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Thermal Performance Analysis of Simple Organic Rankine Cycle with and without Internal Heat Exchanger using EES Code

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Abstract - **In this study, performance of a simple organic Rankine cycle (S-ORC) and organic Rankine cycle with internal heat exchanger (IHX-ORC) have been compared. Two ORC configurations are investigated as follows: S-ORC and IHX-ORC. With respect to different ORC configurations, the first law efficiency, second law efficiency and net work done will be compared under the conditions of different heat source temperatures and heat source flow rates. The effects of working fluid type, heat source temperature domains on the system, thermo-economic performance will be investigated. Furthermore, the effects of pinch point temperature difference in IHX on the IHX-ORC system are analyzed.**

Keywords- **Simple organic Rankine cycle (S-ORC), organic Rankine cycle with internal heat exchanger (IHX-ORC), Heat source temperatures, Heat source flow rates, First law efficiency, Second Law efficiency.**

I. INTRODUCTION

Over the past years, the interest in recovering low grade heat has grown rapidly. Many researchers have come up with several ways of generating electrical power from low temperature heat sources available in solar energy, domestic boilers, biomass and industrial waste heat. Among all these the ORC is considered to be the most suitable due to its simple design and availability of components.

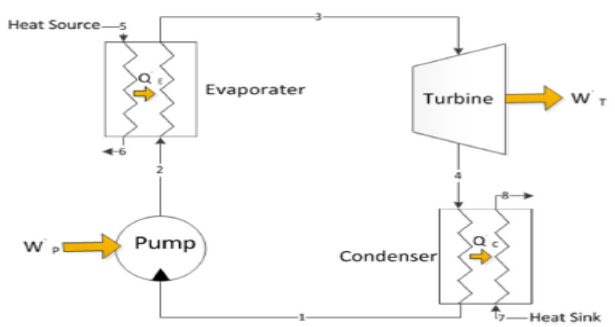
The ORCs use organic working fluids which are more suitable than water in the context of using heat source with low temperatures. The ORC unlike conventional steam cycles is an attractive yardstick for local and small scale power generation. Frank W. Ofledt patented the naphtha engine in 1883 which has the same application as the ORC. The naphtha was used in place of water as working fluid so as to replace the steam engine on boat [5].Petroleum, natural gas and coal are fossil fuels and are non- renewable. Several countries today have been investing money to get new and efficient energy technologies that are alternative for fossil fuels to generate power. Low grade heat is largely available in renewable energy sources and in industrial waste. Utilizing this type of sustainable energy could help to reduce the use of non-renewable energy, thus reducing the environmental impacts of non-renewable energy sources.

Development of efficient and effective technologies is required to generate useful work by using these low grade heat sources. An ORC is a suitable means of carrying out this purpose. The ORC works with a high molecular mass organic working fluid with the characteristic of having a phase change of liquid to vapor occurring at a temperature which is lower than the phase change of water to steam for a given pressure. The recovery of low grade heat can be achieved using organic fluids. These low grade heat sources can be from biomass energy, solar energy, geothermal energy or industrial waste. The ORC converts the low grade heat into work and finally into electricity.

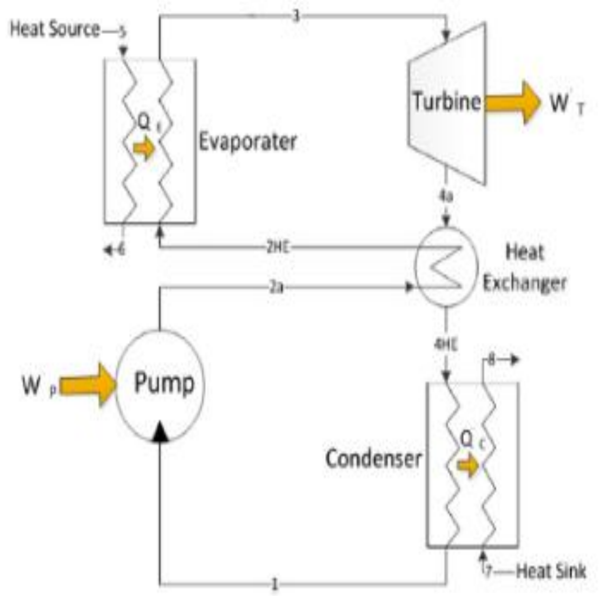
II. METHODOLOGY

1.System Description

In this section, two ORC configurations will be introduced. The schematic diagram of S-ORC and IHX-ORC is shown in Fig. 1. Furthermore, the components and procedures are described.



(a)



(b)

Fig. 1. Schematics of the organic Rankine cycle: (a) S-ORC (b) IHX-ORC.

2.Simple Organic Rankine Cycle

Superheat is necessary to avoid liquid droplet impingement in expander during expansion for wet fluids. Typically, the dryness fraction at the outlet of an expander is kept above 90% [7].

The working fluid absorbs heat from the exhaust flue gas in the evaporator and subsequently vaporizes into saturated vapor (dry and isentropic fluid) or overheated vapor (wet fluid) continuously. Subsequently, the high-pressure vapor flows into the expander to expand and convert into shaft work.

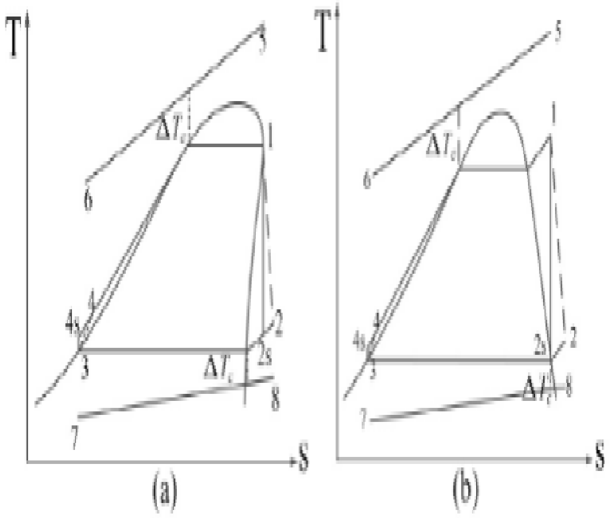


Fig. 2 (a) & (b). T-s diagram for the organic Rankine cycle: (a) S-ORC with dry fluid and (b) with wet fluid.

Following this, the expanded superheated vapor flows into the condenser wherein the vapor is condensed to saturated liquid by the cooling water. The saturated liquid is pumped into the evaporator again to continue the next cycle. Fig.2 (a) and (b) show the T-s diagram of S-ORC.

3.Organic Rankine cycle with internal heat exchanger (IHX-ORC)

The superheat degree of vapor at outlet of expander maintains a high level when dry fluid or higher superheat is selected, and this leads to a significant waste of energy to the heat sink. An increase in the temperature of the working fluid discharged from the outlet of expander is introduced to the inlet of the low-pressure side of IHX. Conversely, the low temperature albeit high pressure working fluid discharged from the pump is introduced to the inlet of high pressure side of IHX. Thus, the excess heat is recovered from the exhausted vapor to the fluid supply to avoid energy wastage. In IHX-ORC, the IHX is combined with superheat as shown in Fig. 3 (a) and (b).

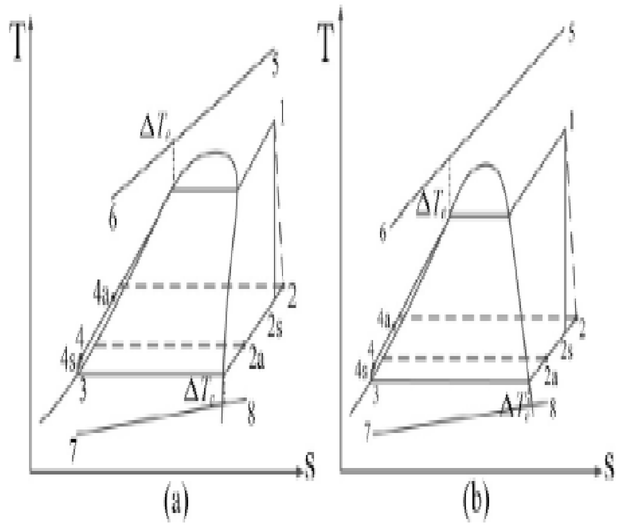


Fig. 3. T-S diagram for the organic Rankine cycle: IHX-ORC with dry fluid (a) and with wet fluid (b).

III. RESULT AND DISCUSSION

1.Effect Of Heat Source Temperature On Thermal Efficiency Of S-Orc

In this section, the effect of heat source temperature on the thermal efficiency of S-ORC system is proposed. Specifically, working fluid R245fa, R152a, R123, R717 and cyclohexane are selected as examples due to good thermodynamic performance as previously discussed.

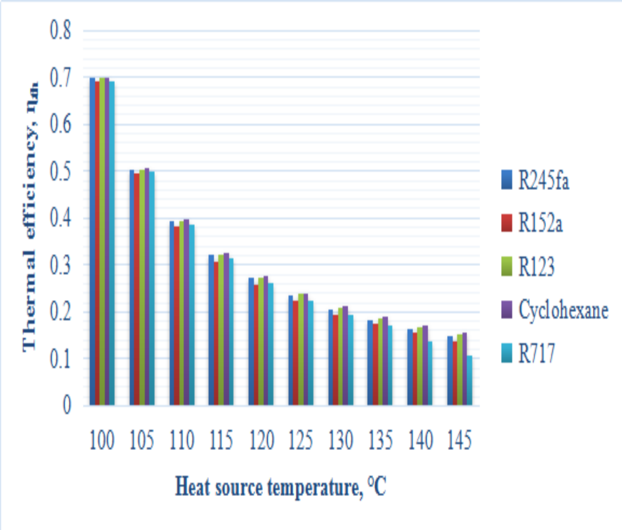


Fig. 4. Variation of thermal efficiency of S-ORC with heat source temperature.

2.Effect Of Heat Source Temperature On Net Work Output

In this section, the effect of heat source temperature on the net work output of SORC system is proposed. Specifically, working fluid R245fa, R152a, R123, R717 and cyclohexane are selected as examples due to good thermodynamic performance as previously discussed.

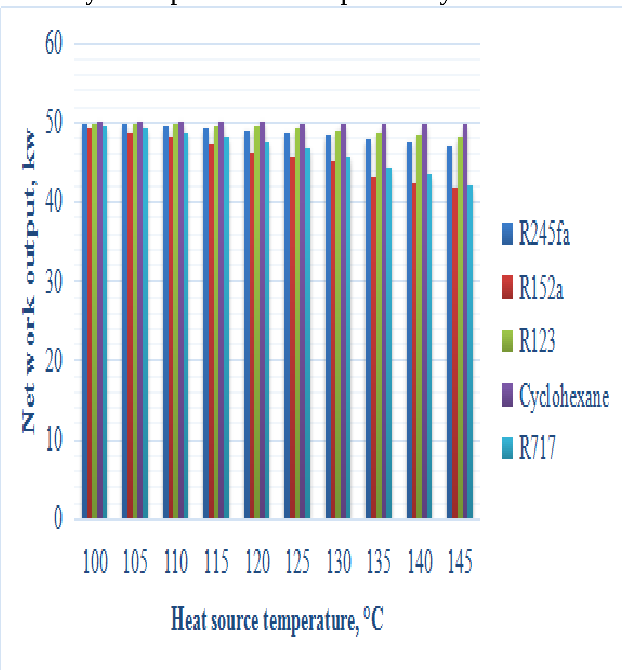


Fig. 5. Variation of net work output of S-ORC with heat source temperature.

3.Effect Of Heat Source Flow Rates On Thermal Efficiency Of S-Orc System

In this section, the effect of heat source flow rates on the thermal efficiency of S-ORC system is proposed. Specifically, working fluid R245fa, R152a, R123, R717 and cyclohexane are selected as examples due to good thermodynamic performance as previously discussed.

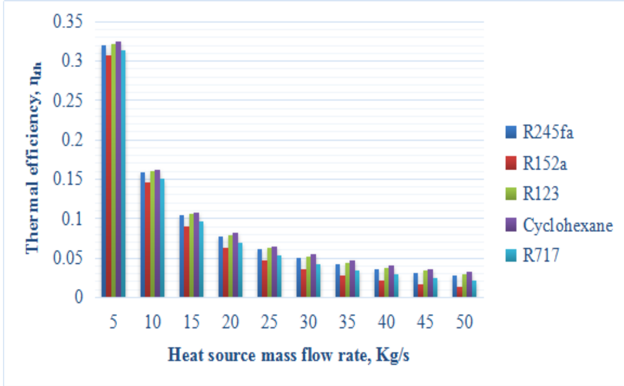


Fig. 6. Variation of thermal efficiency of S-ORC with heat source flow rate.

4. Effect of Heat Source Flow Rates On Net Work Output

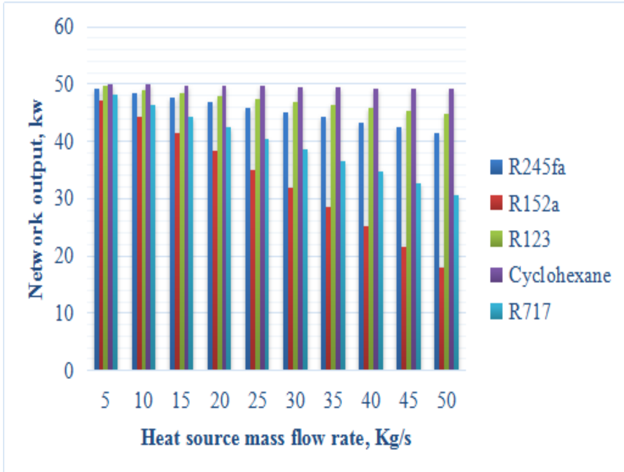


Fig. 7. Variation of network output of S-ORC with heat source flow rate.

In this section, the effect of heat source flow rates on the net work output of S-ORC system is proposed. Specifically, working fluid R245fa, R152a, R123, R717 and cyclohexane are selected as examples due to good thermodynamic performance as previously discussed.

5.Effect Of Heat Source Temperature On First Law Efficiency Of Ihx-Orc System

In this section, the effect of heat source temperature of IHX-ORC on the thermal efficiency of IHX-ORC system is proposed. Specifically, working fluid R245fa, R152a, R123, R717 and cyclohexane are selected as examples due to good thermodynamic performance as previously discussed.

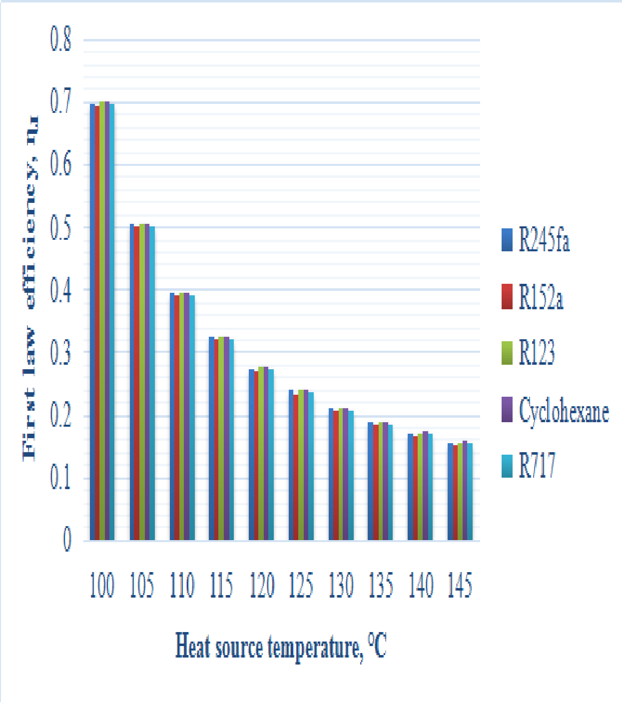


Fig. 8. Variation of first law efficiency of IHX-ORC with heat source temperature.

6.Effect Of Heat Source Temperature On Second Law Efficiency Of Ihx-Orc System

In this section, the effect of heat source temperature of IHX-ORC on the thermal efficiency of IHX-ORC system is proposed. Specifically, working fluid R245fa, R152a, R123, R717 and cyclohexane are selected as examples due to good thermodynamic performance as previously discussed.

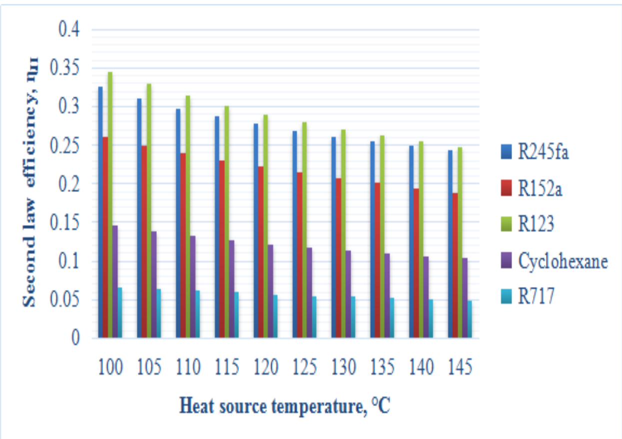


Fig. 9. Variation of second law efficiency of IHX-ORC with heat source temperature.

7. Effect Of Heat Source Temperature On Net Work Done Of Ihx-Orc System

In this section, the effect of heat source temperature of IHX-ORC on net work done of IHX-ORC system is proposed. Specifically, working fluid R245fa, R152a, R123, R717 and cyclohexane are selected as examples due to good thermodynamic performance as previously discussed.

8.Effect Of Heat Source Flow Rates On First Law Efficiency Of Ihx-Orc System

In this section, the effect of heat source flow rates of IHX-ORC on first law efficiency of IHX-ORC system is proposed. Specifically, working fluid R245fa, R152a, R123, R717 and cyclohexane are selected as examples due to good thermodynamic performance as previously discussed.

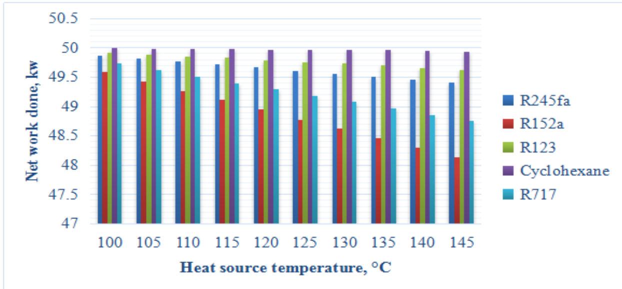


Fig. 10. Variation of net work done of IHX-ORC with heat source temperature.

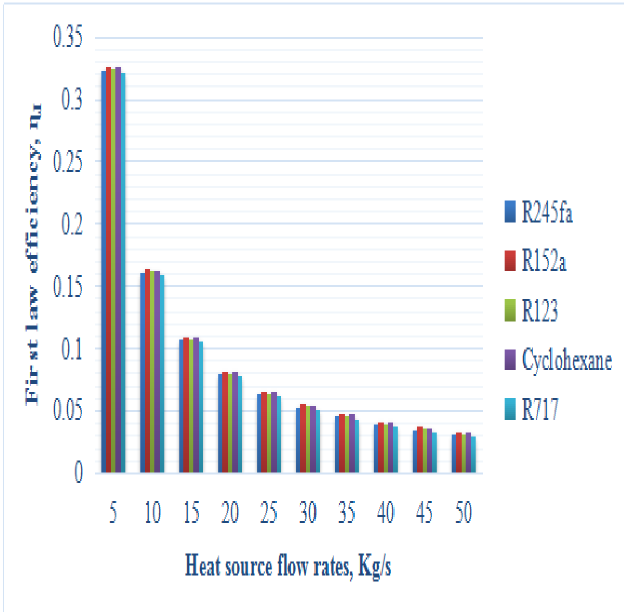


Fig. 11. Variation of first law efficiency of IHX-ORC with heat source flow rate.

9. Effect Of Heat Source Flow Rates On Second Law Efficiency Of Ihx-Orc System

In this section, the effect of heat source flow rates of IHX-ORC on second law efficiency of IHX-ORC system is proposed. Specifically, working fluid R245fa, R152a, R123, R717 and cyclohexane are selected as examples due to good thermodynamic performance as previously discussed.

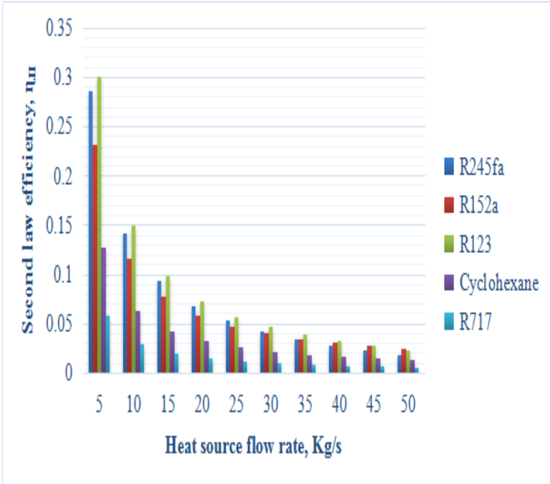


Fig. 12. Variation of second law efficiency of IHX-ORC with heat source flow rate.

10.Effect Of Heat Source Flow Rates On Net Work Done Of Ihx-Orc System

In this section, the effect of heat source flow rates of IHX-ORC on net work done of IHX-ORC system is proposed. Specifically,

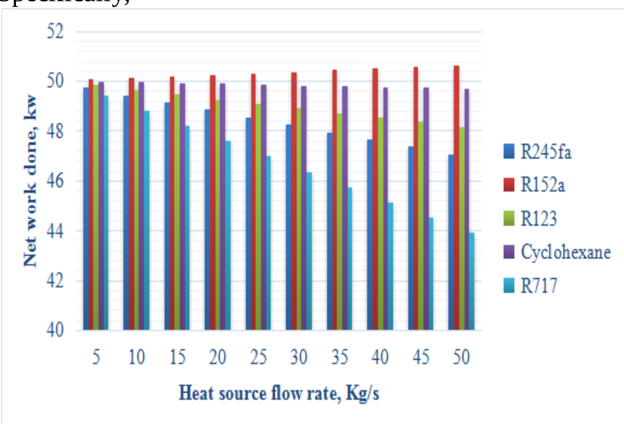


Fig. 13. Variation of net work done of IHX-ORC with heat source flow rate.

R245fa, R152a, R123, R717 and cyclohexane are selected as examples due to good thermodynamic performance as previously discussed.

IV. CONCLUSION

The study investigates the effects of internal heat exchanger on the thermo-economic performance of organic Rankine cycle (ORC) configurations based on fluid properties and heat sources. Following conclusions can be drawn from present study.

- It is observed that with increase in heat source temperature, thermal efficiency of S-ORC system decreases for all refrigerants. Also, the maximum thermal efficiency of S-ORC system was observed when working fluid is cyclohexane.
- It is observed that with increase in heat source temperature, net work done of IHX-ORC system decreases for all refrigerants. Also, the maximum net work done in IHX-ORC system was observed when working fluid is cyclohexane
- It is observed that with increase in heat source temperature, first law efficiency of IHX-ORC system decreases for all refrigerants. Also, the maximum first law efficiency in IHX-ORC system was observed when working fluid is cyclohexane.
- It is observed that with increase in heat source flow rates, first law efficiency of IHX-ORC system decreases for all refrigerants. Also, the maximum first law efficiency in IHX-ORC system was observed when working fluid is R152a.
- It is observed that with increase in heat source flow rates, second law efficiency of IHX-ORC system decreases for all refrigerants. Also, the maximum second law efficiency in IHX-ORC system was observed when working fluid is R123.
- It is observed that with increase in heat source flow rates, net work done of IHX-ORC system decreases for all refrigerants. Also, the maximum net work done in IHX-ORC system was observed when working fluid is R152a.
- With respect to IHX-ORC, the different performance parameters such as heat source temperature, different working fluid and mass flow rates of heat source significantly impact the performance of ORC. The results indicate performance of IHX-ORC is more feasible than S-ORC.
- Maximum net power output are remarkably related to the working fluid but they are less sensitive to ORC configuration. While for the thermal efficiency criterion, it varies noticeably using an internal heat exchanger, nevertheless an exception for the cyclohexane where it varies slightly from a configuration to another.
- Depending on the currently working conditions (low temperature-range and medium mass flow rate of exhaust gas) the most appropriate couple ORC design-working fluid can be suggested as ORC with IHE-cyclohexane.

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