Thermodynamic analysis on ORC by using various refrigerants and refrigerant blends at various operating conditions

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ABSTRACT

This study primarily focuses on Organic Rankine Cycle (ORC) systems and their applications in low temperature waste heat recovery. With the harmful effects of CO$_2$ coming to light and the ever increasing prices of fossil fuels, the importance of low grade heat recovery has grown significantly in the past few years. Several ORC solutions have been proposed to generate electricity from low temperature sources. The ORC systems discussed in this study have applications in various fields such as small-scale cogeneration solar thermal system, exhaust gases from the engine, domestic boilers, etc.

This piece of work presents a thermodynamic analysis for the use of ORC systems to utilize exergy energy or low grade energy to generate power. The working fluids used in this analysis are R12, R113, R134a, R141b, R245ca, and R245fa with pressures ranging from 5 kPa to 1.005 MPa. Here, both the 1st and 2nd laws of thermodynamics have been analyzed by varying system independent parameters at various reference pressures. This paper aims at picking out the most suitable working fluid for the Organic Rankine Cycle among the ones mentioned.

List of symbols

P = pressure [kPa]
Q$_e$ = heat rate [kW]
S = entropy [kJ/(kg K)]
T = temperature [K]
W$_e$ = work [kW]
C$_p$ = specific heat [kJ/(kg K)]
\[I=\text{exergy destruction [kW]}\]
\[N_{th}=\text{thermal efficiency}\]
\[N_{sl}=\text{second law efficiency}\]

1. **Introduction**

Over the last few decades, the world has gone through drastic economic growth. The industrial development has led to an increased energy demand across the globe. The increasing number of vehicles on road and the use of other energy-consuming equipment has further fueled this need for more energy. This demand has mostly been met by an unchecked consumption of fossil fuels which has caused numerous environmental hazards such as global warming, atmospheric pollution, etc. To tackle this, numerous solutions have been proposed worldwide to generate electricity from alternative sources of energy, like low temperature or low power heat sources. Among them, the Organic Rankine Cycle (ORC) system is by far the most suitable alternative to generate power. The components used by this system are a boiler, a work producing expansion device, a condenser and a pump similar to a steam power. However, in case of ORC systems, the working fluid used is an organic substance having a lower boiling point as compared to water and is one which allows power generation from low heat source temperatures.

One major achievement of the ORC system and technology was that with little variations, an analogous ORC system can be used in conjunction with multiple heat sources. The Ongoing technical development of its components, having wide applications in refrigeration, has proved to be extremely helpful for this technology. This technology makes local and small scale power generation possible unlike the other conventional power cycles. These days, OCR systems are easily available commercially in the power range of Megawatts. However, to this day, only a few well suited solutions are known for the kW scale. This chapter attempts to present an overview of the current scenario in the field of ORC technology and dives into its various applications. This cycle is discussed and important issues underlying its use such as optimization, cycle control and fluid selection are closely reviewed.

1.1 **Overview of Rankine Cycle**

The traditional vapor cycle system makes use of water as its main working fluid. It was developed at first as a “Steam Engine”, in which the water is compressed, vaporized, expanded and then subsequently rejected to the atmosphere.

These days, we generally prefer closed-loop cycles, for example the Clausius Rankine cycle which is shown in Figure 1. Here, the liquid water (at point 6) is first pressurized (6-1), heated (1-2) up to the evaporation temperature, vaporized (2-3), and finally superheated (3-4). Mechanical work in the turbine is produced by bringing down the high pressure vapor to the condensing pressure. At last, the cycle is closed through recondensation (5-6) of the low pressure vapor.
Figure 1.1: Working principle of the Clausius Rankine cycle

Figure 1.2: $T$-$s$ diagram of the Rankine Cycle

A $T$-$s$ diagram (Figure 2) is best suited for further analysis since it’s the best at representing the irreversibility in the heat exchangers as well as the turbine. The various phases of the cycle are described below:

6-1: Liquid compression (in the pump): Points 1 and 6 almost completely coincide on the $T$-$s$ diagram. It’s because if the fluid is incompressible and the pump is isentropic, there will be no increase in entropy and the temperature will remain constant as well.

1-2: Liquid Pre-heating: This transformation is isobaric in the ideal cycle and results in an increase in the temperature and entropy.

2-3: Vaporization: The saturation temperature of the liquid is reached and boiling starts resulting in an increase in entropy as the temperature remains constant.

3-4: Superheating: Inside the boiler, the vapor undergoes superheating and results in an increase in the temperature and entropy.

4-5: Expansion: In an ideal cycle the expansion is isentropic making the line 4-5 vertical. The entropy increases due to the irreversibilities in the real cycle.
5-6: Condensation: At the end of expansion, the vapor starts condensing until only liquid is left resulting in an increase in entropy while the temperature remains constant.

In general, the energy consumed by liquid compression consumes much less energy than in the case of a gas. Therefore, in the rankine cycle, the pump consumption is smaller as compared to the electricity generated by the turbine and the net power generation is found to be positive. The efficiency of the cycle is given by the ratio of net output power to the heat flow in the boiler:

The efficiency is typically found close to 30% for the basic cycle presented in Figure 1 and 2.

1.2 Overview of Organic Rankine Cycle

The utilization of low grade waste heat has attracted great interest ever since the rise in concerns of depletion of fossil fuels and global warming.

Such issues can be resolved by efficient energy storage along with the use of low grade renewable energy. The researchers have proposed numerous solutions to convert low grade heat sources into electricity through various thermodynamic cycles, such as the organic rankine cycle, triangle cycle, super critical CO\textsubscript{2} cycle, kalina cycle, and heat pipe technology.

Out of those, ORC is a comparatively more practical way of waste heat recovery, and has been used in many industrial applications. Numerous studies have been done in order to improve the ORC to recover and utilize heat from various heat sources, for example solar energy, geothermal sources and exhaust gas from internal combustion engines.

2. Literature review

The list of ORC applications is ever growing, for example in terms of heat source temperature (ranging from around 100 °C to 300 °C and more), power (ranging from kW to multi MW) or heat source nature (solar, geothermal, waste heat recovery, Biomass, etc.)

For all these applications, a screening of the available working fluids is done, followed by a thermodynamic analysis of their performance for each application.

The work proposes a comparison in terms of thermodynamic performance among a group of working fluids based on a thermodynamic model of the cycle.

For the most common expansion machines, a detailed analysis is then done by analyzing their respective operating maps for all fluids and application types.

2.1 Inference from literature review

The working fluid selection and expansion machine analysis should hence be done during the same process. Similarly, all kinds of expansion machines are not suitable for the imposed working conditions when the working fluid is finally selected.

The positive displacement expander’s maximum internal built in volume ratio is generally not more than 5 and most of the ORC systems function at volume ratios which are much higher.

The prime focus of the approach of the proposed operating map is on the interaction between the working fluid and the expansion machine. It gives operating maps leading to acceptable component sizes efficiencies.
2.2 The effects of working fluids on organic rankine cycle for waste heat recovery

The effects of different working fluids on the thermal and second law efficiencies have been thoroughly investigated. In certain molecules such as water, ammonia, ethanol, the presence of hydrogen bonds is regarded inappropriate as it may result in wet fluid conditions because of the larger vaporization enthalpy. At the appropriate evaporating temperature between the inlet of waste heat and condensing temperature, the maximum value for the second law efficiency is achieved. The second law efficiency is observed to increase along with the inlet temperature and decreases when working fluids of lower critical temperature are used.

2.3 Inference

The study shows that R113 if used can give higher efficiency in an organic Rankine cycle for both first and second law. The plots on various parameters provide a clear picture of performance of various refrigerants under the chosen system operating conditions. The thermal efficiency and second law efficiency have opposite trends with high and low pressure condition. The operating conditions at the intersection points of the second law and thermal efficiency curve are used to find the optimal balance between both these factors. Refrigerant R113 has the highest critical temperature of 427K, R12- 384.9K, R134a -373.95K, R245ca-418K.

3. Components of Rankine cycle

The Various Components of Organic Rankine Cycle (Fig. 1) are:

- Boiler
- Turbine
- Condenser
- Pump

![Figure 1. Rankine Cycle](image)

3.1 Boiler

A Boiler is a heat exchanger where fuel like coal, oil or lignite transfers the heat to water at constant pressure. Water enters at state-1 from the boiler feed pump in form of a compressed liquid and is heated to the saturation temperature (state 3).

The energy balance in the boiler is as follows:
\[ q_{in} = h_3 - h_1 \]

3.2 Turbine

At state 3, the vapor enters the turbine from the boiler outlet, and expands isentropically over the turbine to produce work in the form of rotation of the turbine shaft which is in turn connected to an electrical generator. Neglecting heat transfer with surroundings, the work done by turbine is given by,

\[ W_{\text{turbine\_out}} = h_3 - h_4 \]

3.3 Condenser

Phase change takes place as the vapor enters the condenser and is condensed to liquid form at constant pressure at state 4. This is done by transferring the heat from the steam to the flowing water in the tubes of the condenser. The working fluid leaves the condenser in liquid state at point 5.

Energy rejected in the condenser is given by,

\[ q_{\text{out}} = h_4 - h_3 \]

3.4 Pump

At state 5, water enters the pump after exiting the condenser. The pump then imparts work and raises the pressure of the water. This work is small and can thus be neglected as compared to the work output of the steam turbine. Work done per kg of water on pump is given by,

\[ W_{51} = h_5 - h_1 \]

4. Working fluids

The Organic Compounds having high molecular mass and considered safe for environmental use by ASHRAE are used as Working Fluids for ORC’s. They are categorized into three wide categories namely dry, wet and isentropic according to the slope of the T-s curve (dT/dS) being positive, negative and infinite respectively (Fig. 2). The working fluids used for Organic Rankine Cycle have lower boiling temperature, Large flow rate and high molecular mass.

The Organic fluids have the following advantages:

- The achieved turbine efficiencies are higher due to the higher mass flow rate (leakage decreases)
- The operation is low maintenance
- There is good part load behavior

4.1 Selection of Working Fluids

Crucial characteristics of a good working fluid are good material compatibility, low toxicity, good fluid stability limits, and low flammability, corrosion, and fouling characteristics. Refrigerants are suitable candidates for ORC applications due to their low-toxic characteristics. Another characteristic that must be considered during the selection of an organic fluid is its saturation vapor curve. This characteristic affects the cycle efficiency, fluid applicability, and arrangement of the associated equipment in a power generation system. Dry fluids correspond to a positive slope; wet fluids to a negative slope, while an isentropic fluid has infinitely large slope. Isentropic and Dry fluids showcase better thermal efficiencies as they don’t condense after the fluid passes through the turbine as opposed to the wet fluids that produce condensates after passing through the turbine.

4.2 Selected Working Fluids
The working fluids under investigation for Thermodynamic analysis of Organic Rankine cycle are R12, R113, R134a, R141b, R245ca, R245fa with pressures from 5 kPa to 1.005 MPa.

![Comparison of the working fluids: (a) isentropic, (b) wet, and (c) dry]

**Figure 2.** Selection of working Fluid

### 4.3 PROPERTIES OF REFRIGERENTS

| Refrigerant | Name                          | Molecular Mass | Boiling Point at Atmospheric Pressure (°F) | Freezing Point at Atmospheric Pressure (°F) | Critical Temperature (°F) | Critical Pressure (psi) |
|-------------|-------------------------------|----------------|--------------------------------------------|-------------------------------------------|--------------------------|-------------------------|
| R12         | Dichlorodifluoromethane       | 120.9          | -21.8                                      | -252                                      | 234                      | 597                     |
| R113        | 1,1,2-trichloro-1,2,2-trifluoromethane | 187.3           | 118                                        | -31                                       | 417                      | 499                     |
| R134a       | 1,1,1,2-tetrafluoroethane     | 102.0          | -15                                        | -142                                      | 214                      | 590                     |
| R141b       | 1,1-dichloro-1-fluoroethane   | 116.95         | 89.6                                       | -154                                      | 399.83                   | 610.8                   |
| R245ca      | 1,1,2,2,3-pentafluoropropane  | 134            | 58.8                                       | -160                                      | 308.9                    | 529.5                   |
| R245f       | 1,1,1,3,3-pentfluoropropane   | 134.0          | 78.8                                       | -160                                      | 310                      | 554                     |


5. Graphs and interpretations

Figure 3. Average Efficiency Plot (2nd law efficiency)

Figure 4. Average efficiency plot (thermal efficiency)

It can easily be seen from figure 3 and 4 that, the average second law efficiency and thermal efficiency for various refrigerants reveal that R113 has highest efficiency for both of them, followed by R141b, R134a, R12, R245fa, and R245ca. Hence, the study shows that R113 is the best working fluid for ORC in the operating parameters chosen for study.
Figure 5. High pressure vs Second law efficiency

Figure 5 clearly shows that, as the high pressure is increased for the organic Rankine cycle, the second law efficiency for all the refrigerants taken for study follows a decreasing trend. The slope for each refrigerant remains more or less the same, meaning the rate of decrease of efficiency with increasing high pressure remains same. The abrupt behavior for R245fa could be accounted by the presence of an extra hydrogen bond, which increasing the overall enthalpy of vaporization.

Figure 6. High pressure vs Thermal efficiency

Figure 6 clearly shows that, as the high pressure is increased in for a Rankine cycle, thermal efficiency shows contrasting trend from second law efficiency i.e. it increases with increase in high pressure. Rate of increase of efficiency is same for all refrigerants with R113 having highest efficiency amongst all.
Figure 7. Low pressure vs Second law efficiency

Figure 7 clearly shows that, the second law efficiency increases with increase in low pressure, though the increase is not as prominent as for high pressure curve. R113 shows highest performance efficiency compared to other refrigerants.

Figure 8. Low pressure vs Thermal efficiency

Figure 8 clearly shows that, the thermal efficiency decreases with increase in low pressure and the change is highly prominent. Rate pf decrease of efficiency is same for all the refrigerants and R113 again has highest efficiency.

6. Conclusion

It is found through the above Thermodynamic analysis of The Organic Rankine Cycle for the selection of working fluid that under the chosen operating conditions R113 serves as the best working fluid for both thermal and second law efficiency among the others (R12, R134a, R141b, R245ca, and R245fa). The thermodynamic analysis shows that second law efficiency and thermal efficiency show contrasting trends for same operating conditions hence using the operating Conditions at the intersection points of the thermal and second law Efficiency curve would lead to
the optimal balance between the two. The efficiency of various refrigerants is affected by the presence of hydrogen bond in the molecular structure as it increases the overall enthalpy of vaporization for the molecule, hence requiring more energy to boil the working fluid. Therefore it is advised that the working fluid should have minimum number of hydrogen bonds. The selection of working fluid should also take into consideration the expansion device and other components, as they both have to work in sync for better system output and longer life.

References

[1] Anh Tuan Hoang, Waste heat recovery from diesel engines based on Organic Rankine Cycle, Applied Energy, Volume 231, 2018, ISSN 0306-2619.
[2] Byung-Sik Park, Muhammad Usman, Muhammad Imran, Apostolos Pesyridis, Review of Organic Rankine Cycle experimental data trends, Energy Conversion and Management, Volume 173, 2018, Pages 679-691, ISSN 0196-8904.
[3] A. Mahmoudi, M. Fazli, M.R. Morad, A recent review of waste heat recovery by Organic Rankine Cycle, Applied Thermal Engineering, Volume 143, 2018, Pages 660-675, ISSN 1359-4311, [https://doi.org/10.1016/j.applthermaleng.2018.07.136](https://doi.org/10.1016/j.applthermaleng.2018.07.136).
[4] Kiyarash Rahbar, Saad Mahmoud, Raya K. Al-Dadah, Nima Moazami, Seyed A. Mirhadizadeh, Review of organic Rankine cycle for small-scale applications, Energy Conversion and Management, Volume 134, 2017, Pages 135-155, ISSN 0196-8904.
[5] Muhammad Imran, Fredrik Haglind, Muhammad Asim, Jahan Zeb Alvi, Recent research trends in organic Rankine cycle technology: A bibliometric approach, Renewable and Sustainable Energy Reviews, Volume 81, Part 1, 2018, Pages 552-562, ISSN 1364-0321.
[6] Arnaud Landelle, Nicolas Tauveron, Philippe Haberschill, Rémi Revellin, Stéphane Colasson, Organic Rankine cycle design and performance comparison based on experimental database, Applied Energy, Volume 204, 2017, Pages 1172-1187, ISSN 0306-2619, [https://doi.org/10.1016/j.apenergy.2017.04.012](https://doi.org/10.1016/j.apenergy.2017.04.012).
[7] Mirko Z. Stijepovic, Patrick Linke, Athanasios I. Papadopoulos, Aleksandar S. Grujic, On the role of working fluid properties in Organic Rankine Cycle performance, Applied Thermal Engineering, Volume 36, 2012, Pages 406-413, ISSN 1359-4311.
[8] Mirko Z. Stijepovic, Patrick Linke, Athanasios I. Papadopoulos, Aleksandar S. Grujic, On the role of working fluid properties in Organic Rankine Cycle performance, Applied Thermal Engineering, Volume 36, 2012, Pages 406-413, ISSN 1359-4311.
[9] E.H. Wang, H.G. Zhang, B.Y. Fan, M.G. Ouyang, Y. Zhao, Q.H. Mu, Study of working fluid selection of organic Rankine cycle (ORC) for engine waste heat recovery, Energy, Volume 36, Issue 5, 2011, Pages 3406-3418, ISSN 0360-5442.
[10] Takahisa Yamamoto, Tomohiko Furuhata, Norio Arai, Koichi Mori, Design and testing of the Organic Rankine Cycle, Energy, Volume 26, Issue 3, 2001, Pages 239-251, ISSN 0360-5442, [https://doi.org/10.1016/S0360-5442(00)00063-3](https://doi.org/10.1016/S0360-5442(00)00063-3).
[11] Seok Hun Kang, Design and experimental study of ORC (organic Rankine cycle) and radial turbine using R245fa working fluid, Energy, Volume 41, Issue 1, 2012, Pages 514-524, ISSN 0360-5442, [https://doi.org/10.1016/j.energy.2012.02.035](https://doi.org/10.1016/j.energy.2012.02.035).
[12] Arnaud Landelle, Nicolas Tauveron, Philippe Haberschill, Rémi Revellin, Stéphane Colasson, Organic Rankine cycle design and performance comparison based on experimental database, Applied Energy, Volume 204, 2017, Pages 1172-1187, ISSN 0306-2619, [https://doi.org/10.1016/j.apenergy.2017.04.012](https://doi.org/10.1016/j.apenergy.2017.04.012).