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Working fluid selection of Organic Rankine Cycles

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Abstract

Organic Rankine Cycles (ORCs) are identified as one of the best candidates to generate electricity from low-grade heat sources. ORCs operate on low temperatures and low pressures with comparative to conventional Rankine Cycles. Therefore, organic fluids or refrigerants can be used as the working fluids for ORC applications, instead of water, which is more suitable for high-pressure and high-temperature applications. The performance and the system design of the ORC system are entirely dependent on the working fluid, and hence, working fluid selection for ORCs is utmost important for a particular application, i.e. solar thermal, geothermal or waste heat recovery. Performance of the ORCs for seven (07) working fluids: R-134a, R-245fa, Benzene, Methanol, Ethanol, Acetone and Propane (R-290) have been studied during this work. Results of the study show that Benzene and Methanol based ORC systems perform more efficiently with comparative to the other working fluids considered in the analysis and, they require lower fluid mass flowrates per unit of power generation relative to other fluids used in the analysis.

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Keywords: Organic Rankine Cycle; Solar collectors; Working fluids; Solar energy; Renewable energy

1. Introduction

Power generation from low-temperature energy technologies, i.e. solar thermal, geothermal and low-grade waste heat, are becoming popular due to their environmental friendliness. These low-temperature energy sources are typically available at temperatures of 80 °C to 150 °C. Organic Rankine Cycles (ORCs) have been identified as the most promising heat engines to generate electricity from these low-temperature heat sources.

The history of ORCs starts in 19th century, and it obtained much attention in the 21st century power industry [1]. According to the literature, Willsie built two solar ORC engines using Sulfur Dioxide as the working fluid with capacities of 4.5 kW and 11 kW in 1904. Then, in 1940 D'Amelio designed a geothermal plant using ethylene as the working fluid and operated until 1950 and then decommissioned. When considering the commercial ORC plants, Ormat and Turboden lead the ORC industry. Ormat has constructed more than 3000 units up to 4 kW and

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Nomenclature

h	Enthalpy (kJ/kg)
W	Work extracted or supplied from unit mass working fluid (kJ/kg)
Q	Heat supplied or rejected from a unit mass of working fluid (kJ/kg)
η_{th}	Thermal efficiency
$\dot{m}$	Mass flowrate per unit power output

Subscripts

c	Condenser
e	Expander
evap	Evaporator
p	Pump

more than 500 units of 1–25 MW [2]. However, the performance of the above systems are not available in the literature.

A simple ORC system consists of four main components and are, a pump, an expander/turbine, an evaporator and a condenser. The evaporator and the condenser perform as high-temperature and low-temperature heat reservoirs, respectively. At the same time, the pump circulates the working fluid across the system components, whereas, the turbine generates a useful workout from the cycle, as shown in Fig. 1.

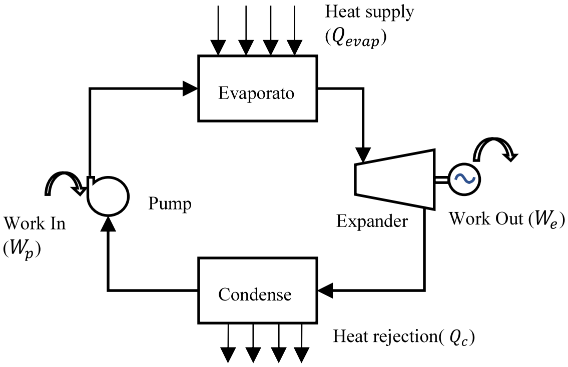

Fig. 1. Schematic diagram of an Organic Rankine Cycle.

Unlike the commonly used Rankine Cycles, which operate on the water as the working fluid (so-called as the steam power cycles), the ORCs operate on organic fluids. Working fluids use for ORCs can be classified into three main categories as dry, wet and isentropic fluids depending on their behavior during the adiabatic expansion [3]. Fluids with simple molecular structures behave as wet fluids, while the fluids with higher complexity act as the dry fluids. Intermediate fluids belong to isentropic fluids [4]. In the selection process of working fluid for a given ORC application, many working fluid properties, i.e. thermo-physical properties (i.e. pressure, temperature, specific volume, latent heat, flash point, specific heat, thermal conductivity), safety, cost, availability, toxicity, chemical stability at high temperatures and environmental factors should be considered. The critical temperature and pressure of the fluid should be acceptable with comparative to the heat source temperatures. The maximum pressure and temperature of the cycle should have to be at least 10 °C lower than the critical values [5]. Moreover, the environmental factors, i.e. Ozone Depletion Potential (ODP) and Global Warming Potential (GWP), should also have to be considered [6] during the selection process.

Many researches have been conducted on working fluid selections for ORCs based on various approaches [7–13]. Most of the previous researches have focused on the formulating selection criteria for refrigerants, i.e. chlorofluorocarbon (CFC), hydrochlorofluorocarbon (HCFC) and hydrofluorocarbon (HFC), as the working fluid [7,14–16].

However, as of today, none of those conventional refrigerants can be used in ORC applications as most of them are phased-out (CFCs) or being phased-down (HCFCs) or will be phasing-down in the near future due to their high ODP and the GWP. Therefore, during this study, the performance of the ORC systems has been analyzed for 07 non-conventional working fluids and are, R-134a, R-245fa, Benzene, Methanol, Ethanol, Acetone and Propane (R-290). HFC refrigerants, R-134a and R-245fa, have been used to compare the performance predicted by the other hydrocarbon fluids and the organic fluids.

During the study, the evaporator temperature of the ORC varied from 100 °C–200 °C by varying the operating pressure of the evaporator. Freely available fluid property software 'CoolProp' was used to evaluate the working fluid properties during the modeling work. An analytical model has been developed to evaluate the performance indicators, i.e. thermal efficiency, work ratio, the specific mass flowrate of the ORC for each working fluid and, to identify the best working fluid to operate the ORC for a given application.

2. Methodology

In this study variation of properties with the variation of different working fluids and condenser and evaporator pressures have been studied. The fundamental equations have been used to simply analyze the performance of different working fluids. Fig. 2 shows the state points of a simple ORC on a T-s diagram for a given working fluid. State points 1-2-3-4 represent a reversible ORC, whereas the state points 1-2^1-3-4^1 represents an irreversible ORC, which has 80% and 70% isentropic efficiencies at the turbine and the pump, respectively. During the study, the frictional losses of the fluid flowing in the pipes were neglected and hence, operating conditions have been assumed in the processes of; isobaric heat supply (at the evaporator), expansion (at the turbine), isobaric heat rejection (at the condenser) and compression (at the pump).

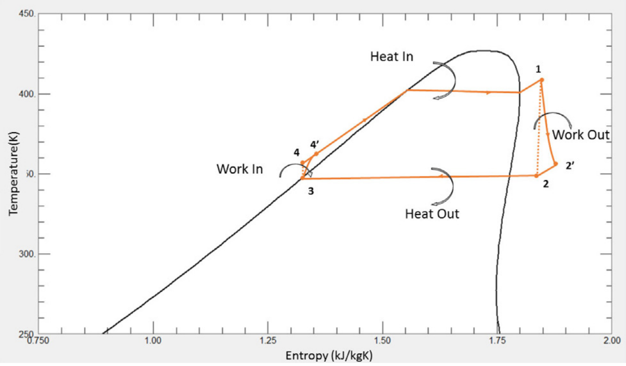

Fig. 2. Organic Rankine Cycle on a T-s diagram.

As the atmospheric temperature of the tropical countries is usually over 25 °C, the condenser temperatures were always set as 30 °C or higher than 30 °C. Besides, the condenser pressures were always considered to be higher than the atmospheric pressure (1 atm) to avoid air leakage into the system. In the study, the performance was evaluated numerically. The evaporator temperatures and pressures were varied to evaluate the variations of thermal efficiencies and mass flowrates per unit power output of the ORCs for different operating conditions. Performance of various organic working fluids were considered and performance of those fluids were analyzed separately (see Table 1).

3. Results

Thermal efficiency and the specific mass flowrate of the ORCs for 07 working fluids have been evaluated for a range of evaporator and condenser pressures and temperatures, as shown in the Figures. Fig. 3 presents the results obtained for R-134a, Fig. 4 presents the results obtained for R-245fa, Fig. 5 presents the results obtained for Benzene, Fig. 6 presents the results obtained for Methanol, Figs. 7 and 8 presents the results obtained for Ethanol, Fig. 9 presents the results obtained for Acetone and, finally, Fig. 10 presents the results obtained for Propane.

Table 1. Properties of working fluids used in study.

Working fluid	Type	Molecular Weight (kg/mol)	Critical Properties		
			Boiling Point °C	Critical Temperature °C	Critical Pressure (Bar)
R134a	Wet	0.102	−26.07	101.06	40.59
R245fa	Dry	0.134	15.04	153.86	36.51
Benzene	Dry	0.078	80.06	288.87	48.94
Methanol	Wet	0.032	64.54	239.35	82.15
Ethanol	Wet	0.046	78.42	241.56	62.68
Acetone	Wet	0.058	56.07	234.95	47.00
Propane	Wet	0.044	−42.11	96.74	42.51

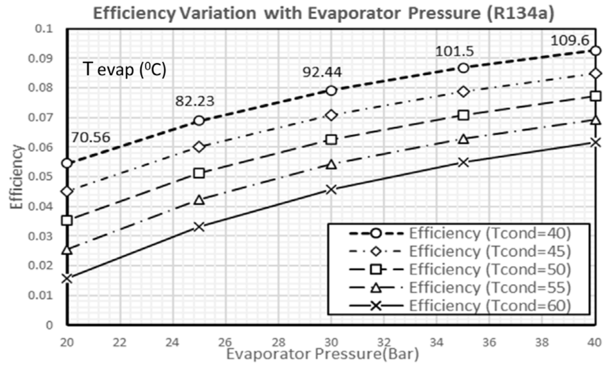

Fig. 3. Mass flowrate variation with evaporator temperature(R134a).

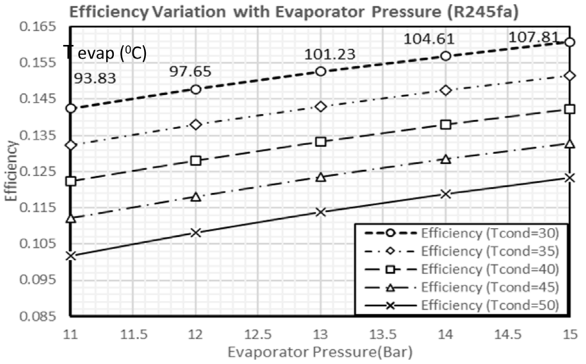

Fig. 4. Efficiency variation with evaporator temperature (R245fa).

4. Discussion

According to the above results, it can be observed that the thermal efficiency of the ORC increases when increasing the evaporator temperature and the pressure. Moreover, the thermal efficiency of the ORC system can be increased by decreasing the condenser operating pressure and temperature. During this analysis, it was always ensured to keep the condenser pressure above 1 atm to eliminate the air leakage into the system. Besides, the amount of fluid mass flow rate to obtain a unit power output was also evaluated and found that when the evaporator pressure increases, the amount of working fluid mass flow rate to produce a unit of power is reduced. On the contrary, it was found that when the condenser temperature increases, the amount of fluid required to produce a unit power output is also increasing. Operating pressures of the evaporators were selected carefully to ensure that the evaporator operating temperatures are within the limits of the low-grade heat sources. Moreover, in some instances, operating temperatures of the evaporator were selected to achieve the minimum pressure ratios for the power generation.

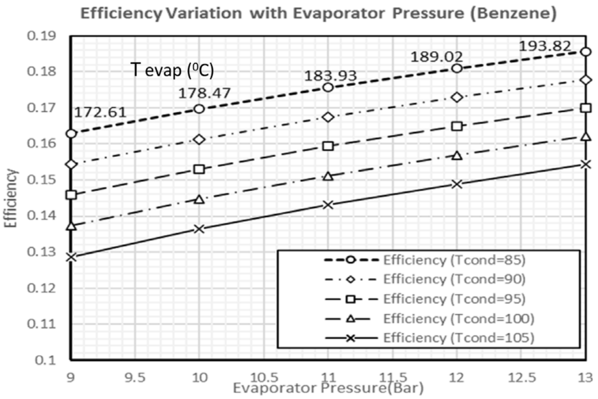

Fig. 5. Efficiency variation with evaporator temperature (Benzene).

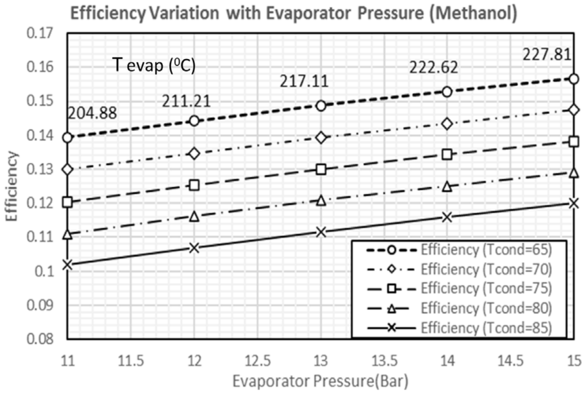

Fig. 6. Efficiency variation with evaporator temperature (Methanol).

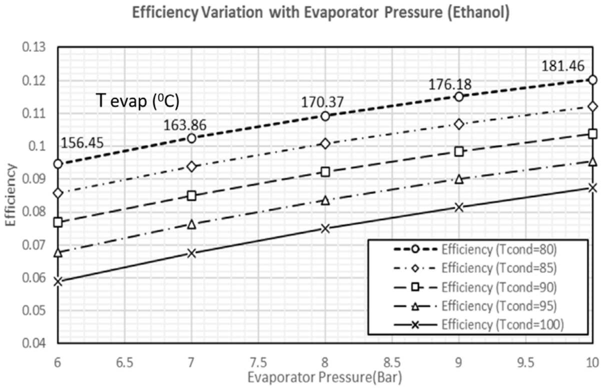

Fig. 7. Efficiency variation with evaporator temperature (Ethanol).

It can be seen that R-134a and R-290 (Propane) need higher operating pressures while resulting in poor performances with comparative to the other working fluids. Moreover, it can be seen that Benzene, Methanol and Ethanol perform at high efficiencies at high temperatures, at the temperatures. However, these operating temperatures can be easily realizable with solar thermal and waste heat of internal combustion engines (ICEs). R-245fa shows the best performance among all at low pressure with evaporator temperatures, which are in between 90–110 °C. However, Ethanol and Acetone shows similar efficiencies in the studied range and the applicability of those two

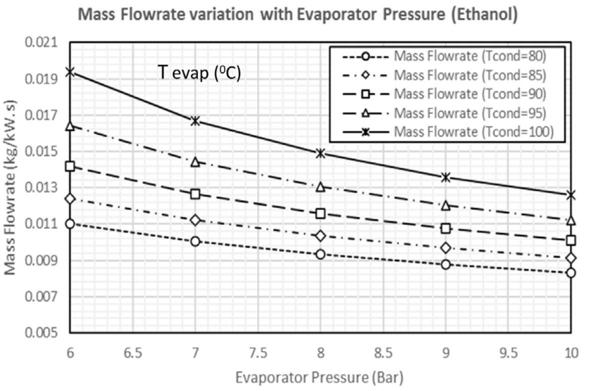

Fig. 8. Mass flowrate variation with evaporator temperature (Ethanol).

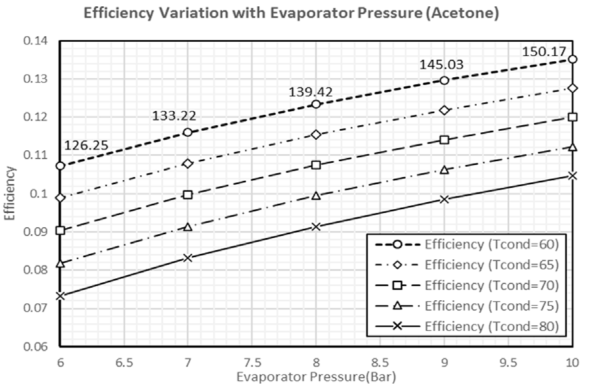

Fig. 9. Efficiency variation with evaporator temperature (Acetone).

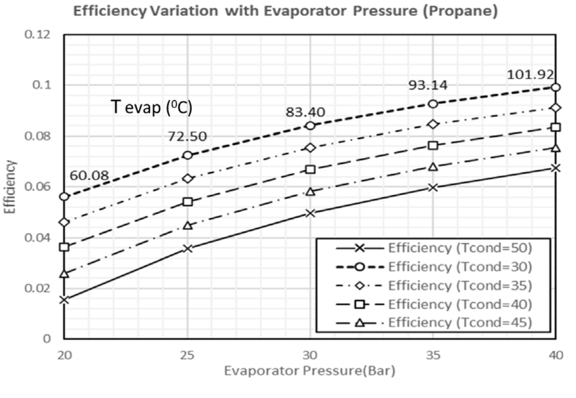

Fig. 10. Efficiency variation with evaporator temperature (Propane).

fluids are thermodynamically the same. Methanol shows similar efficiencies as Ethanol and Acetone, but the evaporator pressure and temperatures are much higher than those fluids. It can be observed that the specific mass flow rate increases when decreasing the efficiency of the ORC. The findings of the study show that the performance of Benzene is significantly higher, and efficiency lies in between 14%–19% at evaporator operating temperatures of 100 °C to 200 °C.

5. Conclusion

This study provides better insight into the performance of ORCs for unconventional working fluids, i.e. Benzene, Acetone, Propane (R-290) Ethanol and Methanol, other than the conventional ORC working fluids R-134a and R-245fa. It was found that thermal efficiency increases with evaporator pressure, and it decreases with the increment of condenser temperature. The primary outcome of this study is the identification Benzene as a working fluid that provides significantly improved efficiencies for a range of operating conditions with comparative to other ORC fluids.

Future work

Currently, an ORC test rig is being fabricated at the Dept. of Mechanical Engineering, University of Moratuwa, Sri Lanka, to conduct the testing with the above-identified fluids to estimate and validate the results obtained this analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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