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(coordinadores)

Proceedings of the 7th International Seminar on ORC Power Systems

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ORC SYSTEM USING R1233ZD(E) FOR WASTE HEAT RECOVERY FROM THE UPSTREAM PROCESS

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ABSTRACT

The upstream is an energy-intensive sector of the petroleum industry. Nearly one-third of the industry's energy is discharged as thermal losses via cooling systems or into the environment. Waste heat recovery (WHR) from upstream processes could significantly reduce current fossil energy's carbon footprint and competitiveness and stimulate the transition to carbon-neutral renewable energy sources by utilizing the free energy generated from WHR to support renewable energy production. In the WHR system, the working fluid selection is critical to the design, thermodynamic performance, operation practicality, and environmental impact of organic Rankine cycles (ORC). This study comparatively examined the ORC performance of six working fluids (easily accessible in Malaysia) for WHR from upstream processes using a thermodynamic model. Results showed that R1233zd(E) is a promising working fluid for WHR due to its zero Global Warming Potential (GWP). The single-loop ORC cycle using R1233zd(E) delivered 6.2% thermal efficiency at a 250°C temperature difference by maintaining an operating pressure ratio of 9:1. These conditions ensured a practical turbine expander design for mechanical work recovery. The WHR process reduced the overall carbon footprint of the upstream product by 6.2%. 373

1 INTRODUCTION

The upstream is one of the most energy-intensive sectors of the petroleum industry due to its significant energy demands. Various upstream processes and equipment in the industry discharge multiple grades of low (≤ 230°C), medium (230 to 650°C), and high (≥ 650°C) temperature waste heat (PBOG, 2013). The thermal losses from co-produced hot liquid, incineration, gas flares, prime movers, amine gas treaters, and natural gas compressors account for one-third of the energy consumed in the industry (EPA, 2015). According to analyses, the waste heat typically discharged into the environment or through cooling systems can be successfully recovered in the industry to significantly reduce the overall carbon footprint of current fossil fuel systems by lowering greenhouse gases (GHG), flue/exhaust emissions, fuel consumption, and operational costs. The utilization of WHR technologies (such as Electric Turbo-compounding (ETC), organic Rankine cycle (ORC), and Thermo-electric generators (TEG)) for power generation, process heat, and heat can stimulate the transition to carbon neutrality by supplying free energy to diversify the energy mix and making renewables a practical and competitive energy source.

The process of WHR using ORCs critically requires the selection of an appropriate working fluid that satisfies the cycle's thermodynamic performance, operational practicality, and environmental impact. Numerous working fluids (e.g., R1233zd(E), R245fa, R134a, and R410a) have been previously examined for application in ORC systems. The performance and efficiency of ORC systems are dependent on the unique properties of the selected working fluid. Therefore, this study aims to investigate the most suitable working fluid for the WHR application at the MTJA gas-holding area in the Gulf of Thailand. This area covering 7,250 km² was created as an interim measure to exploit and equally share the proceeds of the natural resources in the seabed or continental shelf claimed by Malaysia and Thailand (MTJA, n.d.).

2 LITERATURE REVIEW

ORC systems are widely studied for WHR because of their ability to generate power from low to medium-temperature heat sources. The selection of the working fluid is a critical factor affecting ORC systems' performance and environmental impact. Several working fluids, such as R134a, R245fa, and R123, have been investigated. Muhammad *et al.* (2015) investigated low-grade WHR using an ORC system. The system yielded a maximum thermal efficiency of 5.75% and a maximum expander isentropic efficiency of 77.74% using R245fa. Shu *et al.* (2016) reported that R123 is better suited for WHR from heavy-duty diesel engines, while R245fa is more suitable for light- and medium-duty. This observation was attributed to the difference in their thermodynamic properties and limited onboard cooling capacity. An overall 2.8% improvement in the system's thermal efficiency was achieved using R123. Hijriawan *et al.* (2022) demonstrated that a maximum improvement of 3.17% in system efficiency is achievable using R134a as the working fluid. However, hydrofluorocarbons (HFCs) and hydrochlorofluorocarbon (HCFC) working fluids have high global warming potentials (GWPs), which are subject to phase-out regulations. Table 1 compares the environmental impact and thermophysical properties of the ORC working fluids.

Table 1: Environmental impact and thermophysical properties of different ORC working fluids

Working fluid	Class	GWP	ODP	Critical temperature (°C)	Critical pressure (bar)
R123 (A-Gas, n.d.)	HCFC	77	0.0015	183.7	36.6
R245fa (Honeywell, 2013b)	HFC	1,030	None	154.0	36.5
R134a (Honeywell, 2013a)	HFC	1,430	None	101.1	40.6
R410a (Honeywell, 2013c)	HFC	2,088	None	71.4	49.0
R1233zd(E) (Honeywell, 2015)	HFO	1	None	165.5	35.7
R600a (Darment, n.d.; Sinteco, 2020)	HC	3	None	135.0	36.0

GWP – Global warming potential; ODP – Ozone depletion potential; HCFC – hydrochlorofluorocarbon; HFC – hydrofluorocarbon; HFO – hydrofluoroolefin; HC – hydrocarbon.

R1233zd(E) has recently been proposed as an alternative working fluid for ORC systems due to its zero GWP and low ozone depletion potential. Several studies have demonstrated the feasibility of using R1233zd(E) in ORC systems for WHR from diesel engines and exhaust gases. Elahi *et al.* (2022) reported that R1233zd(E) showed better performance compared to R1234ze(Z), R1234ze(E), and R1234yf based on the exergy analysis of WHR using ORC. The working fluid with the higher critical temperature showed better thermal and second-law efficiencies. Rijpkema *et al.* (2021) demonstrated that 0.7% of the engine power of a heavy-duty truck could be recovered using an R1233zd(E)-operated ORC. However, Mariani *et al.* (2022) showed that an equivalent system could produce an additional 8.0% power output from a mechanical engine.

The discrepancies in thermal efficiency improvement can be due to the difference in the cycle's configuration and operating conditions. Therefore, a dedicated ORC working fluid selection study is critical for new applications. It is a relatively inexpensive analytical study that can effectively eliminate unnecessary uncertainties.

To the best of the authors' knowledge, no previous study has investigated using R1233zd(E) as a working fluid for ORC WHR from the upstream process of the petroleum industry. Therefore, this study examines the operational feasibility, thermal efficiency, and environmental impact of using R1233zd(E) in an ORC WHR system for upstream processes. In addition, its performance will be benchmarked with other common ORC working fluids accessible in Malaysia, as given in Table 1. The T-s diagrams of the selected working fluids are shown in Figure 1.

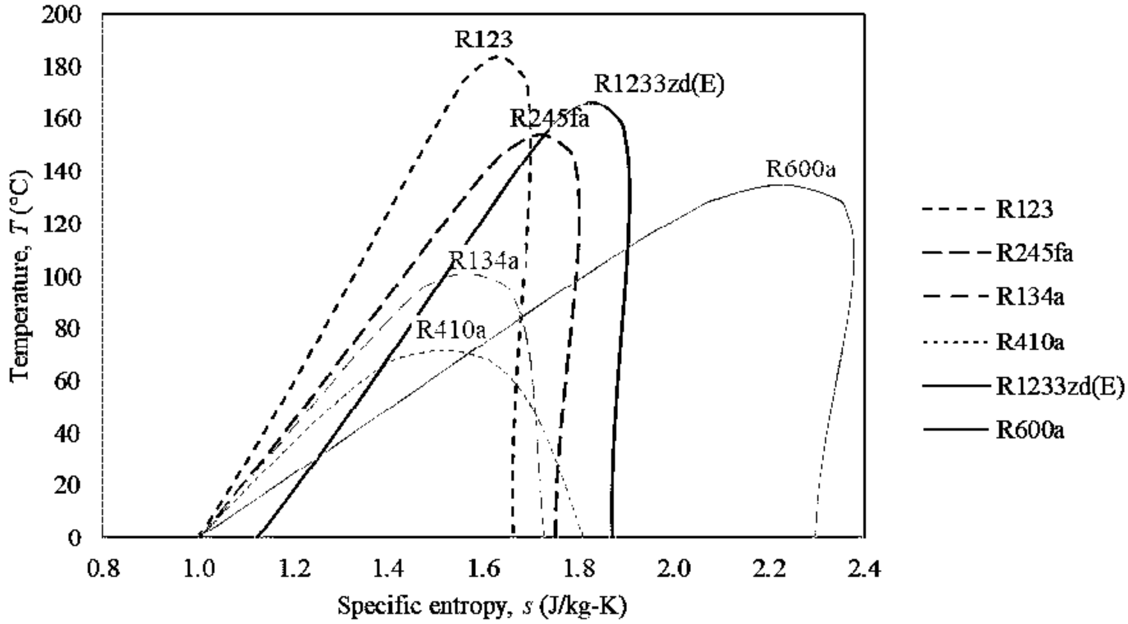

Figure 1: T-S diagram of potential ORC working fluids.

3 METHODOLOGY

The pilot-sized WHR system used in this study has a 260 kW heat source supply. As shown in Figure 2, the system consists of an ETC, ORC, and TEG. The ORC turbine inlet condition is set at 250°C and 27.0 bar (abs). A higher turbine inlet temperature associated with larger power output can simultaneously increase the cycle's thermal efficiency by enabling an economizer for internal WHR. The working fluid temperature at the condenser outlet is controlled within the range of 28.5±1.5°C due to the cooling water temperature limitation.

A thermodynamic model was developed to analyze the performance of the ORC cycle under steady-state conditions. The thermophysical properties of the working fluids were deduced from the CoolProp database (n.d.). All heat exchangers are assumed to achieve energy equilibrium and pressure drop is ranging between 3 kPa and 50 kPa. As a precautionary step, a minimum of 5°C temperature difference between fluids are maintained across all heat exchangers to avoid pinch point problem. The ORC turbine's total-static efficiency was 65%, the turbine generator efficiency was 60% and back work-to-pump efficiency was 20%, resulting in a net ORC output. The governing equations of the thermodynamic model are given as below:

Heat addition into ORC at evaporator:	$q_{in} = h_1 - h_6$	Eq. 1
Energy balance at evaporator:	$\dot{m}_{exh} c_p \left(T_{exh,in} - T_{exh,out}\right) = \dot{m}_{wf}(h_1 - h_6)$	Eq. 2
Heat rejection from ORC at condenser:	$q_{out} = h_4 - h_3$	Eq. 3
Energy balance at condenser:	$\dot{m}_{cw} c_p \left(T_{cw,in} - T_{cw,out}\right) = \dot{m}_{wf}(h_4 - h_3)$	Eq. 4
Energy balance at economizer:	$(h_6 - h_5) = (h_2 - h_3)$	Eq. 5
Pump's specific energy input (back work):	$w_{pump} = v_5(p_6 - p_5)$	Eq. 6
Gross specific work output from turbine:	$w_{turb,gross} = h_1 - h_2$	Eq. 7
Net specific work output from ORC:	$w_{out,net} = \left(w_{\text{turb},gross} \times \eta_{generator}\right) - \left(w_{pump}/\eta_{pump}\right)$	Eq. 8

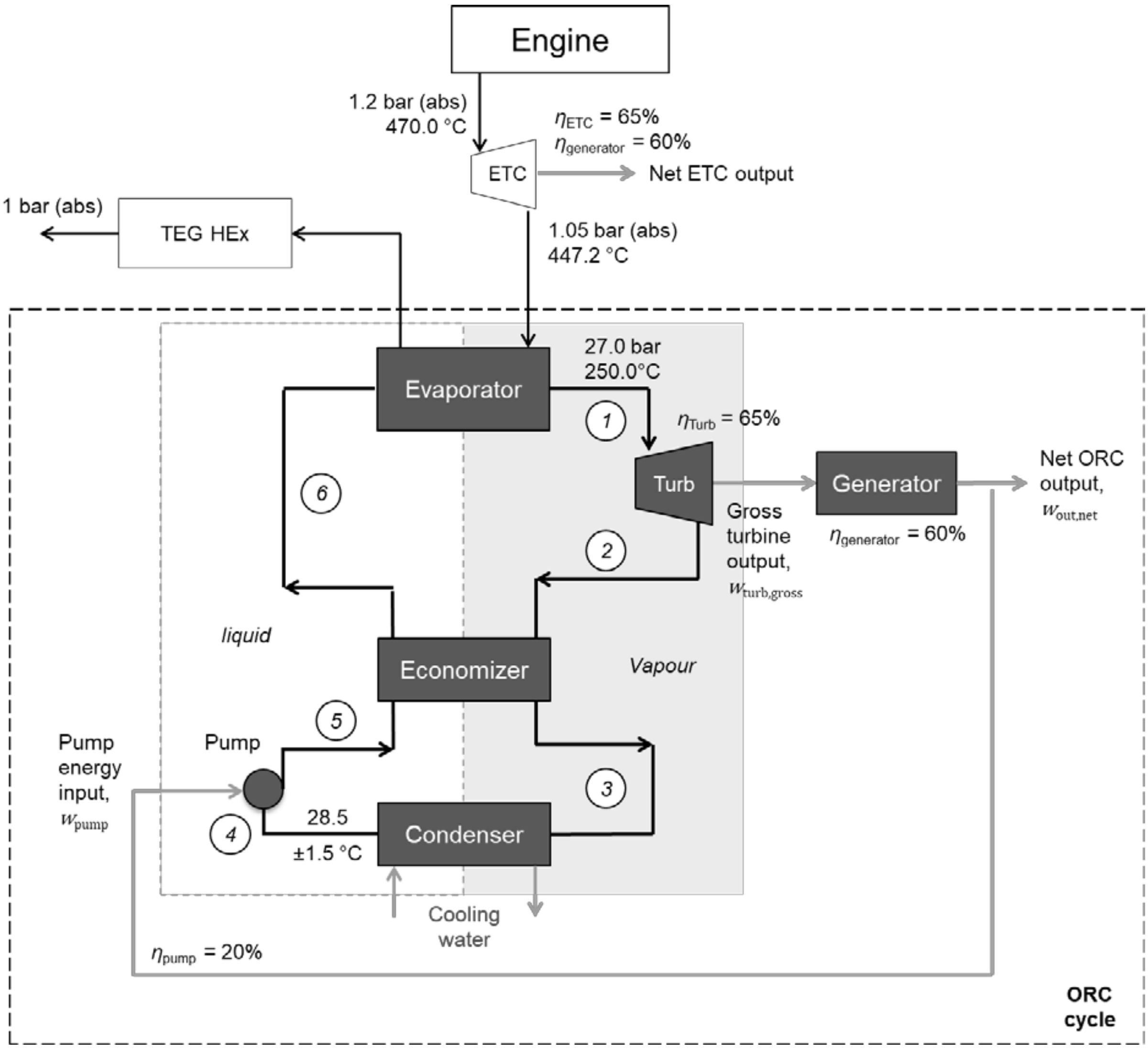

Figure 2: Schematic of the ORC cycle in the pilot-size WHR system.

Figure 1 shows the performance of the six working fluids in the ORC cycle. The choice of working fluids is based on their ease of accessible in Malaysia. The ORC turbine's expansion ratio was adjusted for some working fluids to ensure workability at the given operating conditions while maintaining the condenser outlet pressure above ambient. In the following section, the results of the working fluid analysis are presented.

4 RESULTS AND DISCUSSION

Table 2 provides an overview of the performance parameters of the six ORC working fluids. The examined performance parameters include the resultant specific output power, cycle thermal efficiency, turbine expansion ratio, and condenser outlet temperature. It is worth noting that all working fluids fulfilled the condenser outlet temperature requirements. However, the results indicate that the most efficient working fluid may not necessarily produce the highest output power. For instance, R123 exhibits the highest thermal efficiency (8.0%), but its output power is approximately 43% lower than R600a, which delivers the highest net output of 46.8 kJ/kg despite being less efficient.

Table 2: Performance parameters of the six selected ORC working fluids.

Working fluid	Net specific work output (kJ/kg)	Mass flow rate (kg/s)	Net output power (kW)	Thermal efficiency
R123	26.6		22.1	8.0%
R245fa	24.8		20.6	6.2%
R134a	16.8	0.833	14.0	2.6%
R410a	6.7		5.6	0.6%
R1233zd(E)	24.7		20.6	6.2%
R600a	46.8		39.0	4.4%

Cont'd	Expansion ratio	Thermal power input at evaporator (kW)	Evaporator inlet temperature (°C)	Condenser outlet temperature (°C)
R123	17	180.4	130	28
R245fa	9	200.1	139	27
R134a	3	275.9	75	30
R410a	1.35	336.2	40	30
R1233zd(E)	9	191.2	141	28
R600a	6	469.6	110	28

Figure 3 shows that the cycle's thermal efficiency increases almost linearly with the working fluid's critical temperature, which is consistent with the findings of Elahi *et al.* (2022). However, the increment in net specific work output is not linear, as higher critical temperature working fluids require a larger expansion ratio for the given operating conditions. For example, R123 requires an extremely high expansion ratio (23:1), as depicted in Figure 4. On the other hand, R600a requires significantly higher input (thermal) energy at the evaporator, which is evident from Figure 4. Despite its higher energy consumption, R600a delivers higher net output, and its thermal efficiency ratio adheres to global trends.

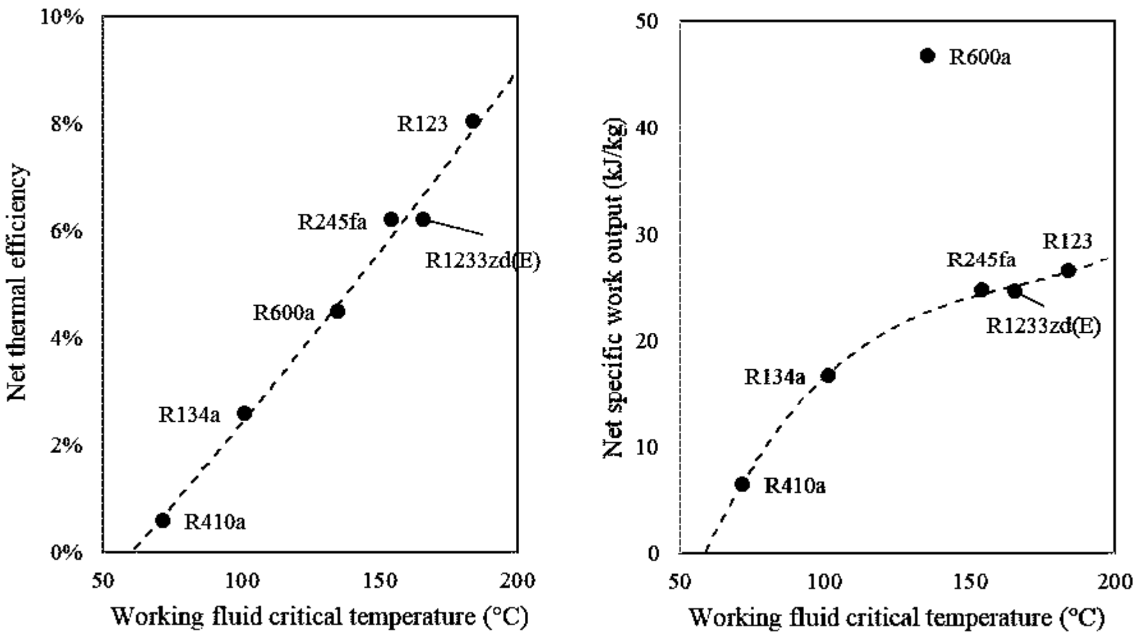

Figure 3: Cycle thermal efficiency and net output at working fluids critical temperatures.

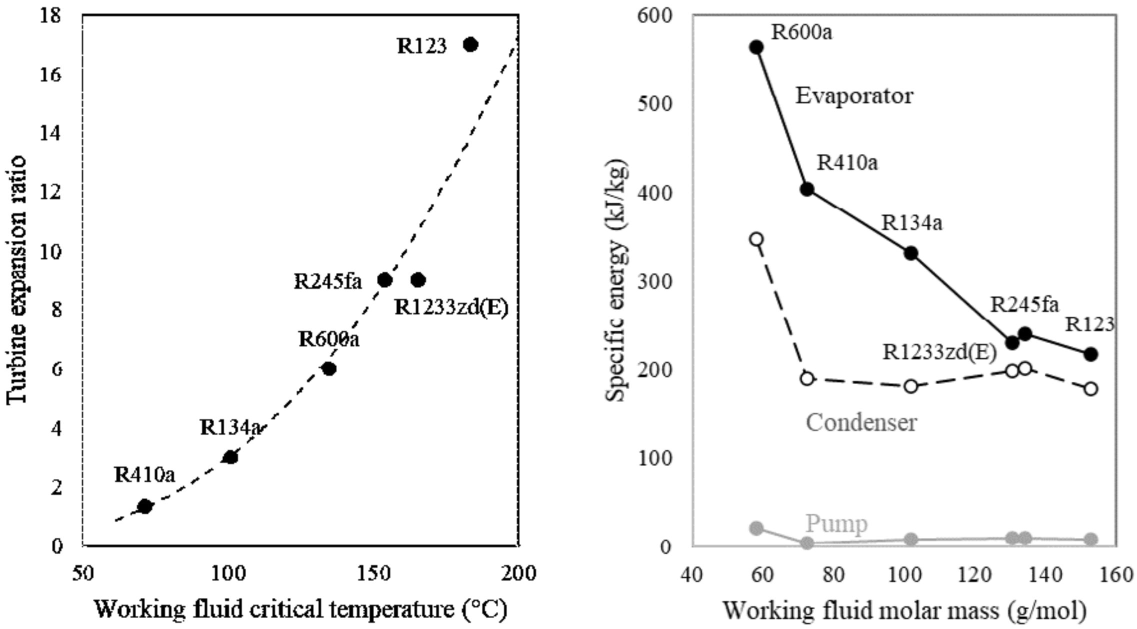

Figure 4: Cycle turbine expansion ratio and thermodynamic properties of working fluids.

The higher energy consumption of R600a is due to its thermophysical properties, such as its specific enthalpy, which is nearly double that of the other working fluids. However, this requires further investigation into the potential of larger heat exchangers to transfer significantly higher heat energy at the evaporator and condenser. Conversely, R245fa, R134a, and R410a are unsuitable due to their higher GWP, even though R245fa exhibits similar thermodynamic performance as the other preferred working fluids. Since the objective of WHR is to mitigate climate change and achieve carbon neutrality, using R245fa is counterintuitive. 378

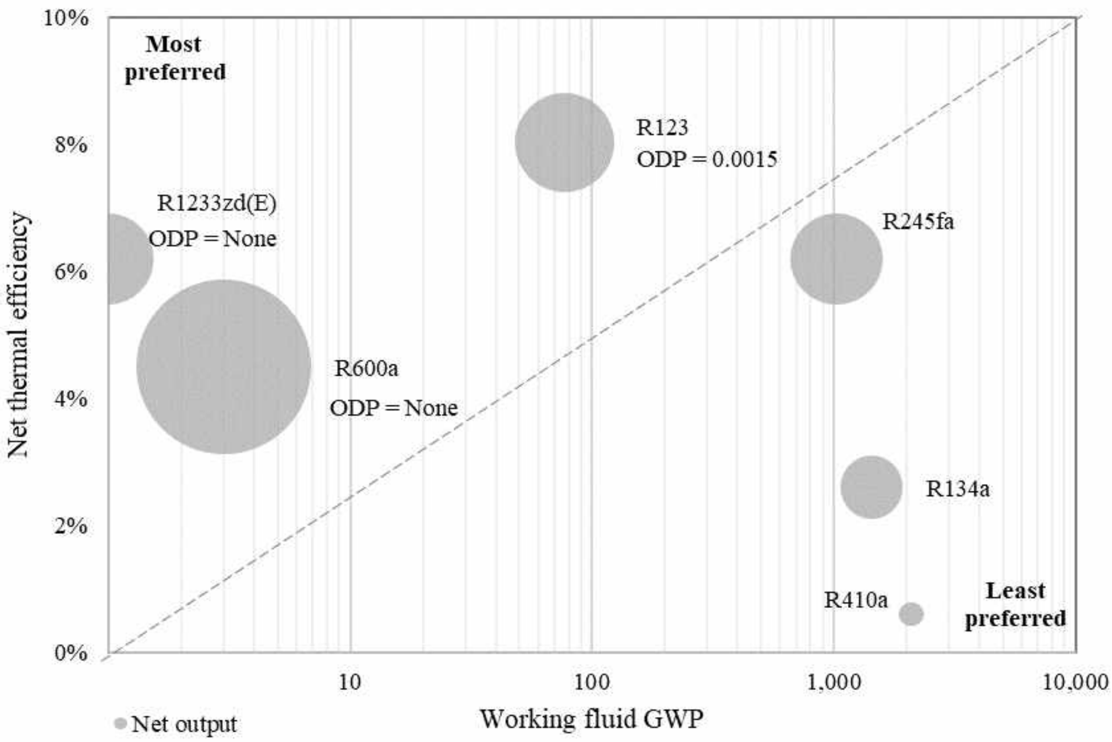

Figure 5: Cycle thermal efficiency and net output based on working fluids' critical temperature.

The cycles' thermodynamic performance and environmental impact (based on GWP) are shown in Figure 5. The most suitable working fluid should exhibit high thermal efficiency but low GWP, as located in the top left corner. Based on GWP, R1233zd(E), R600a, and R123 are the most suitable options. However, R123 has a comparatively higher GWP (77) and ODP (0.0015) than others, which is undesirable for this study. The comparison between R1233zd(E) and R600a shows that the latter only has a lower turbine expansion ratio. The formation of supersonic flow under high expansion ratios is a major challenge in ORC turbine design (Uusitalo & Zocca, 2023), which R600a could mitigate. However, R1233zd(E) has a notably higher thermal efficiency, lower environmental impact, and lower specific energy consumption at the evaporator and condenser. These benefits outweigh its only shortcoming, which indicates turbine design is critical to the ORC cycle for WHR applications.

5 CONCLUSIONS

The thermodynamic and environmental performance of six working fluids were examined for ORC-based WHR for the upstream process. The results showed that:

- R600a has the highest net output power but an inefficient cycle, while R123 has the best thermal efficiency despite a lower output power compared to R600a.
- R245fa, R134a, and R410a are undesirable due to their significantly higher GWP, although their thermodynamic performance was comparable to the preferred working fluids.
- The thermal efficiency of the ORC cycle increased linearly with the working fluid's critical temperature, but the increment in net output energy was non-linear.
- Due to its thermophysical properties, R600a required significantly higher input energy at the evaporator.
- R1233zd(E) and R600a emerged as the preferred working fluids for ORC-based WHR based on thermodynamic and environmental performance analyses.
- ORC turbine design remains a critical requirement for practical ORC-WHR applications. 379

Overall, the study provided valuable insights into selecting ORC-based WHR systems and highlighted the importance of considering thermodynamic and environmental performance factors during the process.

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LIST OF ABBREVIATIONS & SYMBOLS

380

Abbreviations

ETC	Electric Turbo-compounding
GHG	Greenhouse gases
GWP	Global Warming Potential
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
ODP	Ozone depletion potential
ORC	Organic Rankine Cycle
TEG	Thermo-electric generators
WHR	Waste heat recovery

Symbols

c_p	Constant pressure specific heat, J/kg-K
h	Specific enthalpy, J/kg
$\dot{m}$	Mass flow rate, kg/s
η	Efficiency, --
q	Specific energy, J/kg
s	Specific entropy, J/kg-K
T	Temperature, °C or K
v	Specific volume, m^3/kg

Subscripts

1	Evaporator outlet, turbine inlet
2	Turbine outlet, economizer inlet
3	Economizer outlet, condenser inlet
4	Condenser outlet, pump inlet
5	Pump outlet, economizer inlet
6	Economizer outlet, evaporator inlet
cw	Cooling water
exh	Exhaust
generator	Generator
gross	Gross output
in	Input to ORC cycle
net	Net output
out	Output from ORC cycle
pump	Pump
turb	Turbine

This book contains the compilation of works contributed to the *7th International Seminar on Organic Rankine Cycle Power Systems* (ORC 2023), held in Seville between the 4th and 6th of September 2023. The event was hosted by Universidad de Sevilla on behalf of the Knowledge Centre on Organic Rankine Cycle Technology (KCORC), incorporated in The Netherlands.

The ORC conference, organized biennially, stems as the only conference that is specific to ORC technology, therefore gathering a diverse community whose affiliation spans across all the interested stakeholders, not only in this particular technology but also and in a broader context, in the energy transition. Original equipment manufacturers, professional associations, end-users, investors, policy makers, academics, scientists feel at home at ORC 2023.

The almost 100 proceedings in this book cover a wide variety of topics, from fundamentals to system integration through component design, accounting for thermodynamic performance as well as component design. In addition to this, and as a new track in 2023, works on heat pump technology were also accepted in order to raise awareness of the strong ties between both technologies, specifically in energy storage applications.

This book provides an excellent overview of the current maturity of power systems based on Organic Rankine Cycle technology for applications as diverse as geothermal and waste heat recovery in industry or downstream of other prime movers (e.g., marine applications). It is also an excellent source of information to understand the current challenges faced by the technology, stemming from a very competitive market and increasingly stringent environmental regulations.

The organizers of ORC 2023 hope that the reader finds this work as exciting as the attendees to the conference and, maybe, make the decision to join the 8th edition to the conference in 2025.

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