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Thermodynamic analysis and performance of SRC and ORC power generation systems using waste heat source

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ABSTRACT

In this work mathematical models of Steam Rankine Cycle (SRC) and Organic Rankine Cycle (ORC) power systems have been developed to explore the feasibility that combines the fluid-flow temperature, waste heat steam and low-boiling-point organic working fluids for power generation. The effects of the thermodynamic parameters on the SRC and ORC performance are examined. Among the commonly available working fluids, a selection based on environmental and technical criteria was carried out resulting in a list of 8 working fluids: R143a, R245fa, R600a, R124, R134a, RC318, R236fa, and Ammonia. Using the numerical models, we calculate and compare thermal efficiency, generating capacity, etc. of two power systems, namely SRC and ORC under the same heat source conditions. The results show that under the same condition of heat source, ORC has the highest thermal efficiency and power generation.

Keywords*—Waste heat, SRC, ORC, EES, Simulation model, Rankine cycle, Power generation*

1. INTRODUCTION

Waste heat steam is one of the important forms of waste heat emission which is widely used in industrial enterprises such as power plants and iron and steel enterprises. Varieties of waste heat resources account for 68% of all production energy consumption [1], but the utilization rate of waste heat is only 32%, of which the low-temperature waste heat utilization rate is almost zero. If we could utilize and recycle this part of the energy, it will not only solve the energy problem of our country but also reduce environmental pollution in the process of energy production. Based on the status of low waste heat utilization [2, 3], energy recycling technology in fluid-flow temperature has become a research focus increasingly in the related fields. At present, there are mainly two forms of waste heat recovery, heat to heat recovery and heat to electricity recovery. The heat energy, recycled by the first form is not easy to store and was limited by the transmission distance, so it is not usually adopted. The second form primarily has three forms, the Steam Rankine Cycle (SRC) and Organic Rankine Cycle (ORC) [4]. Heat to electricity will convert low-grade thermal energy into electrical energy, which is mainly used in solar thermal power, industrial waste heat power generation, geothermal power generation, biomass power generation, ocean thermal power generation and so on. Traditional SRC employs water and high-pressure steam as the circulating working fluid and the power generation technology which is mainly appropriate for high-temperature heat source like T > 500 C is relatively mature. Due to the water source is rich, with the big latent heat of vaporization, high boiling point, and large specific heat capacity, non-toxic and tasteless, no polluting to the environment, so it's widely used in thermal engineering. Although SRC is the most common technology in the heat to electricity recovery process, it is not suitable for low temperature and pressure condition due to the necessity of high operating temperature and pressure and when the exhaust temperature and pressure are same, the exhaust steam enthalpy of SRC is larger, which increases the heat of the cold source.

2. SYSTEM MODELING

To aid in the analysis of engineering problem it is necessary to realize the Physical model in a mathematical model. To do this, we first write state point equations of thermodynamic properties and then develop a polynomial for thermodynamic properties with the help of a software or, directly taken from the reference.

Therefore this chapter involves the description of a physical model, mass, and energy balance, assumptions, state point equations and thermodynamic properties. We will calculate and compare thermal efficiency, generating capacity, etc. of two power systems, namely SRC, and ORC under the same heat source conditions.

3. SYSTEM DESCRIPTION

3.1 Working principle and mathematical models of SRC and ORC

Rankine cycle waste heat power generation system consists of three subsystems: the heat source (middle-low temperature waste heat steam) system, Rankine Cycle System and cooling source (cooling water) system. The basic principle and process of the ORC system and the traditional SRC system are the same, but the difference lies in that the ORC system employs low-boiling-point organic working fluid instead of water and high-pressure steam. Figure 1 and 2 represent the schematic diagram of two cycles, while figure 3 and 4 are Temperature-Entropy diagrams, the working processes are as follows.

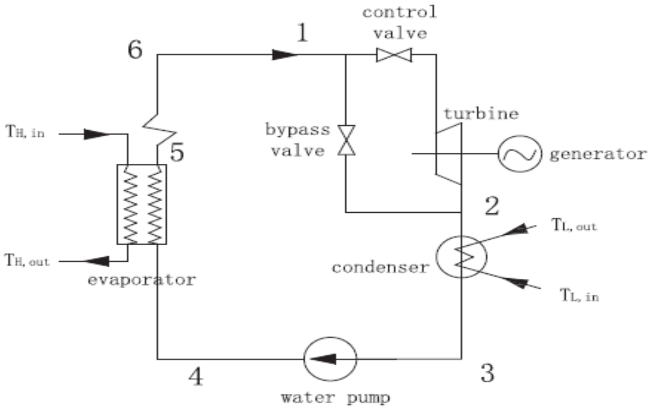

Fig. 1: Schematic of SRC cycle

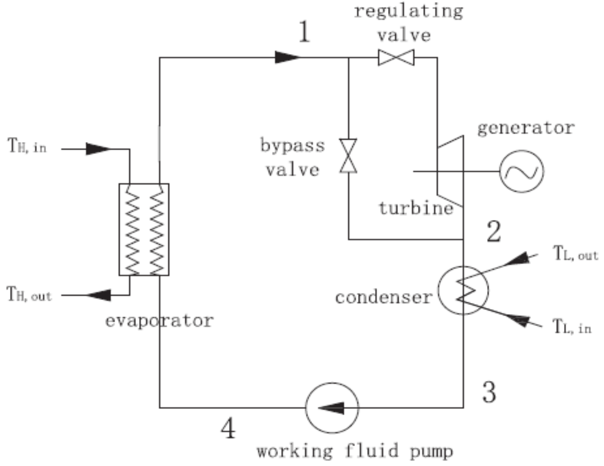

Fig. 2: Schematic of the ORC cycle

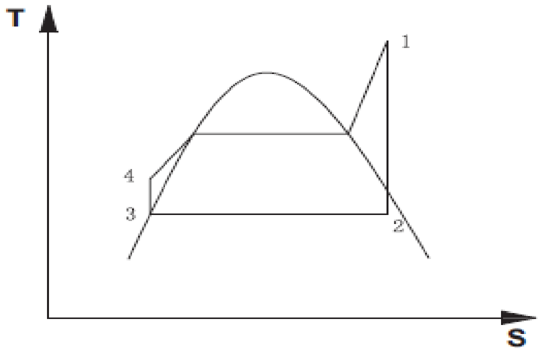

Fig. 3: T-S diagram of SRC cycle

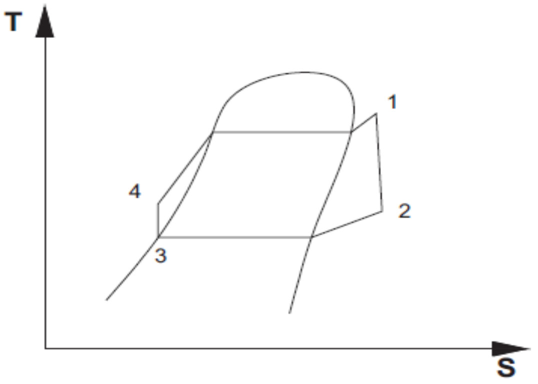

Fig. 4: T-S diagram of SRC cycle

State 1 to 2 is an adiabatic expansion process of working fluid in the turbine, the ideal reversible adiabatic expansion process is regarded as an isentropic process, but the turbine efficiency η_t needs to be considered in the actual calculation process, and then the output power of working fluid in the turbine is W_t:

$$W_t = m_f (h_2 - h_1)\ \eta_t$$

State 2 to 3 is an isobaric exothermic process of working fluid in the condenser, the heat released is Qc:

$$Q_c = m_f (h_2 - h_3)$$

State 3 to 4 is an adiabatic compression process in the working fluid pump, the ideal reversible adiabatic compression process is considered as an isentropic process, but the turbine efficiency η_t needs to be considered in the actual calculation process, and the output power of the working fluid in the turbine is Wp:

$$Wp = m_f (h_4 - h_3)/\ \eta_p$$

State 4 to 1 is an isobaric endothermic process in the evaporator. The heat absorbed in the evaporator is Qe:

$$Qe = m_f (h_1 - h_4)$$

The power generation capacity of unit quality working fluid is P:

$$P = E/m_f = w_t\ \eta_g$$

Where P is system power generation capacity, kW; wt is the specific work of working fluid, kJ/kg; η_g is the generator efficiency, %. The thermal efficiency of the system is η_e.

$$\eta_e = W_{net}/E_{in}$$

Where mf is the mass flow rate of working fluid, kg/s; h is the specific enthalpy of working fluid, kJ/kg; T_0 is the ambient temperature, K; s is the specific entropy of working fluid, kJ/(kg K).

4. RESULTS AND DISCUSSION

4.1 Simulation results of the SRC power generation system

The working fluid of SRC is water. To ensure that the SRC and S-ORC system have the same heat source, the outlet temperature of the turbine is set as 45 ºC, outlet pressure is the corresponding saturation pressure, working fluid condensing temperature is 37 ºC and the turbine isentropic efficiency is 0.8, the pump isentropic efficiency is 0.7.

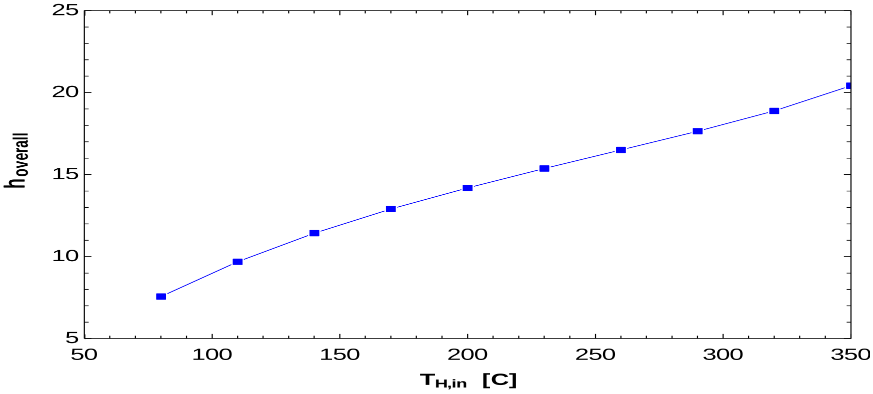

Fig. 5: Variation of overall efficiency with a heat source temperature

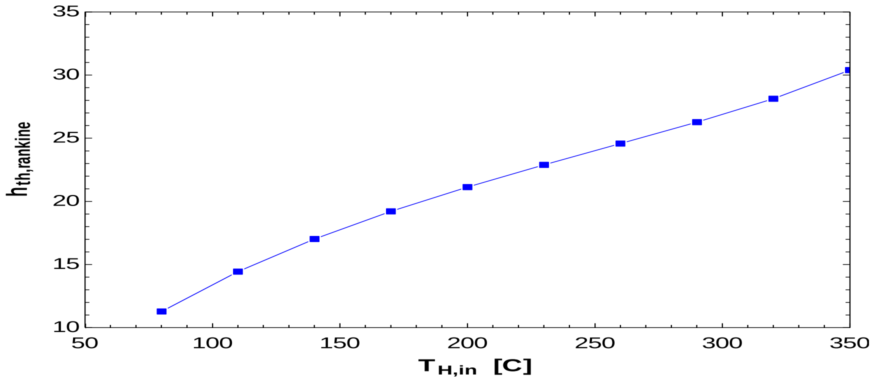

Fig. 6: Variation of Rankine efficiency with a heat source temperature

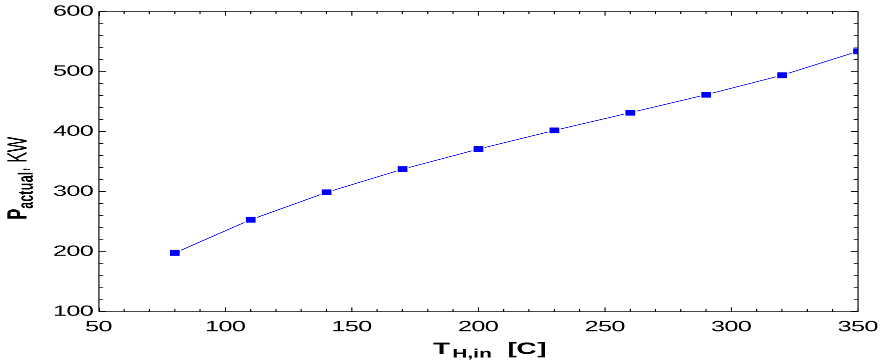

Fig. 7: Variation of power output with heat source temperature

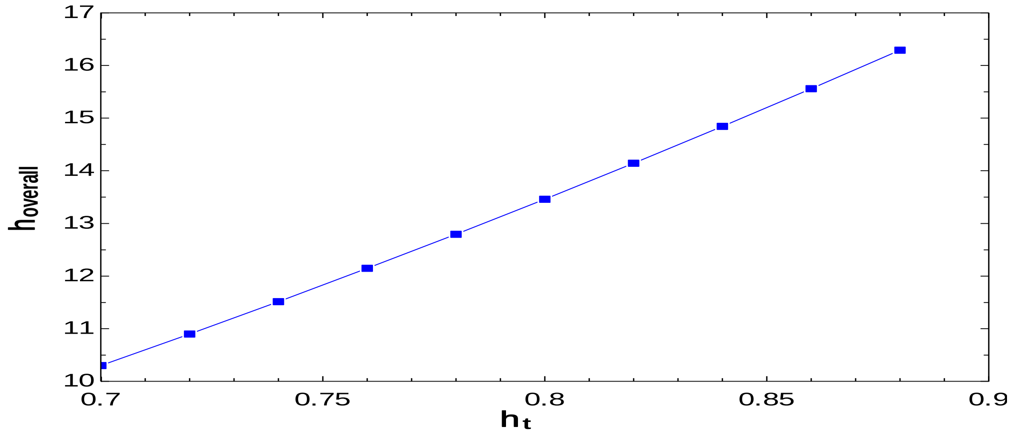

Fig. 8: Variation of overall efficiency with turbine efficiency

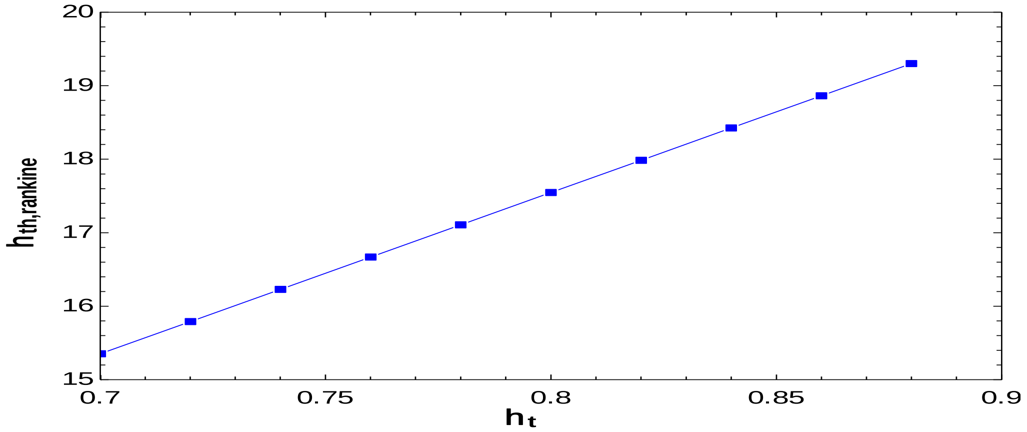

Fig. 9: Variation of Rankine efficiency with turbine efficiency

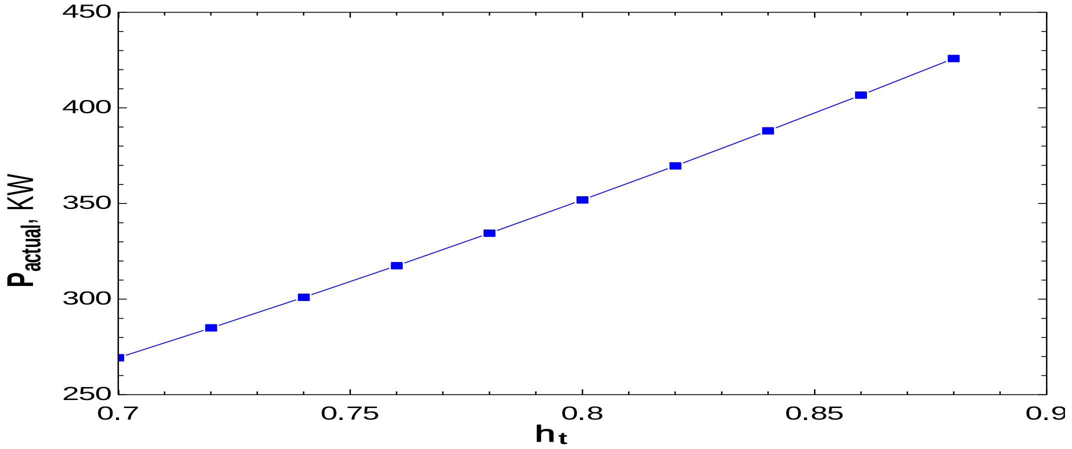

Fig. 10: Variation of power output with turbine efficiency

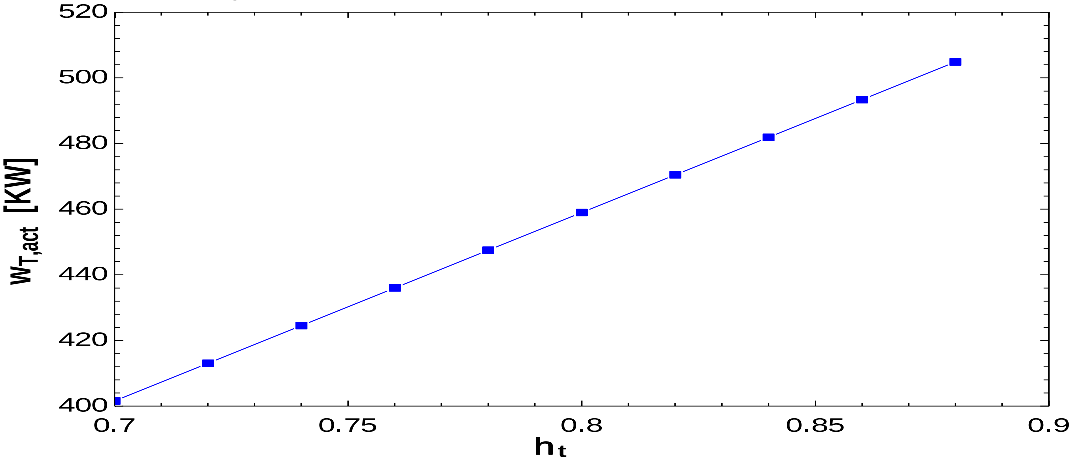

Fig. 11: Variation of turbine work with turbine efficiency

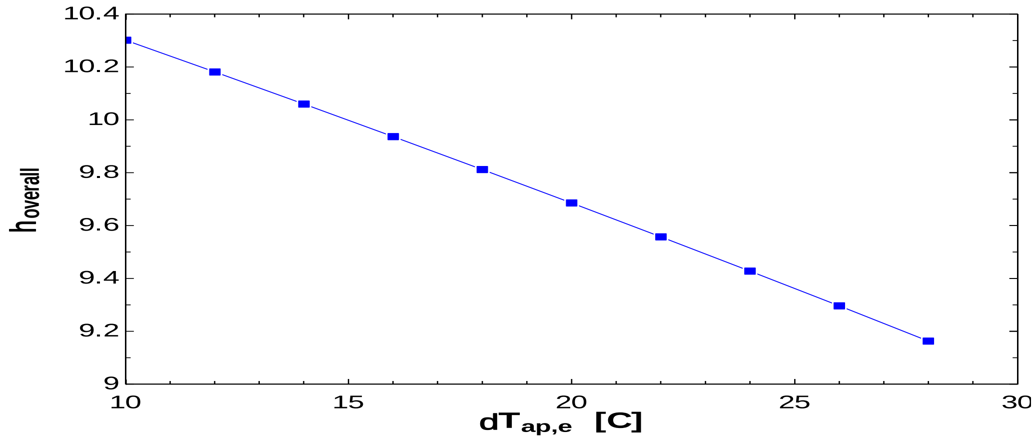

Fig. 12: Variation of overall efficiency with pinch point temperature difference

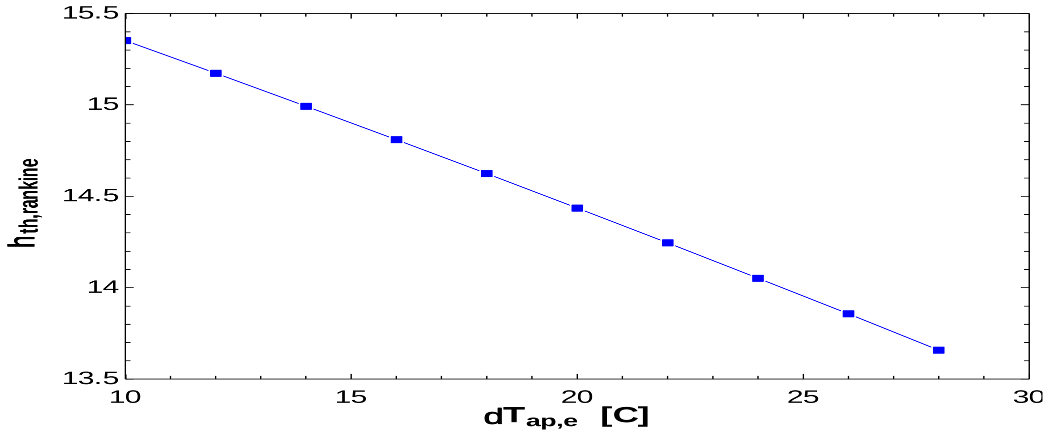

Fig. 13: Variation of Rankine efficiency with pinch point temperature difference

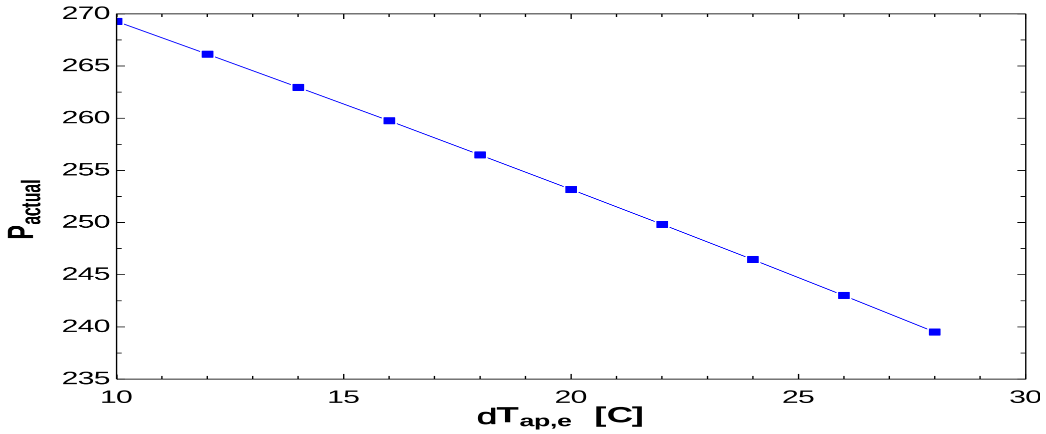

Fig. 14: Variation of power output with pinch point temperature difference

4.2 Simulation results of THE ORC power generation system

In this study different working fluid in the ORCs based on their thermodynamic, environmental and safety properties were used.

4.2.1 Variation of heat source

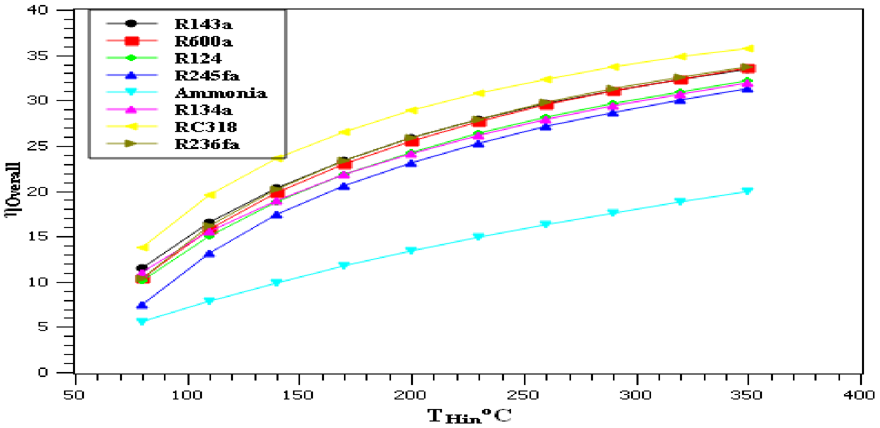

Fig. 15: Variation of overall efficiency with heat source with different working fluids

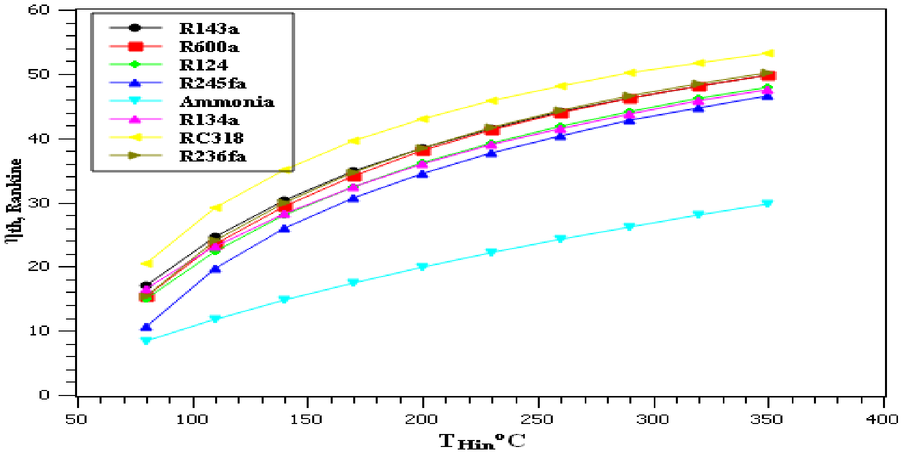

Fig. 16: Variation of Rankine efficiency with heat source with different working fluids

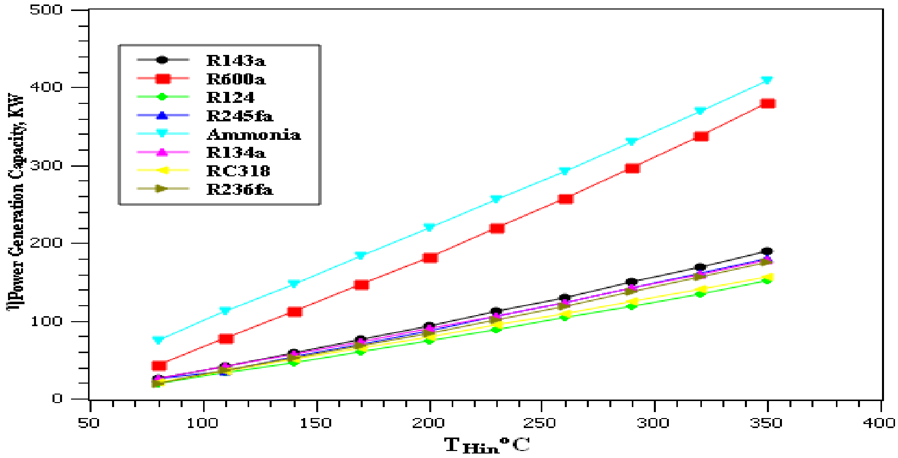

Fig. 17: Variation of power generation with heat source with different working fluids

Figure. 15, shows the variation of overall efficiency with the various heat source temperatures for 8 different working fluids. It is obvious that as the heat source temperature increases, overall efficiency increases for all 8 different working fluids maximum it was achieved with RC318 and minimum it was achieved with ammonia. In figure. 16, shows the variation of Rankine efficiency with the various heat source temperatures for 8 different working fluids. It shows the same trend that as the heat source temperature increases, overall efficiency increases for all 8 different working fluids maximum it was achieved with RC318 and minimum it was achieved with ammonia. In figure. 17, shows the variation of power output with the various heat source temperatures for 8 different working fluids. It is shown that as the heat source temperature increases, power output increases for all 8 different working fluids maximum output it was achieved with ammonia and minimum output it was achieved with R124.

4.2.2 Variation of turbine efficiency: The figure shows the simulation result for the ORC power generation system at different turbine efficiency. For obtaining simulation results turbine efficiency was varied from 70 to 88%. The overall efficiency, ranking efficiency, power generation capacity was evaluated.

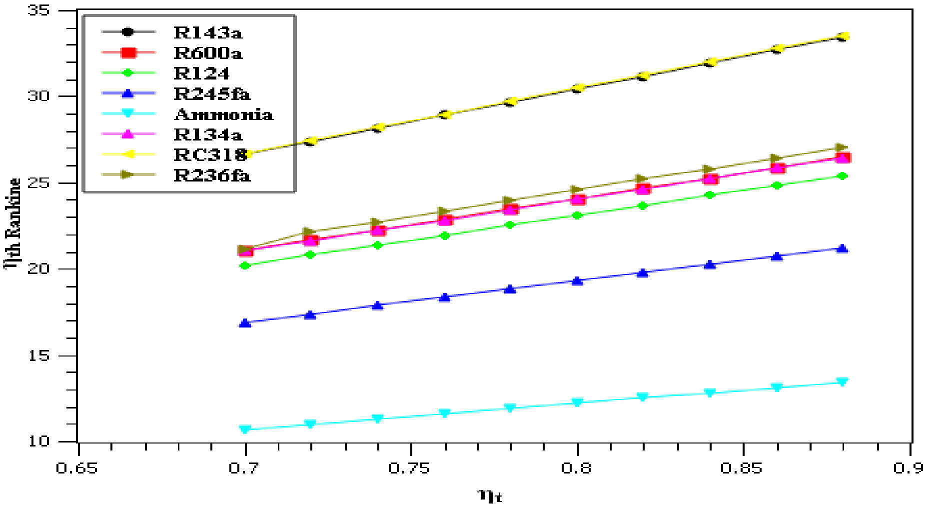

Fig. 18: Variation of Rankine efficiency with turbine efficiency with different working fluids

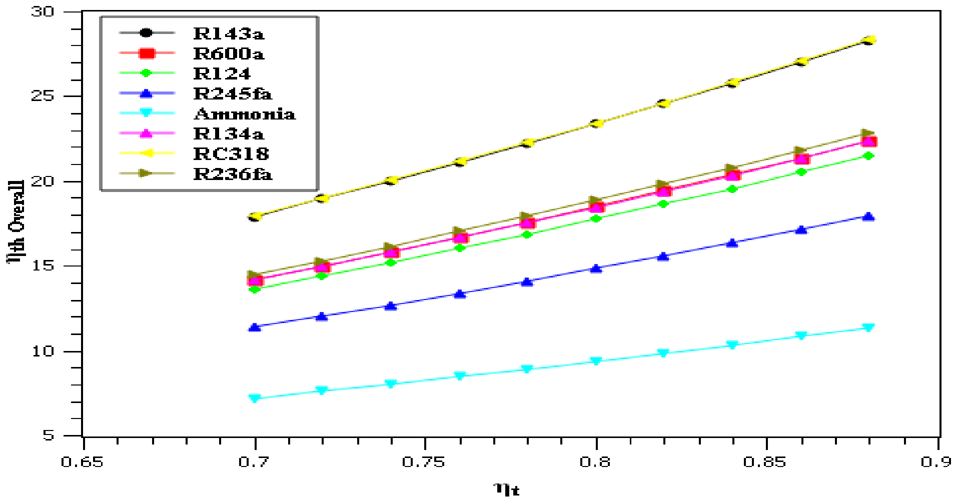

Fig. 19: Variation of overall efficiency with turbine efficiency with different working fluids

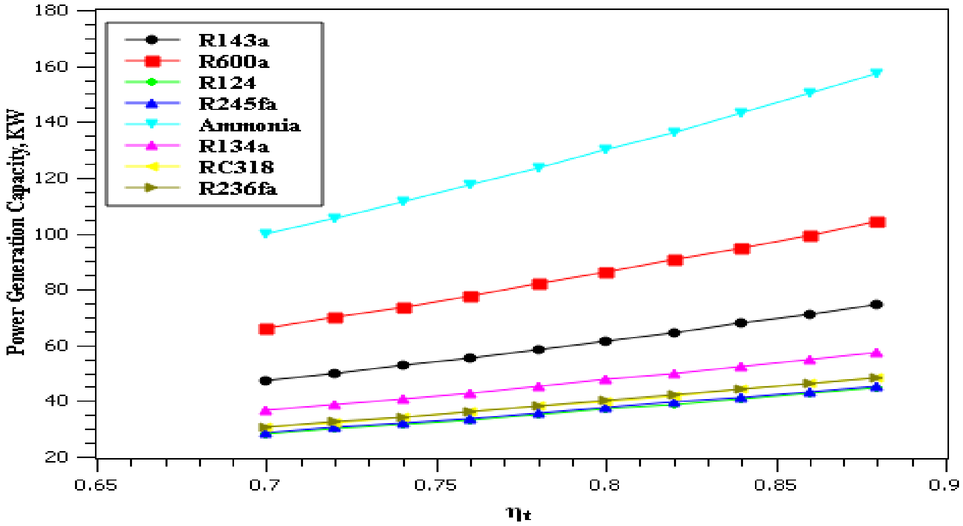

Fig. 20: Variation of power generation capacity with turbine efficiency with different working fluids

As shown by figure 18 and figure 19, R143a has larger overall efficiency over turbine efficiency range 70%-88% while it is low in the case of Ammonia. If the ORC will be operated with larger turbine efficiency, R143a is suggested depending on whether we are more interested in overall efficiency or Rankine efficiency. Through the simulation and calculation of power generation, we know that the power generation of the system increases with the increase in turbine efficiency. As shown by figure 20, Ammonia has larger power generation capacity over the turbine efficiency range 70%-88% while it is low in the case of R245fa. If the ORC will be operated for larger turbine efficiency, Ammonia is suggested depending on whether we are more interested in power generation capacity or not.

4.3 Simulation comparison of SRC and ORC systems: In this section simulation comparison of SRC and ORC has been done with varying heat source temperature, pinch point temperature difference and turbine efficiency.

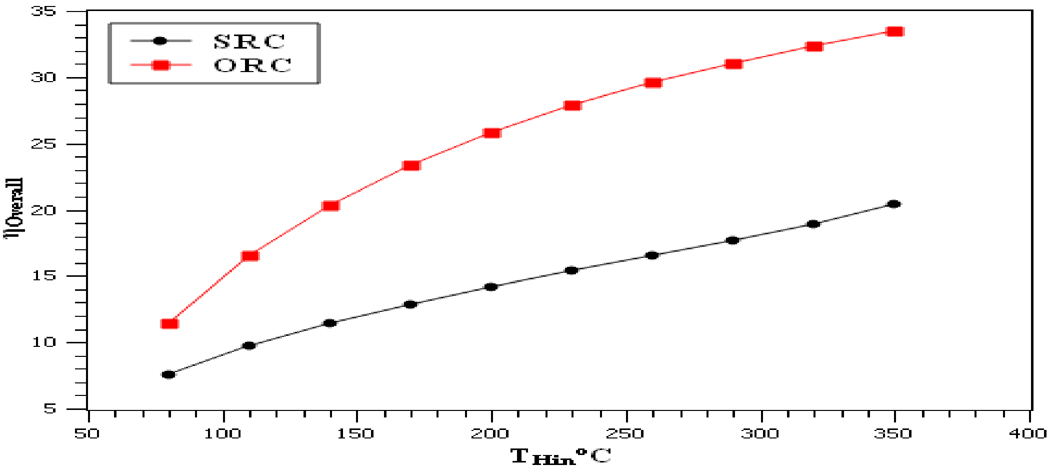

Fig. 21: Overall efficiency with a heat source of SRC and ORC

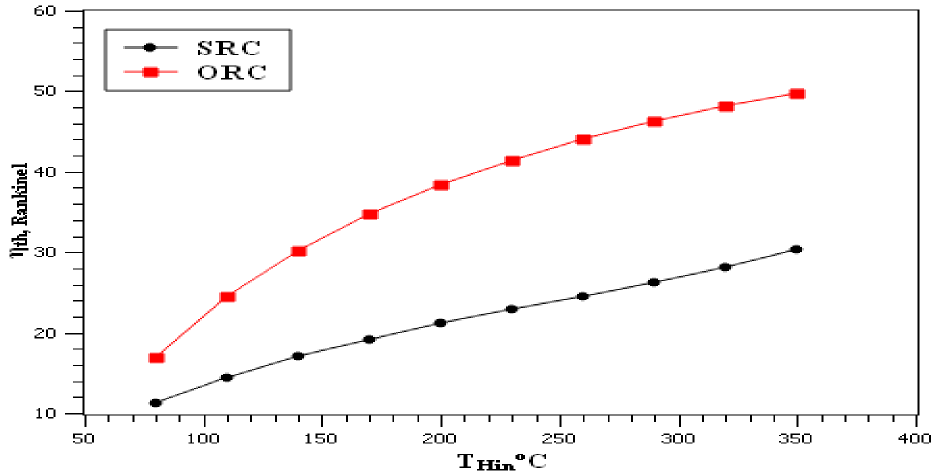

Fig. 22: Rankine efficiency with a heat source of SRC and ORC

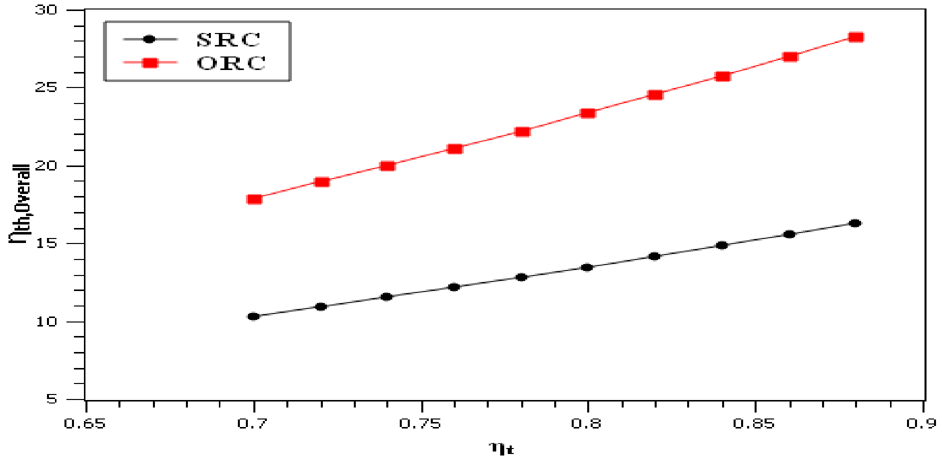

Fig. 23: Overall efficiency with turbine efficiency of SRC and ORC

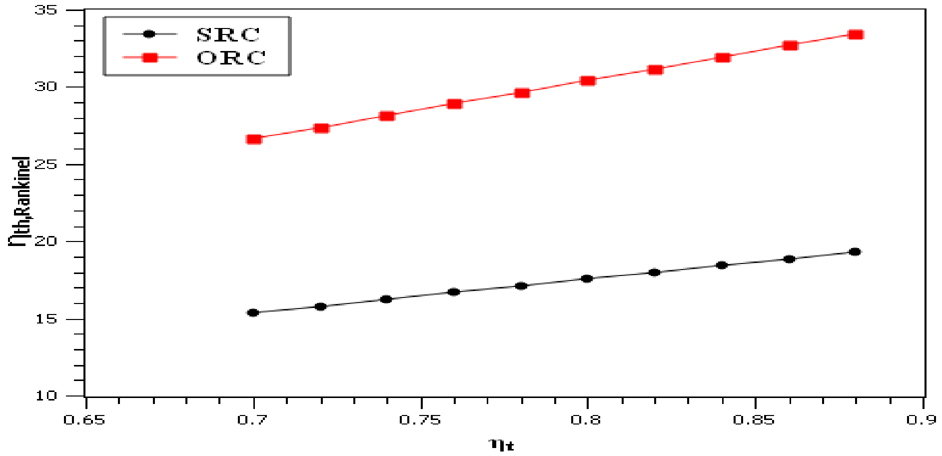

Fig. 24: Rankine efficiency with turbine efficiency of SRC and ORC

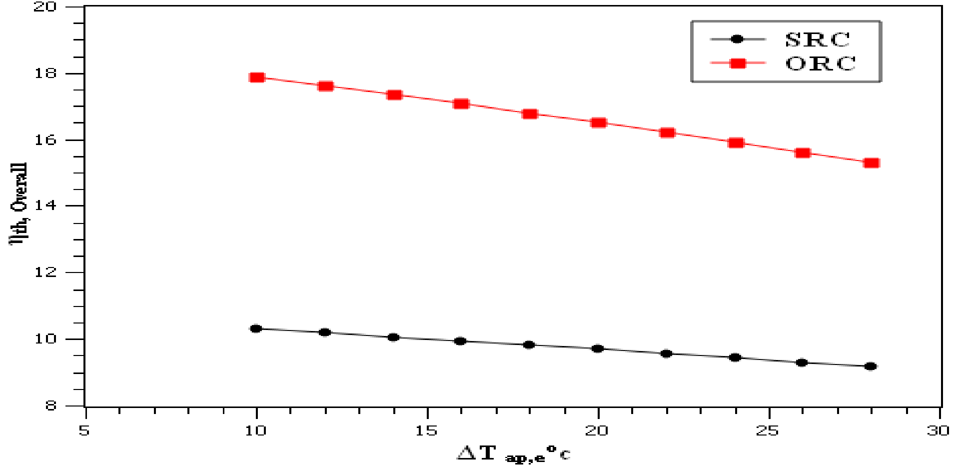

Fig. 25: Overall efficiency with pinch point temperature difference of SRC and ORC

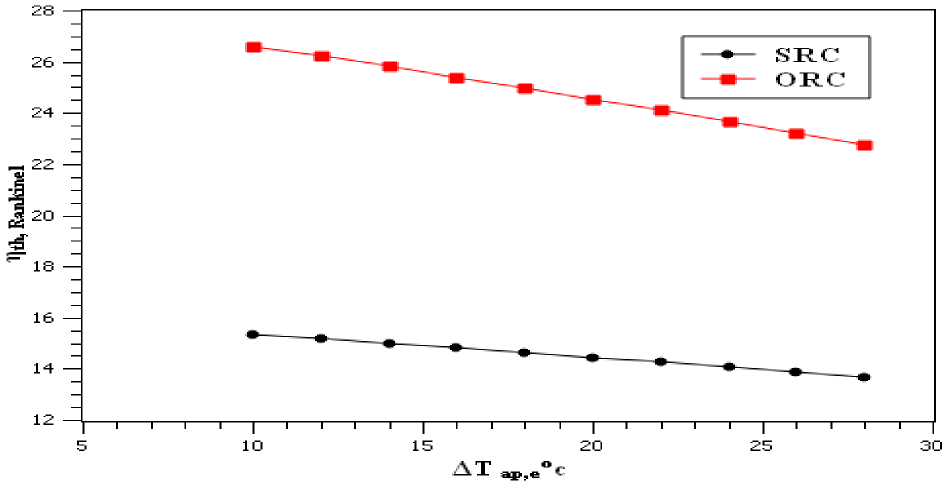

Fig. 26: Rankine efficiency with pinch point temperature difference of SRC and ORC

5. CONCLUSION

In this work, simulations were carried out using the EES software package to analyze thermodynamically the SRC and ORCs utilizing different working fluids. Selecting a suitable working fluid for an ORC system is not an easy task. Only some of the dry and isentropic working fluids are considered. The influence of the working fluid on the resulting SRC and ORC performance in terms of net power output, overall efficiency and Rankine efficiency has been presented.

- It shows that with increase in heat source temperature overall efficiency, ranking efficiency, turbine work and power output increase in case of SRC system.
- R143a has larger overall efficiency over turbine efficiency range 70%-88% while it is low in the case of Ammonia. If the ORC will be operated with larger turbine efficiency, R143a is suggested depending on whether we are more interested in overall efficiency or Rankine efficiency.
- Through the simulation and calculation of power generation, we know that the power generation of the system increases with the increase in turbine efficiency.
- As shown by figure 4.16, Ammonia has larger power generation capacity over the turbine efficiency range 70%-88% while it is low in the case of R245fa. If the ORC will be operated for larger turbine efficiency, Ammonia is suggested depending on whether we are more interested in power generation capacity or not.
- R143a has larger overall efficiency over the pinch point temperature difference range of 10-25 °C while it is low in case of R124. If the ORC will be operated for a larger pinch point temperature difference, R143a is suggested depending on whether we are more interested in overall efficiency or Rankine efficiency.
- Through the simulation and calculation of power generation, we know that the power generation of the system decreases with the increase in pinch point temperature difference.
- Ammonia has a larger power generation capacity over the pinch point temperature difference range of 10-25 °C while it is low in case of R245fa. If the ORC will be operated for a larger pinch point temperature difference, Ammonia is suggested depending on whether we are more interested in power generation capacity or not.
- It is observed that when the heat source temperature is around 100–370 °C, overall efficiency and Rankine efficiency of the ORC system is greater than that of the SRC systems**.**
- It is observed that when the turbine efficiency is varied around 70–80%, overall efficiency and Rankine efficiency of the ORC system is greater than that of the SRC systems**.**
- It is observed that when the pinch point temperature difference is varied around 10–88°C, overall efficiency and Rankine efficiency of the ORC system is greater than that of the SRC systems**.**
- When the waste heat is free, thermal efficiency is only important as far as it is capable of reducing overall system cost per kW of net power produced. Higher refrigerant operating temperatures can easily result in higher equipment cost.

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