Rajeev Kumar et al. 2019, 7:6
ISSN (Online): 2348-4098
ISSN (Print): 2395-4752

International Journal of Science, Engineering and Technology

An Open Access Journal

Performance Analysis of Organic Rankine Cycle (Orc) For Waste Heat Recovery with Different Refrigerant

M.Tech. Scholar Rajeev Kumar
Department of Mechanical Engineering,
PIES Bhopal, MP, India

Prof. Brijendra Yadav
Department of Mechanical Engineering
PIES Bhopal, MP, India

Abstract- In recent years, fossil fuel consumption increases steadily and the excessive utilization of the fuel energy could generate environmental problems such as global warming, ozone layer depletion, air pollution and acid rain. In addition, the energy conversion from primary energy into electricity is low and 60–70% of the energy is lost in terms of waste heat thus the waste heat recovery is necessary to increase the overall energy conversion efficiency. Organic Rankine cycle (ORC) is a promising technology for low grade waste heat recovery.

Keywords- ORC, Heat Source Temperature, thermo-economic analysis.

I. INTRODUCTION

Fossil fuel consumption in the recent years has been increasing and the burning of fossil fuel is said to be a major contributor towards global warming, acid rains, air, water and soil pollution, forest devastation and radioactive substances emissions. Besides the environment, the fossil fuel prices fluctuate considerably, usually going up, with the price of liquid hydrocarbons well over USD 4/gallon in US, and more expensive in most other countries. Most importantly, the quantity of fossil fuels, like petroleum, natural gas and coal can only decrease since they are non-renewable energy resources.

As a result, many countries have been investing billions dollars in new energy technologies and demand for sophisticated power supply options is greatly increased. Currently, recovering low temperature heat, which includes industrial waste heat, geothermal energy, solar heat, biomass, and so on, could be a very critical and sustainable way to solve energy crisis. Comparing to industrial waste heat, geothermal energy and biomass, solar energy has advantages over them due to its usability and low-cost. Utilizing waste heats along with attempts for the use of renewable resources as low grade thermal heat sources have motivated the wider use of ORC. The working principle of an ORC is similar to a Clausius-Rankine steam power plant. However, an ORC system uses an organic working fluid such as R245fa, which is able to condense at a lower pressure and evaporate at a higher pressure. The design of

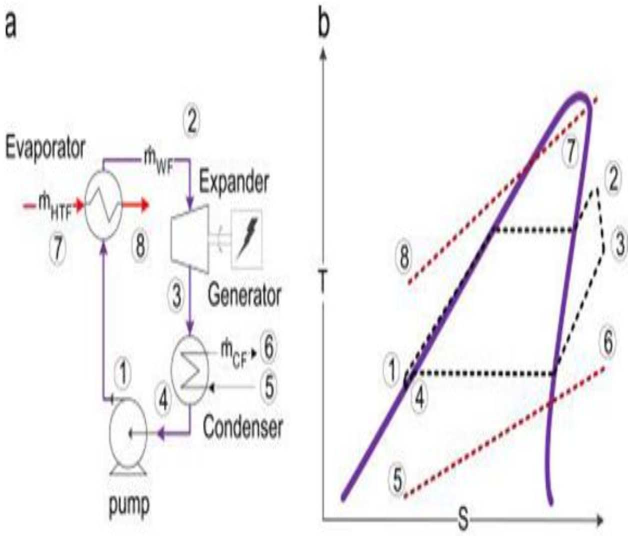


Figure 1: (a) Schematic layout of an ORC system. (b) ORC T-s diagram.

small capacity power systems is capable of recovering a large temperature range of heat sources. Study by Badr et al. states that for low-grade heat sources, an ORC has higher power generation efficiency and is economically viable than that a steam Rankine cycle. Fig. 1.3 (a) illustrates a schematic layout of an ORC system while Fig. 1.3 (b) presents the T-s diagram of the system. The main components of an ORC system comprises of an expander machine, a condenser, a liquid pump and an evaporator.

For a low-grade heat energy conversion system, the conventional steam Rankine cycle cannot achieve both high thermal efficiency and compact system size; thus, it is not an appropriate economic option. This is because a low-grade heat source cannot produce enough steam at high temperatures and pressures required by the steam turbine.

In contrast to the conventional system, an Organic Rankine Cycle (ORC) is a more feasible option for the application of low-grade heat sources in terms of operating parameters, system size and thermal and exergy efficiencies. The working principle of the ORC is similar to Clausius-Rankine steam power plant. However, the system uses an organic working fluid such as R245fa instead, which is able to condense at a lower pressure and evaporate at a higher pressure.

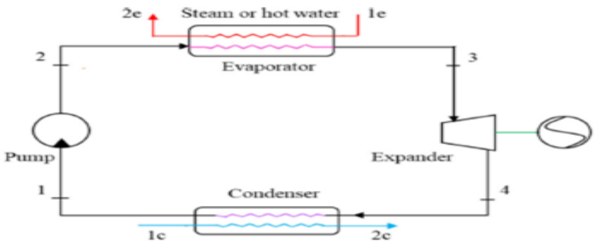
The most challenging aspects of a low-grade energy conversation system design are to select an appropriate working fluid and a highly efficient organic Rankine cycle. Study by Saleh at al. analyzed both subcritical and supercritical ORCs with thirty-one different pure working fluids at a fixed working fluid temperature range.

The thermal efficiencies ranged between 0.36% and 13%, indicating the importance of thermodynamic cycles and working fluid selections. It was also found that supercritical working fluids can receive a greater heat transfer from sensible heat sources such as waste heat compared to those of subcritical ones when considering match able cold and hot side temperature glides in the heat exchanger. Consequently, at the same operating conditions, the working fluid temperature at the turbine inlet will be relatively higher for the supercritical heat addition process and thus will result in higher cycle thermal efficiency.

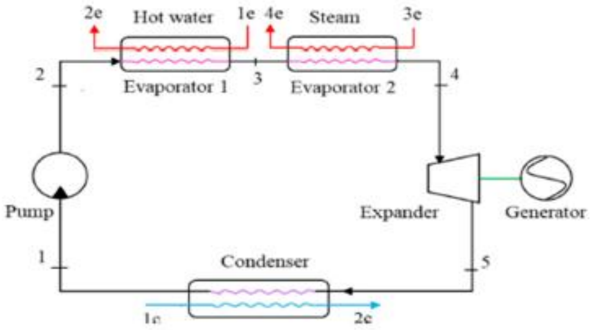
II. METHODOLOGY

1. Schematic Of Organic Rankine Cycle

ORC could be operated with low temperature heat source such as low pressure saturated steam or hot water, but very few study on the external irreversibility during heat exchange with these heat sources at the ORC evaporator has been reported. Higher temperature difference between the heat source and the ORC working fluid results in higher external irreversibility. In this study ,numerical study on the first and the second law performances of a different refrigerant ORC was conducted with different types of heat sources, hot water, saturated steam, and combined hot water/saturated steam having temperature of 80–110 °C. The condensing temperature was kept constant at 40 °C. The pinch (p) between the heat source and evaporating temperatures was varied in a range of 1–10 °C. The effects of the heat source temperatures and the pinch values on the ORC cycle performance were considered. The most suitable heat source at the specified operating conditions was recommended.



(a) Simple ORC cycle with hot water or steam heat source.



(b) Simple ORC cycle with combined hot water/saturated steam heat source.

Figure 2: Simple ORC cycle (Kong et. al. 2019).

2. Thermodynamic cycle

The schematic of a simple ORC cycle is shown in Fig. 3.1(a). The ORC cycle consists of four key components; a pump, a condenser, an evaporator and an expander. During the process, the low pressure working fluid leaves the condenser as saturated liquid (state 1)and it is pumped to the evaporator as high pressure saturated liquid (state 2) at the evaporator. There is heat transfer from the heat source (1e-2e) to the ORC working fluid to get high pressure saturated vapor (state 3).

The high pressure vapor flows into the expander to generate work power. The working fluid leaves the expander as low pressure vapor (state 4) and it is cooled down in the condenser by heat rejection to heat sink (1c-2c). The condensed liquid is pumped to the evaporator to perform a new cycle. Fig. 2(b) also shows the simple ORC cycle when a combined hot water/saturated steam is used as heat source. The evaporator has two units, sensible heat (states 2–3) and latent heat (states 3–4), where hot water and saturated steam are heat sources, respectively.

Fig. 3 shows heat exchange at the evaporator with different kinds of heat sources. It can be seen that the heat source condition could significantly affect the ORC cycle performance due to irreversibility or exergy destruction by heat transfer. When the hot water or the saturated steam heat source is used in Fig. 3(a), the irreversibility is generated due to the temperature difference between the heat sources and the ORC working fluid. The total temperature difference could be reduced by the combined hot water/saturated steam heat source as shown in Fig. 3.2(b) then the irreversibility is reduced.

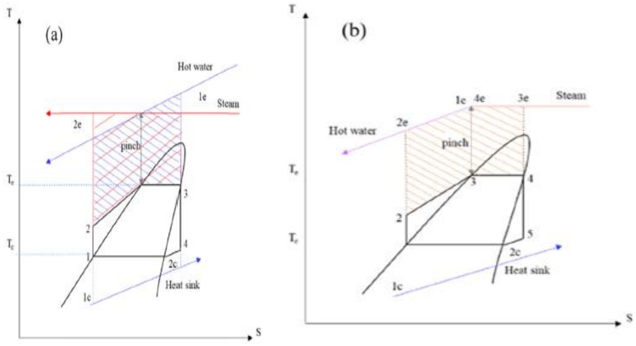


Figure 3: T-s diagrams of ORC cycle with different types of heat sources; (a) hot water or saturated steam heat source, (b) combined hot water/ saturated steam heat source(Kong et. al. 2019).

IV. RESULT AND DISCUSSION

Effect Of Heat Source Temperature On The Performance Of Orc Cycle With Hot Water Or Steam Heat Source

Fig. 4 shows the thermal efficiencies of the ORC for different refrigerant. The mass flow rates of hot water and saturated steam were 2 and 0.2 kg/s, respectively.

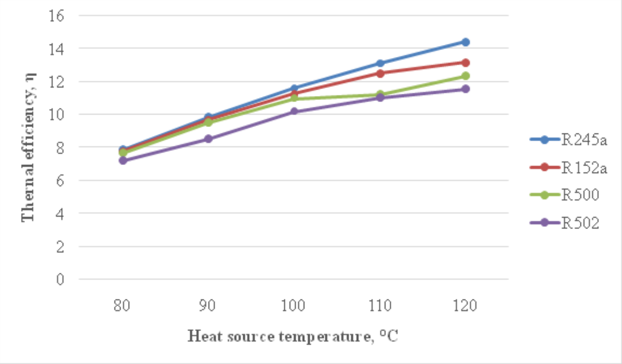


Figure 4: Variation of heat source temperature with thermal efficiency of different refrigerant when steam is used as a heat source.

From the results on the thermal efficiency in Fig. 4, it could be noted that the trend of efficiency for different refrigerant with heat source was similar and the value was increased with the increase of the heat source temperature. Maximum thermal efficiency of ORC was achieved when R245fa was used and lowest is with R502.

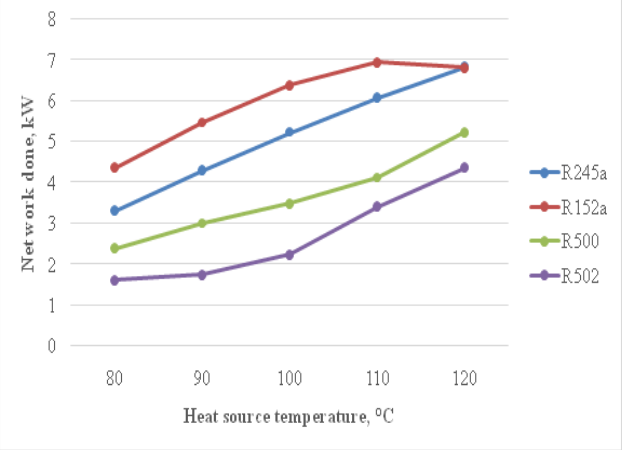


Figure 5: Variation of heat source temperature with net work done of different refrigerant when steam is used as a heat source.

Fig. 5 shows the net work done in the ORC for different refrigerant. The mass flow rates of hot water and saturated steam were 2 and 0.2 kg/s, respectively. It could be noted that the trend of net work donefor different refrigerant with heat source temperature was similar and the value was increased with the increase of the heat source temperature. Maximum net work done in ORC was achieved when R152a was used and lowest is with R502.

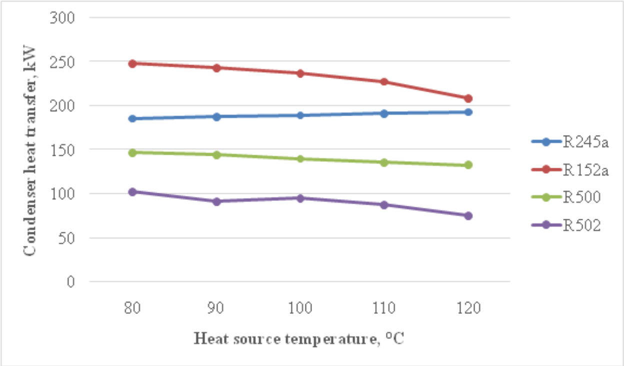


Figure 6: Variation of heat source temperature with condenser heat transfer with different refrigerant when steam is used as a heat source.

Fig. 6 shows the condenser heat transfer in the ORC for different refrigerant. The mass flow rates of hot water and saturated steam were 2 and 0.2 kg/s, respectively. It could be noted that the trend of condenser heat transfer for different refrigerant with heat source temperature was similar and the value was decreased with the increase of the heat source temperature. Maximum condenser heat transfer in ORC was achieved when R152a was used and lowest is with R502.

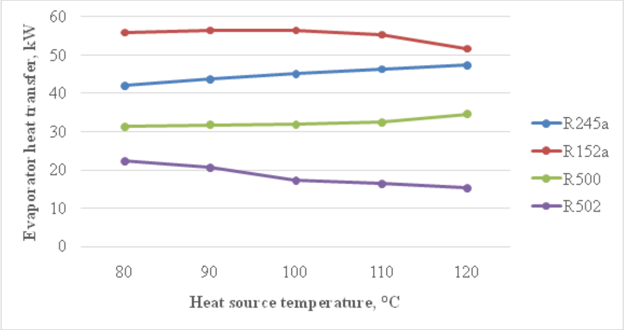


Figure 7: Variation of heat source temperature with evaporator heat transfer for different refrigerant when steam is used as a heat source.

Fig. 7 shows the evaporator heat transfer in the ORC for different refrigerant. The mass flow rates of hot water and saturated steam were 2 and 0.2 kg/s, respectively. It could be noted that the trend of evaporator heat transfer for different refrigerant with heat source temperature was similar and the value was decreased with the increase of the heat source temperature when R152a and R502 was used. Maximum condenser heat transfer in ORC was achieved when R152a was used and lowest is with R502.

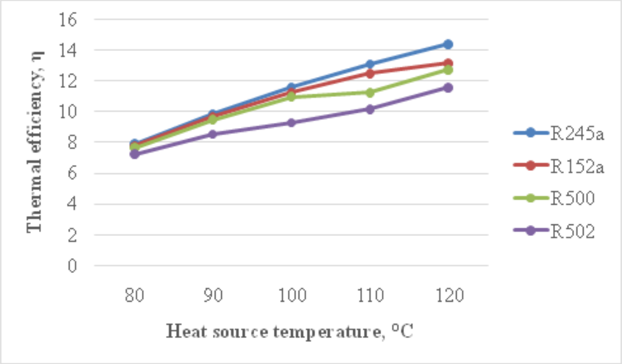


Figure 8: Variation of thermal efficiency with different refrigerant with heat source temperature when hot water is used as a heat source.

Fig. 8 shows the thermal efficiency in the ORC for different refrigerant. The mass flow rates of hot water and saturated steam were 2 and 0.2 kg/s, respectively. It could be noted that the trend of thermal efficiency for different refrigerant with heat source temperature was similar and the value was increased with the increase of the heat source temperature. Maximum thermal efficiencyin ORC was achieved when R245fa was used and lowest is with R502. It is also observed that there was no effect on thermal efficiency with change in heat source from hot water to steam and vice-versa.

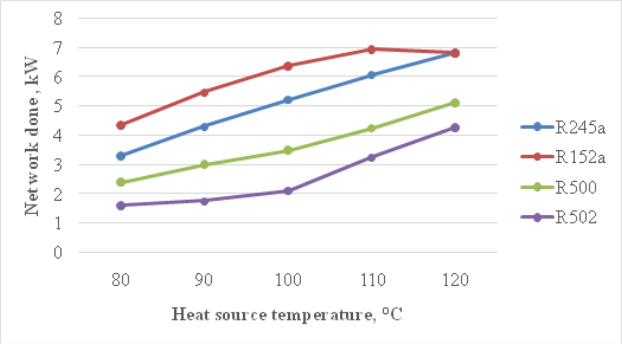


Figure 9: Variation of net work done with different refrigerant with heat source temperature when hot water is used as a heat source.

Fig. 9 shows the net work done for different refrigerant. The mass flow rates of hot water and saturated steam were 2 and 0.2 kg/s, respectively. It could be noted that the trend of net work done for different refrigerant with heat source temperature was similar and the value was increased with the increase of the heat source temperature. Maximum net work done in ORC was achieved when R245fa was used and lowest is with R502.

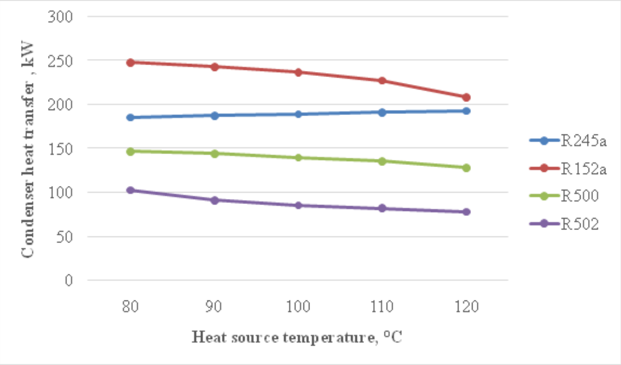


Figure 10: Simulation results of condenser heat transfer of different refrigerant with heat source temperature when hot water is used as a heat source.

Fig. 10 shows the condenser heat transfer for different refrigerant. The mass flow rates of hot water and saturated steam were 2 and 0.2 kg/s, respectively. It could be noted that the trend of condenser heat transfer for different refrigerant with heat source temperature was similar and the value was increased with the increase of the heat source temperature. Maximum net work done in ORC was achieved when R152a was used and lowest is with R502.

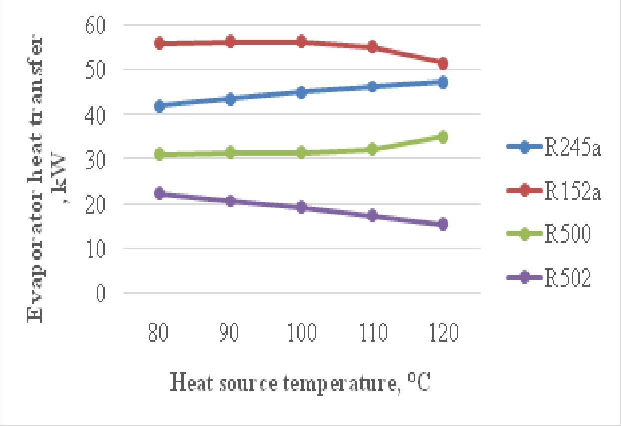


Figure 11: Simulation results of evaporator heat transfer of different refrigerant with heat source temperature when hot water is used as a heat source.

Fig. 11 shows the evaporator heat transfer for different refrigerant. The mass flow rates of hot water and saturated steam were 2 and 0.2 kg/s, respectively. It could be noted that the trend of condenser heat transfer for different refrigerant with heat source temperature was similar and the value was increased with the increase of the heat source temperature. Maximum net work done in ORC was achieved when R152a was used and lowest is with R502.

Effect of Heat Source Temperature On The Performance Of Orc Cycle With Both Hot Water And Steam Heat Source

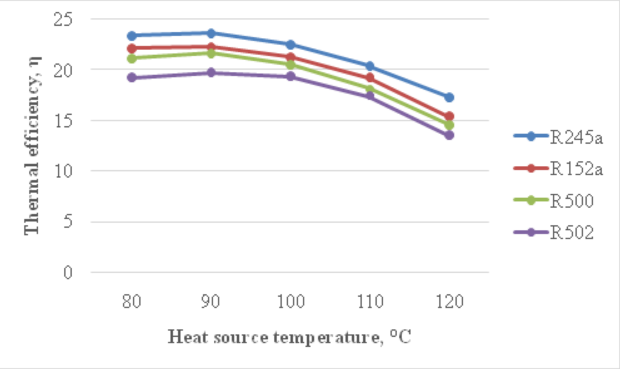


Figure. 12: Variation of thermal efficiency of different refrigerant with heat source temperature when steam is used as a heat source.

Fig. 12 shows the variation of thermal efficiency for different refrigerant. The mass flow rates of hot water and saturated steam were 2 and 0.2 kg/s, respectively. It could be noted that the trend of thermal efficiency of ORC with different refrigerant with heat source temperature was similar and the value was decreased with the increase of the heat source temperature. Maximum net work done in ORC was achieved when R245fa was used and lowest is with R502.

Effect Of Pinch Point Temperature Difference On The Performance Of Orc Cycle With Hot Water Or Steam Heat Source

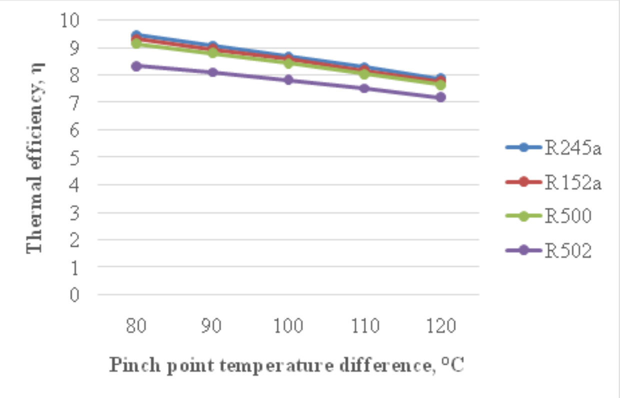


Figure 13: Variation of pinch point temperature differences with thermal efficiency when steam is used as a heat source

The thermal efficiencies of the ORC cycle were numerically studied when the heat source temperature was fixed at 80 °C and the pinch was varied in a range of 2–10 °C. The mass flow rates of hot water and saturated steam were 2 and 0.2 kg/s, respectively. The increase of the pinch value led to the decrease of the thermal efficiencies for different refrigerant. As the pinch temperature difference increased, the ORC evaporating temperature is also reduced then the net useful work (area of 1–2–3–4–5) and the first law efficiency decreased and the combined hot water/saturated steam was still the most suitable heat.

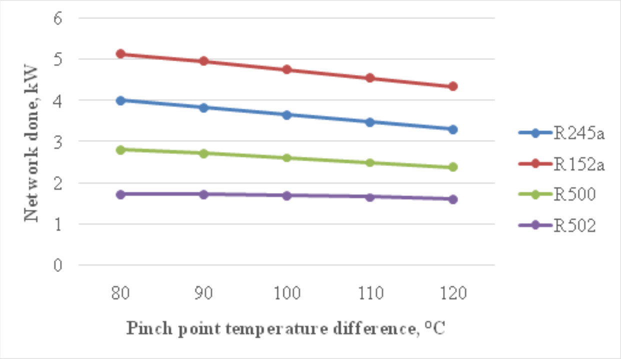


Figure 14: Simulation results of pinch point temperature differences with net work done when steam is used as a heat source.

The net work done of the ORC cycle were numerically studied when the heat source temperature was fixed at 80 °C and the pinch was varied in a range of 2–10 °C. The mass flow rates of hot water and saturated steam were 2 and 0.2 kg/s, respectively. The increase of the pinch value led to the decrease of the thermal efficiencies for different refrigerant. As the pinch temperature difference increased, the ORC evaporating temperature is also reduced then the net useful work (area of 1–2–3–4–5) and the first law efficiency decreased and the combined hot water/saturated steam was still the most suitable heat.

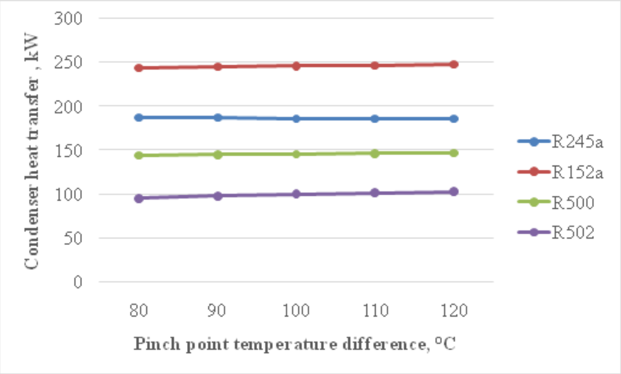


Figure 15: Variation of pinch point temperature differences with condenser heat transfer when steam is used as a heat source.

The condenser heat transfer of the ORC cycle were numerically studied when the heat source temperature was fixed at 80 °C and the pinch was varied in a range of 2–10 °C. The mass flow rates of hot water and saturated steam were 2 and 0.2 kg/s, respectively. The increase of the pinch value led to the decrease of the condenser heat transfer for different refrigerant. As the pinch temperature difference increased, the ORC evaporating temperature is also reduced then the net useful work (area of 1–2–3–4–5) and condenser heat transfer decreased and the combined hotwater/saturated steam was still the most suitable heat.

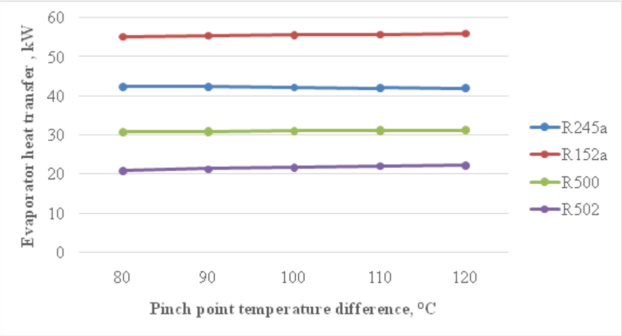


Figure 16: Variation of pinch point temperature differences with evaporator heat transfer when steam is used as a heat source.

The evaporator heat transfer of the ORC cycle were numerically studied when the heat source temperature was fixed at 80 °C and the pinch was varied in a range of 2–10 °C. The mass flow rates of hot water and saturated steam were 2 and 0.2 kg/s, respectively. The increase of the pinch value led to the decrease of the condenser heat transfer for different refrigerant. As the pinch temperature difference increased, the ORC evaporating temperature is also reduced then the net useful work (area of 1–2–3–4–5) and evaporator heat transfer decreased and the combined hot water/saturated steam was still the most suitable heat.

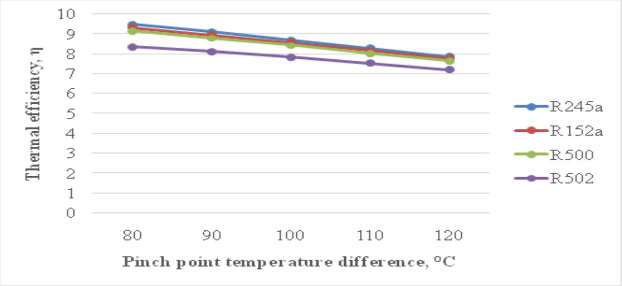


Figure 17: Variation of pinch point temperature differences with thermal efficiency when water is used as a heat source.

The thermal efficiencies of the ORC cycle were numerically studied when the heat source temperature was fixed at 80 °C and the pinch was varied in a range of 2–10 °C. The mass flow rates of hot water and saturated steam were 2 and 0.2 kg/s, respectively. The increase of the pinch value led to the decrease of the thermal efficiency for different refrigerant. As the pinch temperature difference increased, the ORC thermal efficiency is also reduced then the net useful work (area of 1–2–3–4–5) and the combined hot water/saturated steam was still the most suitable heat.

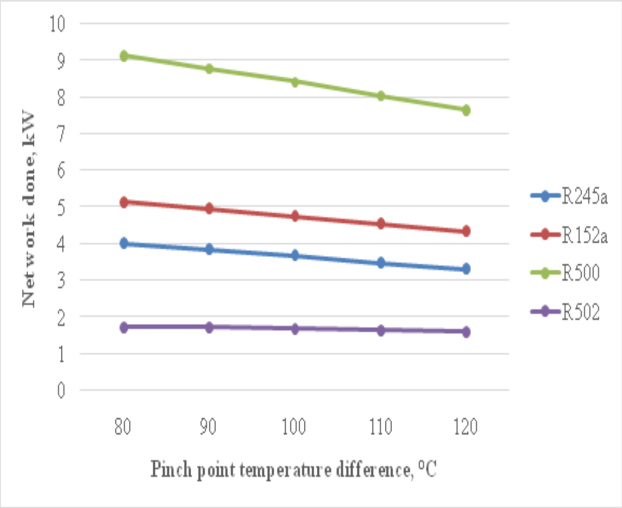


Figure 18: Simulation results of pinch point temperature differences with net work done when water is used as a heat source.

The net work done of the ORC cycle were numerically studied when the heat source temperature was fixed at 80 °C and the pinch was varied in a range of 2–10 °C. The mass flow rates of hot water and saturated steam were 2 and 0.2 kg/s , respectively. The increase of the pinch value led to the decrease of the net work done for different refrigerant. As the pinch temperature difference increased, the ORC thermal efficiency is also reduced then the net useful work (area of 1–2–3–4–5) and the combined hot water/saturated steam was still the most suitable heat.

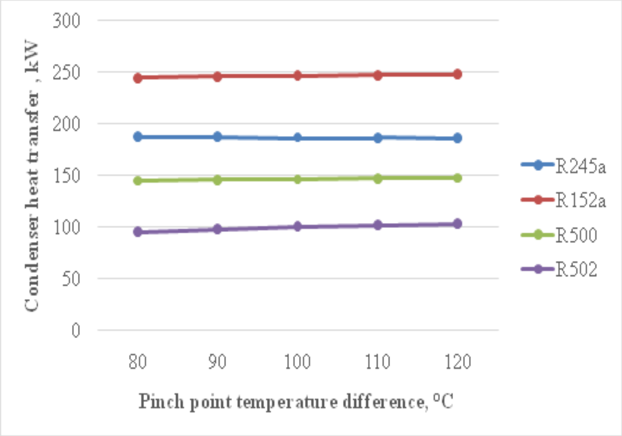


Figure 19: Variation of pinch point temperature differences with condenser heat transfer when water is used as a heat source.

The condenser heat transfer of the ORC cycle were numerically studied when the heat source temperature was fixed at 80 °C and the pinch was varied in a range of 2–10 °C. The mass flow rates of hot water and saturated steam were 2 and 0.2 kg/s, respectively. The increase of the pinch value led to the decrease of the condenser heat transfer for different refrigerant. As the pinch temperature difference increased, the ORC thermal efficiency is also reduced then the net useful work (area of 1–2–3–4–5) and the combined hot water/saturated steam was still the most suitable heat.

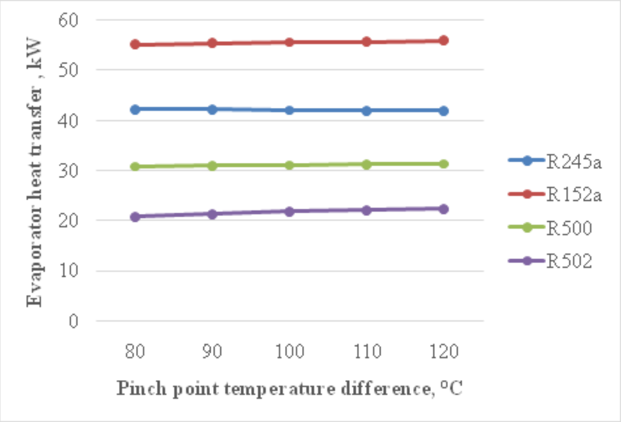


Figure 20: Variation of pinch point temperature differences with evaporator heat transfer when water is used as a heat source.

The evaporator heat transfer of the ORC cycle were numerically studied when the heat source temperature was fixed at 80 °C and the pinch was varied in a range of 2–10 °C. The mass flow rates of hot water and saturated steam were 2 and 0.2 kg/s, respectively. The increase of the pinch value led to the increase of the evaporator heat transfer for different refrigerant. As the pinch temperature difference increased, the ORC thermal efficiency is also reduced then the net useful work (area of 1–2–3–4–5) and the combined hot water/saturated steam was still the most suitable heat.

Effect Of Pinch Point Temperature Difference On The Performance Of Orc Cycle With Both Hot Water And Steam Heat Source

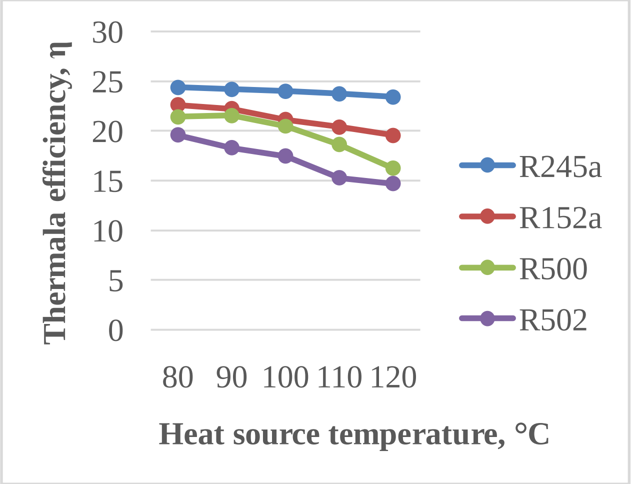


Figure 21: Variation of pinch point temperature differences with thermal efficiency when water is used as a heat source.

The thermal efficiency of the ORC cycle were numerically studied when the heat source temperature was fixed at 80 °C and the pinch was varied in a range of 2–10 °C. The mass flow rates of hot water and saturated steam were 2 and 0.2 kg/s, respectively. The increase of the pinch value led to the increase of the evaporator heat transfer for different refrigerant. As the pinch temperature difference increased, the ORC thermal efficiency is also reduced then the net useful work (area of 1–2–3–4–5) and the combined hotwater/saturated steam was still the most suitable heat.

Effect Of Heat Source Flow Rate On The Performance Of Orc Cycle With Both Hot Water And Steam Heat Source

From the results in Figs. 4.19-4.23, the combined hot water/saturated steam was found to be the most suitable heat source for the ORC due to its highest thermal efficiency. Moreover, the thermal efficiency could also be increased when a suitable hot water flow rate of the combined fluid was found.

The effects of hot water and saturated steam mass flow rates, shown in Fig. 22, on the thermal efficiency were studied carefully to figure out the appropriate hot water flow rate. It could be noted from Fig. 22 that the change of steam mass flow rate affected the thermal efficiency significantly but the decrease of hot water mass flow rate below pinch reduced the thermal efficiency since less temperature difference between the heat source and the sensible heat part of the ORC was obtained.

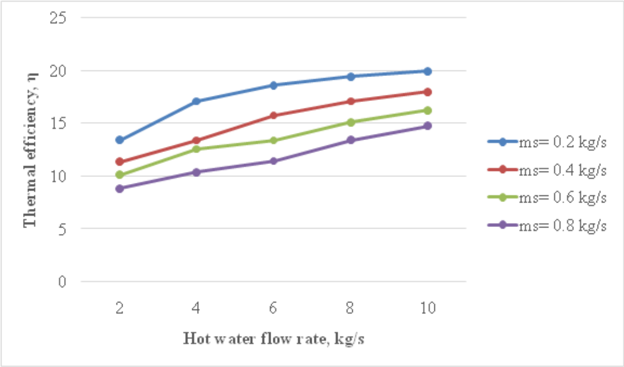


Figure 22: Variation of heat source flow rate with thermal efficiency when water and steam is used as a heat source (R245a).

It could be noted from Fig. 23 that the change of steam mass flow rate affected the thermal efficiency significantly but the decrease of hot water mass flow rate below pinch reduced the thermal efficiency since less temperature difference between the heat source and the sensible heat part of the ORC was obtained.

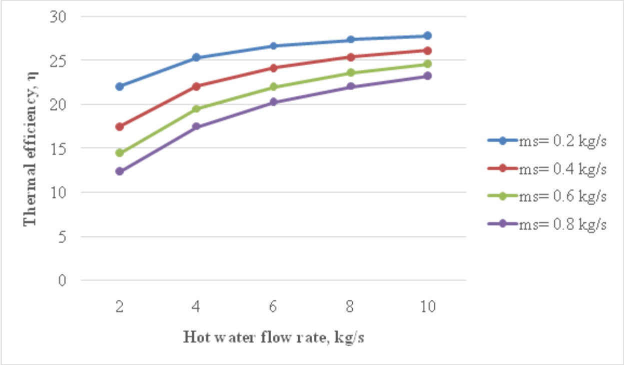


Figure. 23: Variation of heat source flow rate with net work done when water and steam is used as a heat source (R152a).

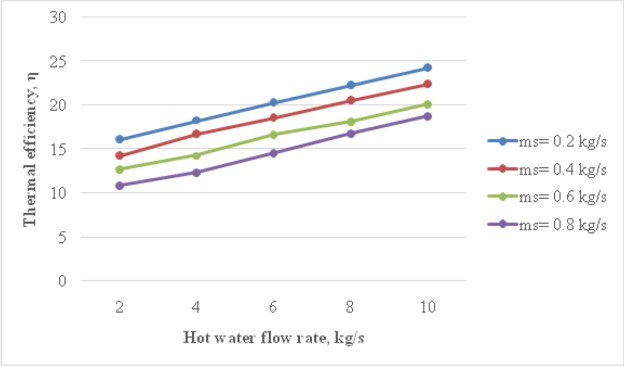


Figure 24: Simulation results of heat source flow rate with net work done when water and steam is used as a heat source (R500)

It could be noted from Fig. 25 that the change of steam mass flow rate affected the thermal efficiency significantly but the decrease of hot water mass flow rate below pinch reduced the thermal efficiency since less temperature difference between the heat source and the sensible heat part of the ORC was obtained.

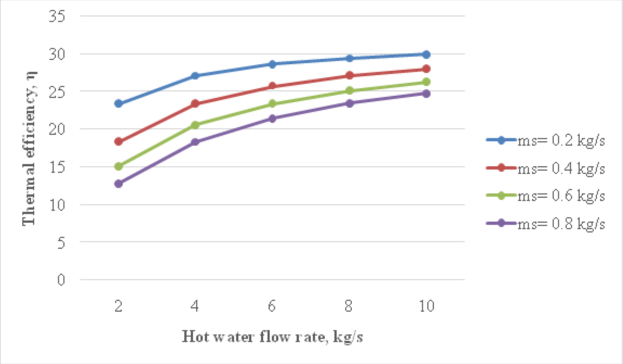


Figure 25: Variation of heat source flow rate with net work done when water and steam is used as a heat source (R502).

Therefore it is seen that with increase in mass flow rate of hot water and steam thermal efficiency increases and maximum thermal efficiency was achieved when R 502 was used.

V. CONCLUSIONS

In this study, theoretical study on the performance analyses of a ORC with different refrigerant was performed with different kinds of heat sources which were hot water, saturated steam and combined hot water/saturated steam at different heat source temperatures and different pinch values. The following conclusion can be drawn:

1. The thermal efficiency increased with the heat source temperature or evaporating temperature of the working fluid at a given value of pinch.
2. The combined hot water/saturated steam was the most suitable heat source that generated lowest exergy destruction in the ORC evaporator and provided highest thermal efficiency followed by the saturated steam and the hot water heat sources.
3. The thermal efficiencies of the ORC cycle decreased with the increase of pinch value for a given value of heat source temperature. The increase of pinch value resulted in greater exergy destruction in the ORC evaporator.
4. Increase of hot water mass flow rate could increase the thermal efficiency of the cycle in case of hot water heat source. On the other hand, the thermal efficiency of the cycle was decreased for combined hot water/saturated steam heat source due to the increase of the exergy destruction below pinch.
5. For combined hot water/saturated steam, the hot water mass flow rate below pinch should not be too low otherwise high heat transfer area was needed this was also confirmed with Kong et al (2019).

REFERENCES

[1]. Kong, R., Deethayat, T., Asanakham, A., Vorayos, N., &Kiatsiriroat, T. (2019). Thermodynamic performance analysis of R245fa organic Rankine cycle (ORC) with different kinds of heat sources at evaporator. Case Studies in Thermal Engineering, 13, 100385.

[2]. Pathak, S., & Shukla, S. K. (2018). A Review on the Performance of Organic Rankine Cycle with Different Heat Sources and Absorption Chillers. Distributed Generation & Alternative Energy Journal, 33(2), 6-37.

[3]. Zhang, C., Liu, C., Xu, X., Li, Q., Wang, S., & Chen, X. (2018). Effects of superheat and internal heat exchanger on thermo-economic performance of organic Rankine cycle based on fluid type and heat sources. Energy, 159, 482-495.

[4]. Abam, F. I., Ekwe, E. B., Effiom, S. O., &Ndukwu, M. C. (2018). A comparative performance analysis and thermo-sustainability indicators of modified low-heat organic Rankine cycles (ORCs): An exergy-based procedure. Energy Reports, 4, 110-118.

[5]. Su, W., Hwang, Y., Deng, S., Zhao, L., & Zhao, D. (2018). Thermodynamic performance comparison of Organic Rankine Cycle between zeotropic mixtures and pure fluids under open heat source. Energy conversion and management, 165, 720-737.

[6]. Pang, K. C., Chen, S. C., Hung, T. C., Feng, Y. Q., Yang, S. C., Wong, K. W., & Lin, J. R. (2017). Experimental study on organic Rankine cycle utilizing R245fa, R123 and their mixtures to investigate the maximum power generation from low-grade heat. Energy, 133, 636-651.

[7]. Feng, Y. Q., Hung, T. C., He, Y. L., Wang, Q., Wang, S., Li, B. X., & Zhang, W. (2017). Operation characteristic and performance comparison of organic Rankine cycle (ORC) for low-grade waste heat using R245fa, R123 and their mixtures. Energy Conversion and Management, 144, 153-163.

[8]. Li, J., Liu, Q., Ge, Z., Duan, Y., & Yang, Z. (2017). Thermodynamic performance analyses and optimization of subcritical and transcritical

organic Rankine cycles using R1234ze (E) for 100–200° C heat sources. Energy conversion and management, 149, 140-154.

[9]. Javanshir, A., &Sarunac, N. (2017). Thermodynamic analysis of a simple Organic Rankine Cycle. Energy, 118, 85-96.

[10]. Sun, W., Yue, X., & Wang, Y. (2017). Exergy efficiency analysis of ORC (Organic Rankine Cycle) and ORC-based combined cycles driven by low-temperature waste heat. Energy Conversion and Management, 135, 63-73.

[11]. Wu, Y., Zhu, Y., & Yu, L. (2016). Thermal and economic performance analysis of zeotropic mixtures for Organic Rankine Cycles. Applied Thermal Engineering, 96, 57-63.

[12]. Lee, H. Y., Park, S. H., & Kim, K. H. (2016). Comparative analysis of thermodynamic performance and optimization of organic flash cycle (OFC) and organic Rankine cycle (ORC). Applied Thermal Engineering, 100, 680-690.

[13]. Sadeghi, M., Nemati, A., &Yari, M. (2016). Thermodynamic analysis and multi-objective optimization of various ORC (organic Rankine cycle) configurations using zeotropic mixtures. Energy, 109, 791-802.

[14]. Geng, D., Du, Y., & Yang, R. (2016). Performance analysis of an organic Rankine cycle for a reverse osmosis desalination system using zeotropic mixtures. Desalination, 381, 38-46.

[15]. Song, J., Gu, C. W., & Ren, X. (2016). Influence of the radial-inflow turbine efficiency prediction on the design and analysis of the Organic Rankine Cycle (ORC) system. Energy Conversion and Management, 123, 308-316.