomass-fired CHP system. Three organic working fluid n-pentane, HFE7000, HFE7100 has been selected for the study. HFE7100 gives least, and n-pentane gives the highest efficiency. Maximum efficiency is predicted about 16.6% with source temperature

Table 4.
Maximum delivery of an ORC employing different working fluids [31]

Working fluid	Maximum T_h(°C)	Minimum T_l(°C)	Maximum η_{th}(%)	Maximum W_{net}(kj/kg)
R-426A	55	25	6.37	11.92
R-218	57	25	5.73	5.03
R-413A	59	25	7.05	12.60
R-423A	90	25	10.28	16.50
R-227ea	91	25	10.11	14.06
R-C318	106	25	11.22	16.20
C_4H_{10}	107	25	10.53	13.87
R-236fa	108	25	12.31	22.93
Isobutane	121	25	13.78	58.08
Butene	125	25	14.78	66.53
Isobutene	125	25	14.65	66.27
E134	125	25	14.79	37.08
R-236ea	132	25	14.29	30.40
Trans-Butene	136	25	15.84	77.05
Butane	138	25	15.48	74.78
R-245fa	140	25	15.57	40.04
C_5F_{12}	141	25	12.37	21.31
Cis-Butene	142	25	16.50	82.09
Neopentane	152	25	15.52	71.78
R-245ca	158	25	16.96	48.20
Isopentane	177	25	17.75	97.10
R-365mfc	177	25	17.55	56.28
Pentane	186	25	18.51	108.12
Acetone	213	25	22.54	155.44
Isohexane	216	25	19.27	123.32
Hexane	226	25	20.08	135.54
Heptane	258	25	20.81	158.24
Cyclohexane	272	25	23.49	170.22
Benzene	274	25	25.79	179.00
Toluene	307	31	25.60	190.82

varied from 100°C to 140°C. Results show that superheating in ORC cycle hurts the performance. Similarly, subcooling in condenser also degrades the performance of the system. The performance of the system depends mainly on ORC fluid, condensing cooling water temperature and hot water temperature in the boiler.

Figure 6. Flue gas-Heat exchanger and modified chimney [47].

Performance with Industrial Waste Heat

Plenty of waste heat are directly dissipated into the environment, therefore losses of thermal energy from many industries. These waste heat could be used to generate the electricity through organic Rankine cycle (ORC). An enormous amount of heat is produced in steel industry due to the production of steel at high temperature [44]. The temperature and type of waste heat are different for different casting production [45]. Sung T. et al. [46] design a 200 kW organic Rankine cycle which runs by the exhaust heat in steel processing industry. With Organic working fluid R245fa, maximum thermal efficiency achieved around 8.6% with source and sink temperature, 140°C and 29.9°C respectively. In a cement factory, an energy and exergy approach is applied for the performance analysis of a cooling section and rotary kiln. The analysis shows that dry fluid R600a shows the least performance and isentropic fluid R245fa gives the best performance. For the sink temperature 303K and source temperature 493K, the thermal efficiency of R245fa and R600a are 13% and 9.8%, and exergy efficiency of R600a and R245fa are 21.7% and 29% respectively [47]. A thermodynamic analysis has been carried out for ORC in a steel industry. It is found from the analysis that energy efficiency around 9.96% and exergy efficiency 47.22% has achieved. In the term of exergy rate evaporator has a significant effect on the efficiency of the system [48]. Guo C. et al. [49] analyzed the performance of the organic Rankine cycle with different working fluid. In this analysis exhaust flue gas from a pulverized coal-fired plant has been considered as a heat source. The temperature of origin was 100°C, and condensing temperature varies from 25°C to 31°C. Results show that organic fluid R290 and R600a gives the thermal efficiency around 9.1 and 9.62%. Mixture working fluid R290/R600a offers highest thermal efficiency around 9.97%.

Performance with Geothermal Energy

Geothermal energy comes from (a) heat stored inside our planet during its formation around 4.5 billion years ago, and from (b) energy released from the decay of radioactive isotopes in Earth, in almost equal parts. Thus geothermal heat energy can be found in many forms like pressurized water, steam and dry rock. This heat energy classified in two ways either by heat transfer mode or by temperature distribution [50]. An enormous amount of heat energy is stored in the geothermal heat source [51]. These heat converted into electricity through organic Rankine cycle by many researchers [52-55]. Li T. et al. [56] evaluate organic Rankine cycle system performance with two cycle configuration series two stage organic Rankin cycle (STORC) and parallel two stage organic Rankine cycle (PTORC). In this study an Objective function is defined as the ratio of net power output to the thermal conductance.

Geothermal source temperature varies from 90 to 120 and condensation temperature 30°C with R245fa as organic working fluid. Analysis shows that Performance of STORC is better than the PTORC. The former configuration increases and later decreases the power output with geothermal water inlet temperature. Total thermal conductance is approximately equal for both configurations. The organic Rankine cycle thermal performance is evaluated with inlet water temperature of geothermal source varies from 100°C to 150°C. Five organic working fluid hexane, pentane (R601), Isopentane (R601a), butane (R600), Isobutane (R600a) are analyzed to find out the best working fluid for the optimal performance. The inlet temperature of cooling water is 20°C and optimal condensing temperature is 29.45°C to 29.75°C for maximum power output. It is found from the result that R600a produce maximum power and highest exergetic efficiency for inlet temperature more than 120°C [57]. To optimize the power of an ORC system a thermodynamic model is built for hydro fluorine carbon and hydrocarbon working fluids. Results shows that for the optimal power output source temperature lies within 110°C to 130°C [58].

Performance with Ocean Thermal Energy

Earth's surface covered with oceans more than 70% and it is the largest storage system in the world. There is a natural thermal gradient appears at a particular depth in the oceans, so ocean thermal energy conversion technology can extract power through these temperature gradients. The water temperature varies from 20°C to 29°C at a depth of 50 m in oceans. Organic Rankine cycle can successfully generate power through these low grade heat. The warm surface of ocean considers as a source and water temperature at a 50 m act as sink for the ORC system. In the ocean thermal energy conversion system optimization is carried out for exergy efficiency of organic Rankine cycle. R134a and ammonia has been chosen as organic working fluid. Different operational parameters warm seawater flow rate, warm seawater temperature, condenser and evaporator temperatures are varied to achieve maximum net power output. Results shows that for maximum net power output ammonia is better choice [59]. Jung H. et al. [60] studied the ocean thermal energy conversion system in which the heat source was considered as exhaust of steam power plant rather than warm surface temperature of sea. They conclude that such heat source is beneficial as temperature is fixed at 32°C. Thermodynamic analysis, selection of working fluid and topping steam cycle were the main outcome of this study. Also results shows that this system can reduce the power consumption of pump, condensing temperature and condensing vacuum. Wang et al. [61] study the feasibility of combined solar energy with OTEC for electricity generation. They also find out the effect of various parameter like turbine inlet pressure and temperature, turbine exit quality and condensing temperature on the system efficiency. The effect of wet fluid (i.e. R500, R11, and R152a) and dry fluid (R123, R114, and R113) has been analyzed on the system efficiency. They conclude that the wet fluids show better performance than the dry fluids.

Performance with Internal Combustion Engine Exhaust

Around 65% energy is wasted from the internal combustion engines through the cooling liquid and exhaust gas [62]. Many thermodynamic cycles proposed to recover the waste heat from engines such as Brayton cycle, organic Rankine cycle (ORC), Kalina cycle, Stirling cycle and adsorption cycles [63, 64]. ORC is most suited thermodynamic cycle for the power generation from the waste of internal combustion engines [65]. Wang et al. [66] made a thermodynamic model in Matlab to analyze the different working fluid to find out the suitable organic fluid for engine waste heat application. The temperature of source was 600K and the condensing temperature varied from 300K to 360K. Analysis shows that, for a fixed output of 10 kW R245fa and R245ca are most environment friendly organic fluids. Also R123, R11, R113, R141b shows higher thermodynamic performance than other fluids. Zhang et al. [67] developed and tested an organic Rankine cycle system with diesel engine exhaust for waste heat recovery. Maximum power is found around 10.38 kW with a single screw type expander as expansion device. Also thermal efficiency and design temperature are 6.48% and 550°C respectively. R245fa and R123 are extensively used in the lab and companies as a working fluid for organic Rankine cycle. Experiments have been conducted to find out the suitable working fluid for the waste heat of vehicles. It is shown from the result that R245fa is best suited for the source temperature 150°C and light and medium duty engines. Working fluid R123 is best for heavy duty engines and the reference temperature above 150°C [68]. A performance comparison of two working fluid R245fa and R1233zd has been conducted experimentally for organic Rankine cycle with radial inward flow turbine. The waste heat produced by truck exhaust considered as a heat source with temperature around 300°C.

Results shows that the R1233zd is better than the R245fa in the terms of power generation and performance [69].

Performance with Gas Turbine Exhaust

In a large-scale gas turbine power plant the temperature of exhaust gas is around 500°C to 600°C. This temperature range is able to produce steam which run the Steam power cycle and it is most suited application for the waste heat recovery in gas turbine power plant. However during 90's with the development of micro gas turbine, it is possible to make a plant with capacity less than 500 kW. The exhaust gas temperature of such plant are generally less than 400°C. Organic Rankine cycle can be successfully integrate in the plant for waste heat recovery in such temperature range. A thermodynamic analysis is carried out to enhance the performance of gas turbine for 100 kW capacity with ORC as bottoming cycle. It has been found from the analysis that electrical output increases about 33.3% with MM (hexamethyl disiloxane) as working fluid [70]. A part load and rated performance is analyzed with eight working fluid including toluene, Isopentane, R245fa and MM for five gas turbines. The ORC cycle used as a bottoming cycle. The goal of this study was to optimize the efficiency of system with different procedure to capture maximum waste heat. Results indicate that for constant mass flow rate the organic Rankine cycle produces optimum power for any conditions [71]. A thermodynamic analysis is carried out using R123 as a working fluid to evaluate the performance of gas turbine. It is found that combustion chamber of gas turbine shows maximum exergy destruction. Also efficiency of gas turbine increases with increasing in compressor pressure ratio [72].

Performance with Auxiliary Heat Source

Many authors has been conducted experiment on the Organic Rankine Cycle based on auxiliary heat source. Kim D.K. et al. [73] do a parametric study and evaluate the performance of the ORC with reference temperature around 80°C and R245fa as a working fluid. They found that with increase in the refrigerant charge the performance of the system first increases and then decreases. Also the performance of the system evaluated with condensing temperature from 20°C to 35°C. Increase in the sink temperature leads to reduction in the power and efficiency of the system due to decrease in the pressure ratio. An experimental study conducted with R245fa working fluid and 3 kW capacity

ORC. Performance checked against various operational parameter like pressure drop and condensing temperature with source temperature around 100°C. Results show that pressure drop is highly sensitive to the system performance also higher condensing temperature leads to deteriorating the performance of the system. Sink Temperature varies from 21.86°C to 43.63°C. The maximum expander power and thermal efficiency is achieved around 2.64 kW and 5.92% respectively [74]. Hsieh J.C. et al. [75] examined a transcritical organic Rankine cycle experimentally with temperature of high side from 90-100 in both supercritical and subcritical state. R218 has been selected as working fluid. Output power is not significantly affected by increase in hot source temperature. Thermal efficiency achieved around 5.7% with reference temperature 90 and 5.28% at 100°C.

Above literature shows that the performance of ORC affects with different operational parameters. The increment in the source temperature leads to small increase in the performance of the system. The increase in the condensing temperature shows the reduction in power and efficiency of ORC. The high cooling water temperature also degrades the performance of ORC. A wide range of organic working fluid has been tested to find out the best organic fluid regarding performance. But different heat source required different working fluid for optimal performance. A low-grade waste heat is also goes wasted after the heat exchange in the evaporator of ORC. These low-grade waste heat available at the exit of evaporator could be used to run the absorption chillers to satisfy the cooling requirement [76].

ORC WITH ABSORPTION CHILLERS

In the current time, vapor compression system is most suitable technology to provide cold energy. These systems consume a lot of electricity to run the compressor of the system. In the absorption refrigeration system, a compressor is replaced by a generator, and an absorber and its working are depended upon the absorbing principle rather than compression process [1]. Absorption refrigeration system works on the fluid mixtures. The fluid mixture consists of a refrigerant and an absorbing material. The refrigerant mixes in the absorbing material and this mixture passes through the generator of the system. In the generator, the refrigerant converted into pressurized vapor phase with the heat, whereas in the compression refrigeration system the refrigerant vapor is pressurized by the compressor. The main benefit of using absorption refrigeration system is that it requires a very little or no electricity [2]. To generate refrigerant vapor in the absorption system, there is a need of heat input into the generator. Solar collectors provided such heat to run the absorption system and known as solar operated absorption refrigeration systems [3]. Absorption chillers can integrate with ORC in two ways i.e. uncoupled and coupled system.

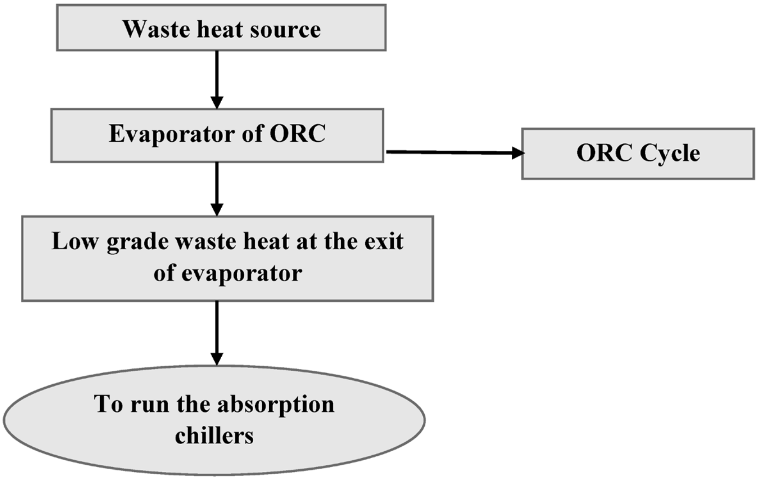

Figure 7. Flow diagram of uncoupled organic Rankine cycle (ORC) and absorption chillers (AC)

Types of Absorption chillers

Three types of absorption chillers are available single effect, double effect and triple effect absorption chillers. Among three types of absorption chillers system, single effect absorption chillers required low generator temperature to run the system. Also the configuration are different from each other.

Single Effect Absorption Refrigeration System

The most common type of single effect absorption refrigeration system is Water/Lithium Bromide system. The main component of the cycle is absorber, condenser, evaporator and generator. Water used as a refrigerant and Lithium Bromide as an absorber. The condenser and generator are located at one side as their pressures are equal. The evapo-

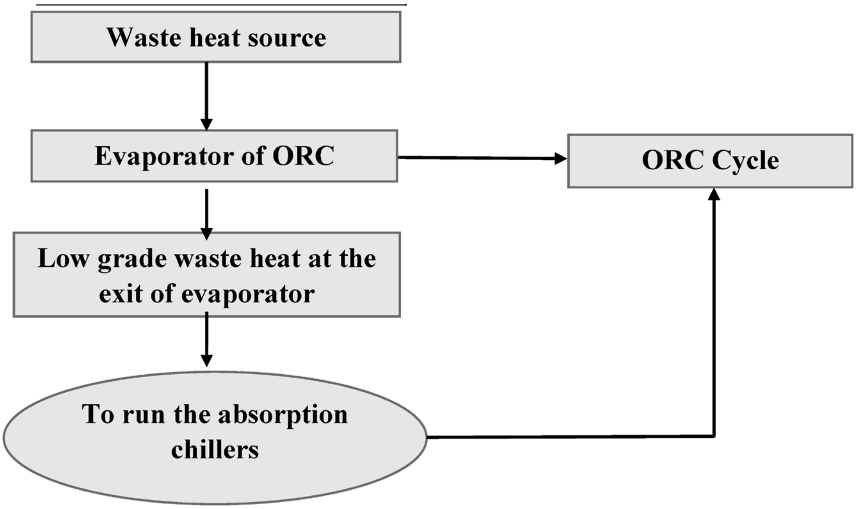

Figure 8. Flow diagram of coupled organic Rankine cycle (ORC) and absorption chillers (AC)

rator and absorber are located on the one hand as these components hold same pressure. The energy transfer is given in the Schematic diagram. The input energy is delivered in the generator to operate the whole system. The input heat can be electrical energy or any other waste heat like solar energy. Marian A. et al. [4] analyzed the exergetic performance of combined power and cooling generation system with solar energy as a heat source. In this analysis, they combined organic Rankine cycle and lithium bromide absorption refrigeration system. The temperature of solar collector varies from 115°C to 140°C. The heat transfer fluid at the exit of the evaporator of organic Rankine cycle uses as the heat source in the generator of an absorption chiller. The generator temperature of chiller varies from 70°C to 100°C. Results indicate that above system satisfied cooling and power demand of a building and maximum COP of the refrigeration system and efficiency of ORC system are achieved around 0.78 and 10.15% respectively. Also, most irreversibility occurs in the condenser.

Chaiyat N. et al. [5] conducted an experiment to increase the performance of organic Rankine cycle with absorption chillers. The inlet and outlet temperature of heat transfer fluid temperature for ORC system are 90°C-120°C and 70°C-90°C. The outlet temperature of heat transfer fluid at 70°C-90°C act as a generator temperature to run the absorption chiller. The working fluid of ORC and absorption chillers are R245fa and H_2O/LiBr respectively. From the experimental results, it is found that the cooling water temperature decreases to 15°C, as it passes through the evaporator of the chiller. As the cooling water temperature reduces, the condensing temperature of ORC section decreases and the efficiency increases about 7%.

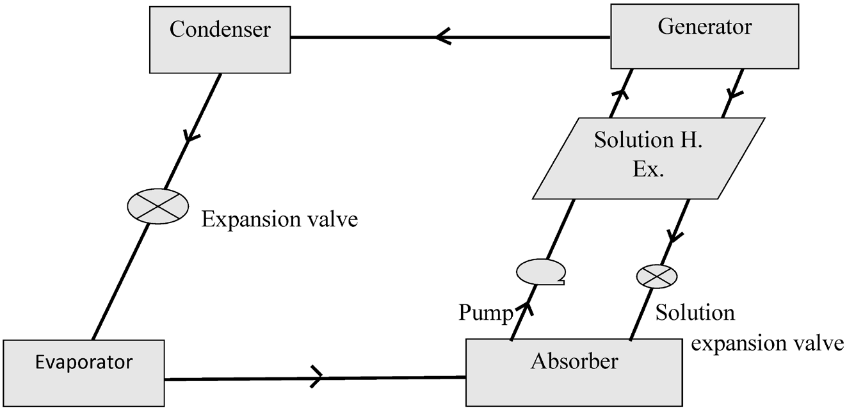

Figure 9. Single effect absorption refrigeration system

Also, the coefficient of performance of the chiller is about 0.66. A thermodynamic analysis and a parametric study are carried out for a system which is composed of organic Rankine cycle, absorption chiller, and gas turbine. This combined cooling, heating and power generation used for residential purpose. ORC turbine inlet temperature is in the range of 319°C to 360°C. The parametric analysis shows that gas turbine inlet temperature, pressure ratio, the inlet temperature of ORC turbine are the most important parameter for the power and efficiency of the system. The maximum cooling and maximum power generation of the system are 8 kW and 30 kW. It is also found that the coefficient of performance of absorption chiller is 0.61 and efficiency of the system are 67.6% [6]. Sun W. et al. [7] analyzed and optimized the performance of organic Rankine cycle system with different parameters including the degree of superheating, evaporation temperature and condensing temperature. In this study, they also combined the ORC system with Absorption refrigeration cycle (ARC) and Ejector refrigeration cycle (ERC). Both configurations satisfied the cooling and power generation. Grosu L. et al. [8] evaluate the performance of organic Rankine cycle and Absorption refrigeration system using exergy analysis. They suggest that the performance of cooling system strongly depends upon the generator temperature. It means the inlet and outlet temperature of heat transfer fluid is a most important parameter for both systems. A solution heat exchanger in the absorption unit and a recovery heat exchanger on the condenser side increase the exergetic performance of combined cooling and power generation system. Singh O.K. [9] simulate the performance of combined cycle Brayton-Rankine cycle power plant with ammonia-water absorption refrigeration system under the Indian weather condition. Results show that thermal efficiency of the plant in winter season is more than the summer months.

Double Effect Absorption Refrigeration System

The single effect absorption refrigeration system operates at a low temperature of waste heat. Double-effect absorption system is used for the high-temperature waste heat application. The coefficient of performance of double effect system is better than the single effect system and lies from 1 to 1.3. The single effect system can be changed into double effect by incorporating low and high heat exchanger between absorber and generator. Generator and condenser are divided into two parts i.e. low section and upper section. Double-effect absorption system can be divided into three different configurations series flow, parallel flow and reverse parallel flow depending upon the flow of solution in the cycle (ASHARE 2010) [10]. Winston R. et al. [11] analyzed the performance of double effect absorption chillers which is run by the non-tracking external compound parabolic concentrators (XCPC). The temperature of collector maintained from 160°C to 200°C. It is found from the analysis that the coefficient of performance of chiller is around 0.99.

Triple Effect Absorption Refrigeration System

The triple-effect absorption refrigeration system requires a high-temperature heat as the comparison to double effect system. These systems consist of three generators and solution is generated in three generators. Double-effect absorption system can be converted into triple effect by adding a high-temperature generator. Alvarez M. et al. [12] simulate the performance of the triple-effect absorption refrigeration system with working fluid as aqueous nitrate solution. Simulation result shows that maximum coefficient of performance is achieved around 1.73 with the cooling water temperature 30°C and hot source temperature 250°C.

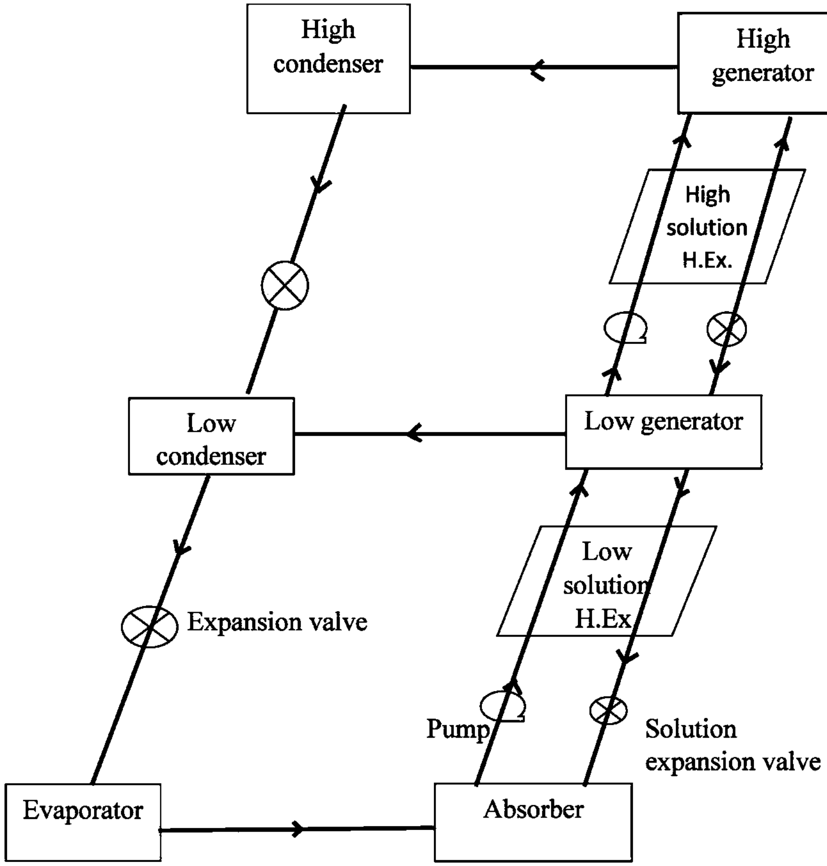

Figure 10. Double effect absorption chiller

From the above literature, it is evident that single effect absorption chillers are successfully run by the low-grade waste heat available at the exit of an evaporator of ORC. It also satisfied the system of combined cooling and power generation from a single heat source. The evaporator of ARS system can reduce the cooling water temperature of organic Rankine cycle system. Due to the reduction in cooling water temperature the condensing temperature decreases and performance of ORC increases. In the most of the studies, general working fluid pair LiBr/H_2O are used. The double and triple effect absorption chillers are difficult to run by such low-grade heat as their temperature requirement is quite high. So generally single effect absorption chillers are preferred for organic Rankine cycle.

RESEARCH GAP AND FUTURE DEVELOPMENTS

From the literature review, it is found there are plenty of available waste heat sources like solar energy, biomass energy, geothermal energy, ocean energy, industrial waste, IC engine and gas turbine exhaust heat. These sources can be effectively used by organic Rankine cycle (ORC) to generate power. The literature also shows that several ORC simulation and modeling studies for different heat sources. Most of the previous work was focused on investigating the performance of ORC system with varying different operational parameters like source temperature, sink temperature degree of superheating and pressure drop. Energy and exergy analyses was also carried out by some authors. A wide range of working fluid is tried for optimal performance of ORC. For each heat source, ORC system requires different working fluid, no one working fluid works for all conditions. Also in the most of the previous studies, the condensing temperature was assumed to be constant and less than 40°C. The condensing temperature depends upon the atmospheric conditions, and very little attention is given to the condenser performance under different climatic conditions and seasons of the year. In countries like India, ambient temperature varies drastically throughout the year. For such weather conditions, there is need to evaluate the performance of ORC with varying condensing temperature throughout the year; particularly considering that high condensing temperature has an adverse effect on the performance of ORC system. Also, the literature review shows that low-grade waste heat at the exit of the evaporator can be used to run the absorption chillers, and make a system of combined cooling and power generation system. A few studies have been conducted for combined ORC and absorption chillers. Most of such studies focused on energy and exergy analysis and theoretical analysis. A very few experimental studies were found for such combined configurations. Also, diffusion absorption refrigeration (DAR) are never used in ORC cycle. Its unique quality is that it requires no input power and can be run by low-grade waste heat. So, future research should comprehend:

(1) Experimental analysis of small-scale organic Rankine cycle (ORC) under varying Indian climatic conditions.

(2) Waste heat available at the exit of the evaporator will be used to run the diffusion absorption refrigeration (DAR) system to satisfy combined cooling and power generation from a single heat source.

(3) A DAR system will be used as a coupled cycle with ORC to increase the performance of ORC system, with the decrease in condensing temperature.

CONCLUSION

This article reviews the performance of organic Rankine cycle for different heat sources like biomass energy, solar energy, etc. For waste heat recovery application ORC is the best-suited cycle. Most of the studies in previous literature were focused on the performance of ORC for different operational parameters. But little attention is given to condenser performance under different ambient temperatures. As condensing temperature varies annual seasons and time of day, there is a need to check the performance of condenser for such varying conditions. This review found a lot of theoretical and experimental work has been conducted to find out a suitable ORC working fluid. It is hard to find a single working fluid suitable for all waste heat sources. The reviewed literature also describes the feasibility of running absorption chillers with the ORC cycle. Most of the author theoretically analyzed the thermodynamic performance of such combined cycle. Less attention is given for experimental work in the above-reported literature. Review of the literature suggests that only the single effect absorption chiller is well suited for ORC, and that double and triple effect absorption chillers are difficult to run by ORC, as they require high generator temperatures. All the absorption chillers consume some amount of power to run the system pump. The diffusion absorption refrigeration (DAR) are never integrated into the ORC system. These pumpless refrigeration systems can combine with the ORC to satisfy both, cooling and power generation. Finally, the evaporator of DAR system can be used to reduce the temperature of cooling water to increase the power and performance of the ORC system. As such DAR+ORC system contains no moving parts and requires no electrical energy to operate, it can be one step closer towards sustainable or green energy.

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