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Effect of climatic conditions on performance of ORC using environment-friendly working fluids – special reference to India

Efficient heat recovery from low-grade heat sources is an achievable scientific frontier in the coming decade. One of the promising technologies in waste heat recovery is the organic Rankine cycle (ORC) system. Major obstacles to low-grade heat recovery include economic viability, scale, system efficiency, and exergy efficiency. In low temperature ORC systems, the cost of condenser becomes significant and hence air-cooled condenser is a feasible option. However, the performance of the air-cooled condenser is sensitive to the variation in ambient air conditions. India, being a tropical country, have villages and cities whose average temperature varies from -2°C in winter to 50°C in summer. The present work involves the study of heat transfer effects on the condenser using common organic working fluids and quantifying the consequences of environmental temperature variations. The constant thermal evaporator load is supplied with a medium-enthalpy heat source at 100 and 150°C. The atmospheric temperature associated with heat rejection from the condenser is varied from 273K to 313K for 5 working fluids. A MATLAB model of the ORC system is developed to study the effect of condenser performance on the first and second law efficiency of the ORC system. The MATLAB model is used to investigate the effect of varying inlet temperatures of the working fluid on the performance of ORC system to choose an organic working fluid suitable for Indian climatic conditions. R365 mfc, and R1233zd exhibit higher expander work and show higher heat rejection. At higher heat source temperatures of 150°C, the simulation shows a higher second law efficiency for the working fluid R1224yd(Z), which has critical temperature closed to the heat source temperature.

Keywords: Organic rankine cycle, organic working fluid, condenser performance, heat transfer rate

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1.0 Introduction

Population growth and increasing energy demand has led the engineers and technologists to explore various energy resources to meet the energy needs of the mankind. Technologies are being developed and improved to enhance the efficiency of power cycles used in electricity production. Most of the power plants generating electricity worldwide work on Brayton cycles, Rankine cycles and combined Brayton – Rankine cycle operating on fossil-based fuels or nuclear energy. Electricity generation from renewable energy sources and industrial waste heat are gaining traction in the recent past as the pollution from fossil-based power is becoming a serious global environmental concern due to release of greenhouse gas (GHG) emissions causing depletion of ozone layer leading to global warming and climate change (Kumar and Rakshit 2021; Pathak and Shukla 2018). In this regard, several research problems are being addressed worldwide to provide a solution to produce useful energy using renewable energy resources (Ahmadi et al. 2020; Baral and Kim 2014). Prominent among them are solar photovoltaics, solar thermal, biomass, tidal, geothermal etc. ORC based system is gaining prominence as a viable technology to produce energy from renewable sources such as solar, biomass and industrial waste heat. Organic Rankine cycle is based on the ordinary steam Rankine cycle (SRC) with water/steam being replaced by an organic working fluid (OWF). In ORC power extraction from the working fluid can be done at medium and low temperatures without the need of high temperature unlike the high pressure steam as required in SRC working on fossil-based fuels. Moreover, the ORC system can be used to provide a decentralized energy solution with minimal or no GHG emissions (Laouid et al. 2021).

2.0 ORC mathematical model

Research has been carried out on the modelling and analysis of ORC system using waste heat from the industrial process (Kumar and Rakshit 2021; Loni et al. 2021). Li et al (Li, Ge, and Tassou 2017) conducted experimental investigation on a small scale ORC system with R245f as the OWF to study the effect of condenser cooling water temperatures and OWF superheat at turbine inlet on the performance of the ORC system. Experimental investigations were performed on solar ORC system to predict its performance based on different OWF (Bhagyashekar 2020). Reddy and Bhagyasekhar (Reddy and Bhagyashekar 2021) analysed the performance of ORC system using scroll compressor as expander device for pressures varying between 0.5 bar to 4.5 bar using solar thermal energy. The exergy efficiency for the system was reported to be influenced by the condenser performance and the value was around 27.52%. Zhao et al. (Zhao et al. 2018) investigated a solar driven combined cycled heat and power ORC system and reported maximum overall economic exergy efficiency of 40.95% for the n-octane working fluid for a constant condenser temperature. Thus, it is evident that ORC system performance is greatly affected by condenser inlet fluid temperatures. As the condenser takes in the cooling fluid at ambient temperatures, its performance is thus dependent on the ambient temperatures of the location of the ORC system. The ambient temperature varies from -2ºC in winter to 50ºC in summer in different regions of the Indian subcontinent (Burgess et al. 2017). Therefore, an ORC system that can accommodate a single OWF suitable for varying ambient conditions will provide a substantial benefit to the research community as well as economical advantage for commercialization of the technology.

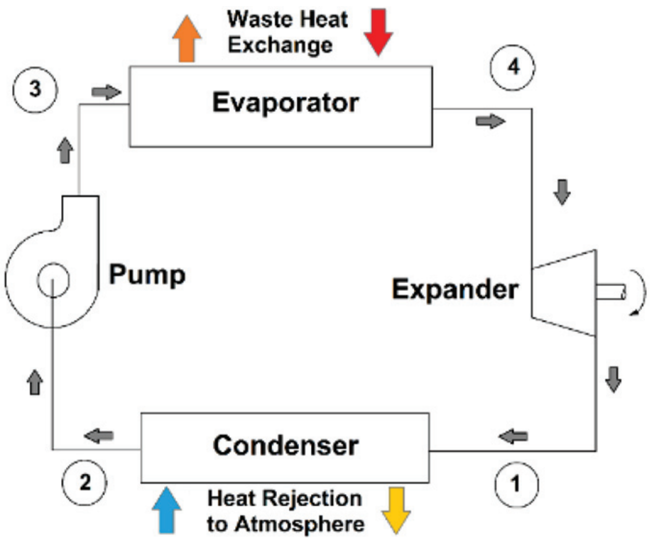

Fig.1: Description of a basic ORC system

The present study focuses on the effect of condenser performance on the overall efficiency of the ORC system. A mathematical model is proposed to investigate the effect of varying inlet temperatures of the condenser fluid on the ORC system and to choose an OWF suitable to work with wide range of condenser inlet temperatures. The OWF is shortlisted from the ASHRAE database based on global warming potential, ozone depletion potential, safety and

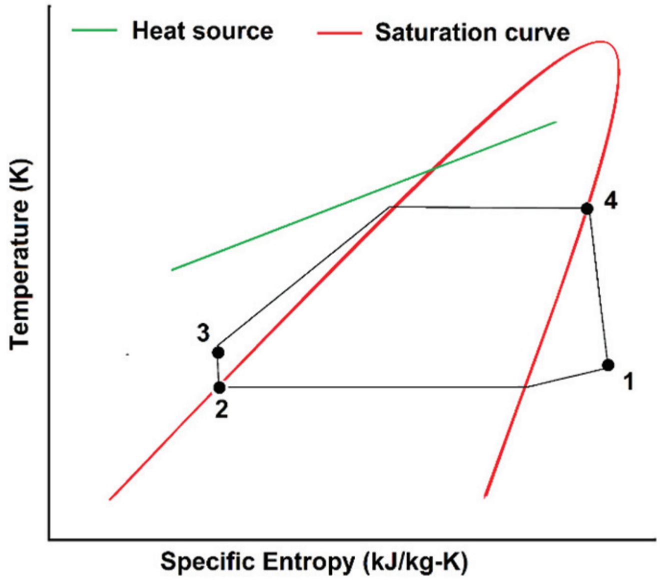

Fig.2: Organic Rankine thermodynamic cycle represented in temperature-specific entropy property diagram

critical pressure/critical temperature. The ORC system for five shortlisted OWF is analysed to arrive at a single working fluid suitable to wide range of ambient temperatures of -5ºC to 40ºC.

3.0 Mathematical modelling of ORC

The energy exchange process in each component of the ORC system is modelled in MATLAB using the following heat transfer equations.

The heat input (Q_{in}) is modelled as:

$$Q_{in} = m_R(\mathrm{h}_{evp,o} - \mathrm{h}_{evp,i}) \quad \text{... (1)}$$

The work produced by ORC system is shown below:

$$W_{exp} = m_R(\mathrm{h}_{exp,i} - \mathrm{h}_{exp,o}) \quad \text{... (2)}$$

The heat rejected in the condenser (Q_{out}) is expressed by the equation:

$$Q_{out} = m_R(h_{con,i} - h_{con,o}) \quad \text{... (3)}$$

The pump work modeled with a motor efficiency is considered as 70% to 80% (Loni et al. 2021).

$$W_p = \frac{m_R(\mathrm{h}_{p,o} - \mathrm{h}_{p,i})}{\eta_{motor}} \quad \text{... (4)}$$

The performance parameters is given by:

$$\eta_{Carnot} = 1 - \frac{T_L}{T_H} \quad \text{... (5)}$$

First law efficiency:

$$\eta_I = \frac{W_{exp} - W_P}{Q_{in}} \quad \text{... (6)}$$

Second law efficiency:

$$\eta_{II} = \frac{\eta_I}{\eta_{Carnot}} \quad \text{... (7)}$$

4.0 Selection of the organic working fluid

The working fluids were selected from the ASHRAE database is recorded, based on global warming potential, ozone depletion potential, safety and critical pressure/critical temperature. A total of five best organic fluids were selected such that their critical pressures and temperature were well suited to work in the condenser inlet temperature range of -5^{o}C to 40^{o}C. Thermo-physical properties of organic working fluid is obtained from REFPROP software (Lemmon et al. 2018)

5.0 Results and discussion

The performance of ORC is greatly influenced by various factors such as evaporator and condenser pressures and temperatures of the working fluids used in the cycle. Generally, the heat input and waste heat source temperatures remain in the range of 373K to 423K, which are independent of geographical locations.

The condenser temperature is dependent on climatic conditions that affects the performance of air-cooled condensers posing challenge to get the optimum work output from ORC. One possibility of improving the performance lies in the selection of working fluids which can give the optimum work output for changing condenser inlet temperatures.

The work carried out addresses the issue of selecting the working fluid for ORC by understanding its behaviour for changing climatic conditions in all the critical components of the cycle. Further, the study elucidates a method to calculate the performance parameters of the ORC without considering the thermo-physical properties of the working fluids.

A parametric study on single stage organic rankine cycle was carried out for the selected working fluids (R365mfc, R1224yd(Z), R1233zd(E) , R1336mzz(Z) and RE347mcc) at heat source temperatures of 100^{o}C and 150^{o}C as the available heat input from the renewable and industrial waste heat source lies in this range (Pathak and Shukla 2018). The heat sink temperatures are varied from 268K to 308K. The data obtained from the study is analyzed and optimum working fluid is proposed.

Fig.3 shows the variation in condenser pressure for changing heat sink temperature for the selected working fluids. It can be observed that, the condenser pressure increases with increase in heat sink temperature. R1224yd(Z) exhibits higher values of condenser pressures and contributes to higher heat transfer. Fig.4 shows the variation in the expander work for changing heat sink temperature while heat source is constant at 100^{o}C and 150^{o}C. It can be observed that the increasing heat sink temperature reduces the expander work showing negative impact on the work output of the cycle. Increasing heat source temperature for the given heat sink temperature seems to be advantageous as it increases the expander work. However, it can be

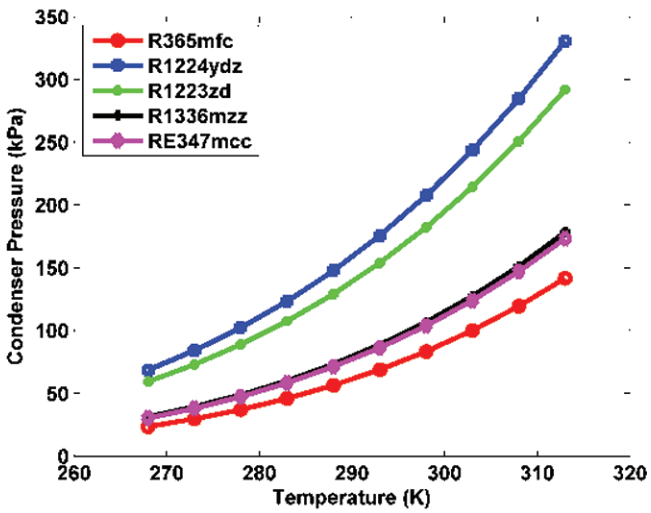

Fig.3: Condenser pressure for changing heat sink temperature

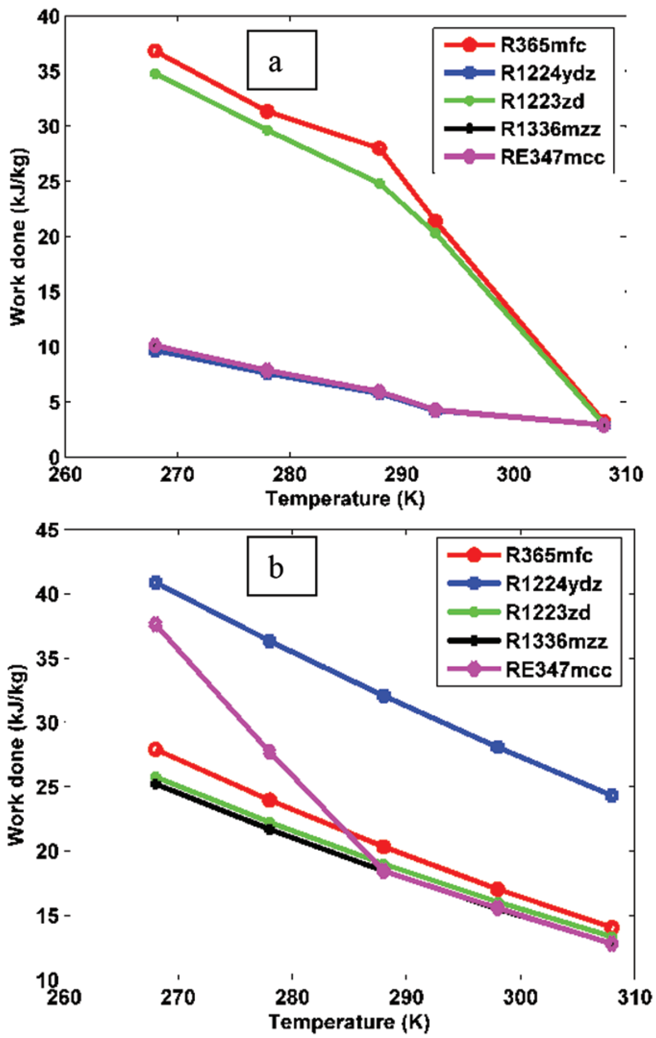

Fig.4: Expander work for (a) heat source at 100^{o}C and (b) heat source at 150^{o}C for varying condenser temperature

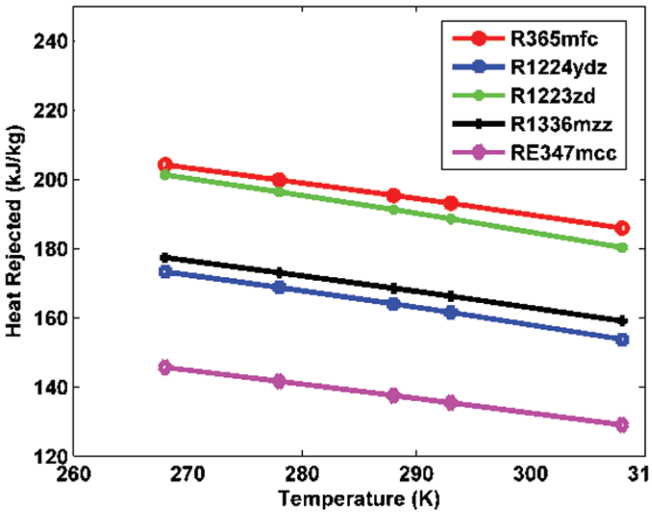

Fig.5: Heat rejection in the condenser for heat source at 100^{o}C and at 150^{o}C show similar behaviour

concluded that the regions that are hotter can extract required work from ORC by increasing heat source temperature. Among the selected working fluids R365mfc exhibits the highest expander work at lower sink temperature when the heat source is at 100^{o}C, which is followed by R1233zd(E). R1224yd(Z) exhibited highest expander work when heat source temperature was increased from 100^{o}C to 150^{o}C.

Fig.5 shows the heat rejection in condenser for varying heat sink temperature at heat source temperatures of 100^{o}C and 150oC. A decreasing trend of heat rejection in condenser for increasing heat sink temperature is observed. R365mfc shows the highest heat rejection at the given range of heat sink temperatures followed by R1233zd(E), R1336mzz(Z), R1224yd(Z) and RE347mcc. The order and the amount of heat rejection remains same for heat source temperature of 150^{o}C.

Fig.6 shows the variation in thermal efficiency (first law efficiency) for varying heat sink temperatures for heat source temperatures of 100^{o}C and 150^{o}C. It can be seen from the

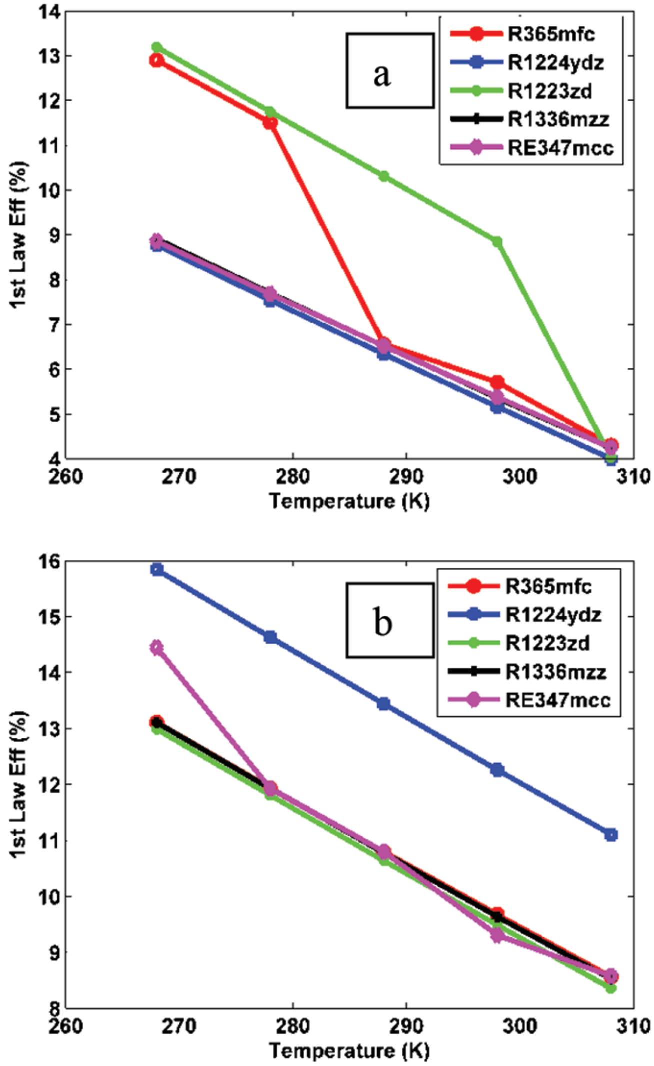

Fig.6: First law efficiency of the ORC system for for (a) heat source @ 100^{o}C and (b) heat source @ 150^{o}C

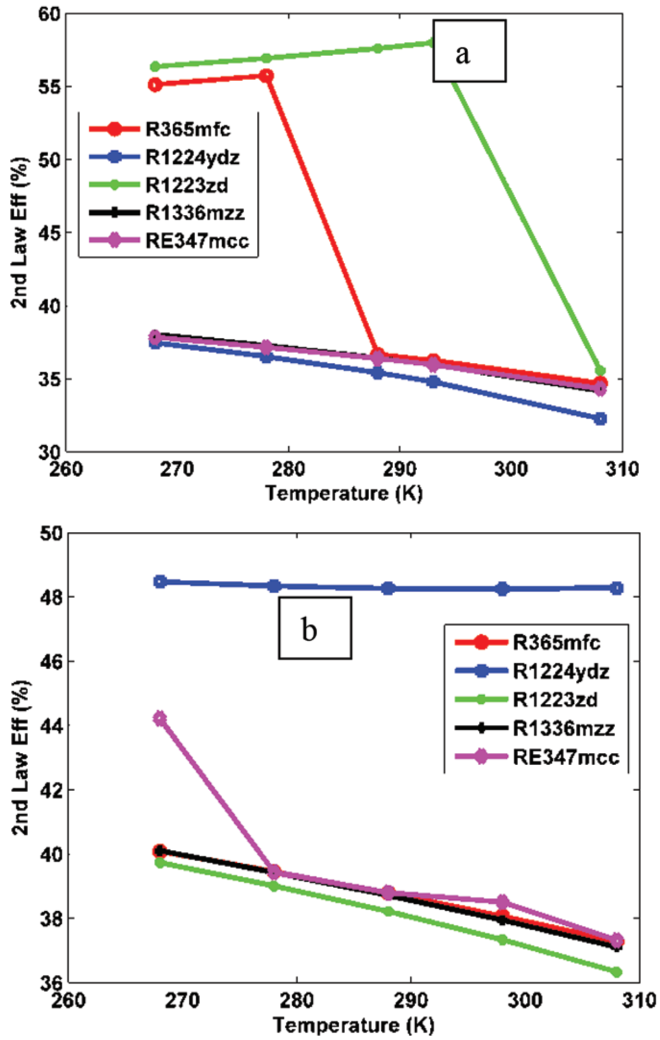

Fig.7: Second law efficiency for (a) heat source at 100^{o}C and (b) heat source at 150^{o}C

Fig.6, that the thermal efficiency of ORC reduces with increasing heat sink temperature whereas it increases with increasing heat source temperature. R365mfc and R1233zd(E) exhibit highest thermal efficiency at lower sink temperatures. The efficiency of R1233zd(E) suddenly drops after 275K and becomes equal to the thermal efficiency of the remaining working fluids namely R1224yd(Z), R1233mzz(Z) and R347mcc. R1224yd(Z) results in higher thermal efficiency at heat source temperature of 150°C as it exhibits higher expander work at this heat source temperature as exhibited in Fig.4b. The remaining working fluids show similar behaviour for increasing heat sink temperature with lower thermal efficiency. Fig.7 shows the variation in the second law efficiency for increasing heat sink temperature.

From the Fig.7 it can be understood that the second law efficiency remains almost same for all the working fluids at the given range of heat sink temperatures when the source temperature is at 150°C. However, R1224yd(Z) shows the highest second law efficiency for the heat source temperature of 100°C. The behaviour of R1233zd(E) and R365mfc becomes peculiar showing a sudden reduction in second law efficiency for sink temperature between 275K and 295K. Overall it can be seen from the Fig.7 that the increase in heat source temperatures from 100°C to 150°C has a positive impact on second law efficiency.

6.0 Conclusions

The heat transfer effects on the condenser are studied from the ORC mathematical model developed using MATLAB for heat source temperatures of 100°C and 150°C to investigate the suitability of a single working fluid for varying Indian climatic conditions. R1224yd(Z) exhibits highest values of condenser pressures and also resulted in highest expander work when heat source temperature was increased from 100°C to 150°C. Thus the second law efficiency for R1224yd(Z) was also found to be highest among other working fluids. It is concluded that R1224yd(Z) is best suited as the ORC working fluid under varying air condenser inlet temperatures for maximum power output and efficiency.

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