Study Of Organic Rankine Cycle with Different Organic Fluids at Various Temperature & Pressure: A Review.

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Abstract - *Increasing emissions of CO_2 and fuel prices lead to more efforts in discovering a solution to reduce the environmental waste heat. One of the solutions is the organic rankine cycle system. Organic rankine cycle is one of the promising exhaust heat recovery systems which is extensively used to recover low to medium grade heat rather than the traditional steam rankine cycle system. ORC which operates under a lower operating temperature and pressure rather than the traditional steam Rankine cycle system permits a lower grade heat to act as fuel for operations. Low-grade heat refers to low to mid-temperature heat with a low energy density that cannot be converted to electrical energy efficiently by the traditional steam Rankine cycle due to the higher operating temperature and pressure requirements. This creates a wider range of applications for organic rankine cycle systems which would be unachievable with traditional steam Rankine cycle systems. Conditional to the industrial process the waste heat energy is rejected at a different temperature, which makes the optimal choice of the working fluid of great importance. Therefore a few aspects of the working fluid selection are also presented in this study. This study helps in understanding the organic rankine cycle system and identifying the best possible organic fluids for various ORC applications depending on the operating conditions.*

Key Words: ORC, Rankine cycle, steam rankine cycle, low-grade heat, working fluid.

1.INTRODUCTION

The Rankine cycle is a simplified thermodynamic cycle that describes how some heat engines, such as steam turbines or reciprocating steam engines, extract mechanical work from a fluid as it passes between a heat source and a heat sink.

Heat energy is given to the system via a boiler, which converts the working fluid, which is commonly water, to a high-pressure gaseous state, i.e., steam, to drive a turbine. The fluid is allowed to condense back into a liquid condition after passing through the turbine as waste heat energy is rejected before being returned to the boiler, completing the cycle.

There are four main processes in the Rankine cycle.

Process 1–2: Process 1-2 is the isentropic compression process. In this process, the working fluid which is water is pumped from low pressure to high pressure. As the fluid is in a liquid state at this stage, the pump needs slight input energy.

Process 2–3: Process 2-3 is a constant pressure heat addition process. In this process, the high-pressure liquid arrives in a boiler, where it is heated at constant pressure by an external heat source to become dry saturated vapour.

Process 3–4: Process 3-4 is an isentropic expansion process. The dry saturated vapour expands through a turbine which produces power. This decreases the temperature and pressure of the vapour, and some condensation may occur.

Process 4–1: Process 4-1 is a constant pressure heat rejection process. The wet vapour then arrives at a condenser, where it is condensed at a constant pressure to become a saturated liquid.

Organic Rankine Cycle

ORC is primarily a modification of the classic steam Rankine cycle. The operating concept of ORC and steam Rankine cycle is the same, the only variation is the replacement of water as the working fluid in the steam Rankine cycle with an organic refrigerant in the organic Rankine cycle. Here, organic means compounds made up of carbon, hydrogen, and oxygen. In the organic rankine cycle, an organic working fluid is initially pumped from a lower pressure to a higher pressure. Then the high-pressure fluid come to a heat source known as a boiler where it is heated at constant pressure until it becomes dry saturated vapour. then, this vapour expands through a turbine where mechanical work is produced and converted to electrical energy. The wet vapour enters the condenser where it is condensed back into a saturated liquid and the cycle starts again.

Advantages of organic rankine cycle over steam rankine cycle

1)Lower maintenance cost: As ORC systems operate at lower temperatures and pressure and have limited moving components; therefore, the cost of maintenance is reduced.

2)Minimal supervision required: As the ORC system operates at a lower operating pressure, this generally removes the requirement for an operator to monitor organic rankine cycle systems. Maximum systems come with computerized remotely monitored control units.

3)Greater equipment durability: As ORC systems operate at a lower pressure as well as turbine speed, due to this the mechanical stresses on the equipment are lower. Also, by changing water with organic fluid as the working fluid, moisture which is responsible for turbine blades erosion during vapour expansion is eliminated.

Applications of organic rankine cycle:

Organic Rankine cycles can be useful for applications where the heat source may have a temperature of about 100 ^{0}C to 300 ^{0}C, like

1. low- temperature solar thermal energy
2. Geothermal energy
3. utilizing industrial waste heat
4. Biomass
5. Solar

1.1 Working fluid selection criteria

A better-working fluid for Organic Rankine Cycle will satisfy the following criteria:

1. Thermodynamic criteria:

a. Triple point temperature < ambient temperature < critical point temperature.

b. Higher net power output as well as higher thermal efficiency.

c. Acceptable pressures at operating temperatures.

2. Safety criteria:

a. Non-toxic.

b. Non-flammable.

3. Environmentally friendly criteria:

a. Low global warming potential (GWP).

b. Low ozone depletion potential (ODP).

4. Lower cost.

5. Easily available.

6. non-corrosive to the materials of the components

Ozone depletion potential (ODP)

The ozone depletion potential (ODP) of a chemical molecule is the relative quantity of ozone depletion that it may produce, with trichlorofluoromethane (CCl_3F, often known as R-11 or CFC-11) having an ODP of 1. It is defined as "the integrated change in total ozone per unit mass emission of a specified ozone-depleting substance relative to the integrated change in total ozone per unit mass emission of CFC-11" by the World Meteorological Organization. (2018, United Nations Environment Programme)

Global warming potential (GWP)

A gas's global warming potential (GWP) is a measure of how much heat it traps in the Earth's atmosphere over a certain period (usually 20, 100, or 500 years), in comparison to carbon dioxide (CO_2), whose GWP is standardized to 1. 2013 (Intergovernmental Panel on Climate Change)

The GWP of a gas depends on the subsequent factors:

1)The absorption of infra-red radiation by a certain chemical species (the higher the absorption, the higher the value of GWP).

2)Its absorbing wavelengths spectral position specifically, if the gas efficiently absorbs radiation of a wavelength where the atmosphere is honestly transparent, then that gas will have a significant impact on global warming, and hence a larger value of GWP.

3)The atmospheric lifetime of that given chemical species (longer the lifetime of that chemical species, the higher the value of GWP).

The global warming potential of a gas mixture may be calculated by taking a mass-fraction-weighted average of the GWPs of the individual gases that make up the gas mixture. (Environmental Program of the United Nations, 2018)

ASHRAE safety groups

The American Society for Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) assigns numbers and safety classifications to the refrigerants based on their toxicity and flammability data submitted by the refrigerant's producer, in a two-character classification naming where:

The first character is either "A" which is for lower toxicity or "B" which is for higher toxicity.

The second character is either "1" for no flame propagation, "2" for lower flammability, or "3" which is for higher flammability.

It is brief in table 2-1 below.

Table -1: Safety classification of working fluids

	Lower toxicity	Higher toxicity
Higher flammability	A3	B3
Lower flammability	A2	B2
No flame propagation	A1	B1

2. Literature review

Irjet Xiaojun Zhang et al. (2016) have studied Steam Rankine Cycle (SRC), Organic Rankine Cycle (ORC), and Steam-Organic Rankine Cycle (S-ORC) power systems, and also, they developed a fine mathematical model to examine the viability of generating electricity by mixing low-boiling-point organic working fluids with fluid-low temperature (150-350 °C) waste heat steam. They measured and compared the thermal efficiency, exergy efficiency, operating pressure, producing capacity, etc. of three power systems—SRC, ORC, and S-ORC—under identical heat source circumstances using numerical models. The researchers conclude that the organic Rankine cycle has the maximum thermal efficiency, energy efficiency, and power generation under conditions of a heat source between 150 and 210 °C, whereas the S-ORC performs noticeably better between 210 and 350 °C. Compared to the SRC and ORC power systems, it has better exergy and thermal efficiency.

Carlo Carcascia et al. (2016) have studied an organic Rankine Cycle combined with an intercooler gas turbine. In this study, they carried out thermodynamic analyses using four different types of organic fluids which are namely toluene, benzene, cyclopentane, and cyclohexane. They found that the organic rankine cycle can be a promising choice for waste heat recovery at low to medium temperatures. Low exhaust temperature is a characteristic of an intercooler gas turbine, and the Organic Rankine Cycle, which may operate at temperatures lower than those of a Rankine cycle, may offer an exciting way to raise the power plant's efficiency. The result shows that using benzene and cyclohexane, the power of combined power plant can be increased of about 20.4 MW and the electric efficiency of the combined plant can reach 54.4%. Results show that toluene and cyclopentane are not the right fluid choice for this plant configuration.

H.M.D.P. Herath et al. (2020) have studied the organic Rankine cycle's performance for seven working fluids which are R-134a, R-245fa, Benzene, Methanol, Ethanol, Acetone, and Propane. Work Results of the study show that Benzene and Methanol-based ORC systems perform more efficiently compare to the other working fluids considered in the analysis and, they require lower fluid mass flowrates per unit of power generation compared to other fluids used in the analysis.

Peter Arvay et al. (2011) This study shows calculations and quantitative results for theoretical organic rankine cycle operation. These calculations include the system's energy production at various waste heat temperatures. Economic cost calculations are also provided to determine the straightforward payback period for various system sizes. The necessity of year-round functioning is shown by the examination of two prospective applications. Additionally, the viability of organic rankine cycles in sectors with consistent low-grade waste heat is assessed using existing technology. The list includes a wide range of additional models as well as several instances of plug-and-play devices. Some of these plug-and-play models serve to highlight how simple it is to execute and how quickly it might be done. Numerical analysis and various case studies are used to prove that an organic rankine cycle can be a useful and economical means of waste heat recovery.

Alison Auld et al. (2013) have studied theoretical organic Rankine cycles powered by three different waste heat sources. The heat sources that are all found in industrial processes span range of energy scales capable of powering the organic Rankine cycle from 10 kW to 10 MW. A novel method of pinch point analysis is presented in this study, allowing variable heat input to the organic rankine cycle. The results show that, at a constant ORC working fluid mass flow rate, fluid selection has no effect on the ORC's ability to recover waste heat. However, the ORC working fluid selection influences the turbine inlet temperature at which the highest work production is obtained.

Alok Manas Dubey et al. (2018) have studied complete survey of ORC literature that includes ORC configurations, applications, modelling, and optimization. Internal regeneration, solution circuit, vapour liquid ejector, two stage evaporation, and double pressure have all been extensively researched and analysed in terms of organic Rankine cycle performance and optimization. Result shows that the double-pressure ORC system has a better performance than single-pressure ORC system.

B. Vanslambroucka et al. (2012) In this work, they compare the cycle efficiency of a simple steam Rankine cycle with an organic Rankine cycle using thermodynamic analysis. They investigate some of the most often employed organic fluids, including R245fa, toluene, pentane, cyclopentane, Solkatherm and two silicon oils, and they study the application area of several working fluids based on their physical features (MM and MDM). Computer simulations allow them to see the impact of many process factors, temperatures at the turbine's inlet and condenser, isentropic efficiency, vapour quality, pressure, and the presence of a regenerator. They also show that the condenser circumstances and the heat source's temperature level are the key determinants of thermal efficiency and that the heat source's temperature profile is the main constraint on the evaporation temperature and pressure levels. Finally, they discuss a few broad and financial factors that may affect the decision between an ORC and a steam cycle. The following are the key findings they derive from this study. First, ORCs may work in conjunction with low temperature heat sources with low to moderate evaporation pressure and still surpass steam cycles. Next, because of their increased mass flow, ORCs require larger feed pumps, which affects the net electric power.

G Eryanto1 et.al (2018) In this research study, Engineering Equation Solution (EES) simulation program is used to run the system in operation conditions. A reasonable study is conducted using the organic rankine cycle (ORC), Regenerative organic rankine cycle (RORC), and RORC with Internal Heat Exchanger (IHE). After the experimental work results show that RORC with IHE has the highest value for both energy efficiency (21.74%) and exergy efficiency (25.26%) while net power formed 5479 kW. This shows the addition of IHE can growth these factors, improve performance and decrease energy degradation from the cycle.

Sylvain Quoilin et al. have studied an overview of the present state of the art in the organic rankine cycle technology and disclosures the main target applications. The modeling of such a cycle is described and issues such as fluid selection, optimization, or control of the cycle are systematically reviewed.

Chen et al. (2010) conducted a review of 35 subcritical and supercritical working fluids. Their findings indicate that low-critical-temperature wet fluids like R-32, R-125, and R-143a are promising for the supercritical Rankine cycle. Isentropic fluids may be employed in both subcritical and supercritical Rankine cycles without requiring the superheating that wet fluids require due to turbine difficulties. Isentropic fluids having critical temperatures exceeding 125°C include R-141b, R-123, R-21, R-245ca, R-245fa, R-236ea, and R-142b. In the case of low temperature heat sources, their utilization is recommended in subcritical cycles rather than supercritical cycles. Both subcritical and supercritical Rankine cycles can utilize dry fluids. Superheating is not recommended in the first situation. Their findings also indicate that isentropic and dry fluids are preferable in subcritical Rankine cycles.

Hanzhi Wanga et al. (2016) have studied, hydrofluoroethers, such as HFE7000, HFE7100, and HFE7500, were used as working fluids under constant environmental conditions to analyze the organic Rankine cycle. To parametrically evaluate the first and second law efficiencies, power output, and turbine size factor with an increase in turbine entrance temperature, they developed computer program. The results reveal that HFE7000 performs better given the net power production under the specified operating circumstances and generates the highest thermodynamic efficiencies. Furthermore, when compared to HFE7100 and HFE7500, HFE7000 has the lowest turbine size factor. As a result, it is suggested that HFE7000 be utilized as the working fluid in ORC to generate electricity from low-grade heat.

Suyog S. Bajaj et al. (2016) have studied organic rankine cycle system with due consideration to the working fluids and its applications in the waste heat recovery system. An organic rankine cycle is a device that can transform thermal energy into mechanical work and then electricity at relatively low temperatures between 80 and 350 °C. It can significantly contribute to enhancing the energy efficiency of both new and current energy-intensive applications.

Lakew and Bolland (2010) investigated the efficiency of several working fluids in a straightforward ORC cycle, including R-134a, R-123, R-227ea, R-245fa, R-290, and n-Pentane. They determined the heat exchanger and turbine's necessary sizes. R-227a had the highest power output when the heat source temperature was between 80 and 160°C, while R-134 offers a comparable figure. The most productive material was R-245fa when the source temperature was more than 160°C. They discovered that R-134a required a larger area on the heat exchanger surfaces.

Toffolo et al. (2010) have studied ORC system's off-design model that was aimed at the best-operating conditions. Thermal sources for the system were deemed to be geothermal sources with temperatures between 130 and 180°C. Working media were regarded as R-134a and isobutane. They supported the finding that the R-134a supercritical cycle outperformed the isobutane subcritical cycle under non-design circumstances.

Sauret and Rowalds (2011) have studied 150°C geothermal heat source using five different fluids: R-134a, R-143a, R-236fa, R-245fa, and n-Pentane. They were chosen based on a balance of desirable parameters, including low flammability, low toxicity, and relatively inert behaviour, as well as their theoretical thermodynamic performance. The result shows that the R-134a-based cycle had the best performance.

He et al. (2012) proposed theoretical formula to determine the working fluids ideal evaporation temperature used in a simple subcritical Rankine cycle. It was thought that net power production was an objective function. The heat source had a temperature of 150 °C. They looked at 22 different fluids, and the best options they found were R-114, R-245fa, R-123, R-601a, n-pentane, R-141b, and R-113.

Quoilin et al. (2013) have studied an overview of the numerous working fluids suggested by previous investigations in the literature, noting the temperature at which they were studied for evaporation and condensation. The result shows that when the evaporation temperature is near 100°C, fluids like R-123, R-124, ammonia, pentane, R-152a, R-245ca, R-290, and R-600 may be appropriate. For temperatures around 120°C, R-113, R-227ea, R-236ea, R-245fa, and n-hexane were recommended; for temperatures around 150°C, R-123, R-236ea, R-245ca, and R-245fa were recommended.

Macian et al. (2013) investigated a waste heat recovery system for heavy duty vehicle engines. Working fluids were assumed to be water and R-245fa. R-245fa was chosen because it can be used to utilise low-temperature heat source. The results showed that water resulted in a greater power production due to the ability to better utilize the high temperature heat produced by the exhaust gas. However, due to the lower space requirements, the cycle with R-245fa was chosen the most practical alternative. The organic cycle's highest evaporation temperature was 150°C.

Wang Z.Q. et al. (2012) presented a working fluid selection method in which the heat exchanger area per power output unit and the heat recovery factor were used as screening criteria. The heat recovery factor was defined as the ratio between the exploited energy and the available energy of the heat source. They considered 13 different fluids, with R-123 being the best choice for heat sources with temperatures ranging from 100 to 180°C, and R-141b being the best choice for heat sources with temperatures more than 180°C.

Dai et al. (2009) investigated the performance of ten different working fluids in a simple subcritical Rankine cycle for waste heat recovery system. An evaporator, a turbine, a condenser, and a pump were all part of the system. The usage of an internal regenerator was also studied. They identified R-236ea as the fluid with the highest exergy efficiency under a waste heat source temperature of 145°C. They also indicated that a regenerator cannot increase the system's performance.

3. CONCLUSION

In this study article, a literature review of the organic rankine cycle system has been presented. The choice of working fluids for organic rankine cycle applications has been systematically reviewed in this paper. It has been explored how to choose pure and azeotropic working fluids for the organic rankine cycle. When selecting the most appropriate organic working fluid, it is crucial to take into account its thermophysical characteristics, stability, environmental impacts, safety and compatibility, availability, and cost. An overview of the organic rankine cycle technology is provided in this research article.

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