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Experimental study of thermodynamic assessment of a small scale solar thermal system

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ABSTRACT

In this study, a scaled solar thermal system, which utilises HFE 7000, an environmentally friendly organic fluid has been designed, commissioned and tested to investigate the system performance. The proposed system comprises a flat-plate solar energy collector, a rotary vane expander, a brazed type water-cooled condenser, a pump and a heat recovery unit. In the experimental system, the flat-plate collector is employed to convert HFE-7000 into high temperature superheated vapour, which is then used to drive the rotary vane expander, as well as to generate mechanical work.

Furthermore, a heat recovery unit is employed to utilise the condensation heat. This heat recovery unit consists of a domestic hot water tank which is connected to the condenser. Energy and exergy analysis have been conducted to assess the thermodynamic performance of the system. It has been found that the collector can transfer 3564.2 W heat to the working fluid (HFE 7000) which accounts for the 57.53% of the total energy on the collector surface. The rotary vane expander generates 146.74 W mechanical work with an isentropic efficiency of 58.66%. In the heat recovery unit, 23.2% of the total rejected heat (3406.48 W) from the condenser is recovered in the hot water tank and it is harnessed to heat the water temperature in the domestic hot water tank up to 22.41 °C which subsequently will be utilised for secondary applications. The net work output and the first law efficiency of the solar ORC is found to be 135.96 W and 3.81% respectively. Exergy analysis demonstrates that the most exergy destruction rate takes place in the flat plate collector (431 W), which is the thermal source of the system. Post collector, it is followed by the expander (95 W), the condenser (32.3 W) and the pump (3.8 W) respectively. Exergy analysis results also show that the second law efficiency of the solar ORC is 17.8% at reference temperature of 15 °C. Parametric study analysis reveals that both increase in the expander inlet pressure and the degree of superheat enhances the thermodynamic performance of the solar ORC.

1. Introduction

Large scale energy utilisation has become a vital concern due to the increase in the demand of energy use in the last decades. At the same time, use of conventional energy sources such as fossil fuels has brought many environmental problems. Climate change and global warming, which is the main issues resulted from the release of harmful substances into the atmosphere have been forcing us to explore alternative energy sources [1,2].

Solar energy is a free, clean and abundant alternative energy source and it can be utilised by means of solar photovoltaic (PV) and solar thermal systems [3]. Although solar PVs have become one of the most representative ways of electricity generation in rural areas, high costs of PV panels, limited efficiency and requirement of expensive batteries are the main disadvantages of such systems [4].

Medium and high temperature solar thermal systems where concentrated solar collectors such as parabolic through [5,6], linear Fresnel [7] and parabolic dish [8] are used have been suggested and developed over the last decades. However, these systems need high initial cost and complex tracking devices [9].

An organic Rankine cycle, which has the same system configuration as conventional Rankine cycle uses organic substances (refrigerants or hydrocarbons) instead of water as a working fluid [10]. Using organic fluids with a lower boiling temperature than water allows these systems to utilise low temperature heat from various renewable energy sources [11]. As a result, non-concentrated low temperature flat plate collectors can be employed in organic Rankine cycles to generate power and heat simultaneously [12].

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Nomenclature

A	area (m^2)
CFCs	chlorofluorocarbons
e	specific exergy (J/kg)
$\dot{E}x$	exergy rate (W)
h	enthalpy (J/kg)
HCFCs	hydrochlorofluorocarbons
HFCs	hydrofluorocarbons
HFEs	hydrofluoroethers
L	litre
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
I	solar radiation (W/m^2)
ORC	organic Rankine cycle
$\dot{Q}$	heat transfer rate (W)
$\dot{Q}_u$	useful heat gain (W)
PFCs	perfluorocarbons
PV	photovoltaic
RO	reverse osmosis
s	entropy (J/kg K)
t	time (s)
T	temperature (°C)
V	volume (m^3)
$\dot{W}$	work rate (W)

Subscripts

amb	ambient
col	collector
cond	condenser
dest	destruction
exp	expander
fin	final
in	inlet
int	initial
out	outlet
p	plate
rec	recovery
s	isentropic
sat	saturation
sol	solar
st	storage
u	useful
w	water
wf	working fluid
0	reference (dead) state

Greek symbols

ρ	density (kg/m^3)
η	first law efficiency
ε	second law efficiency

Various refrigerants have been used and analysed in solar organic Rankine cycles for both mechanical work and heat generation. Manolakos et al. [13–15] suggested a low-temperature solar thermal power system utilising HFC-134a for reverse osmosis (RO) desalination. The mechanical work generated in the expander of the cycle is used for the pumping purpose of the RO desalination. An experimental study of solar organic Rankine cycle using HFC-245fa was conducted by [9]. In this study, two stationary collectors which are flat-plate and evacuated tube were employed in the experiments. Collector efficiencies of evacuated tube and flat-plate were found 71.6% and 55.2% respectively. The solar thermal power system, including heat regeneration was also analysed in [16]. In this study R-245fa was used as a working fluid of the cycle and maximum thermal efficiency of 9% was obtained with heat regeneration [16]. In another study, recuperative solar thermal cycle with HFC-245fa was designed and constructed by Wang et al. [17]. It was found that the recuperator did not have any effect on the improvement of the system thermal efficiency, which was about 3.67% [17]. Not only pure refrigerants but also zeotropic mixtures were studied in solar thermal systems. Wang et al. [18] carried out an experimental study of low-temperature solar thermal system considering pure HFC-245fa, a zeotropic mixture of (HFC-245fa/HFC-152a, 0.9/0.1) and another mixture of (HFC-245fa/HFC-152a, 0.7/0.3). Since the efficiency of the collector and the system found higher in zeotropic mixtures it is concluded that zeotropic mixtures have a potential to improve the overall efficiency of such systems [18].

In addition to refrigerants, CO_2 which is a natural fluid was also examined in many solar powered supercritical cycle studies. Zhang et al. [19] carried out an experimental study to examine a solar thermal power cycle performance where supercritical CO_2 was utilised as a working fluid. They concluded that the heat collection efficiency of the collector reached 70% and the system achieved 8.78–9.45% power generation efficiency [19]. Another solar thermal power system using CO_2 was proposed and built in Yamaguchi et al. [20]. A throttling valve was used in order to simulate pressure drop in turbine and to study the system performance. They concluded that solar collector can be used for heating of CO_2 in the cycle up to 165 °C. The power generation efficiency of the cycle is estimated for 25% and the heat recovery efficiency for 65% [20].

Thermodynamic analysis considering energy and exergy methods is an essential tool to investigate not only the quantity, but also the quality of energy used in a system [21] and it is also important for designing and analysing thermal systems [22].

Many studies, including energy and exergy analysis of solar thermal power systems have been conducted by various researchers. Singh et al. [23] conducted the first and second laws analysis of a solar thermal power system integrated with parabolic through collector. It is reported that the highest energy loss occurred in the condenser whereas parabolic through collector/receiver component was found to be the source of main exergy losses in the system [23]. Exergy analysis of parabolic through collector combined with steam and organic Rankine cycle has been examined by [24]. Among the considered various refrigerants R-134a gives the best exergetic performance with an efficiency of 26% [24]. Combined exergetic and exergoeconomic analysis of an integrated solar cycle system was carried out by [25]. In this study, genetic algorithm was utilised for the optimisation procedure to minimise the investment cost of equipment and the cost of exergy destruction. Results showed that for optimum operation, total cost rate decreased by 11% [25]. Elsafi [26] applied exergy and exergoeconomic analysis methods to a commercial-size solar power plant using parabolic through collectors. Exergy and exergy costing balance equations are formulated for each component. It is reported that the highest exergy destruction was calculated for the solar field (63,319 kW) and it was followed by the condenser (4187.5 kW) [26].

Although numerous experimental and simulation studies have been reported on the thermal performance evaluation of small scale solar organic Rankine cycles, detailed thermodynamic analysis of such systems considering energy and exergy methods has