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Conceptual modeling of nano fluid ORC for solar thermal polygeneration

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Abstract

A model has been developed for thermodynamic cycle of the solar thermal production of power, heating and cooling utilizing nano fluid as a working fluid in Organic Rankine Cycle. The proposed working fluid provides enhancement in power, heating, and cooling as useful outputs. Initial studies were performed with silver-nano pentane as a working fluid in the cycle. This work extends the application of the cycle to working fluids consisting of organic fluid mixtures. Nano Organic fluid could be used successfully in solar thermal power plants, as working fluids in Rankine cycles. An advantage of using nano fluid as a working fluid is that there are mature experiences with building components for these fluids. A commercially available modeling program has been used to model and investigate the performance of the system. The potential and advantages of using nano fluid are discussed. It is found that the thermodynamic efficiencies achievable with nano organic fluid, under optimum conditions, are higher than those obtained from the base fluid. Further, the size of heat exchangers, evaporator, and condenser are lower than those using the base fluid.

Keywords: Solar thermal; Organic Rankine Cycle, nano fluid ORC; polygeneration; nORC

1. Introduction

There will be an incredible challenge to meet the society’s sustainable energy development in the future; the fossil fuels currently are limited resources and could be increasingly replaced by renewable energy sources [1,2], consequently limiting pollutants’ emissions, causing an adverse effect on the environment and particularly CO_2 emissions into the atmosphere. Among the available renewable sources, solar energy as the most abundant permanent energy resource on the earth could play an essential role in

Nomenclature

A	area, m^2
D	diameter, m
G_{beam}	beam solar insolation, W/m^2
H	enthalpy J/Kg
k	conductivity, W/m K
L	length, m

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P	pressure, Pa
Q	heat power, W
s	specific entropy, J/(kg K)
T	temperature, °C
U	heat transfer coefficient, $W/(m^2 K)$
W	power
W	width
Greek symbols	
α	absorptivity
β	collector tilt angle
η	efficiency
δ	declination angle
ρ	density, kg/m3
ω	hour angle
Cp	Specific heat (J/Kg °C)

terms satisfying energy demand, in particular regions which boast the highest solar radiation levels [3].

Many technologies have been offered for generation of heat and power from solar energy in which solar thermal systems can play a significant role, mainly because of the capability of decoupling solar energy from electricity production by utilizing thermal storage [4]. Concentrating Solar Power (CSP) technology, also known as solar thermal power, is turning into an attractive alternative to produce electricity; it utilizes sunlight by using mirrors to focus the sun's energy and convert it into high-temperature heat. Different types of CSP technologies available in the market make use of different alternative collector technological approaches: trough systems with line-focusing, power tower systems, and dish/engine systems with Point-focusing system [5,6]. Solar Parabolic Trough Collectors (PTC) thermal electric power systems, as one of the available lowest-cost solar-electric options, are the most mature of the CSP technologies [7–9]. PTC thermal power systems range from small remote power systems (a few kilowatts, kW) up to grid-connected power plants (megawatts, MW) [10,11].

Solar thermal power system works like a conventional power plants by utilizing solar energy as a heat source for driving thermodynamic power cycle [12], by mainly coupled to the traditional steam Rankine cycle [13]. The solar field, or thermal energy storage system (TES), supplies heat to the power block by heat transfer fluid (HTF) to generate high pressure steam for running the steam turbine [14].

Recently, aiming to supply heat and power in industrial and residential sectors, the interest in small and medium scale solar plant has been increased. In small scale systems, the steam Rankine cycle does not give a satisfactory performance in generating electricity from low temperature energy sources due to: low thermal efficiencies caused by low boiler pressures, high turbine volumetric flow ratios, and low vapor pressures in the condenser. The organic Rankine cycle, which uses organic fluids with a low boiling point instead of water, is one of the promising technologies for recovering heat from low temperature heat sources [15,16]; it has been used in a broad range of power and temperature levels: geothermal power plant, solar power plant as well as compact cogenerative plant utilized waste heat [17].

The working fluid plays a key role in ORC process and is determined by the application, cycle architecture and heat source level. Organic fluids have higher pressures compared to the steam and since most of them are dry (positive slope in the T-S diagram) or isentropic fluids, they do not require superheating before expansion [18]. Nevertheless, besides the thermodynamic properties, flammability, stability, toxicity, and according to international regulations, the protection of the ozone layer and the emission reduction of greenhouse gases should be considered [19]. Some pure as well as mixtures of organic fluids are investigated in literatures [20,21]. However, few experimental data have been published from operational solar ORC systems. Manolakos et al. worked with R134a as a working fluid and evacuated tube collector in a 2 kWe low-temperature solar ORC and reported an overall efficiency below 4% [22]. Wang et al. obtained overall efficiency of 3.2% with flat plate collectors (collector efficiency was 55%), and 4.2% with evacuated tube collectors (collector efficiency was 71%) in a 1.6 kWe solar ORC in their research with using a rolling piston expander and R245fa [23]. Similarly, there are a few articles for modeling of such a system. Jing et al. predicted overall efficiency 7.9% for ORC cycle with R123 and coupled to compound parabolic collector [24]. Forristall presented a model for the solar collectors only and validated it by the solar electric generating systems plants [25].

Nanotechnology provides new opportunities to process and produce nanofluids. Nanofluids are dilute liquid suspensions of nanoparticles or nano fibers with length scale smaller than 50 nm in a base fluid such as water, oils, refrigerants, or hydrocarbons, and have been reported to enhance substantially higher thermal conductivity and heat transfer coefficient than expected from based fluid [26,27]. Several articles stated the potential benefits on heat-transfer applications of nanofluids [28,29].

In this study, small scale solar thermal ORC polygeneration system making use of solar parabolic trough field and silver-nano pentane as a working fluid, for efficient conversion of solar heat source, is modeled and evaluated.

2. System descriptions

Figure 1, shows a schematic process flow diagram represented majority of parts within the system consisting of solar field, thermal energy storage, a vapor expansion power block for generating electricity as well as an optional polygeneration block.

The solar field is modular and consists of many rows of single-axis tracking parabolic trough solar collectors (due to the lower cost and ease of installation), which aligned on the north-south horizontal axis. During the day, the collectors track the sun from east to west for continuously focusing the sun on the receiver achieving a higher annual collector efficiency and smaller auxiliary energy requirement [30].

The HTF is heated up with circulation through the receiver, and then returns to the evaporator in the power block. The HTF exchanges its heat with working fluid (nano organic fluid) in evaporator where it evaporates and eventually superheats, then after it goes to the small separator. The superheated working fluid fed to two-stage expander to produce electricity, and then the outlet passes through the recuperator.

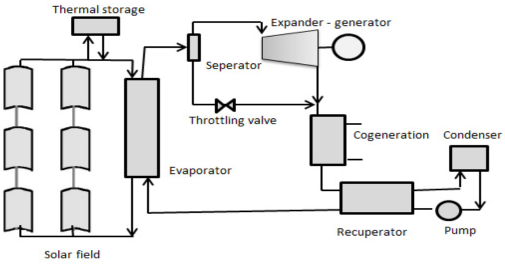

Fig. 1. Component schematic diagram of the system

The remaining heat can be used for heating and cooling systems [31] and finally fluid is condensed in an air condenser. After preheating nano organic fluid pressurized and then returns to the working fluid side of the solar heat exchanger. Thermal energy storage subsystem is integrated for both increasing the operation time and eliminating variations of the heat source (solar irradiation). The cooled HTF is recirculated through the solar field, after passing the HTF side of the solar heat exchangers.

3. Modeling

The steady state model of the system is developed and examined in full load case. The average solar insolation is used for calculation of heat source flux. Moreover, it is assumed that the thermal energy storage is enough sized in order to maintain constant temperature to HTF during low insolation periods; hence, the fluctuation in solar source is not considered in this paper.

In this study, the solar ORC polygeneration utilized nano organic fluid (n-pentane and silver nanoparticles) as a working fluid, is modeled by using the Aspen Plus modeling software (). User defined custom modeler blocks and properties are defined. In addition, some functions with experimental data and calculator block, for prediction of nano organic fluid properties and working conditions of components, are incorporated into the software.

3.1. Heat transfer fluid

Different fluids as a HTF such as mono ethylene glycol (MEG), propylene glycol (PG) and di-ethylene glycol (DEG), Therminol VP1 synthetic oil, Downtherm Q, have been presented in literatures [32]. The HTF used in this

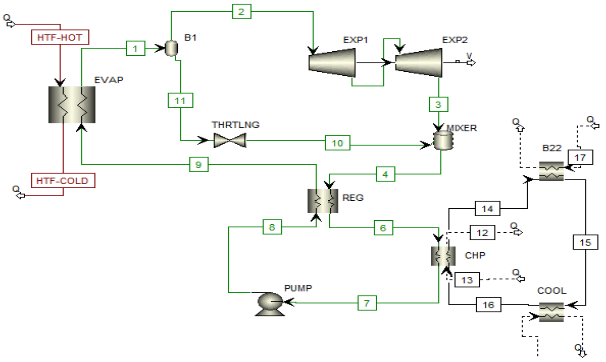

Fig. 2. Aspen plus model of the nano fluid ORC cycle

model is low-vapor-pressure petrole , Caloria HT-43. Some properties of Caloria-HT43 as a function of tempe

Table 1. HTF (Caloria HT43) properties as a function of temperature in degrees Celsius

Property	Equation
Density	$\rho = -1.265\times10^{-4}\times T^2 - 6.617\times10^{-1}\times T + 8.85\times10^2$
Enthalpy (J/Kg)	$H = 1.94\times T^2 + 1.6060\times10^3\times T$
Specific heat (J/Kg °C)	$C_p = 3.88T + 1.606\times10^3$

3.2. The solar source

Concentrated solar power systems require abundant direct solar radiation to reach the higher temperature in HTF. This limits CSP to hot and dry territories, with high level of direct normal irradiance (DNI). They include North Africa, Middle East, Southern Africa, Australia, the Western United States and parts of South America. Solar heat source in the model is calculated based on the DNI in Seville, Spain (Latitude 37°) with DNI around 2100 kWh/m^2 per year () [33].

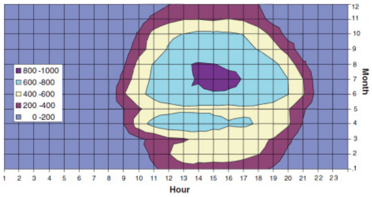

Fig. 3. Distribution of the mean monthly DNI for Seville, Spain, in W/m^2.

3.3. Parabolic trough collector

Some research has been done the modeling of parabolic trough collector (PTC) by using Engineering Equation Solver (EES), based on the heat collector element (HCE) performance model [25,34]. In the present work, solar field is modeled as a constant heat source flux. The thermal energy produced by solar field, per unit area of collector, is calculated by the following equation[35]:

$$Q'_u = \eta_{optical}.G_{bn}W.\cos\theta.K_\theta k_\theta \eta_{shading,\theta}.F_e - Q'_{loss} \qquad (1)$$

Where $\eta_{optical}$ is the optical efficiency for direct normal incident (DNI) radiation, G_{beam} is the DNI radiation, W is the collector aperture width, θ refers to incidence angle, K_θ is the incidence angle modifier (IAM), k_θ is longitudinal shading correlation, $\eta_{shading,\theta}$ is lateral shading correlation, F_e is soiling factor, and Q'_{loss} is the field heat loss. The incident angle for North-South orientation, where δ is a declination angle, β as a collector tilt angle, and ω as the hour angle is determined by the following equation, where shading corrections, and field heat losses comes from literatures [35]:

$$\cos\theta = \cos\delta\sin\beta\sin\omega + \cos\beta(\cos\phi\cos\omega\cos\delta + \sin\phi\sin\delta) \qquad (2)$$

3.4. Evaporator model

In medium sized ORC, introducing the two stage evaporator configuration helps to avoid pinch point construction between the working fluid in ORC and thermal oil side [36]. The two stage heat exchangers can reduce the heat transfer irreversibility between HTF and nano fluid. However, in small size system,

due to the installation of additional parts, one stage evaporator is assumed. The evaporator is characterized by UA value, which corresponds to heat transfer coefficient (U) and heat transfer area (A) [37].

3.5. Working fluid

Although there is a broad range of working fluids, only a few are applicable in commercial ORC systems. [20]. Utilizing nano fluid permits a higher variety on the choice of working fluid. Enhancement in nano fluid boiling heat transfer is a vital issue, and could make the heat exchanging process more efficient. Nucleate boiling is an efficient heat-transfer mechanism in boiling regimes; however, the critical heat flux (CHF), where heat transfer is maximized, is an important concern [38]. An increase in CHF of nano fluid would allow for more compact and effective heating and cooling components, and potentially revolutionize heat transfer.

The candidate base fluid is n-pentane; some articles stated it as a working fluid in ORC cycle [39,40]; also, it is used in 1MWe concentrating solar power ORC plant in Arizona [41].

In the present work, nano fluid Organic Rankine Cycle (nORC), working fluid is n-pentane as a base fluid with silver nanoparticles (0.5%W/v, size<20 nm). Silver nanoparticles are free from agglomeration, and ideal for use in a variety of innovative applications. The transmission electron microscopy (TEM) images of silver nano particles with the 20nm diameter are shown in [42].

Aspen plus, uses its property data sources, thermophysical properties via DETHERM, and Physical Property Data System (PPDS) data bank of the NEL [43]. However, to adopt the software to recognize and use the properties of nano organic fluid, instead of the organic base fluid, calculator blocks for predicting the altered properties and consequent changes, are incorporated into the software. This approach succeeds to empower the Aspen plus to treat with nanofluids in nORC [44].

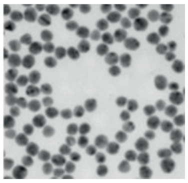

Fig. 4. TEM images of silver nanoparticles (d= 20 nm)

3.6. Expansion machine

Performance of the ORC system strongly correlates with the expander. However, the choice of expander strongly depends on the working fluid properties, operating conditions, and size of the system. Expanders can be categorized as two types: velocity type such as axial turbine, and volume type such as screw expanders, scroll expanders, and reciprocal expanders [45]. In the model, a hermetic scroll expander, which has high efficiency, simple manufacturing and tolerable two-phase is selected [46,47].

3.7. Condenser model

Dry fluids leave the expander in superheat, which results in more cooling load and waste heat [20]. In order to increase cycle efficiency, using CHP mode of the ORC cycle would be of interest. In the present model, parameters for heating and cooling are integrated as a thermal load or by choosing temperatures of streams in condenser as a fixed parameter to reach the maximum possible efficiency.

To reduce water utilization, the air condenser is selected. Fan power consumption is a function of heat transfer rate, and the pressure in the condenser sets above the atmospheric pressure in order to prevent leakage cool air into the system.

3.8. Performance of model

The system is investigated by considering the fixed parameters and optimizing the free parameters for each component with some assumptions (

$$\eta_{total} = (P_{ele} + Q_{CHP}) / Q_{solar} \qquad (3)$$

4. Results and discussion

This section aims at discussing thermodynamic and physical properties of the silver-nano pentane as well as the possibility and influence of using silver-nano pentane as a working fluid in ORC systems.

4.1. Silver- nano pentane fluid, thermodynamic and physical properties

The performance of ORC systems intensely depends on working fluid properties, which affects system efficiency, operating conditions, environmental impact and economic viability. Although, obtaining properties of nano fluid via chemical and physical route is difficult, followings are some important points.

- Boiling temperature: Adding silver nanoparticles, gives a higher boiling point compared to pentane.
- Freezing point: In ORC, the freezing point of the working fluid must be lower than the lowest temperature of the cycle. Although the pentane as a base fluid has safe freezing temperature, but the silver-nano pentane has a lower freezing point.
- Conductivity: Silver-nano pentane (according to the Hamilton–Crosser model and approximate by the Maxwell model [48]) displays higher conductivity (16.1w/m.k), than pure pentane (0.136 w/m.k). Hence, a high heat transfer coefficient in the heat exchangers can be obtained.
- Viscosity: Proposed nanofluid viscosity can be calculated according to the formula in the literature [49], which is 395 µPa s. in comparison with 240 µPa s for pentane. It means that it is required to maintain more friction losses in heat exchangers and pipes.

) in the Aspen plus model.

Table 2. Assumptions in Aspen plus model

parameter	Value (range)
Turbine efficiency	0.75
Generator efficiency	0.94
Recuperator effectiveness	0.8
Exchangers pinch point	7 to 9 °C
Air cooling	27 °C

The total efficiency of the system in CHP mode, η_{tot} would be calculated by equation , where P_{el} is the electrical power generated by the cycle, Q_{CHP} refers to total heat used for heating and absorption cooling, and Q_{solar} is thermal energy given by HTF, comes from the solar field. In condensing mode (only electricity generation) Q_{CHP} would be zero.

$$\eta_{total} = (P_{ele} + Q_{CHP}) / Q_{solar} \qquad (3)$$

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- Viscosity: Proposed nanofluid viscosity can be calculated according to the formula in the literature [49], which is 395 µPa s. in comparison with 240 µPa s for pentane. It means that it is required to maintain more friction losses in heat exchangers and pipes.
- Critical temperature: For certain evaporation and condensation temperatures, a good efficiency is acquired from fluids with higher critical temperature. However, a low condensation pressure could conflict with turbine and plant design [50]. Proposed working fluid (silver-nano pentane) shows a higher critical temperature in comparison with pentane.
- Limitations of safety and environmental: Pentane has zero Ozone Depleting Potential (ODP) and very low Global Warming Potential (GWP) [51]. Hence, the silver-nano pentane is a suitable working fluid.

5.2. Performance of the nORC, power only and CHP modes

The model examined for two cases: power only, in which there is no thermal demand for the heating and cooling, and the next is CHP mode, which heat uses for the polygeneration section.

The overall system efficiencies for different condenser pressures are plotted in . The results of the model show a significant increase (almost more than 10% increases) in electricity generation for all temperature ranges in condenser, with using of silver-nano pentane instead of pentane. Because most of the heat losses are from the evaporator and exchangers, using the nano organic fluid increase the heat transfer coefficients thus the cycle shows higher efficiency.

In CHP mode, due to better exploit the heat source in the optional polygeneration, the efficiencies of the system is higher than power only mode. Condenser pressure and inlet and outlet streams' temperature are significant parameters in CHP mode. The condenser pressure is fixed, higher than the power only case. Electrical, thermal, and total efficiencies in both working fluids (pentane or silver-nano pentane) are shown in (). Although, the electrical efficiencies are a lower than power only cases, due to the heat recovery in heating and cooling services, and reducing fan power the total efficiencies are increased.

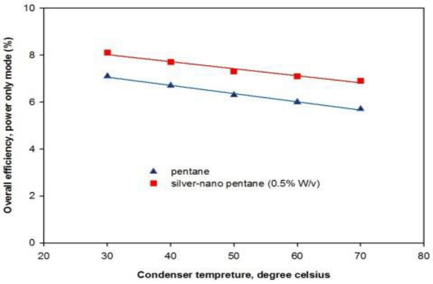

Fig. 5. Overall efficiency of the system for power only mode with different condenser temperature for two working fluid

6. Conclusions

The application of nano fluid as a working fluid in solar ORC systems to a combined heat, power and cooling systems has been studied. It is shown that nano fluid can be used in the cycle. Moreover, based on

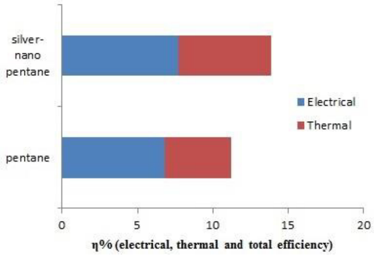

Fig. 6. Electrical, thermal and total efficiency of CHP for silver-nano pentane and pure pentane

the modeling, silver-nano pentane offers better cycle efficiencies in comparison with pentane. Silver-nano pentane has an inherent advantage with employing smaller size heat exchangers and expander. Moreover, using nano organic fluid as a working fluid, improves the efficiency of the proposed cycle.

Even though part-load analysis is not presented in this work, the proposed Aspen plus model allows investigating the system with different nano organic fluids as well as working conditions.

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