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Effect of Evaporation and Condensation Temperature on Performance of Organic Rankine System Using R134a, R417A, R422D, R245fa

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Abstract

Organic Rankine Cycles (ORCs) are identified as one of the most promising technologies for generating electricity from low-grade heat sources. Unlike conventional Rankine cycles, ORCs operate at lower temperatures and pressures. This allows them to utilize organic fluids or refrigerants as the working fluid instead of water, which is better suited for high-pressure and high-temperature applications. The performance and design of an ORC system are heavily dependent on the chosen working fluid. Therefore, selecting the right working fluid is crucial for a specific application, such as solar thermal, geothermal, or waste heat recovery. This study analyzed the performance of ORCs using four different working fluids: R-134a, R-245fa, R417A, and R422D. The researchers investigated how variations in condensation and evaporation temperatures affect thermal efficiency, mass flow rate, pump power, and turbine pressure ratio. The Engineering Equation Solver (EES) program was used for analyses. The results demonstrated that condensation and evaporation temperatures significantly influence system performance. The study found that ORC systems using R417A and R422D exhibited higher efficiencies compared to the other working fluids analyzed. Additionally, these fluids required lower mass flow rates per unit of power generation compared to the other fluids.

Keywords: Organic Rankine Systems, Working fluids, Performance.

1. Introduction

As human society advances, we confront a growing energy crisis and environmental challenges due to our energy consumption. Fortunately, a solution exists: utilizing medium-low grade thermal energy. This includes recovering waste heat and employing renewable and sustainable energy sources. The Organic Rankine Cycle (ORC) has emerged as a popular and promising technology for harnessing this abundant, yet often underutilized, energy source [1-4].

Several review papers on Organic Rankine Cycles (ORCs) have emerged in recent years. Park et al. focused on performance of experimental ORC, analyzing and reporting key data on prototypes, developed systems, and current trends [5]. Focusing on waste heat recovery, Tartière and Astolfi analyzed the evolution of the ORC market and its diverse applications. Additionally, they explored the technology's future prospects and potential for market growth [6]. Pethurajan et al. conducted a bibliographic review on selecting turbines for ORCs and their applications in topping or bottoming cycles [7]. Additionally, Haghighi et al. and Ahmadi et al. presented bibliographic reviews on geothermal ORCs. Both studies focused on analyzing basic ORCs, ORCs with recuperators, and regenerative ORCs for electricity generation [8,9]. Haghighi et al. primarily concentrated on modeling and optimizing ORCs using various working fluids, reporting energy and exergy efficiency values [9]. Ahmadi et al. carried out a comprehensive analysis focusing on economic factors like levelized cost of electricity and electricity production cost. Their study also included a comparative analysis of these factors with conventional power generation systems, expanding their findings [8]. Finally, Wieland et al. discussed recent advancements and future market perspectives for ORCs. While these reviews cover diverse topics, they primarily center on basic ORC systems. Several studies have focused on identifying optimal working fluids for ORCs from a thermodynamic perspective [10]. Zhang et al. investigated 57 fluids by analyzing their saturated vapor curves. They categorized the fluids into wet, dry, and isentropic classifications. Their research showed that the area of the triangle formed by the critical point and the saturated conditions at the turning point has a significant impact on performance of system. Notably, R123 fluids exhibited the best performance among the studied fluids [11]. A new method for finding the best working fluids for low temperature ORC applications is described by Györke et al. and Imre et al. The method uses a relationship between a specific property of the working fluid in its saturated vapour state to identify optimal fluids for low-temperature ORCs [12,13]. Blondel et al. investigated zeotropic mixtures as potential working fluids of ORCs. They suggested new, semi-empirical heat transfer correlations for both evaporator and condenser processes. Additionally, they evaluated how heat source characteristics (low and high temperatures) affect cycle performance. Interestingly, their findings suggest that zeotropic mixtures with low temperature glide values may not offer significant performance advantages compared to pure fluids [14]. Yang et al. investigated the connection between critical temperatures and boiling temperatures for a wide range of over 250 potential working fluids in ORCs. The relationship between critical temperature and maximum net power remained significant even with variations in reduced boiling temperature, specifically within the temperature range of 150 °C to 200 °C [15]. A method to directly link specific properties of working fluids to the overall performance of an ORC system by Fan et al. was developed [16]. Zhang and Li investigated the behavior of "super-dry" working fluids in regenerative ORC systems designed for medium and low temperature heat sources [17]. Bahrami et al. reviewed low GWP working fluids for ORC applications. Their study explored methodologies for selecting working fluids and considered alternative options such as hydrocarbons, hydrofluorochemicals, and even mixtures [18].

In this study, the effect of condensation and evaporation temperatures on performance of the system operating with 4 different working fluids accepted to be used in ORC systems in the literature was investigated. There are many studies on ORC systems. In this study, unlike the literature, comparative thermodynamic analysis of R134a, R417A, R422D (isentropic) and R245fa (dry) working fluids were performed. Thermodynamic analysis was performed using the EES program.

2. ORC System Description

A basic ORC system comprises four fundamental components: a condenser, an evaporator, an expander, and a pump. Figure 1 shows the basic configuration of an ORC system. As shown, the liquid is pumped to a higher-pressure state (2) from a saturated condition (1) by the pump prior to entering the evaporator. In the evaporator, heat is introduced, resulting in the evaporation of the liquid (3). Subsequently, the working fluid expands in the expander (4), thereby generating power as its pressure decreases. Subsequently, the fluid enters the condenser, where it undergoes a phase transition back into a liquid state (1), thereby completing the cycle. This ORC system is sometimes called a single-stage ORC due to its use as the single evaporator [19].

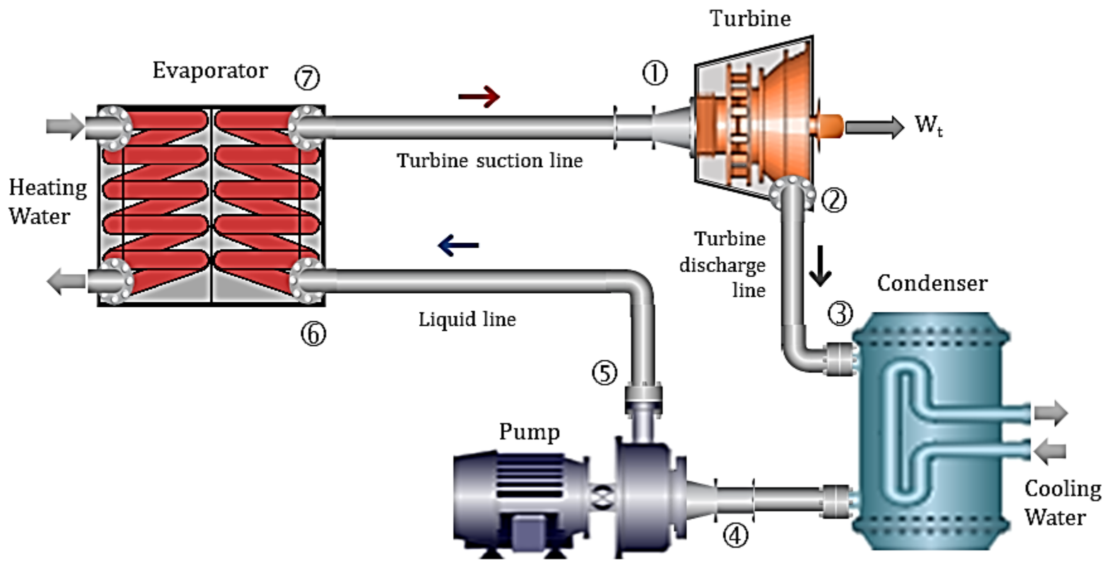

Fig.1. Schematic diagram of basic an ORC system

3. Working Fluid Selection

The selection of a working fluid for an ORC system is crucial. The type of fluid directly affects the cycle's operating parameters and overall efficiency. The shape of a working fluid's saturation vapor curve is a critical property for ORC systems. This characteristic significantly impacts the fluid's suitability, the cycle's overall efficiency, and even the configuration of equipment needed within the power generation system [20,21]. The temperature-entropy (T–s) diagram typically shows three categories of vapor saturation curves (Fig. 2). These categories are:

- Dry fluid: The curve has positive slopes.
- Wet fluid: The curve has negative slopes.
- Isentropic fluid: The curve has slopes approaching positive infinity.

Because the saturation vapor curve for a wet fluid has a negative slope, the turbine's outlet stream typically contains a significant amount of saturated liquid. The presence of liquid inside the turbine can damage the turbine blades and also reduce the turbine isentropic efficiency. The amount of vapor remaining in the turbine outlet (dryness fraction) needs to be above 85%. To achieve this dryness requirement with a wet working fluid entering the turbine, superheating is necessary. However, superheating comes with drawbacks. Heat transfer in the vapor phase has a lower coefficient, which significantly increases the required heat transfer area and consequently raises the cost of the superheater. Additionally, superheaters can introduce other operational challenges. Fortunately, 'isentropic' and 'dry' fluids eliminate the need for superheating altogether. This avoids the potential damage caused by liquid droplets impacting the turbine blades. Since superheating is not required, there's no need for the additional equipment associated with it. Therefore, 'dry' or 'isentropic' working fluids are better suited for ORC systems [21]. Therefore, dry (R245fa) and isentropic (R134a, R417A, and R422D) working fluids are selected in this study. Table 1 provides information on working fluid properties and selection criteria.

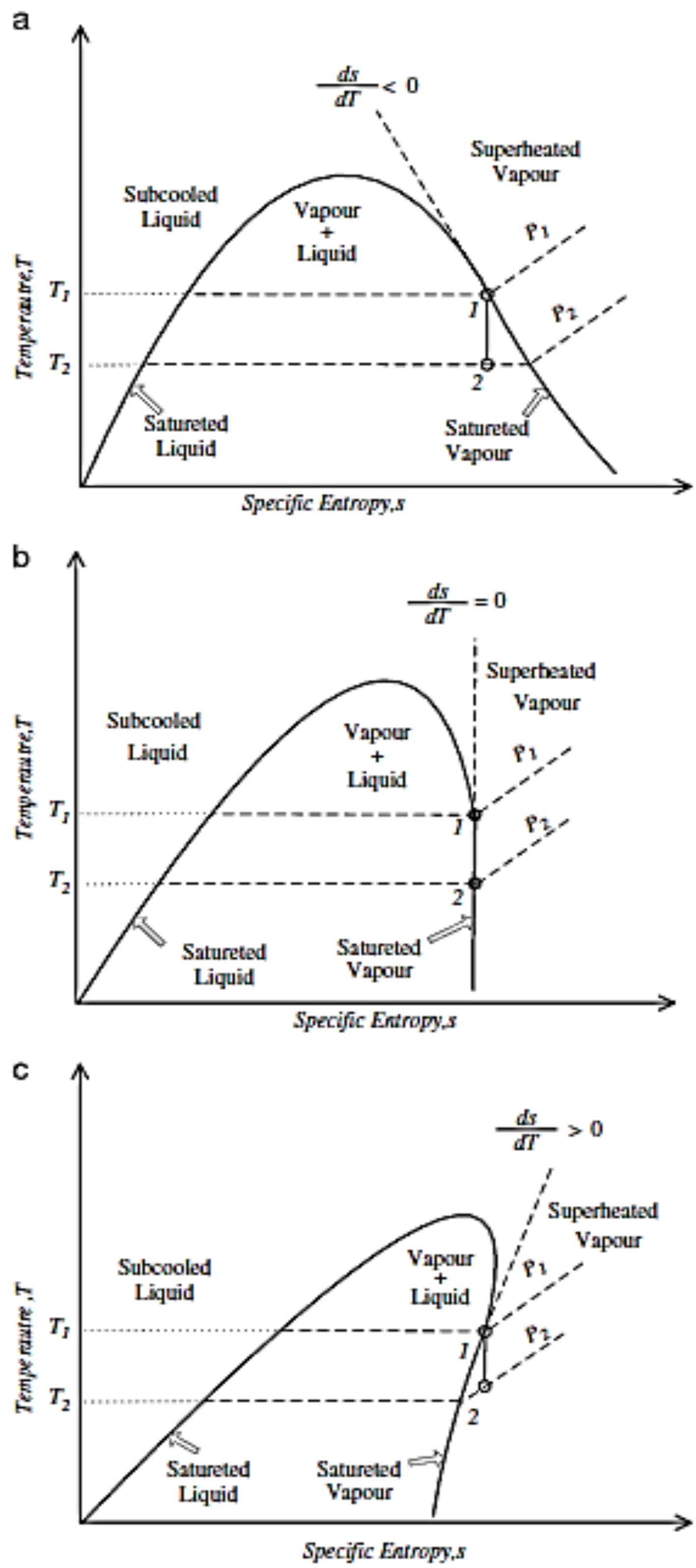

Fig. 2. Diagrams T–s for different fluids (a) wet,(b) isentropic and (c) dry [20].

Table 1. Working fluid properties and selection criteria [22].

Refr.	Critical temp. (°C)	Critical pressure (MPa)	Normal boiling point (°C)	Ozone depleting potential (ODP)	Global warming potential (GWP)	Safety level (Ashrae)	Heat source temp. (°C)	Remarks
R134a	101.06	4.0592	-26.3	0.06	1430	A1	80.848	Due to its negative boiling point, R134a is an appropriate isentropic working fluid for small systems.
R417A	87.04	4.036	-	0.0	2346	A1	69.632	It is accepted that R417A is a zeotropic fluid
R422D	79.56	3.903	-	0.0	2729	A1	63.648	It is accepted that R422A is a zeotropic fluid
R245fa	154.05	3.640	15.0	0.0	1030	B1	123.24	R245fa is a dry working fluid. With due consideration of the relevant environmental parameters, it is therefore deemed to be acceptable.

4. Research Method

Thermodynamic analysis of the ORC system is based on applying the mass and energy equations for each process, as shown in Figure 1. The thermodynamic analysis was carried out using the Engineering Equation Solver (EES). The ORC system consists of four main components: condenser, pump, evaporator, and turbine, which are steady-state flow devices. Therefore, the four processes that make up the ORC can be treated as a steady flow process, and these processes can be analyzed using the relevant thermodynamic equilibrium and equations expressed as [23,24]:

$$(Q_{in} - Q_{out}) + (W_p - W_t) = m_r(h_{out} - h_{in}) \quad (1)$$

The processes of evaporator and condenser do not any input of work and the pump and turbine can be regarded as isentropic. Therefore, the relationship between the input and output energies for each of these components can be expressed as follows:

a) The power required for the pumping of the condensed liquid working fluid to the intake side of the boiler is calculated using the following equation:

$$W_p = \frac{m_r(h_5 - h_4)}{\eta_p} \quad (2)$$

b) In a boiler, heat is introduced to the liquid working fluid, resulting in a phase change to a gaseous state. Using the following formula, the boiler's necessary calorific value is determined:

$$Q_{in} = m_r(h_7 - h_6) \quad (3)$$

c) The turbine power is produced by the expansion of the working fluid from a high-pressure state to a condensing state in gaseous form; the output power is determined by the following equation:

$$W_t = m_r \eta_t (h_1 - h_2) \quad (4)$$

d) For the condenser, a specific quantity of heat is released into the environmental air. This heat released can be calculated using the following equation:

$$Q_{out} = m_r(h_3 - h_4) \quad (5)$$

The following formula is used to calculate thermal efficiency, which is usually used to assess the effectiveness of ORC systems:

$$\eta_{th} = \frac{W_{out}}{Q_{in}} = \frac{(W_t - W_p)}{Q_{in}} \quad (6)$$

The parameters and assumptions presented in Table 2 have been selected on the basis of the operational ranges of ORC systems that have been employed as small-scale power plants.

Table 2. Parameters and assumptions used in research

Parameter	**Unit**	**Value**
Turbine output power	kW	60
Turbine inlet temperature	ºC	77; 75; 72; 69; 66; 63
Condensing temperature	ºC	28; 31; 34; 37; 40; 43
Turbine isentropic efficiency		0.82
Pump isentropic efficiency		0.73

5. Result and Discussion

The mass flow rate, pumping power consumption, turbine pressure ratio and thermal efficiency of the ORCs for four fluids have been calculated for a range of evaporator temperature, as seen in the Figures 3-6. Fig. 3 gives the effect of evaporation temperature on the mass flow rate of the working fluids in the ORC system with the condensation temperature held constant at 34 ºC. It can be seen that increasing the evaporation temperature results in a decrease in the mass flow rate of the working fluids in the system. The mass flow rate of R422D and R417A are lower than R134a and R245fa.

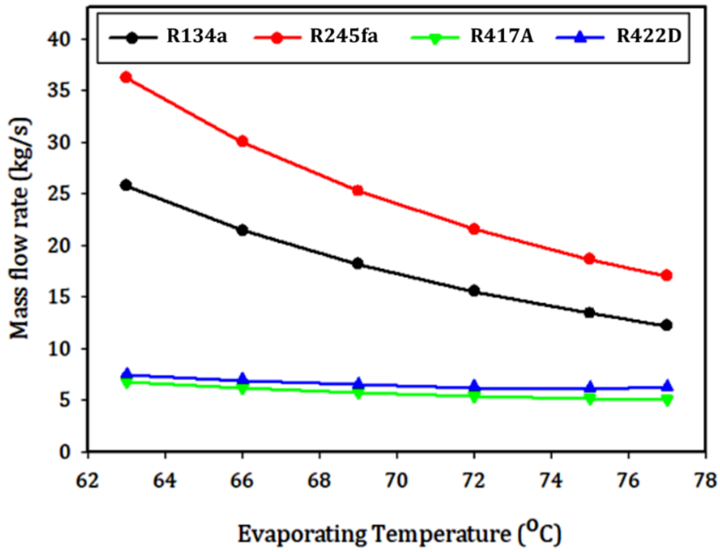

Fig. 3. Effect of evaporation temperature on mass flow rate of working fluid at $T_{condensing}$=34°C

Fig. 4 presents the effect of evaporation temperature on the pumping power consumption of the working fluids in the ORC system with the condensation temperature held constant at 34 °C. The pumping power with increasing the evaporation temperature in the system decrease for R134a and R245fa. However, in the ORC system operating with R422D and R417A fluids, it was observed that the pumping power increased with increasing evaporator temperature. The pumping power to circulate R134a is much greater than the other three working fluids.

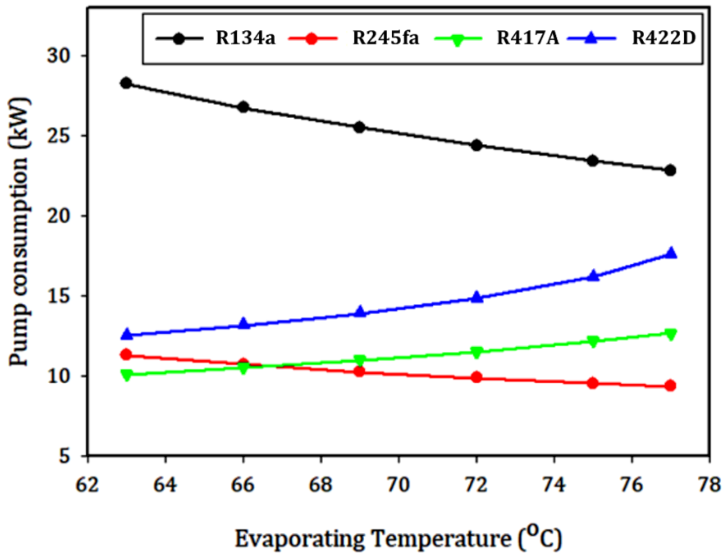

Fig. 4 Effect of evaporating temperature on pumping power consumption at $T_{condensing}$ =34°C

Fig. 5 shows the turbine pressure ratio against the evaporating temperature for four different working fluids. The turbine pressure ratio of all four refrigerants increases as the evaporating temperature increases. The ORC system using R245fa has a higher turbine pressure ratio of 40% compared to the other three working fluids.

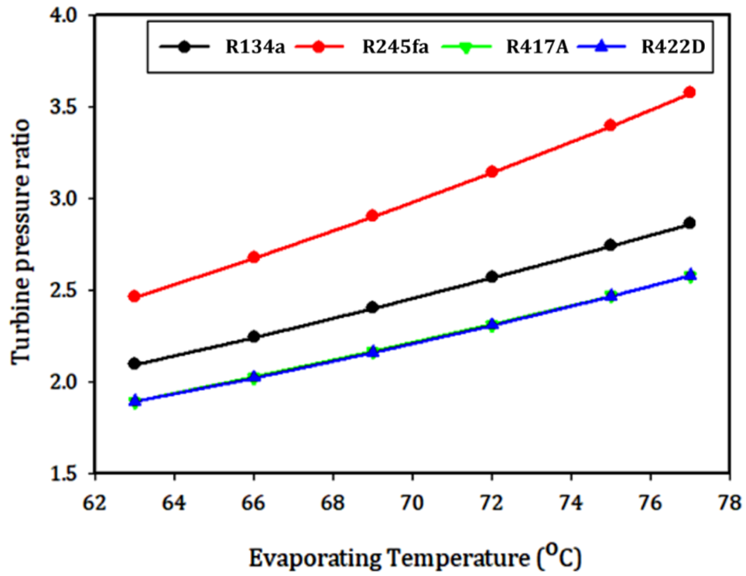

Fig.5 Effect of evaporation temperature on pressure ratio in turbine at $T_{condensing}$ =34°C

Fig. 6 shows that the thermal efficiency of working fluids decreases as the evaporating temperature increases. R422D and R417A is the most efficient fluids at all evaporating temperatures, followed by R134a and R245fa.

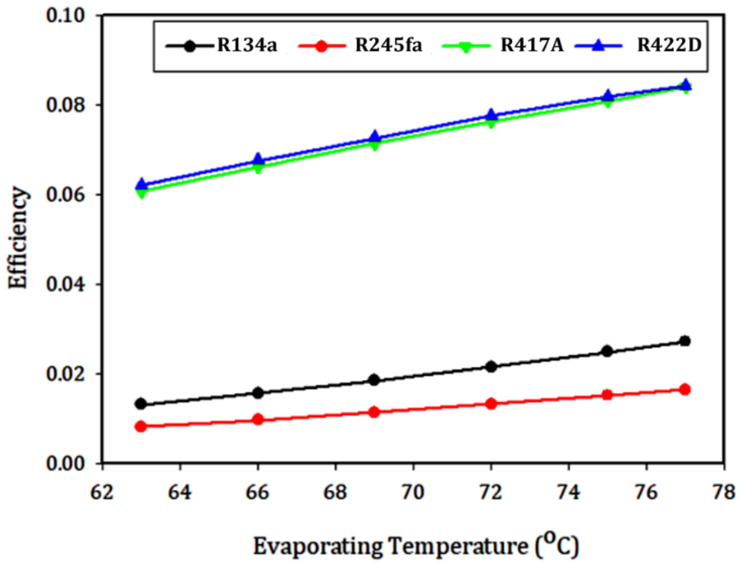

Fig. 6. Effect of evaporation temperature on system thermal efficiency at $T_{condensing}$=34°C

Fig. 7 gives the mass flow rate of four different refrigerants (R134a, R245fa, R417A, and R422D) as a function of condensing temperature at 72°C evaporation temperature. The mass flow rate increases as the condensing temperature increases for all four refrigerants. R245fa has the highest mass flow rate, followed by R134a, R422D, and R417A.

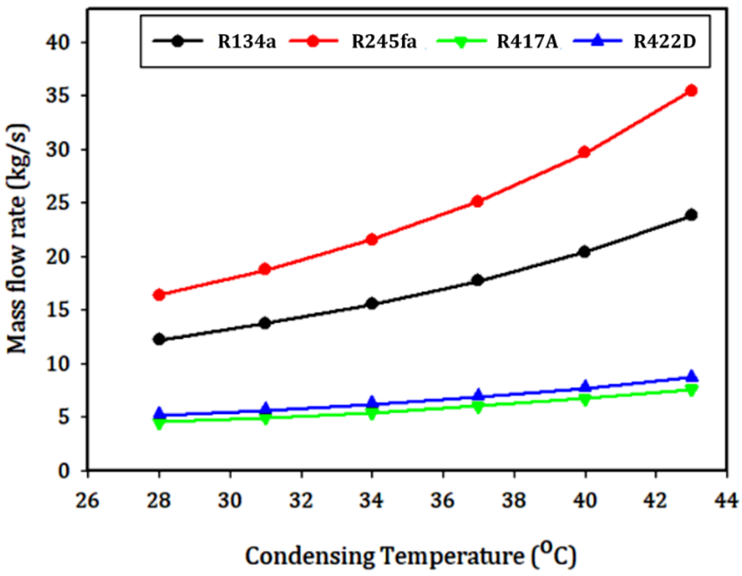

Fig. 7. Effect of the condensation temperature on the mass flow rate of the working fluid at $T_{evaporating}$=72°C

As can be seen Fig. 8, as the condensation temperature increases, the pumping power required will also increase. Although the mass flow rate of R245fa is higher than that of R134a, the pumping power used to circulate R245fa in the ORC system is % 53 lower than that of R134a. The pumping power to R134a is much greater than the other three working fluids.

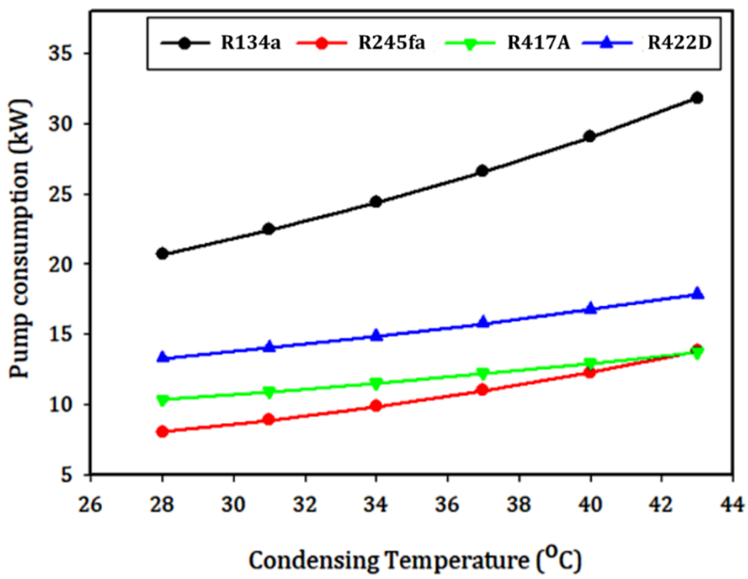

Fig. 8. Effect of condensing temperature on pumping power consumption at $T_{evaporating}$=72°C

Fig. 9 shows that the turbine pressure ratio decreases as the condenser temperature increases. This is because the turbine pressure ratio is a measure of the turbine efficiency, and the efficiency of the turbine decreases as the condenser temperature increases. The ORC system using R245fa has a higher turbine pressure ratio of compared to the other three working fluids.

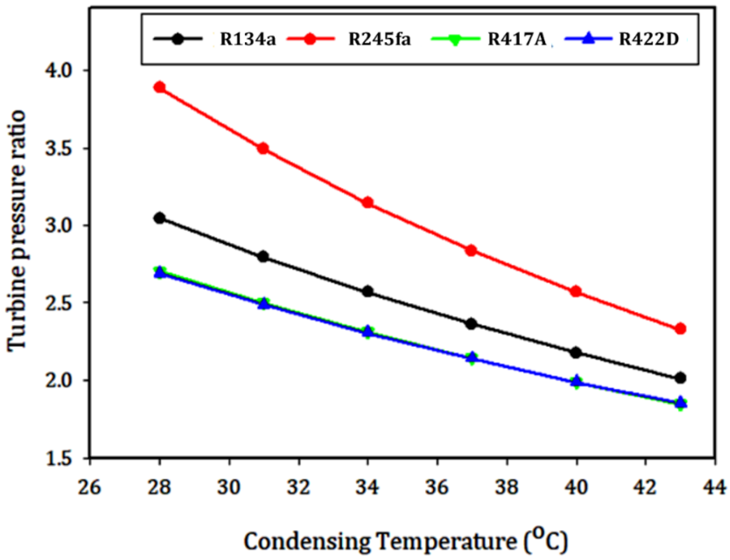

Fig. 9. Effect of condensation temperature on pressure ratio in turbine at $T_{evaporating}$=72°C

Fig. 10 presents the relationship between the condensing temperature and the efficiency of four different refrigerants. The efficiency of all four fluids decreases as the condensing temperature increases. However, the thermal efficiency varies depending on the working fluid. R422D and R417A have the highest thermal efficiency, followed by R134a and R245fa.

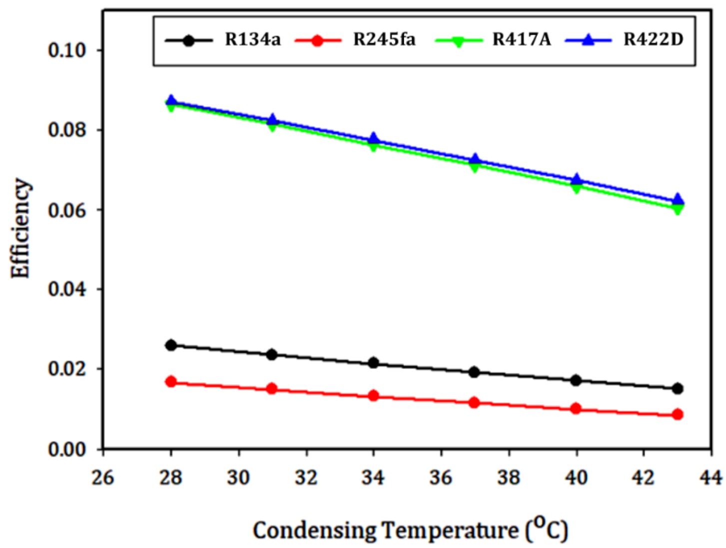

Fig. 10. Effect of condensation temperature on system thermal efficiency at $T_{evaporating}$=72°C

6. Conclusions

This study examines the possible future use of isentropic (R134a, R422D and R417A) and dry (R245fa) acceptable working fluids in ORC systems. The study found that ORC systems using R417A and R422D exhibited higher efficiencies compared to the other working fluids analyzed. Since evaluating the optimal performance for each working fluid individually can be challenging, a common approach involves simulating the cycle using a thermodynamic model. This allows for a direct comparison of four working fluids against R422D and R417A. The study revealed that thermal efficiency rises with increasing evaporator temperature but falls as condenser temperature increases. Notably, this research identified R422D and R417A as working fluids that deliver significantly improved efficiencies across a range of operating conditions compared to other organic Rankine cycle (ORC) fluids.

Author Contributions

Erkan Dikmen: Writing-original draft, Investigation, Conceptualization, Visualization, Analaysis.

Arzu Şencan Şahin: Investigation, Supervision, Methodology, Conceptualization Writing-Review& editing.

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