Assessment of the thermal efficiency of subcritical power generation cycles using environmentally friendly fluids at various heat source temperatures

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Abstract
This study aims to investigate the effect of the various heat source temperature (T_max) on thermal efficiency (η_th) for the organic rankine cycle (ORC), trilateral flash cycle (TFC), and partial evaporator (PE-ORC). For this purpose, HFE7000, HFE7100, and HFE7500 were used as working fluids (WFs). The results indicate that by using HFE7000, the maximum η_th was obtained for all used power cycles and temperature ranges. Compared to HFE7100, HFE7500 has higher η_th at TFC, and PE-ORC at low T_max, while HFE7100 has the maximum value at high T_max. The η_th at T_max = 353 K for TFC were 8.71%, 8.34%, and 8.59%, while for ORC 12.38%, 11.82%, and 11.71% for HFE7000, HFE7100, and HFE7500, respectively. At T_max = 423 K for TFC were 17.65%, 16.26%, and 16.52%, while for ORC were 18.56%, 17.38%, and 16.59% for HFE7000, HFE7100, and HFE7500, respectively. The η_th results indicate that the maximum improvement at TFC by using HFE7000, and the minimum was at HFE7100, while for ORC, the maximum was at HFE7000, and the minimum was at HFE7500. Therefore, the HFE7000 fluid behaves as normal dry fluids at any used temperature, while HFE7100 as normal dry WFs at low T_max while behaving as very dry WFs at T_max extremely close to its T_cr. HFE7500 behaves as very dry working fluids. The η_th intersections temperature was at T_max = 425.2 K and T_max = 455.9 K for HFE7500 and HFE7100, respectively. However, there is no η_th intersection for HFE7000.

KEYWORDS
heat source temperature, subcritical cycles, thermal efficiency, working fluids

Abbreviations: cond, condenser; cr, critical point; eva, evaporator; GWP, global warming potential; h, Enthalpy, [kJ/kg]; max, maximum; min, minimum; ODP, ozone depletion potential; ORC, organic Rankine cycle; P, pressure, [MPa]; PE-ORC, partial evaporator; Q, heat, [kW]; s, entropy, [kJ/kg.K]; T, temperature, [K]; TFC, trilateral flash cycle; WF, working fluid; x, dryness fraction, [-]; η_is,exp, expander isentropic efficiency, %; η_is, pump, pump isentropic efficiency, %; η_th, thermal efficiency, [-]; ṁ, mass flow rate, kg/s.

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INTRODUCTION

One of the major motivators for improving the thermal performance of power plants is an increase in energy demand continuously as a result of the increase in population and industrial sector in the world. Therefore, organic rankine cycle (ORC) is regarded as one of the best cycles for addressing the energy shortage since it uses low and medium temperatures, becoming more attractive in power generation sectors.\(^1\)–\(^3\) Chlorofluorocarbon (CFC), hydrochlorofluorocarbon (HCFC), hydrofluorocarbon (HFC), hydrofluoroolefins (HFO), hydrocarbon (HC), and hydrofluoroether (HFE) employ as organic working fluids in ORC. Many of them have excellent thermodynamics performance. Nevertheless, most of them were forbidden due to becoming a threat to human life and living organisms due to ozone depletion potential (ODP) and high global warming potential (GWP).\(^4\) The working fluid is the most important parameter in power cycles, and due to their properties variations, the cycle performance can be considerably affected in terms of thermodynamics, environment, and economics.\(^5\),\(^6\) The mentioned organic working fluids can use in the following cycles, ORC,\(^7\)–\(^9\) TFC,\(^10,\)\(^11\) and PE-ORC\(^12,\)\(^13\) under specific criteria. Therefore, there are many challenges in selecting the most appropriate working fluid.\(^14\) Besides the thermodynamic performance, other criteria should be considered, such as selecting environmentally friendly fluids, economic suitability, preferable boiling temperature, chemical stability, non-flammability, and low toxicity. According to the mentioned criteria, the HFEs match these factors, precisely HFE7000 and HFE7100.\(^15,\)\(^16\)

In recent years, many efforts have been made to substitute high-GWP WFs with low-GWP. For example, HFCs were developed to replace HCFCs with high ODP and GWP.\(^17\) Consequently, thermodynamic performance cannot be considered the only sole criterion for selecting the working fluid. However, other criteria are also more attractive, such as environmental regulation parameters such as ODP, GWP, atmospheric lifetime, critical temperature, and cost,\(^18\)–\(^20\) as mentioned before. Therefore, choosing a WF is a competitive process, requiring a compromise between cost, safety, performance, and environmental effect. Hydrofluoroethers (HFEs) match the above factors and belong to a family of promising fluids that find application potential both in scientific research and in many industrial areas; for example, in addition to use in ORC, they can be used in other applications.\(^21\)–\(^23\) HFEs fluids are attractive due to their low GWP (remains around 500) and zero ODP, which leads the researchers to pay specific attention to their utilization in the near future.\(^24,\)\(^25\) Therefore, The 3M company developed a range of low GWP fluids for a variety of applications such as ORC and centrifugal; the HFE7000 is one of them.\(^26\) Despite the HFE being described as attractive organic fluids, only a few theoretical and experimental investigations have been done to date; we will brief some of them. The ORC was investigated under constant external conditions using HFE7100, HFE7000, and HFE7500 as working fluids. The effect of increasing the turbine entrance temperature on thermal performance was studied. According to the findings, the \(\eta_{th}\) for the HFE7000, HFE7100, and HFE7500 increased from 7.76% to 12.58%, 7.55% to 12.09%, and 7.54% to 11.95%, respectively, with an increased temperature from 340 to 385 K. The highest \(\eta_{th}\) was obtained by using HFE7000, followed by HFE7100, while by using HFE7500, the minimum value was obtained.\(^24\) While by increasing the temperature from 343 to 383 K, the \(\eta_{th}\) increased from 7.01% to 10.69%, 6.84% to 10.33%, and 6.83% to 10.25%, for the HFE 7000, HFE 7100, and HFE 7500, respectively.\(^27\) HFE7000 was used in the ORC-based micro-CHP for domestic applications,\(^28\) while HFE7100 was investigated in a small ORC.\(^29\) HFE7000 was investigated experimentally for condensation heat transfer in ORC beside the R245fa and Novec649.\(^30\) Furthermore, HFE7100 was experimentally and numerically analyzed.\(^30\) Other HFEs (not included in this present study), such as HFE245fa2, HFE347mcc, HFE245cb2, HFE245mc, and RE143a, were investigated under different parameters for the various purpose.\(^31\)–\(^33\) A feasibility study of HFEs (HFE7000 and HFE7100) as direct replacements for HFC245fa has been conducted using the soft-SAFT model, which is based on technical criteria centered on thermal efficiency and working and service fluid consumption. The results indicated that the HFEs could not compensate for the efficiency of R245fa but appeared as promising replacements, capable of approaching system requirements operating precisely at low pressure with low cooling water and heating fluid flow rates while exhibiting lower GWP values.\(^34\) In another aspect, the expander type has a strong correlation between the working fluids and thermal performance for ORC; for example, the results indicated that the thermal performance (thermal efficiency, net power output) for ORC by using HFE7000 (multivane) is higher than isopentane (which using vane expander).\(^20\) In the mixture phase, the zeotropic mixture of Novec TM649 and HFE7000 (% wt 80/20) was used as an alternative to the traditional R-134a and R-245fa, which demonstrated good performance.\(^25\) Due to zero ODP, low GWP, a very short atmospheric lifetime compared to HFC, nonflammable compared to HCs and HFO, and minimal toxicity, HFEs consider a good candidate for use as working fluids in energy conversion.
systems and lead us to pay specific attention to their utilization in the near future; therefore, this study aims to analyze the $\eta_{th}$ in the subcritical ORC, TFC, and PE-ORC by using three kinds of HFE (HFE7000, HFE7100, and HFE7500), with various $T_{\text{max}}$. Also, showing HFEs behaviors (normal dry or very dry working fluids) and compared them to some of the other selected fluids in different categories such as HCs, HFCs, and HCFCs in $\eta_{th}$ terms.

2 | SYSTEM DESCRIPTION

In comparing TFC, PE-ORC, and ORC, the condition and values of the working fluids thermal properties at the expander inlet are critical factors to consider. TFC has a zero vapor quality ($x = 0$), ORC has a unity vapor quality ($x = 1$), and PE-ORC has a multiphase ($0 < x < 1$) state. All mentioned cycles have the same components with the same functions and processes, while there is a small difference, using merely a liquid heater for TFC, a liquid heater plus evaporator for ORC, and a heater plus partial evaporator for PE-ORC. However, The schematic diagram of subcritical cycles consists of the evaporator/heater (eva), expander (exp), condenser (cond), and pump, as depicted in Figure 1A. The pump supplies the cycle pressure, and the working fluid is pressurized from a saturated liquid state to a high-pressure subcooled state (from state 1 to state 2) as the actual pressurization process, while the state (1–2 s) is the isentropic pressurization process. In the evaporator/heater, the working fluid is heated (TFC) and vaporized (ORC), or partial evaporation (PE-ORC) into a high-pressure vapor state (from state 2 to state 3** [TFC], or 3* [PE-ORC], or 3 [ORC]) by the external heat source.

In the expander, the high-pressure vapor expands (in a two-phase region) using the wet type, or the expansion stops in a dry (superheated) region in case using dry working fluids for ORC as shown in Figure 1B, AND occasionally (with very dry fluids), this can happen with PE-ORC and TFC as well. Therefore the recuperative heat exchanger (which is outside of the scope of this study) is required to add between points (4 and 5) to remove some of the residual heat after the gas expanded in the expander. However, the current study investigated the basic power cycles (free of heat exchanger recuperative). The enthalpy turns into work (from state 3** to state 4** [TFC], or 3* to state 4* [PE-ORC], or 3 to state 4 [ORC]) as an actual expansion process, while the state (3** to 4 s**, 3* to 4 s*, and 3 to 4 s) is the isentropic expansion process. The low-pressure vapor flows into the condenser and is liquefied by the heat sink (from state 4** to state 1 [TFC], or 4* to state 1 [PE-ORC], or 5 to state 1 [ORC]). Finally, the working fluid flows into the pump and is pumped into the evaporator/heater again to finish the cycle.

2.1 | Design assumptions and thermodynamics models

2.1.1 | Design assumptions

One of the most critical parameters that determine the structure and size of an ORC system is the heat source temperature. The heat sources can be categorized into three classes depending upon the temperature range:
The geothermal heat source temperature (low temperature) can range between 353 and 423 K. Moreover, for solar collectors and waste heat recovery (WHR) (medium or high heat source temperature), it can be up to 700 K. The heat sink can be an air cooler or water with a temperature range 283–298 K. In the current study, the cycle modeling assumptions are summarized in Table 1. Namely, maximal and minimal temperature, typical efficiencies for the expander and pump, mass flow, and temperature increments were assumed. The \( T_{\text{max}} \) varies between 353 and 433 K with increments of 10 K when comparing the three investigated fluids (HFEs), while the range increased to 463 K to compare between HFE7100 and HFE7500 and 533 K for HFE7500. The second step is to choose condenser temperature \( (T_{\text{min}}) \), which is defined as the mean temperature between the temperature inlet and outlet of cooling water. This study assumed the \( T_{\text{min}} \) to keep constant at 293 K (20°C). In the comparison scenario between HFEs fluids and other categories (HC, HFC, and HCFC), the investigation was implemented at \( T_{\text{max}} = 363 \) K. The isentropic efficiencies of the turbine and the pump were 85% and 80%, respectively. The mass flow rate is 1 kg/s and was assumed constant for all cases.

### 2.1.2 Models

The simulation model was built to calculate the \( \eta_{\text{th}} \) of TFC, ORC, and PE-ORC, which was the target of this study. Frictional losses of the fluid flowing in the pipes and heat loss were neglected during this study. The following models were employed for calculations:

The isentropic efficiency of the pump \( (\eta_{\text{is,pump}}) \) expressed by

\[
\eta_{\text{is,pump}} = \frac{h_2 - h_1}{h_2 - h_3},
\]

and the pump work \( (W_p) \) defined as

\[
W_p = \dot{m}(h_2 - h_1),
\]

The isentropic efficiency of the turbine \( (\eta_{\text{is,exp}}) \) expressed by

\[
\eta_{\text{is,exp}} = \frac{h_3 - h_4}{h_3 - h_4},
\]

and the turbine work \( (W_T) \) defined as

\[
W_T = \dot{m}(h_3 - h_4).
\]

The \( W_{\text{net}} \) is calculated by the below equation.

\[
W_{\text{net}} = W_T - W_p.
\]

The amount of heat added in the cycle is computed by the below equation.

\[
Q_{\text{add}} = \dot{m}(h_3 - h_2),
\]

where \( h \) is the actual specific enthalpy \( (kJ/kg) \), \( h_s \) is the ideal specific enthalpy \( (kJ/kg) \), and \( \dot{m} \) is mass flow rate \( (kg/s) \).

The \( \eta_{\text{th}} \) of the cycle is defined as shown in the below equation

\[
\eta_{\text{th}} = \frac{W_{\text{net}}}{Q_{\text{add}}}. \tag{7}
\]

For TFC and PE-ORC same model and parameters were used except for \( h_{3*} \) at \( (T_{\text{eva}}, x = 0) \) and \( h_{3*} \) at \( (T_{\text{eva}}, x = 0.1–0.9) \).

### 2.2 Working fluids selection

It is hard to find suitable working fluids that satisfy all the required criteria regardless of their application dependant, and the characteristics of the working fluid significantly affect the cycle performance. Therefore, should consider all parameters when selecting the working fluids, for example, thermo-physical fluid properties, safety operation (nonflammability and low toxicity), environmental conditions (zero ODP and low GWP), and critical temperatures. Due to the legislation constraints applied to third-generation refrigerants, some new-generation refrigerants, such as HFEs, and HFOs, have appeared as new candidates. HFOs represent a realistic alternative due to their excellent environmental properties, but because of their high flammability, their applications are limited or at least prevent their use as single compounds from a safety perspective; therefore, they are recommended to blend with HFCs, to reduce
their flammability. However, the mixture phase and HFOs are outside the scope of this study. HFEs with outstanding thermophysical characteristics, low GWP, minimal toxicity, and nonflammability can be recommended as long-term solutions. Compared to CFCs, HCFCs, and HFCs, HFEs have zero ODP and a very low GWP, which means they are the most environmentally friendly, leading to replacing strong greenhouse gases such as HCFCs and HFCs. Also, HFE features nonflammable, which makes it better than HCs, and HFOs in this respect.

Among the HFEs fluids, HFE7000, HFE7100, and HFE7500 are selected in the present study because they have lower GWP than other HFEs fluids (such as HFE245fa2 and HFE245cb2), which have GWP close to traditional fluids R245fa. The shape of various working fluids T-s diagrams significantly impacts their expansion properties and assists in predicting their state, which is strongly dependent on their molecular structure. However, in the T-s diagram, the slope of the saturation vapor curve might be positive, negative, or vertical, which refers to the state of working fluids wet, dry, or isentropic, respectively. Based on economic and technical considerations, superheating is required in wet fluids to prevent the formation of droplets in the expander, which makes the cycle costly; consequently, isentropic and dry fluids are recommended in ORC. Therefore, all investigated fluids in the study are classified as dry or isentropic, which was one reason for selecting these working fluids. In addition, they have favorable thermal physical properties such as boiling point temperature, critical temperature, and critical pressure. Also, the selected fluids showed good performance in ORC. Therefore, they were recommended and studied as candidates in ORC systems. The main properties and types of the selected fluids are listed in Table 2.

### 3 RESULTS AND DISCUSSION

This study evaluates and compares subcritical ORC, TFC, and PE-ORC $\eta_{th}$ by employing HFE7000, HFE7100, and HFE7500 as working fluids under various $T_{\text{max}}$, also comparing the HFEs fluids to some selected HC, HFC, and HCFC fluids.

The effect of the $T_{\text{max}}$ (with various ranges, 353, 383, 403, and 423 K) on the $\eta_{th}$ of all cycles are presented in Figure 2. Generally, the $\eta_{th}$ increased with increasing $T_{\text{max}}$ for all cycles. At the low $T_{\text{max}}$, the maximum $\eta_{th}$ was by HFE7000 for all investigated cycles followed by HFE7500 except at PE-ORC ($x = 0.9$) and ORC; the maximum was by HFE7100. When the $T_{\text{max}} = 383$ K, the maximum $\eta_{th}$ was by HFE7000 for all power cycles (ORC, TFC, and PE-ORC), followed by HFE7500, except in PE-ORC ($x = 0.8$ and 0.9), and ORC, it has the minimum value, while the maximum was by HFE7100. It was observed that HFE7000 improved more than other fluids (HFE7000 and HFE7500); for example, with increasing $T_{\text{max}}$ from 353 to 383 K, HFE7000 had a greater $\eta_{th}$ improvement, it was (3.31%), followed by HFE7100 (2.98%) and HFE7500 (2.77%), respectively, in ORC. While in TFC, the $\eta_{th}$ improvement with HFE7000 was greater than the others, followed by HFE7500, except in PE-ORC ($x = 0.8$ and 0.9), and ORC. In TFC, the $\eta_{th}$ improvement with HFE7000 was greater than the others, followed by HFE7500. The improvement was (3.9%, 3.6%, and 3.7%) for HFE7000, HFE7100, and HFE7500, respectively. Generally, PE-ORC has greater $\eta_{th}$ than ORC and TFC; consequently, PE-ORC is adequately run by HFEs fluids; for example, at $T_{\text{max}} = 353$ K with using HFE7000,

| Fluids  | Type   | Category | BPT (K) | $T_{cr}$ (K) | $P_{cr}$ (MPa) | GWP   | ODP   | Flammability |
|---------|--------|----------|---------|-------------|--------------|-------|-------|--------------|
| HFE7000 | HFE    | Dry      | 307     | 438         | 2.48         | 370   | 0     | Non          |
| HFE7100 | HFE    | Dry      | 334.2   | 468.3       | 2.23         | 390   | 0     | Non          |
| HFE7500 | HFE    | Dry      | 403.2   | 534.2       | 1.550        | 100   | 0     | Non          |
| Pentane | HC     | Isentropic | 309.21  | 469.7       | 3.37         | 4     | 0     | High flammable |
| Hexane  | HC     | Isentropic | 341.86  | 507.82      | 3.034        | 3     | 0     | High flammable |
| R236fa  | HFC    | Dry      | 271.71  | 398.07      | 3.2          | 6300  | 0     | None         |
| R227ea  | HFC    | Dry      | 256.73  | 375.95      | 2.999        | 3500  | 0     | None         |
| R141b   | HCFC   | Isentropic | 305.2   | 477.5       | 4.212        | 725   | 0.12  | Lower flammable |
| R124    | HCFC   | Isentropic | 261.187 | 395.425     | 3.624        | 610   | 0.03  | None         |

Abbreviations: GWP, global warming potential; HC, hydrocarbon; HCFC, hydrochlorofluorocarbon; HFC, hydrofluorocarbon; HFE, hydrofluoroether; ODP, ozone depletion potential; WF, working fluid.
the maximum $\eta_{th}$ was at PE-ORC ($x = 0.9$) was 0.1253, while it was 0.1238, and 0.0871 for ORC, and TFC respectively. While by using the HFE7100, the PE-ORC still has a higher $\eta_{th}$ than other cycles, it was 0.1207 at ($x = 0.8$), and the $\eta_{th}$ for ORC and TFC was 0.1182 and 0.0834, respectively. Therefore, it concluded that using HFEs fluids at low heat source temperature, the $\eta_{th}$ in the PE-ORC is higher than in ORC and TFC.

At $T_{\text{max}} = 403$ K, the HFE7000 still has a higher $\eta_{th}$ than other investigated HFE. Moreover, followed by HFE7500 at TFC and PE-ORC ($x = 0.1$–0.4), and it has the minimum $\eta_{th}$ for the rest dryness fraction. The ORC, and PE-ORC ($x = 0.5$–0.9) has higher $\eta_{th}$ than HFE7500. The maximum $\eta_{th}$ was at PE-ORC for all HFEs, and it was 0.1747 (at $x = 0.8$), 0.1660 ($x = 0.7$), and 0.1644 ($x = 0.6$) for HFE7000, HFE7100, and HFE7500, respectively.

By increasing heat source temperature to $T_{\text{max}} = 423$ K, the $\eta_{th}$ using HFE7000 has a higher value than others. The HFE7500 has a minimum $\eta_{th}$ except at TFC, and PE-ORC ($x = 0.1$) has a higher $\eta_{th}$. The maximum $\eta_{th}$ was at PE-ORC, it was 0.1866 (at $x = 0.7$), 0.1773 (at $x = 0.6$), and 0.1732 (at $x = 0.7$) by using HFE7000, HFE7100, and HFE7500, respectively. As mentioned, PE-ORC has a higher $\eta_{th}$ than the ORC and TFC. The $\eta_{th}$ increasing ratio between $T_{\text{max}} = 353$–423 K was 6.1% for ORC, while it was 8.9% for TFC, which means with increasing $T_{\text{max}}$, the $\eta_{th}$ for TFC is overcome ORC. For additional temperature ranges, $T_{\text{max}} = 363, 373, 393, 413, 433$ K, see Appendix A.

The effect of $T_{\text{max}}$ on $\eta_{th}$ for all investigated cycles by using HFE7100 and HFE7500 only (Due to the HFE7000 $T_{\text{cr}}$ [438 K] being out of the heat source temperature range) is presented in Figure 3. When $T_{\text{max}} = 443$ K, the $\eta_{th}$ by using HFE7100 was higher than HFE7500 for all power investigated cycles. Among all cycles, by using HFE7100, the PE-ORC has a higher $\eta_{th}$ than TFC, and ORC for all dryness ($x = 0.1$–0.9) except at ($x = 0.1$) has a lower value than ORC. The maximum $\eta_{th}$ for PE-ORC between itself was (at

**Figure 2**: $\eta_{th}$ for organic Rankine cycle (ORC), partial evaporator-ORC, and trilateral flash cycle by using all investigated fluids at various $T_{\text{max}} = 353, 383, 403$, and 423 K.

![Graph showing $\eta_{th}$ for ORC, PE-ORC, and TFC at various $T_{\text{max}}$](image-url)
\( x = 0.6 \), which was 0.1859, followed by \((x = 0.5\) and \(x = 0.7\)). The efficiencies at \((x = 0.5\) and \(x = 0.6\)) were 0.1858 and 0.1856, respectively. While for ORC and TFC, the \( \eta_{th} \) was 0.1830 and 0.1797, respectively. By using HFE7500, the maximum \( \eta_{th} \) was at PE-ORC compared to ORC and TFC at all ranges of dryness fraction \((x)\). The maximum \( \eta_{th} \) of PE-ORC between itself was \((x = 0.4)\), which was 0.1791, followed by dryness fraction \((x = 0.3\) and \(x = 0.5\)), and the efficiencies were 0.1790 and 0.1787, respectively. The \( \eta_{th} \) for TFC and ORC were 0.1759 and 0.1720, respectively. Moreover, it was observed that TFC \( \eta_{th} \) is overtake the \( \eta_{th} \) of ORC, which was justified by the higher \( \eta_{th} \) improvement ratio of the TFC compared to its counterpart ORC. At \( T_{\text{max}} = 453 \) K, the maximum for all cycles was at HFE7100, and the minimum was HFE7500. Among the investigated cycles by using HFE7100, the maximum \( \eta_{th} \) was at PE-ORC at all dryness fractions \((x)\), followed by ORC and TFC. The maximum \( \eta_{th} \) for PE-ORC was \((x = 0.5)\), which was 0.1895, followed by \((x = 0.4)\), which was 0.1894, then the rest dryness fraction. While the ORC \( \eta_{th} \) was 0.1869, and the minimum was at TFC with \( \eta_{th} \) equal to 0.1863.

By using HFE7500, the maximum \( \eta_{th} \) was at PE-ORC, followed by TFC and ORC, respectively. At the dryness fraction \((x = 0.3)\), PE-ORC has the maximum \( \eta_{th} \), which was 0.1811, followed by the rest dryness \((x)\). In contrast, the \( \eta_{th} \) of ORC was 0.1743, which is lower than the \( \eta_{th} \) of TFC, which was 0.1793. Therefore, one can see how TFC \( \eta_{th} \) overcomes ORC at high heat source temperatures by using HFE7500.

At \( T_{\text{max}} = 463 \) K, by using HFE7100, the maximum \( \eta_{th} \) was at PE-ORC \((x = 0.4)\), which was 0.19253, followed by \((x = 0.3)\) with \( \eta_{th} \) 0.19252, and then the rest dryness. The thermal efficiency for TFC and ORC was 0.1918 and 0.1905, respectively. By using HFE7500, PE-ORC has a higher \( \eta_{th} \) than ORC and TFC, and the ORC has the minimum. The \( \eta_{th} \) comparison among the PE-ORC itself (by using different values of dryness \([x]\)) showed that the maximum \( \eta_{th} \) was \((x = 0.3)\), and it was 0.1828, followed by \((x = 0.2)\), which was 0.1827. The TFC \( \eta_{th} \) overcomes ORC. Therefore, one can see that with increasing \( T_{\text{max}} \), the PE-ORC has better performance, followed by TFC, and the worst was at ORC.

In brief, from the above paragraphs observed that with increasing the \( T_{\text{max}} \), the maximum \( \eta_{th} \) start to shift.
toward the lower (x); consequently, the increment ratio of $\eta_{th}$ in TFC is higher than ORC. For example, the maximum $\eta_{th}$ for PE-ORC was (at $x = 0.6, 0.5, \text{and} 0.4$) for $T_{\text{max}}$ (443, 453, and 463 K), respectively, by using HFE7100. In contrast, the maximum $\eta_{th}$ for PE-ORC was (at $x = 0.4$ and 0.3) for $T_{\text{max}} = 443, 453$, and 463 K, respectively, by using HFE7500. In contrast, the $\eta_{th}$ comparison between TFC and ORC showed that the $\eta_{th}$ for ORC overcame TFC for both $T_{\text{max}} = 443$ and 453 K by using HFE7100, while TFC overcomes ORC by using HFE7500. By increasing $T_{\text{max}}$ to 463 K, the $\eta_{th}$ for TFC overcomes ORC for both investigated HFEs fluids (HFE7100 and HFE7500).

The relation between $\eta_{th}$ for all cycles with various $T_{\text{max}}$ by using HFE7500 is presented in Figure 4. It shows that HFE7500 behaves as normal dry fluids at the low $T_{\text{max}}$. Therefore, the ORC $\eta_{th}$ is greater than TFC. At the same time, PE-ORC has a higher $\eta_{th}$ at a specific $x$, as shown in part (A), with $T_{\text{max}}$ varying between 353 and 533 K. Increasing $T_{\text{max}}$ (especially at $T_{\text{max}} = 413$ K or above), ones can see the maximum $\eta_{th}$ for PE-ORC occurred at ($x = 0.5, \text{or} x < 0.5$) while it was at higher $x$ ($x = 0.5, \text{or} x > 0.5$) with low temperature (especially $T_{\text{max}} = 403$ K, or lower), as shown in parts (B and C), where the temperature range was 413–533 K as shown in part (B), and 433–533 K for part (C). Part (D) shows HFE7500 behaves at $T_{\text{max}} = 483–533$ K. It was observed that TFC $\eta_{th}$ improved more than ORC, which guided it to outperform the ORC and PE-ORC precisely at $T_{\text{max}}$ 503, 513, and 533 K. The $\eta_{th}$ started to decrease at $T_{\text{max}} = 513$ K, which means that $\eta_{th}$ decreased with increasing $T_{\text{max}}$ close to its $T_{cr}$. From Figure 4, it can be concluded that the improvement of TFC at high $T_{\text{max}}$ is more than an improvement in ORC, and PE-ORC, which let it overcome them in the $\eta_{th}$ aspect.

The $\eta_{th}$ comparison for ORC and TFC by using HFEs fluids at $T_{\text{max}} = 293$ K–$T_{cr}$ and $T_{\text{min}} = 293$ K is presented in Figure 5. Generally, the $\eta_{th}$ for ORC and TFC increases with increasing heat source temperature and decreases with increasing heat source quite close to the working fluids $T_{cr}$ for ORC by using HFE7000, while for TFC by using both HFE7100 and HFE7500. The temperature of the maximum $\eta_{th}$ was 436.53 K by using HFE7000. Whereas for HFE7100 and HFE7500, the temperature of the maximum $\eta_{th}$ is 467.5 and 526.89 K, respectively. The $\eta_{th}$ for ORC outperforms its counterpart TFC by using HFE7000, and there is no intersection between the $\eta_{th}$ of ORC and TFC curves except at $T_{cr}$.

**Figure 4** $\eta_{th}$ for organic Rankine cycle (ORC), partial evaporator-ORC, and trilateral flash cycle by using HFE7500 fluid at various $T_{\text{max}}$ 353–533 K.
Therefore, the results indicated that HFE7000 behaves as normal dry working (ORC $\eta_{th}$ greater than TFC, and there is no intersection between the efficiencies at a specific temperature).\textsuperscript{67,68} While by using HFE7500, there is the intersection between the $\eta_{th}$ of ORC and TFC; thus, the results indicate that HFE7500 behaves as very dry working fluids (which has $\eta_{th}$ intersection at a specific temperature, and TFC $\eta_{th}$ will be greater than ORC at high heat source temperature), see Ahmed et al.\textsuperscript{67,69} Concerning HFE7100, there is the intersection between the $\eta_{th}$ curve for ORC and TFC at a temperature extremely close to its $T_{cr}$; therefore, it behaves as normal dry fluid at low heat source temperature and behaves as very dry working fluids at a specific temperature that is close to its $T_{cr}$. The temperature of thermal efficiencies intersections was at $T = 425.2$ K while it has $T_{cr} = 534.2$ K and $T = 455.9$ K while its $T_{cr}$ is 468.4 K for HFE7500, and HFE7100, respectively. However, there is no $\eta_{th}$ intersection for HFE7000, and the $\eta_{th}$ for TFC and ORC are equal at $T_{cr}$.

The $\eta_{th}$ comparison between the HFEs, and other selected fluids of the different categories in the investigation cycles (ORC, TFC, and PE-ORC) at $T_{max} = 363$ K and $T_{min} = 293$ K is presented in Figure 6. The other selected categories were HC (Pentane, Hexane), HFC (R236fa, R227ea), and HCFC (R141b, R124).

The comparison between HFEs, and HC is depicted in Figure 6A; the $\eta_{th}$ by using Hexane is higher than HFEs at ORC, and some of PE-ORC ($x = 0.2–0.9$), while it has a lower $\eta_{th}$ at TFC compared to all investigated HFEs, while at PE-ORC ($x = 0.1$) it has lower value compared to HFE7000, and HFE7500 only. Using the Pentane, ORC and PE-ORC have a higher $\eta_{th}$ than all HFEs, while TFC has a lower value than HFE7000 and HFE7500.

The $\eta_{th}$ comparison between HFEs, and HFC is depicted in Figure 6B. The $\eta_{th}$ of ORC and some of PE-ORC ($x = 0.4–0.9$) by using HFE7000 is higher than R227ea, while at PE-ORC ($x = 0.5–0.8$), it is higher than R227ea by using HFE7500. At the same time, PE-ORC ($x = 0.6–0.8$) has a higher value than R227ea by using HFE7100. For the rest cycle (TFC, ORC, and other parts of PE-ORC), the R227ea performance is better than HFEs fluids. The ORC, TFC, and some parts of PE-ORC which use R236fa have higher $\eta_{th}$ than HFEs, while HFEs have higher $\eta_{th}$ than HFC at PE-ORC at ($x = 0.4–0.8$) by using HFE7000, and at ($x = 0.5–0.6$) by using HFE7500.
Compared to R227ea, HFE7100 performs better at PE-ORC ($x = 0.6$ and $x = 0.7$), while comparing it to HFE7000, the HFE7000 performs better at ORC and PE-ORC ($x = 0.4$–0.9).

The $\eta_{th}$ comparison between HFEs and HCFC is presented in Figure 6C. Compared to HFEs, the TFC by using R141b has a lower $\eta_{th}$ than HFE7000, while it has a maximum compared to the rest of HFE7500 and FFE7100 at all cycles. Compared to HFEs, the R124 performs better in the aspect of the $\eta_{th}$ for all investigated cycles, except at PE-ORC ($x = 0.6$–0.8), the HFE 7000 performs better than R124.

**Figure 6** Comparison hydrofluoroethers fluids with others at $T_{\text{max}} = 363$ K; (A) hydrocarbon, (B) hydrofluorocarbon, and (C) hydrochlorofluorocarbon

4 | THERMAL EFFICIENCY COMPARISON OF ORC

In this section, we compare the current results of $\eta_{th}$ with the literature studies, which used HFEs (HFE7000, HFE7100, and HFE7500) as working fluids in ORC. All the $\eta_{th}$ results for previous and current studies are listed in Table 3. Despite small differences in the values, they agree with the results obtained in the current study; for example, all references and the current study agrees that the $\eta_{th}$ increased with increasing $T_{\text{max}}$. Meanwhile, HFE7000 provides the highest $\eta_{th}$ compared to HFE7100 and HFE7500, followed by HFE7100, and the minimum was at HFE7500. The value difference in the comparison is justified by using different operating parameters in the calculation. For example, the used isentropic efficiency for the turbine and pump was 70%.27 Another study used 80%,24 while in the reference,63 they were 85% and 65% for turbine and pump, respectively. The operating parameters for the current study are listed in Table 1. The mass flow rate was 1 kg/s,24,27 while in the reference,63 the analysis was implemented without a mass flow rate. In addition, there is a small difference in the $T_{\text{min}}$, precisely in references.24,27
CONCLUSION

This study evaluated and compared subcritical ORC, TFC, and PE-ORC \( \eta_{th} \) using HFE7000, HFE7100, and HFE7500 as working fluids and compared some of the selected working fluids in different categories such as HC (Hexane and Pentane), HFC (R236fa and R226ea), and HCFC (R141b and R124). Generally, the \( \eta_{th} \) increased with increasing \( T_{\text{max}} \). HFE7000 has better performance for all cycles and temperature ranges (353–433 K). Compared to HFE7100, HFE7500 has good performance at TFC and some specific dryness (various dryness) in the PE-ORC, except at ORC at low \( T_{\text{max}} \) (353 K), while with increasing \( T_{\text{max}} \) above the mentioned range up to \( T_{\text{max}} = 423 \text{ K} \), the cycle (ORC and PE-ORC) which using HFE7100 performs better than which using HFE7500, while at TFC vice versa. With increasing \( T_{\text{max}} \) (above 433 K), HFE7100 performs better than HFE7500 in all cycles (TFC, ORC, and PE-ORC). The \( \eta_{th} \) improvement for TFC is greater than ORC with all investigated fluids, but the ratio of improvement with using HFE7500 is higher than its counterparts. The ratio of \( \eta_{th} \) improvement in TFC was higher than its counterpart, while by using HFE7500, ORC is greater than ORC, and there is no intersection between the efficiencies at a specific temperature) as other fluids (some of HC, CO\(_2\), and Water) which are studied in Ahmed et al.\(^{67,68}\) While HFE7500 behaves as very dry working fluids (which has \( \eta_{th} \) intersection at a specific temperature and TFC \( \eta_{th} \) greater than ORC), as dodecane, see Ahmed et al.\(^{67,69}\) HFE7100 behaves as normal dry working fluids at low \( T_{\text{max}} \) and as very dry working fluids at a temperature close to its \( T_{\text{cr}} \). The thermal efficiencies intersections temperature was at \( T = 425.2 \text{ K} \) while \( T_{\text{cr}} = 534.2 \text{ K} \), and \( T = 455.9 \text{ K} \) while its \( T_{\text{cr}} \) is 468.4 K for HFE7500 and HFE7100, respectively. However, there is no \( \eta_{th} \) intersection for HFE7000; see Figure 5 for all investigated fluids. Generally, the maximum \( \eta_{th} \) for all investigated cycles was at PE-ORC, for all \( T_{\text{max}} \) ranges, except at high \( T_{\text{max}} = 503 \text{ K} \) by using HFE7500, the maximum was at TFC. The recommendation summarized is, HFEs should be studied in the near future, specifically in the PE-ORC, and TFC, because on some occasions, these fluids outperform the other investigated fluids (HC, HFC, and HCFC) at least in \( \eta_{th} \) terms.

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| Reference | HFE7000 (%) | HFE7100 (%) | HFE7500 (%) | \( T_{\text{max}} \) | \( T_{\text{min}} \) |
|-----------|-------------|-------------|-------------|----------------|----------------|
| [27]      | 8.5         | 8.0         | 7.7         | 353            | 301            |
| [27]      | 10.02       | 9.6         | 9.4         | 373            | 301            |
| [27]      | 10.69       | 10.33       | 10.25       | 383            | 301            |
| [24]      | 9.3         | 9.05        | 9.0         | 353            | 298            |
| [24]      | 11.5        | 11.1        | 11.0        | 373            | 298            |
| [24]      | 12.4        | 11.7        | 11.6        | 383            | 298            |
| [63]      | 13.4        | 12.9        | -           | 373            | 293            |
| [63]      | 14.9        | 14.3        | -           | 393            | 293            |
| Current   | 12.3        | 11.8        | 11.7        | 373            | 293            |
| Current   | 14.7        | 13.94       | 13.7        | 373            | 293            |
| Current   | 15.6        | 14.8        | 14.49       | 383            | 293            |
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APPENDIX A: THERMAL EFFICIENCY INVESTIGATION FOR POWER GENERATION CYCLES (TFC, PE-ORC, AND ORC)

To achieve more results, a wide range of $T_{\text{max}}$ 363, 373, 393, 413, 433 K were used for all investigated working fluids (HFE7000, HFE7100, and HFE7500) and power generation cycles in this study. For all $T_{\text{max}}$ ranges, the results indicated that Among the three possibilities, HFE7000 provides the highest $\eta_{\text{th}}$ for all investigated power cycles (ORC, TFC, and PE-ORC). Compared to HFE7500, HFE7100 has a higher $\eta_{\text{th}}$ in ORC, while in TFC, it has a lower $\eta_{\text{th}}$ except at high $T_{\text{max}} = 433$ K. In PE-ORC, by using HFE7100 and HFE7500, the highest $\eta_{\text{th}}$ depends on the dryness fraction values ($x$). At $T_{\text{max}} = 363$K, the HFE7500 has a higher $\eta_{\text{th}}$ HFE7100 for all dryness except at ($x = 0.9$). At $T_{\text{max}} = 373$ K, HFE7100 has a higher $\eta_{\text{th}}$ at ($x = 0.8$ and $0.9$), while at $T_{\text{max}} = 393$ K, it has the maximum at ($x = 0.7$–$0.9$). $T_{\text{max}} = 413$ K has the maximum at ($x = 0.4$–$0.9$), while at $T_{\text{max}} = 433$ K, the $\eta_{\text{th}}$ for PE-ORC by using HFE7100 overcomes HFE7500 entirely at all dryness ranges.

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