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Exergetic and heat load optimization of high temperature organic Rankine cycle

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A R T I C L E I N F O

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A B S T R A C T

This paper presents an optimization of a high temperature organic Rankine cycle (ORC) system providing the basis for optimal fluid selection and subsequent design parameters based on the working fluid selected. The working fluids used are m-xylene, propylcyclohexane and decane having high critical temperatures. The proposed system deals with the application of biomass due to the high content heat available during its combustion. The system is optimized through non-dominated sorting genetic algorithm (NSGA-II) by taking the prime operators such as; exergetic efficiency (η_{ex}) to extract maximum work and total heat transfer requirement (UA) to get a prediction of the heat transfer area and hence the cost of the system. The parameters subjected to constraints for optimization are evaporation pressure, degree of superheating and pinch point conditions at heat exchangers. The optimization results exhibit an increase of 22.9% for propylcyclohexane and 45.5% for decane in UA values, relative to m-xylene. Highest exergetic efficiency values for m-xylene among three working fluids further ensures its use in the system as the most viable option from both thermodynamic and economic aspect. Moreover, optimal evaporation pressure range is evaluated by taking the maximum and minimum of exergetic efficiency and UA value, respectively. Both objective functions show negative trend with increase in degree of superheating, with less significant drop. As the pinch point value increases, the UA value decreases showing significantly smaller areas of heat transfer and less cost, but with low exergetic efficiency, therefore, moderate pinch point condition of 8–10 °C is recommended.

1. Introduction

The urge to explore new green resources of energy is a heedful process in current era due to two reasons; first, the fossil fuels are getting depleted, and second, the adverse environmental impact of fossil fuels. The United Nations Framework Convention on Climate Change (UNFCCC) Paris agreement in 2015, has proposed to mitigate global warming by controlling Earth temperature [1]. The convention concluded with an agenda to limit the average global temperature below 2 °C and undertake efforts to bind the temperature rise to 1.5 °C above pre-industrial levels. This will substantially influence the climate change and will be achieved by the reduction of greenhouse gas emissions. Combustion of fossils ensue greenhouse gases i.e. carbon dioxide, methane, nitrogen oxides etc., which are regarded as menace to our environment. Intergovernmental Panel on Climate Change (IPCC), suggested that unpredictable climatic changes take place which makes the weather colder, hotter, wetter, and drier, and ultimately, the sea level climbs up making certain parts of the land uninhabitable [2]. Hence, substitute energy sources are needed to implement that are potential remedies to cope with global warming and can equally provide a considerable amount of energy. Low heat resources are playing a vital role in providing compact, portable and easy to install green energy solutions compared to fossils. Many researchers have focused on biomass waste conversion into energy [3]. Others have concentrated on solar energy as source of environmental friendly energy source [4]. Geothermal heat utilization for the energy generation is also recommended for some parts of the earth [5]. Power plants and huge engine waste heat employment as energy source have immense applications towards energy generation [6]. These low temperature resources will not only provide alternative energy but will lessen the adverse effects of unutilised heat on the climate. Organic Rankine cycle (ORC) has been demonstrated in the recent past as the optimal option to adopt as green energy solution which addresses both fossils depletion and also greenhouse gases mitigation [7]. The pros of the ORC have been mainly such as the simplicity of the system and the adoption of organic working fluid instead of water, as described in a review article by P. Colonna et al. [8]. Generally, organic fluid has the advantage over water as it bears low boiling point and suitable to be used at low

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Nomenclature

Abbreviations

UNFCCC	United Nations Framework Convention on Climate Change
IPCC	Intergovernmental Panel on Climate Change
CHP	combined heat and power system
m	mass flow rate [kg/sec]
h	specific enthalpy [kJ/kg]
Q	heat [kW]
W	work [kW]
η	efficiency
c_p	heat capacity [kJ/kg K]
e	specific exergy [kW/kg]
s	specific entropy [kJ/kg K]
T	temperature
I	exergy destruction [kW]
ϕ	availability ratio
E	exergy flow [kW]

Subscripts

in	inflow
out	outflow
me	log mean temperature difference in evaporator
mc	log mean temperature difference in condenser
w	cooling water
s	source/thermal oil
net	total
o	dead state
cond	condenser
evap	evaporator
ex	exergy
t, tur	turbine
p, pum	pump
d	destruction
wf	working fluid

temperatures and pressures [9]. Domestic power generation systems are gaining immense importance via ORC application. High temperature ORC has wide range of applications from industrial point of view, but it has appeared quite challenging due to the scarcity of working fluid that matches the high temperature profile. Shu et al. [10] investigated on alkanes as high temperature working fluids in organic Rankine cycle based on diesel engine waste heat as source. They performed the study with three different categories of alkanes; linear, branched, and cyclo. Inlet temperature of the exhaust gases was taken as 519 °C. The results revealed that linear and branched alkanes did not perform well compared to the cyclo alkanes which showed reasonable cycle efficiency and work output. The research also examined the comparison to steam cycle at such high temperature which inferred that alkanes produced better results for specifically diesel engine exhaust waste heat applications. Siloxanes are also an option for high temperature ORCs but there is an attached concern of high vacuum required to condense into saturated liquid as described by Cao et al. [11].

Braimakis and Karellas [12] optimized the regenerative ORC systems with inclusion of open feed and closed feed heat exchangers for the maximum value of energetic efficiency. The decision variables were the evaporation pressure, bleed pressure and bleed fraction of the open and closed feed heat exchanger. It was concluded that recuperative simple ORC has high efficiency than non-recuperative, and open feed and closed feed forward circulation ORC exhibited efficiency gains of 8.05% and 9.05%, respectively. Jang and Lee [13] worked on a domestic scale biomass ORC-CHP system to evaluate the optimal operating conditions with eight working fluids. Initial screening was done by taking into consideration the environmental and thermodynamic properties of the working fluids by reviewing 107 fluids. Four types of micro ORC-CHP configurations were taken for analysis keeping ORC performance and CHP gains as the optimization prime functions. Group A comprising of working fluids HCFC-141b, cyclo-pentane, iso-pentane, n-pentane and diethyl ether gave the lowest refrigerant mass flowrate, highest ORC efficiency, lowest heat input to the evaporator and highest CHP efficiencies.

For the implementation of ORC, cost of the components are the major barrier to commercialise the technology in the industrial world. Recently many studies have been conducted to optimize the cost of the system and their energetic performances. Dumont et al. [14] conducted technical and economic optimization of biogas ORC system for subcritical, wet expansion and trans critical configurations. The aim of the study was to compare the three architectures of the ORC keeping in view the expanders limitation. The optimization was done for the payback period, net present value, profitability index and internal rate of return for 500 kW biogas power plant. The optimized results from such ORC systems can save up to 600 MWh of energy per year with a payback period of 3 years. Imran et al. [15] studied the regenerative ORC with objective functions as thermal efficiency and specific investment cost. The average increase in cycle efficiency in single stage regenerative ORC was observed as 1.01% w.r.t. basic ORC with additional cost of 187 $/kW, while for double stage regenerative ORC it was 1.45% and 297 $/kW, respectively. Similar investigations were done for the economic assessment of space heating and cooling with different sources of ORC systems [16,17]. Wang et al. [18] reported a study employing energetic parametric analysis and optimization of the ORC system with three working fluids. The fitness parameter was chosen as a ratio of work output to the surface area of the heat exchangers considering the system performance and economic aspects. It was deduced that work output increases with turbine inlet pressure while heat transfer area decreases. Whereas, both of these parameters showed decreasing trends upon increment of pinch temperature difference. The optimized parameters expressed a small value of overall heat transfer area but eventually decreased the work output too. Therefore, it was recommended by the authors that further investigations are required with multi-objective optimization including exergy analysis.

Many previous studies have been carried out to investigate the thermodynamic and economic model of the ORC systems for various applications. Researchers provide cost prognosis by taking the face values of the components of the system which vary quite often due to inflation. On the other hand, selection of working fluid based on the heat transfer requirement and exergetic efficiency can provide generic basis for the assessment of thermodynamic and economic aspects of the overall system. This study intends to optimize the high temperature ORC systems suitable for the biomass application and gives the basis for optimum fluid selection for such systems. The optimal fluid will minimize the cost of the system and at the same time provide maximum possible exergy performance. The assessment of the system is accomplished with the aid of genetic algorithm by keeping the objective functions as; exergetic efficiency that makes the system better in terms of maximum possible work output and total heat transfer requirement of the system which proposes the average heat transfer area of the heat exchangers and suggests the cost of the system. The design variables such as evaporation pressure, degree of superheating and pinch point temperature difference at evaporator and condenser are selected as parameters to check their influence upon the objective functions. Furthermore, the optimum values are suggested for the design parameters based on the fluid selected for the proposed system.