Multi-objective optimization of CuO based organic Rankine cycle operated using R245ca

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Abstract. The present work deals with multi objective optimization of nanofluid based Organic Rankine Cycle (ORC) to utilise waste heat energy. Working fluid considered for the study is R245ca for its good thermodynamic properties and lower Global Warming Potential (GWP) compared to the conventional fluids used in the waste heat recovery system. Heat Transfer Search (HTS) algorithm is used to optimize the objective functions which tends to maximize thermal efficiency and minimize Levelised Energy Cost (LEC). To enhance heat transfer between the working fluid and source fluid, nanoparticles are added to the source fluid. Application of nanofluids in the heat transfer system helps in maximizing recovery of the waste heat in the heat exchangers. Based on the availability and cost, CuO nanoparticles are considered for the study. Effect of Pinch Point Temperature Difference (PPTD) and concentration of nanoparticles in heat exchangers is studied and discussed. Results showed that nanofluids based ORC gives maximum thermal efficiency of 18.50% at LEC of 2.59 \$/kWh. Total reduction of 7.11% in LEC can be achieved using nanofluids.

1 Introduction

With increasing demand of energy in today's technological world, energy conservation and recovery is one of the major challenge in the field of engineering. Conventional fossil fuels are on the verge of depletion and need has arisen to develop sustainable energy generation techniques. One such technology is Organic Rankine Cycle (ORC) which recovers waste heat energy from different sources and generates electrical energy using organic fluids [1]. Many research has been done to improve the performance of ORC system and to recover maximum possible amount of energy.

Organic Rankine cycle is primarily used to recover waste heat energy in the form of hot gases which otherwise will vent out to the atmosphere. Stream of heating source is passed through evaporator wherein heat exchange takes place with an organic working fluid having low boiling point and high critical temperature. Superheated vapour of the working fluid which is usually refrigerant is fed to the expander which converts thermal energy of the refrigerant to mechanical energy of the expander shaft. Shaft of the expander is connected to generator set to produce electrical energy.

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Low pressure superheated vapour of refrigerant undergoes phase change and thermal energy is liberated to the atmosphere with the help of heat carrying fluid in the condenser. Pump is used to pressurize the liquid refrigerant and fed back to the evaporator to repeat the process. Schematic diagram of the process is given in Fig. 1.

Fig. 1. Schematic diagram ORC system and T-S diagram of thermodynamic processes.

Many researchers have worked upon the selection of working fluid based on the different criteria like high critical temperature, minimum global warming potential, toxicity, thermal stability etc. Saleh et al. [2] did comparative analysis 31 pure working fluids for thermodynamic performances on the basis of the BACKONE equation of state. Wang et al. [3] studied the thermodynamic performance of the ORC system using nine organic working fluids to recover waste heat from internal combustion engines. The results showed that R245fa and R245ca were the most environmentally friendly working fluids. Xu Zhang et al. [4] concluded during his study that R245ca was obtained as the most cost-effective working fluid with the shortest static investment payback period (SIPP), among the six candidates.

The conventional fluids like water and oil exhibits poor thermal properties as compared to solid metals. To enhance the heat transfer characteristics by improvising thermo- physical properties of the conventional fluids, nanofluids have been area of great interest for the researchers [5]. Addition of nanoparticles in base fluid results in formation of nanofluids and eventually enhances heat transfer of the fluid [6, 7]. Viscosity, thermal conductivity, density and specific heat are the important thermos-physical properties which determine the behaviour of nanofluids in a heat transfer system. Das et al. [8] performed experiments with five different nanofluids i.e., Al_2O_3 , CuO , ZnO , SiO_2 and TiO_2 . Results showed that increase in temperature and concentration increases thermal conductivity. With increasing concentration, thermal conductivity of the nanofluids increases because of the Brownian motion and it results in augmented heat transfer mechanism [9]. Experiments performed by Kole and Dey [10] showed enhancement of thermal conductivity by 10.4% with concentration of 0.025 at room temperature. Density is also an important property as it affects Reynolds number, pressure loss and Nusselt number [11].

Remaining sections of the paper are organized as follows. Section 2 describes the thermos-economic model of the system to optimize the objective function of the systems. Section 3 illustrates the optimization algorithm applied to the thermos-economic model. Section 4 presents application example of the considered ORC system and includes results and discussion. Lastly, conclusion of the present work is described in section 5.

2 Thermo-economic model

In this section, mathematical equations and fundamental correlations used to determine heat transfer characteristics is discussed. Thermo-physical properties of nanofluids are determined from the previous researches and well developed empirical relations. Leon et al. [12] described the importance of particle size and interfacial layer and equation suggested by him is used to calculate thermal conductivity.

$$K_{eff} = \frac{(K_{np} - K_l)\phi K_l [2\beta_1^3 - \beta^3 + 1] + (K_{np} + 2K_l)\beta_1^3 [\phi\beta^3(K_l - K_f) + K_f]}{\beta_1^3(K_{np} + 2K_l) - (K_{np} - K_l)\phi[\beta_1^3 + \beta^3 - 1]} \quad (1)$$

To determine density, viscosity and specific heat of the nanofluids, correlation given by Pak and Cho [13], Brinkman [14] and Xuan [15] respectively was used.

$$\rho_{nf} = (1 - \phi)\rho_f + \phi\rho_{np} \quad (2)$$

$$\mu_{nf} = \mu_{bf} (1 - \phi)^{-2.5} \quad (3)$$

$$C_{p,nf} = \frac{(1 - \phi)\rho_f C_{p,f} + \phi\rho_p C_{p,np}}{\rho_{nf}} \quad (4)$$

Thermodynamic properties of few nanofluids which are conventionally used is listed in Table 1.

Table 1. Thermodynamic properties of nanofluids.

Material	Thermal Conductivity, W/mK	Density, kg/m ³	Viscosity, Pa s	Specific heat, J/kg K
Water	0.6072	997.04	8.94 x 10 ⁻⁴	4183
Fe ₃ O ₄	80.4	5180	-	670
Al ₂ O ₃	40	3900	-	880
CuO	33	6400	-	530

In this study shell and tube heat exchangers are used for the evaporation and condensation process and nanofluids are used for heat transfer with working fluid which is R245ca. Incorporation of nanofluids reduces required heat transfer surface area and hence it reduces total cost involved in the system. Equivalent diameter of the shell is calculated using Eq. (5).

$$D_e = \frac{4(p_t^2 - \frac{\pi d_o^2}{4})}{\pi d_o} \quad (5)$$

Heat transfer coefficient is presented in terms of Nusselt number and it is calculated as given in Eq. (6). It is well known fact that Nusselt number is dependent on Reynolds number and Prandtl number as presented in Eq. (7).

$$h = \frac{Nu \times k}{D_e} \quad (6)$$

$$Nu = 0.0266 \times Re_f^{0.85} \times Pr_f^{0.333} \tag{7}$$

Using values of heat transfer coefficient for shell side and tube side, overall heat transfer coefficient of the heat exchanger is determined and its magnitude is used to determine heat transfer surface area of the heat exchanger. Logarithmic Mean Temperature Difference (LMTD) between the working fluids is calculated at the inlet and outlet to determine the heat transfer characteristics and to deduce value of overall heat transfer coefficient.

$$\frac{1}{U_o} = \frac{1}{h_{fs}} + \frac{d_o \ln(\frac{d_o}{d_i})}{2K_w} + \frac{1}{h_{fT}} \frac{d_o}{d_i} \tag{8}$$

$$A_{HX} = \frac{Q_t}{U_o \times LMTD} \tag{9}$$

Total cost of the individual components is calculated from [16] using Chemical Engineering Plant Cost Index (CEPCI) for the year 2017. Bare module cost of the equipment is calculated using purchase cost and bare module cost factor as shown in Eq. (10) and (11).

$$\log C_{p,X} = K_{1,X} + K_{2,X} \log Y + K_{3,X} (\log Y^2) \tag{10}$$

$$C_{bm,X} = C_{p,X} F_{bm,X} \tag{11}$$

Purchase cost largely depends on type of equipment (X) and its respective performance parameter (Y). For turbine and pump, Y denotes power output and input respectively whereas for heat exchangers it denotes heat transfer area. Value of coefficients and operating parameters is given in Table 2 and Table 3 respectively.

Table 2. Cost coefficients for individual components.

X	Y	Unit	K _{1,x}	K _{2,x}	K _{3,x}	F _{bm,x}
Evaporator	Area	m ²	4.3247	-0.3030	0.1634	2.9
Turbine	Power output	W _t	2.7051	1.4398	-0.1776	3.5
Condenser	Area	m ²	4.3247	-0.3030	0.1634	2.9
Pump	Power input	W _p	3.3892	0.0536	0.1538	2.8

Table 3. Operating parameters of ORC system.

Parameters	Unit	Value
Heat source temperature	°C	140
Evaporation pressure	kPa	1400
Mass flow rate of heat source	°C	17.6
Cooling water inlet temperature	°C	20
Mass flow rate of cooling water	kg/s	34.6
Turbine ratio	-	9.5
Turbine efficiency	%	85
Pump efficiency	%	85

3 Optimization

Newly developed heat transfer search (HTS) algorithm by Patel et al. [17] is used to optimize objective functions. It is based on the fundamentals of heat transfer which involves energy is transferred via conduction, convection and radiation. A body aims to look for thermal equilibrium using the previously mentioned modes and becomes stable with the environment. Three different phases are used for the optimization process viz. conduction phase, convection phase and radiation phase which holds equal importance in the algorithm. A random number is generated from the population and based on the selection accepted values of objective function are updated provided they have enhanced values than the prior. Results are strengthened using the updating of solution through individual phase.

Multi objective heat transfer search (MOHTS) algorithm renders simultaneous solutions for more than one objective function. MOHTS algorithm incorporates the non-dominated solution and save the obtained solutions in an external archive [18]. The MOHTS algorithm uses ϵ -dominance based updating method to check the domination of the solution in the archive [19]. More details about the MOHTS algorithm is available in the references [20, 21]. Objective functions for the current study are thermal efficiency and LEC which are given as Eq. (12) and (13). Bounds of the variables is specified in Table 3.

$$f(x_1) = \eta_{th} = \frac{W_t - W_p}{Q_{in}} \tag{12}$$

$$f(x_2) = LEC = \frac{CRF \times C_{t,2017} + C_m}{t_{op}W_{net}} \tag{13}$$

Table 4. Cost coefficients for individual components.

Design Variables	Lower Bound	Upper Bound
PPTD _{eva} , °C	4	10
PPTD _{cond} , °C	4	10
concentration _{eva} , % v/v	1	10
concentration _{cond} , % v/v	1	10

4 Results and discussion

In this section, optimum result obtained from the HTS optimization algorithm is discussed and reported followed by distribution of design variables. Design variables for the investigation are PPTD and concentration of nanoparticles in heat exchangers.

4.1 Multi-objective optimization

Comparison of Pareto optimal curve for conventional ORC with CuO based ORC is shown in Figure 2. The optimization algorithm tends to achieve maximum thermal efficiency for the system with minimum LEC. In case of conventional ORC system, maximum thermal efficiency of 18.5% is achieved with a levelised cost of 2.66 \$/kWh whereas minimum thermal efficiency of 12.31% was achieved at cost of 2.50 \$/kWh. It is observed that

incorporation of nanofluids enhance heat recovery and reduces heat transfer surface area of heat exchangers which eventually reduces LEC.

Nanofluid based ORC showed improved performance at lower efficiency compared to conventional cycle. Minimum levelised cost of 2.43 \$/kWh is incurred at minimum thermal efficiency of 12.68% however, for maximum thermal efficiency of 18.50% is achieved at maximum cost of 2.59 \$/kWh. Pinch point temperature difference in condenser showed disperse distribution ranging from 6°C to 10°C, whereas for evaporator it ranges from 5°C to 6°C for different optimal points. Concentration of nanoparticles have significant effect on heat transfer and it is observed for condenser majority of the optimal points resembles maximum concentration. Overall 7.11% reduction in LEC is observed for nanofluids based ORC compared to conventional system.

Fig. 2. Pareto optimal curve for multi objective optimization.

4.2 Distribution of design variables

Figure 3 shows the distribution of design variables obtained from the optimal curve. It can be interpreted from the results that effect of concentration of nanoparticles in evaporator is invariable and it don't play any vital role in achieving the optimal results and show constant value. However there is significant distribution observed for PPTD in heat exchangers and concentration of nanoparticles in condenser.

Fig. 3. Distribution of design variables during multi-objective optimization of nanofluid based ORC
 (a) concentration of nanoparticles for condenser (b) concentration of nanoparticles for evaporator
 (c) pinch point temperature difference for condenser (d) pinch point temperature difference for evaporator.

5 Conclusion

The current study addresses multi-objective thermo-economic optimization of nanofluid based organic Rankine cycle system. Based on the criteria of lesser global warming potential and good thermal stability R245ca is used for the investigation. Objective of the study is to maximize the thermal efficiency and minimize LEC for the life cycle of 20 years. Heat transfer search algorithm is used to optimize the objectives of the study. From the Pareto optimal curve it can be deduced that LEC of nanoparticles based ORC is always lesser for any given value of thermal efficiency. Reduction of 7.11% is observed in levelised energy cost by incorporation of nanofluids in the heat transfer fluid. Distribution of design variables is presented and it can be concluded that concentration of nanoparticles and pinch point temperature difference in condenser shows scattered distribution and contributes significantly to attain optimal results. It can be comprehended that incorporation of nanoparticles in heat transfer system will yield enhanced thermal performance and waste heat energy shall be recovered at greater extent.

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