Thermodynamic analysis of organic Rankine cycle with Hydrofluoroethers as working fluids

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Abstract. This paper presents the analysis of organic Rankine cycle (ORC) using hydrofluoroethers (HFEs) such as HFE7000, HFE7100 and HFE7500 as working fluids under external conditions. HFE’s has been chosen over chlorofluorocarbons (CFC’s) and hydrochlorofluorocarbons (HCFC’s) as it is environmentally friendly. Both the CFC’s and the HCFC’s possess ozone depletion potential (ODP), while the hydrofluorocarbons (HFC’s) have relatively significant global warming potential (GWP). The HFE’s that have excellent thermophysical properties and low toxicity can be recommended as a long term solution to the environmental issues. The HFE’s have zero ODP and very low GWP compared to the CFC’s, HCFC’s and HFC’s. A thermodynamic model has been developed using Engineering Equation Solver (EES) software to simulate the system under steady state conditions. Parametric analysis is conducted to examine the effects of some thermodynamic parameters on the system performance using different working fluids. When turbine inlet temperature was varied from 70°C to 110°C keeping condensation temperature fixed at 28°C, HFE7000 produces the maximum thermodynamic efficiency and performs better in view of the net work output under the given working conditions. However, when evaporation pressure was kept constant at 1.2 bar and condensation temperature was varied from 20°C to 30°C, HFE7500 produced the maximum efficiency of 12.3% in comparison with 7.6% for HFE7100 and 4.1% for HFE7000. The work demonstrates the use of hydrofluoroethers as working fluid in ORC.

Keywords: Thermodynamic model, Hydrofluoroether, organic Rankine cycle, Ozone depletion potential

1. Introduction

Over the recent few years, world’s demand for has increased tremendously because of mechanical advancement and innovative upgradation. The consumption of conventional energy resources (coal, gas, oil etc) has gone up significantly leading to the rise in greenhouse gas emissions. The global warming problem has prompted the world to shift to more sustainable and renewable modes of energy resources. Waste heat recovery is one such sustainable option to generate power, since most of the industries emit unutilized waste heat to the atmosphere. Although, steam turbines are widely used in the energy production process, it is not suitable for extraction of power from low temperature heat sources such as waste heat emanating from industries. Organic Rankine cycle (ORC) technology is adopted for the processes having low temperature less than 150°C as depicted by Ozdil et al.[1]. An ORC power cycle has the same operating principle as that of the conventional Rankine cycle except for the fact that the former uses organic refrigerant as the working fluid. This was demonstrated in detail by James et al. [2]. This technology has been used by many researchers for the extraction of power from low grade heat source such as biomass, solar, geothermal and waste heat recovery. ORC operates at lower temperature and pressure compared to conventional steam power plants, thus resulting in a lower cost of installation. Kuo et al. [3] explained how low temperature ORC system can
be implemented using a single stage expander because of lower operating pressure ratios in comparison with multi stage turbines. In ORC systems, choosing suitable working fluid is also an important factor to ensure safe and stable operation of the system. Wang et al., Mago et al. and Wei et al. have used a variety of working fluids for ORC applications. Thermophysical properties, chemical stability, environmental impact and cost are some of the factors that need to be factored in before the selection of the working fluid. This includes HCFCs, HFCs and Freons [4-6]. Wang et al [4] conducted a detailed analysis of a solar driven regenerative ORC. The major working fluids investigated in this study were R245fa, R123, Isobutane and R134a. Mago et al. [5] investigated regenerative ORCs using dry organic fluids (R113, R245ca, R123 and Isobutane) to convert waste heat to power, with boiling points varying from -12 °C to 48 °C. Wei et al [6] analysed and optimized an exhaust heat driven ORC by using R245fa as the working fluid.

Some of the ORC working fluids used by Liu et al. , Wang et al., Helvaci & Khan and Guoquan Qiu , such as freons and CFCs are ozone depleting substances and hence detrimental to the environment. HCFCs and HFCs have a high global warming potential (GWP), [7-10]. Despite their high GWPs, HFC refrigerants are used in various ORC applications. The hydrofluoroethers (HFEs) that has excellent thermophysical properties and low toxicity can be used as an ORC fluid. The HFEs has zero ODP and very low value of GWP compared to conventional ORC fluids, and is environmentally friendly. In this particular work, a sensitivity analysis has been conducted to study the effect of key thermodynamic parameters such as turbine inlet temperature and condensation temperature on the performance of the system using HFE7000, HFE7100 and HFE7500 as the working fluids. The net power output, thermal efficiency and mass flow rate across the turbine are selected as performance indicators in the analysis.

2. Thermodynamic analysis

Certain assumptions were made to simplify the analysis. These are as follows:

a) The calculated points are obtained when the system has reached steady state.
b) The working fluid is in saturated liquid state at the condenser outlet.
c) Pressure drops in heat exchangers and connecting pipes are neglected.
d) The fouling effects of the heat exchanger are negligible.

![Fig 1: Conceptual diagram of ORC power block](image)

ORC cycle is modelled using the laws of mass and energy conservation. The ORC system consists of 4 major components as shown in fig 1. It consists of evaporator, turbine, condenser and a working fluid pump. The processes involved are as follows:
1-2: Isentropic compression process in the pump
2-3: Isobaric heat absorption process in the evaporator.
3-4: Isentropic expansion process in the expander.
4-1: Isobaric heat rejection process in the condenser.

The details of the mathematical model are expressed as follows:

Pump work is given by,

$$\dot{w}_p = \dot{m}_{wf} v_1 \times \frac{(P_2 - P_1)}{\eta_p}$$  \hspace{1cm} (1)

The heat exchange in the evaporator can be expressed as

$$\dot{Q} = \dot{m}_{wf} \times (h_3 - h_2)$$  \hspace{1cm} (2)

Work done by the expander,

$$\dot{w}_t = \dot{m}_{wf} \times (h_3 - h_4)$$  \hspace{1cm} (3)

$$\eta_{th} = \frac{h_3 - h_4}{h_3 - h_{as}}$$  \hspace{1cm} (4)

$$\dot{w}_t = \dot{m}_{wf} \times (h_3 - h_{as}) \times \eta_t$$  \hspace{1cm} (5)

3. Results & Discussion

The fundamental purpose of this work is to carry out sensitivity analysis of important thermodynamic parameters such as turbine entry temperature and condensation temperature. The effect of these parameters on net work output, mass flow rate and thermal efficiency is examined. Thermodynamic assessment of different HFE fluids under varying conditions of turbine inlet temperature and condensation temperature is carried out using Engineering equation solver (EES). In this particular investigation, the state of the fluid at the turbine inlet is saturated vapour. As HFEs used in this study are dry fluids, there is no necessity of superheating before expansion. The input parameters are tabulated in table 1.

| Sl No | Input parameter                          | Value       |
|------|-----------------------------------------|-------------|
| 1    | Heat source temperature                 | 150°C       |
| 2    | Heat source mass flow rate              | 1.0 kg/s    |
| 3    | Turbine and pump isentropic efficiency  | 0.7         |
| 4    | Condensing temperature                  | 28°C        |
| 5    | Pinch point temperature difference      | 5°C         |

3.1 Effect of turbine inlet temperature on the performance of the ORC system

This analysis is based on the assumption that all working fluids were at saturated condition at the turbine entry and condensation temperature fixed at 28°C. Variation of net work output and change in mass flow rate of the ORC working fluid with increase in turbine inlet temperature is depicted in fig 2 and fig 3 respectively. Also, impact of turbine entry temperature on thermal efficiency is illustrated in fig 4. The turbine inlet temperature was varied from 70°C to 110°C. Enthalpy drop across the turbine increased and the mass flow rate decreased with increase in turbine inlet temperature. Larger enthalpy difference at higher turbine inlet temperatures can be attributed to the fact that the evaporation temperature and the pinch point temperature difference remains constant throughout. This also facilitates the mass flow rate of the working fluid to reduce due to energy balance. The net work output for HFE7000, HFE7100 and HFE7500 increased with turbine inlet temperature firstly, reached
a peak value before it decreased again. Among the 3 working fluids, HFE7500 produces least work output under the given constraints. In the low turbine inlet temperature range (70 °C to 90 °C) HFE7000 and HFE7100 produces almost same net power output. Thermal efficiency shows an increasing trend with increase in turbine inlet temperature. The thermal efficiency increased approximately from 7.01% to 10.69% for HFE7000, 6.84% to 10.33% for HFE7100 and 6.83% to 10.25% for HFE7500 with increase in turbine inlet temperature from 70 °C to 110 °C.

**Fig 2:** Variation of net work output with turbine inlet temperature

**Fig 3:** Variation of mass flow rate of ORC fluid with turbine inlet temperature
3.2 Effect of condensation temperature on the performance of the ORC system

The evaporation pressure is fixed at 1.2 bar and the condensation temperature is changed from 20 °C to 30 °C for all 3 working fluids. Enthalpy drop across the expander drops resulting in the drop in net work output and the mass flow rate remains constant as shown in fig 5 and fig 6 respectively. The thermal efficiency also shows a marginal decrease with increase in condensation temperature. It can be observed that even though HFE7100 produces high net work output, HFE7500 is most efficient among the 3 fluids under the given constraints of evaporating pressure and condensation temperatures as evident in fig 7. The maximum thermal efficiency when HFE7500 was used was 12.3% when compared with 4.1% for HFE7000 and 7.6% for HFE7100.
Fig 6: Variation of mass flow rate of ORC fluid with condensation temperature

Fig 7: Variation of thermal efficiency with condensation temperature

Concluding remarks
ORC system has been thermodynamically analysed using HFE7000, HFE7100 and HFE7500 as the working fluids. A computer code has been developed for the thermodynamic assessment of different HFE fluids (HFE7000, HFE7100 and HFE7500) under varying conditions of turbine inlet temperature and condensation temperature. Based on this analysis it is found that

- With the increasing turbine inlet temperatures, for all working fluids, the net work output has an optimum value because of the peak, thermal efficiency of the ORC increases and the mass flow rate of the working fluid decreases.
When turbine inlet temperature was varied keeping condensation temperature constant at 28 °C, HFE7000 performed well with respect to net work output and thermal efficiency in comparison with other working fluids.

For a set evaporation pressure of 1.2 bar for all working fluids, when condensation temperature was varied, HFE7500 was found to be the most efficient among the 3 working fluids.

Hence, for a given condensation temperature, it is a good choice to use HFE7000 as the working fluid in ORC for extraction of power from low temperature heat source.

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### Nomenclature

| Symbol | Description                        |
|--------|------------------------------------|
| $\dot{w}$ | Work output in kW                  |
| $\dot{Q}$ | Heat input to evaporator in kW     |
| $h$    | Enthalpy in kJ/kg                  |
| $\dot{m}$ | Mass flow rate in kg/s             |
| $\eta$ | Efficiency                         |
| $v$    | Specific volume in m$^3$/kg        |
| PPTD   | Pinch point temperature difference |

### Subscripts

| Subscript | Description                  |
|-----------|------------------------------|
| t         | Turbine                      |
| p         | Pump                         |
| wf        | Working fluid                |
| 1,2,3,4,4s| Thermodynamic states         |
| th        | Thermal                      |