Efficiency Improvement and Comparative Studies of Solar Organic Rankine Systems using Nanofluids

Raghav. S, Karthik. D, Nithin. K, Badarinarayana. K

***Abstract:** Solar power generation has emerged as one of the most rapidly growing sources of renewable energy. The solar thermal system with a Rankine cycle used to harness solar energy and generate electricity from a low temperature heat source is an emerging technology. The major drawback of solar thermal power generation is its poor efficiency, which is around 10% to 15%. Although prior attempts to improve the efficiency of the solar thermal system and use of Nano fluids in heat transfer applications have been carried out, very little work has been carried out using Nano fluids in Rankine cycle systems. Thus, the objective of the research undertaken was to primarily improve the efficiency of a small-scale solar thermal system by selecting working fluids, optimizing the system parameters and using Nano fluids with improved heat transfer properties for capturing heat. Thermodynamic simulation tool Aspen Hysys was used to carry out simulations of the Rankine and Regenerative Rankine systems. The system was simulated with combinations of Dowtherm-Cu O/Ag/Al2O3/TiO2 as the heat transfer fluid, and n-butane, n-pentane, n-hexane, or R-134a as the working fluid. System parameters such as mass flow, temperature, and pressure were optimized to obtain maximum power output and efficiency, keeping the system constraints and practicality in mind. The use of Nano fluids improved heat transfer to the working fluid in the heat exchanger by a maximum of 50%. The efficiency of the basic Rankine cycle was determined 16.03% for n-pentane, 14.90% for n-hexane, 13.83% for n-butane, and 9.82% for R-134a as the working fluid. Further, the use of regeneration improved the efficiency of the system by 6%, 3 %, 7% and 2% respectively. Highest efficiency of 27.96% was obtained when 6% volume concentration of Al2O3 was used in the heat transfer fluid, and n-pentane was used as the working fluid in the Regenerative Rankine cycle.*

***Keywords:** Solar Organic Rankine Cycle, Nano-fluids, Heat Transfer, Simulation, Optimization, Aspen Hysys*

I. INTRODUCTION

Solar energy has been one of the fastest growing renewable sources of energy in the world in the past decade. In countries like India,

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Solar energy is said to have the highest potential among all the renewable sources for power generation. The target capacity for solar energy in India is set to 100GW by the year 2022 [1] and 280GW by the year 2030, giving rise to a lot of opportunities and scope for development in the field of Solar Energy. Conventionally, solar energy is tapped through the use of photovoltaic cells. An alternative method of capturing solar energy is through the use of a Rankine cycle system. The Rankine cycle is one of the most commonly used cycles to predict the performance of steam turbine systems. It is an idealized thermodynamic cycle of a heat engine in which heat is converted into mechanical work. Commonly, water is used as the working fluid in a Rankine cycle where steam is produced by heating water through use of conventional fuels such as coal, nuclear power and fossil fuels. On the other hand, when a low temperature heat source such as the sun are to be used to heat the working fluid, alternative working fluids have to be chosen to effectively capture the low-grade heat. The use of an organic fluid - a high molecular mass fluid with a low boiling point- allows Rankine cycle heat recovery from lower temperature sources and facilitates effective transformation of low temperature heat into useful electrical energy [2] [3] [4] [5] [6]. A distinct advantage of using organic fluids in a Solar Rankine cycle arises from the nature of their T-S curve. The saturation vapor curve in organic fluids has a positive slope, preventing cavitation at low discharge pressures of the turbine. Moreover, use of organic fluids enable the system to be operated at much lower pressures as opposed to a conventional Rankine cycle, thus leading to small-scale and low-cost installations. A significant drawback of small scale Solar Organic Rankine systems is its low efficiency, which typically ranges between 10-15% [7]. Efficiency improvements in Rankine cycles are traditionally brought about through the use of reheating and regeneration [5] [6] [7] [8]. The use of Regeneration and reheating results in the addition of heat at elevated temperatures, thereby improving efficiency. In recent years, the use of Nano fluids in the field of heat transfer has become common due to the superior heat transfer characteristics they impart. This unique feature can thus be employed to ensure that a higher heat transfer from the heat capturing loop to the power generation loop can be achieved, resulting in higher efficiencies. Various researchers have evaluated the enhanced heat transfer achievable through the use of Nano fluids. Eastman et al [9] and Xuan and Qiang [10] concluded that Nano particles such as Cu O and Al2O3 added to a base fluid are likely to improve heat transfer significantly by increasing the effective thermal conductivity of the base fluid they are added to.

The mechanism responsible for the unusual improvement in heat transfer characteristics of Nano fluids was summarized by Wen et al [11] and Keblinski [12]. Eastman [13] in his studies determined that the dramatic improvement in thermal conductivity of a Nano fluid was mainly due to the decreasing particle size in the suspension. Further, research by Singh [14], Sarit [15] and Albadr et al [16] reveals that the enhancement of thermal conductivity of Nano fluids shows a dramatic increase with temperature and the rate of this increase depends on the concentration of Nano particles. The results pertaining to use of Nano fluids in heat transfer applications indicate numerous advantages, making it a suitable candidate for use in a Solar Organic Rankine system to mitigate the low efficiency. Otani car [17] suggested that the large increase in surface area due to the extremely small particle size makes Nano fluid-based systems suitable for application in solar thermal systems.

Saadat far et al [18] in his study concluded that the efficiencies obtained by using Nano fluids in the Rankine cycle are higher than those obtained from the base fluid. The results and conclusions drawn by various fellow researchers pertaining to Nano fluids and the scope for efficiency improvements in a Rankine system thus proved to be a source of motivation for the study undertaken. The study analytically evaluated the potential of using nanoparticles such as CuO, Ag, Al_2O_3, and TiO_2 in the heat transfer stage of a Solar Rankine system instead of the power generation stage of the Rankine system citing certain drawbacks in the latter such as clogging, damage to the impellers and blades of the pump and turbine due to peening. Nanoparticles were added to a thermic fluid called Dowtherm-G, a popular thermic fluid used in industry for heat transfer applications. The volume concentration of the nanoparticles in the Nano fluid was varied from 1% to 6%. Evaluations regarding the improved heat transfer characteristics of Nano fluids were mostly based on experimental data and conventional heat transfer models fail to predict the properties of Nano fluids accurately. Alternatively, mathematical models specific to Nano fluids were employed.

Xuan and Reitzel [19] suggested a formula to calculate the specific heat of a Nano fluid whereas Yu and Choi [20] derived a mathematical equation to closely represent the enhanced thermal conductivity in a Nano fluid. The friction factor and Nusselt number for a Nano fluid was predicted accurately up to 6% volume concentration by Duangthongsuk and Wong wises [21]. The study thus utilized the above findings to successfully predict the heat transfer characteristics of a Nano fluid. Further, simulation of the Rankine cycle was carried out on the process simulation software Aspen Hysys using organic fluids such as n-pentane, n-butane, n-hexane and R134-a [3,4] owing to the favorable characteristics they imparted. The simulation aimed at improving the efficiency of power generation. Generally, efficiency improvements in Rankine cycles are carried out through reheating and regeneration. Reheating is used in Rankine cycles that operate at higher temperatures and pressures which give rise to numerous technical difficulties. Regeneration on the other hand is commonly used in power plants and was deemed suitable to improve the efficiency of the Rankine cycle used in the Solar Rankine system. Apart from regeneration, system parameters were optimized subject to physical constraints that were introduced to simulate a real-life scenario. The study also conducted a comprehensive comparison study using Dowtherm-CuO/Ag/Al_2O_3/TiO_2 (Nano fluid) in the heat capture stage, and n-butane, n-pentane, n-hexane, or R-134a (organic fluids) as the working fluid in the Rankine cycle. The 16 combinations involving different Nano fluids and organic fluids were subjected to both heat transfer evaluations as well as Rankine cycle simulations to determine the Nano fluid – working fluid combination that imparted the highest efficiency.

II. METHODOLOGY ADOPTED

2.1 Selection of working fluids

The selection of a working fluid is a trade-off between thermodynamic specifications, safety, environmental and economy aspects [3, 4]. The following criteria were considered while choosing the working fluids n-pentane, n-butane, n-hexane and R134a for use in the Rankine cycle.

2.1.1 Characteristic T-S curve

The slope of the saturation vapor line in fluids can be negative, positive or infinite. While the saturation vapor line of water has a negative slope, organic fluids such as n-pentane, n-hexane, n-butane are seen to have a positive saturated vapor line as shown in Figure 1. Fluids with positive and infinite slopes have enormous advantages for turbo machinery expanders. These working fluids leave the boiler and expander as superheated vapor and eliminate the risk of cavitation in case of using turbo machinery expanders. Secondly, use of such organic fluids permits expansion of the vapor to lower pressures. Furthermore, there is no need for overheating the vapor as superheated states can be achieved through relatively lesser heat addition, thus facilitating the use of a smaller and cheaper heat exchanger (evaporator).

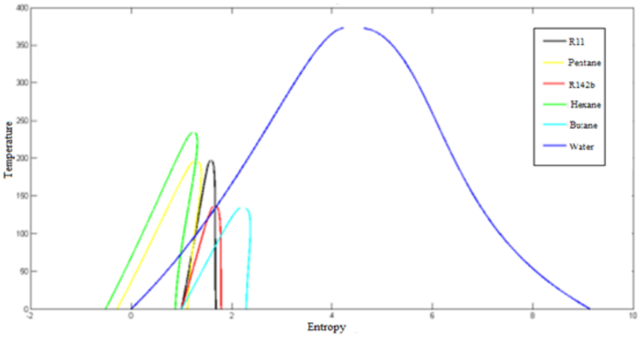

Chart 1: T-S curve of working fluids consideration [3, 5]

2.1.2 Thermodynamic, Environmental and Safety Criteria

Since the low temperature sources provide the necessary heat for a Solar Rankine system, temperatures are typically lower as compared to a conventional Rankine cycle. It is thus desirable to use liquids with low boiling points. Low boiling points of organic fluids facilitate operation at superheated states at fairly lower temperatures as compared to temperatures required while using water as a working fluid. Further, two other important factors that are considered while selecting the working fluid are a liquid's Ozone depletion potential (ODP) and its Global Warming Potential (GWP). The properties of the fluids under consideration are shown in Table 1.

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Table 1: Boiling points, ODP and GWP of working fluids under consideration

Working Fluids	Density (kg/m^3)	Boiling Point (ºC)	Specific Heat (kJ/kgK)	GWP	ODP
Pentane	626	36.1	2.31	<25	0
Butane	2.48	-1	1.69	3	0
Hexane	654.8	68	3.07	3	0
R-134A	4.25	-26.3	1.34	1300	0

2.2 Nano particles used for enhancing heat transfer

Nanoparticles have been studied extensively by various researchers for their potential benefits in heat transfer applications. Four such Nano-particles namely, Al_2O_3, CuO, TiO_2, Ag were seen to have potential for use in heat transfer applications [11, 21, 22] and were used in this study for further evaluation in a Solar Rankine setup. The properties of the nanoparticles considered are as listed in Table 2. The 4 nanoparticles were combined with a thermic fluid in the heat capturing loop in various proportions ranging from 1-6% to observe changes in the heat transfer. The volume concentration of nanoparticles was restricted to 6% as the tendency to settle down in the fluid medium increases beyond this and the error in the mathematical models used to predict the properties begin to become significant [21].

Table 2: Properties of Nano-particles under consideration

Nano- Particle	Density (kg/m^3)	Thermal Conductivity (W/m.K)	Specific heat (J/kg.K)
Ag	10500	418	0.235
Al_2O_3	3880	20	0.773
CuO	6310	78	0.603
TiO_2	4320	6	0.831

2.3 Heat Exchanger Computations

A typical Solar Rankine System consisting of a heat capturing loop and a Power generating loop is shown in Figure 2. The Nano-fluid in the heat capturing loop consists of a thermic fluid Dowtherm-G as the base fluid and nanoparticles such as Al_2O_3, CuO, Ag and TiO_2. Although the software has a capability of simulating the cycle with liquid-solid mixtures, on using a Nano fluid, it has been reported that the accuracy of the simulation software decreases linearly on increasing the suspended nanoparticles volumetric concentration. Moreover, previous attempts to use Nano fluids on Aspen Hysys highlighted the process modeling software's incapability to accurately predict the Nano fluid's properties [23]. Hence, a mathematical approach was taken to evaluate the heat transferred from the heat capture loop to the power generation loop through the heat exchanger. The corresponding heat transferred was then inputted as a parameter in the simulation software to simulate a Rankine cycle.

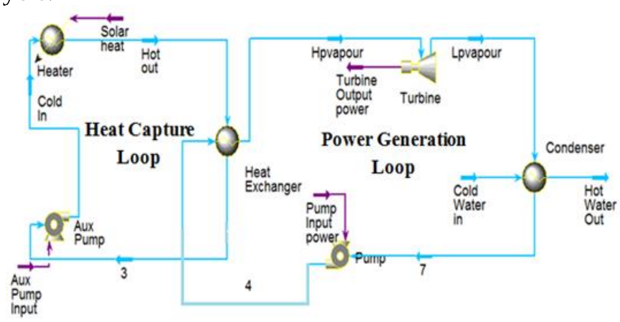

Figure 2: A typical Solar Rankine System

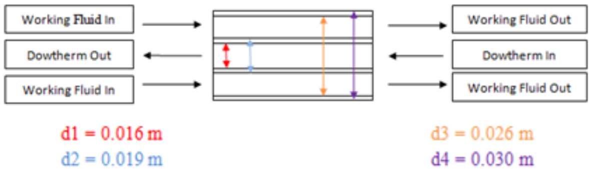

Figure 3: Cross section of the Heat Exchanger

A shell and tube heat exchanger modeled as shown in Figure 3 was used to predict the properties of the Nano fluids and the increase in heat transfer. The heat captured was transferred to the power generation loop through the heat exchanger where it was utilized to heat the working fluid.

Nano fluid properties and heat exchanger calculations were computed using the following formulae:

1. Density (ρ):

The Nano fluid density is calculated using Pak and Cho relation [24]:

$$\rho_{nf} = (1- \phi)\ \rho_f + \phi\ \rho_p$$

2. Specific Heat (C_p):

The specific heat of the Nano fluid is calculated using Xuan and Roetzal [19] relation:

$$(\rho \times C_p)_{nf} = (1- \phi)\ (\rho \times C_p)_f + \phi(\rho \times C_p)_p$$

3. Thermal conductivity (k):

The thermal conductivity of the Nano fluid is calculated using Yu and Choi relation [20]:

$$k_{nf} = k_f \times (k_p + 2k_f - 2\phi(k_f - k_p)) / (k_p + 2k_f + \phi(k_f + k_p))$$

4. Dynamic Viscosity (µ):

Drew and Passman [25] suggested the well-known Einstein's equation for calculating viscosity of Nano fluid, which is applicable to spherical particles in volume fractions less than 6.0 volume%:

$$\mu_{nf} = (1+2.5\phi) \times \mu_f$$

5. Friction factor (f):

The friction factor for Nano fluids is given by Duangthongsuk and Wongwises relation [21]:

$$f = 0.961\ Re^{-0.375}\ \phi^{0.052}$$

6. Nusselt number (Nu):

The Nusselt number for Nano fluids is given [16]:

$$Nu = 0.074\ Re^{0.707}\ Pr^{0.385}\ \phi^{0.074}$$

Known parameters such as mass flow, density, diameters, viscosity, specific heat and conductivity of the Nano-fluid fluid and working fluid are used to compute other parameters such as viscosity, specific heat, conductivity, Prandtl number, Reynolds number, friction factor and Heat transfer coefficient on the hot and cold side of heat exchanger to determine the heat transferred in the heat exchanger.

2.4 Rankine Cycle Simulation using Aspen Hysys

Aspen Hysys by Aspen Technology is among the major process simulator that is widely used in thermodynamic process industries involving steady-state analysis. System simulation involves the calculation of operating variables such as pressure, temperature and flow rates of energy and fluids in a thermal system operating in a steady state.

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The equations for performance characteristics of the components and the thermodynamic properties along with the energy and mass balance form a set of simultaneous equations relating the operating variables.

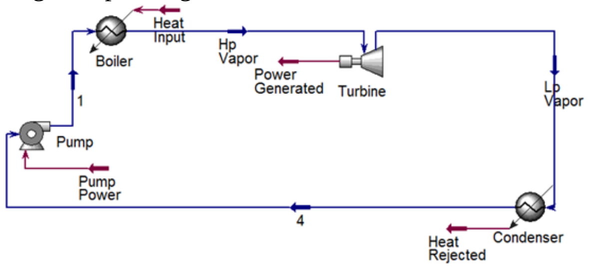

Figure 4: Basic Rankine Cycle on Aspen Hysys

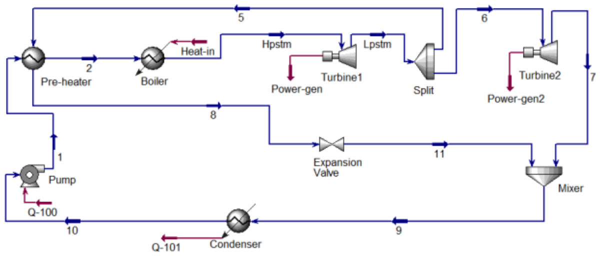

Figure 5: Regenerative Rankine Cycle on Aspen Hysys

The power generation loop primarily consists of a Rankine cycle setup or Regenerative Rankine cycle setup as shown in Figure 4 and Figure 5 respectively. Working fluids such as n-pentane, n-butane, n-hexane and R134a circulate in the power generation loop. Based on the power output required and the amount of heat available, pressures, temperatures, mass flows etc. are specified at different stages of the cycle.

2.5 Methodology of Selecting System Parameters

The constraints that are enforced on the Rankine system play a pivotal role in determining the pressures, flow ratios and mass flow rates and temperatures in the system. The constraints applied serve to simulate real-life conditions and prevents over predicting the efficiency. The constraints employed in the simulations are listed as follows:

a. Condenser outlet temperature shown in Figure 5 (stream 10) was maintained at least 15-20°C higher than room temperature. A primary reason for this was to simulate the use of water at room temperature in the condenser to cool the vapour exiting the turbine. To achieve temperatures close to room temperatures using water as the coolant demands large condensers which apart from being infeasible, elevates costs and complexity.

b. Vapor fraction of the fluid in streams shown in Figure 4 and Figure 5 at the inlet of the turbines is always ensured to be unity. It is advisable that only vapour enter the turbines as any moisture or liquid in the turbine inlet stream will result in cavitation of the turbine blades resulting in damage to the turbine, which by far is the most expensive component in the Solar Rankine system.

c. The **temperatures** of fluid streams entering and exiting the Heat exchanger or Pre-heater, shown in Figure 5 are monitored to ensure that they are practically possible to achieve. Temperature differences of about 15-20 0C are industrially accepted standards while designing a heat exchanger. To achieve lower temperature differences, the heat exchanger size will be unnecessarily large and may not be economically feasible.

d. Critical Pressure of the working fluid determines the pump operating pressure. While operating pressures are always kept as high as possible to improve efficiency, operating over critical pressures are avoided. Super critical systems encounter several problems that can be tackled only through critical design of turbines and pumps with close tolerances which results in increased cost. Moreover, high operating pressures leads to faster wear of moving components and demands better and sophisticated sealing systems.

2.6 Optimization of the Rankine Cycle Parameters

The power output of the turbines was optimized to obtain maximum efficiency for the given constraints through an iterative process. System variables such as pump pressure, mass flow rates, flow ratios, turbine discharge pressures in the Rankine cycle were varied in small steps over the given feasible range of values leading to all possible system parameter combinations within the set range. Consequently, the corresponding power outputs for the combinations were computed. The various combinations of system parameters were further scrutinized to ensure that constraints pertaining to condenser outlet temperature, vapor fraction at the turbine inlet and outlet, temperatures of the inlet and outlet streams of the heat exchanger were met. The system parameter combinations that did not satisfy the criteria set were filtered out. Among the cases that satisfied the constraints with regards to pressures, temperatures, vapor fraction, mass flows etc. the combination of system parameters imparting maximum efficiency was determined, in the process lending the Rankine cycle with optimized parameters.

III. RESULTS AND DISCUSSIONS

Heat exchanger calculations were carried out by determining the overall heat transfer coefficient on the hot and cold side out the heat exchanger. The calculations were carried out for a constant mass flow rate of 300kg/hr and temperature difference of 200°C of the Nano fluid.

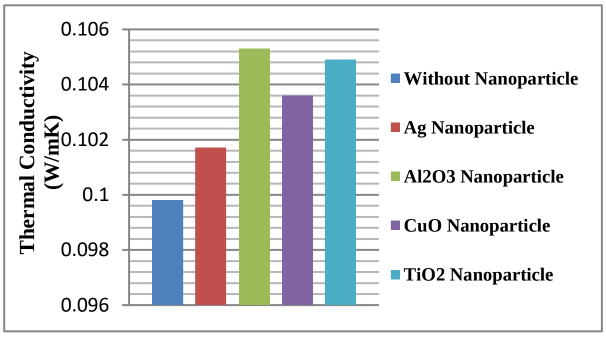

Chart 2: Thermal conductivity of the thermic fluid with and without nanoparticles

The mass flow and temperature difference set in the heat capture loop ensured that the amount of heat captured and transferred without the use of nanoparticles was 39.16kW. These system parameter values were set to ensure that a Rankine system producing roughly about 5-10kW could be designed, considering the efficiency of typical Rankine cycle systems to range between 15-20%.

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The mass flow rate of the working fluid, pump discharge pressure, turbine discharge pressures, flow ratios etc. in the power generation loop were set at optimum values which were determined during the optimization process so that the efficiency of the Rankine cycle was the maximum. In general, it was observed that a significant increase in heat transfer is achieved through the addition of nanoparticles in the heat capture loop. The increase in heat transfer can be attributed to the improvement in thermal conductivity of the thermic fluid on the addition of nanoparticles. The comparison of thermal conductivities with and without the use of nanoparticles in Dowtherm-G is shown in Chart 2. It can be seen that the addition Al_2O_3 and TiO_2 to the thermic fluid (Dowtherm-G) in the heat capture loop produces the most improvement to the thermal conductivity and leads to maximum heat transfer. The corresponding values of heat transferred from various possible combinations of the Nano fluids in the heat capturing loop to working fluids in the power generation loop are shown in Chart 3. The percentage of increase in heat transfer is seen to range from 28% to 50% for different combinations. The heat transfer occurring in the heat exchanger also depended on the volume concentrations of nanoparticles in the thermic fluid. Heat transfer rates peaked at volume concentrations of 2%, 6%, 4% and 6% for Ag, Al_2O_3, CuO and TiO_2 respectively. Although the study involved computing the efficiencies and heat transferred at various volume concentrations of the nanoparticle in the thermic fluid, results reported in Charts 2, 3, 4 and 5 correspond to the volume concentration at which heat transfer rates peaked. Heat transfer computed through heat exchanger calculations in the heat capture loop was used as an input for the Rankine cycle analysis. Simulations were carried out for both, the standard Rankine cycle as well as the Regenerative Rankine cycle using the process modeling software, Aspen Hysys.

For a given heat input, the optimum values of pump pressure, mass flow rates, flow ratios and turbine discharge pressures were obtained through the optimization process to maximize efficiency. The values of the system parameters post optimization are shown in Table 3. The pump pressure in all the cases is maintained as close to the critical pressure of the fluid as possible to ensure maximum efficiency. The turbine discharge pressures are determined based on the temperature at the outlet stream, typically above room temperatures, while maintaining a positive pressure in the system so as to ensure that vacuum is not created within the system. In case of the Regenerative Rankine cycle the discharge pressures at the high pressure turbine and the low pressure turbine is controlled along with the ratio of the bleed stream from the high pressure turbine to the feed water heater. The pump power required ranged from 0.42kW to 0.86kW. This was primarily dictated by the mass flow rate of the working fluid in the system. The power consumed by the pump is negligible as compared to the power produced by the turbine and has little impact on the efficiency of the Rankine cycle itself. The power produced by the turbines in the Rankine cycle ranges from 5kW to 11kW and is shown in Chart 4. In the Rankine cycle, Pentane is seen to be the most effective working fluid when used in conjunction with Al_2O_3 or TiO_2 nanoparticles added to Dowtherm in the heat capture loop. A maximum power output of 11.14kW was obtained for the combination involving Al_2O_3 nanoparticle in the heat capture loop at 6% volume concentration and Pentane in the regenerative Rankine cycle. On the other hand, the working fluid R134a is seen to be least effective while used in the Rankine cycle, with turbine output in the range of 5-7kW.

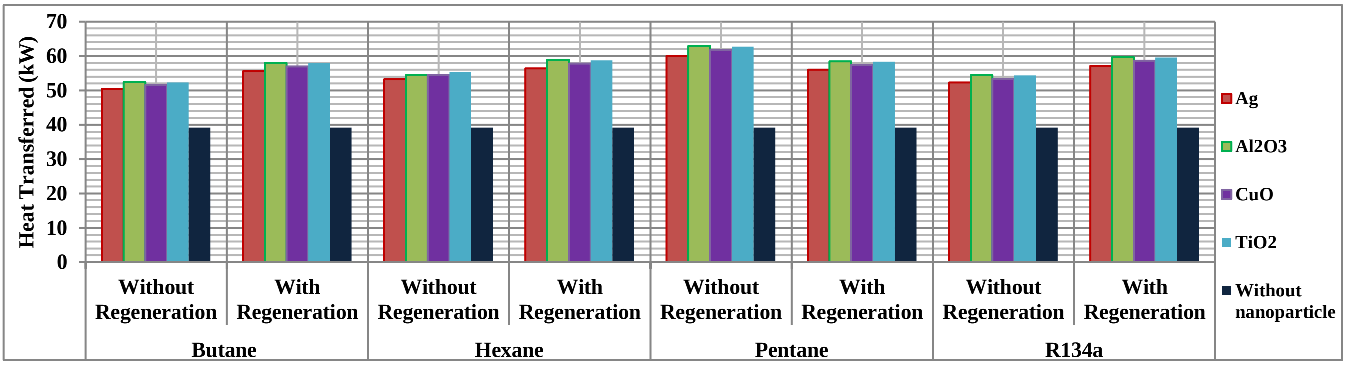

Chart 3: Comparison of maximum heat transferred in the heat exchanger for various combinations of working and nanofluids

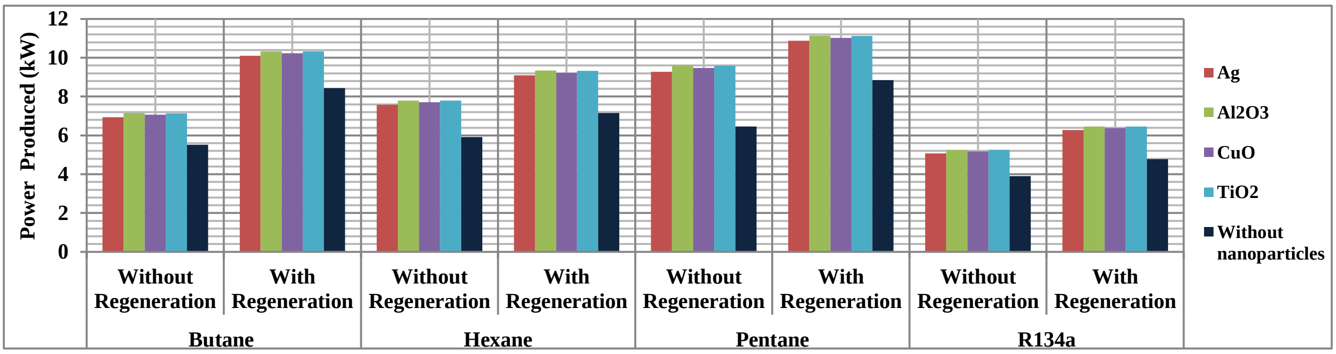

Chart 4: Comparison of power produced for various combinations of working fluids and Nano fluid

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Table 3: Optimized Rankine cycle parameters for different working fluids without nanoparticles

System Parameters	Butane		Hexane		Pentane		R134a	
	Regeneration	Without Regeneration	Regeneration	Without Regeneration	Regeneration	Without Regeneration	Regeneration	Without Regeneration
Mass Flow (kg/hr)	390	280	325	240	350	250	810	610
Pump Pressure (bar)	37	37	30	30	32	33	40	40
Turbine Discharge Pressure (bar)	6.8 / 4	4.4	2.5 / 1.2	1.1	3 / 1.3	1.3	17.8 / 11	11.7
Turbine Output(kW)	5.51	8.435	5.919	7.155	6.462	8.85	3.905	4.77
Pump Input Power (kW)	0.86	0.61	0.56	0.42	0.66	0.48	0.76	0.56
Flow Ratio	0.50	-NA-	0.30	-NA-	0.42	-NA-	0.33	-NA-

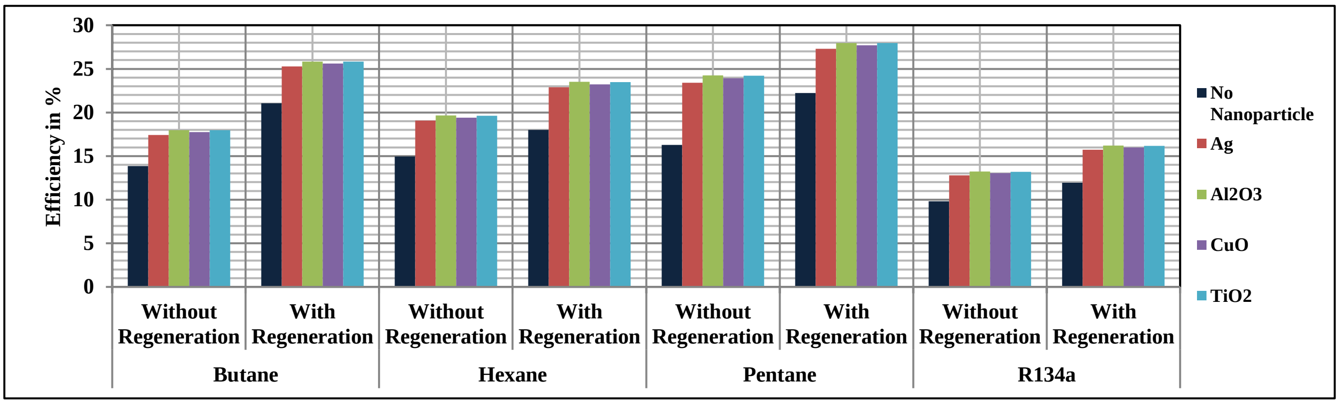

Chart 5: Comparison of efficiencies of the Solar Organic Rankine system for various combinations of working and Nano fluids

A comprehensive comparison of the efficiencies achieved through different working fluids and volume concentrations of Nano particles without the use of regeneration in the Rankine Cycle is shown in Charts 6-9.

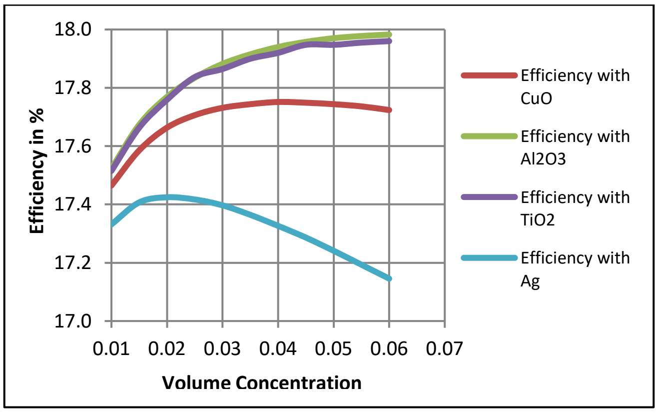

Chart 6: Comparison of efficiencies of Rankine cycle (without regeneration) with Butane and different nanoparticles in the heat capture loop

Similarly, the efficiencies achieved through different working fluids and volume concentrations of Nano particles with the use of regeneration in the Rankine Cycle is shown in Charts 10-13. The efficiency of the Rankine system was improved in two stages in this study. The first stage of efficiency improvement involved was carried out in the heat capturing loop.

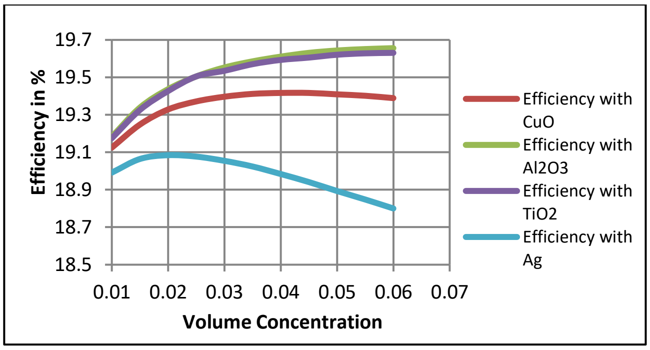

Chart 7: Comparison of efficiencies of Rankine cycle (without regeneration) with Hexane and different nanoparticles in the heat capture loop

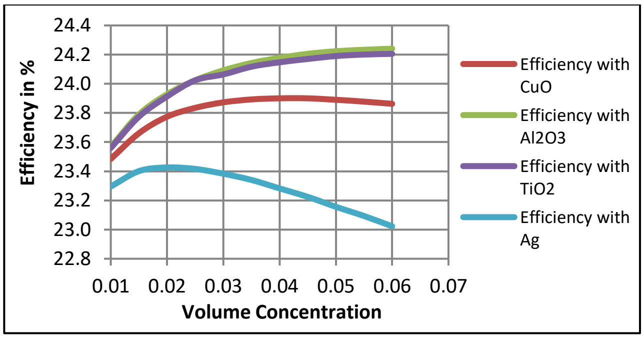

Chart 8: Comparison of efficiencies of Rankine cycle (without regeneration) with Pentane and different nanoparticles in the heat capture loop

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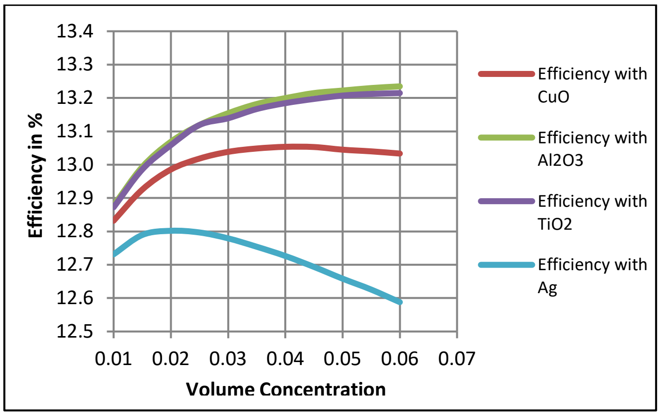

Chart 9: Comparison of efficiencies of Rankine cycle (without regeneration) with R134a and different nanoparticles in the heat capture loop

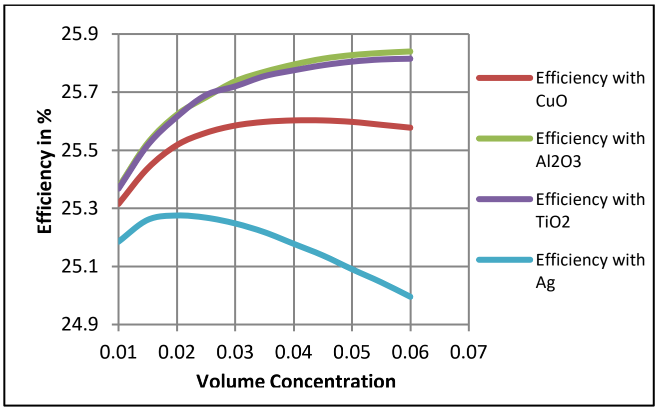

Chart 10: Comparison of efficiencies of Rankine cycle (with regeneration) with Butane and different nanoparticles in the heat capture loop

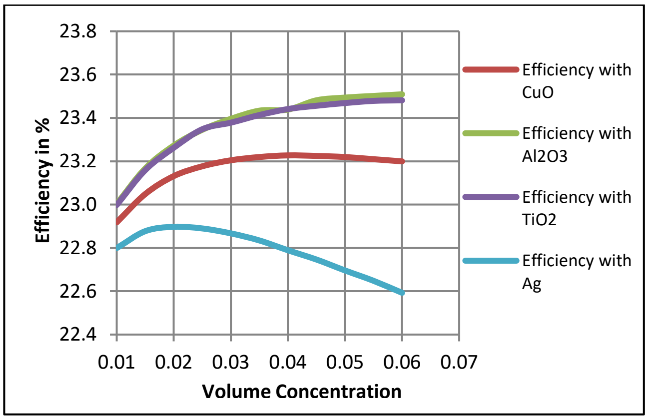

Chart 11: Comparison of efficiencies of Rankine cycle (with regeneration) with Hexane and different nanoparticles in the heat capture loop

Considering the fact that source of heat in this case i.e. the heat from the sun is almost infinite, it is desirable to tap as much heat as possible from the sun. Thus, the addition of Nanoparticles in the heat capture loop increases the amount of heat transferred to the Rankine cycle. The second stage of efficiency improvement was achieved through the use of regeneration in the Rankine cycle itself. The use of regeneration further improved the overall efficiency of the system by 4% to 10% by reducing the wastage of heat rejected during the condensation process.

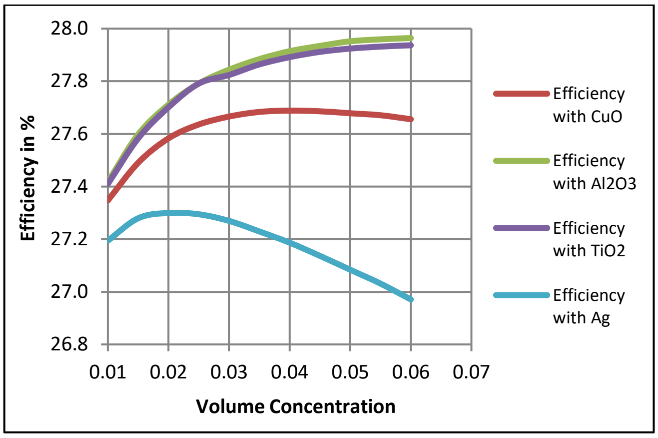

Chart 12: Comparison of efficiencies of Rankine cycle (with regeneration) with Pentane and different nanoparticles in the heat capture loop

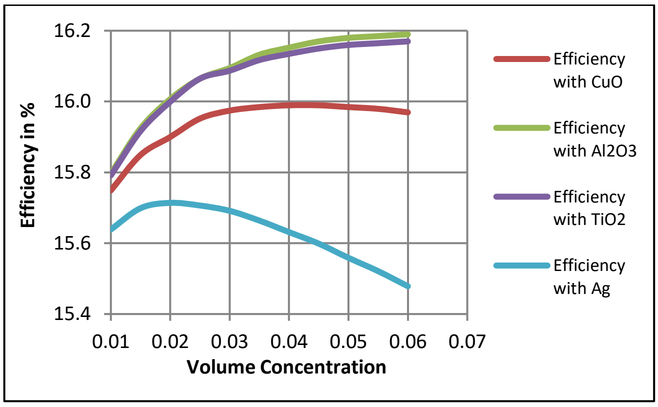

Chart 13: Comparison of efficiencies of Rankine cycle (with regeneration) with R134a and different nanoparticles in the heat capture loop

The resulting overall improvement in efficiency of the Solar Organic Rankine System is as shown in Chart 5. A maximum efficiency of 27.96% was observed on using Al2O3 nanoparticles with Dowtherm in the heat capture loop and Pentane as the working fluid in the regenerative Rankine cycle. This improvement in efficiency observed was quite significant considering the fact that the efficiency of a similar system without the use of nanoparticles or regeneration stood at about 16.3%.

IV. CONCLUSIONS

In this study several possible candidates of working fluids and Nano fluids which may be suitable for use in a Solar Organic Rankine system were evaluated. The following are the conclusions of the study in brief:

- Organic fluids such as n-butane, n-pentane, n-hexane, R-134a are ideal for use in a Solar Rankine system considering their thermodynamic, physical properties and environmental impact.
- Efficiency improvements of up to 10% were observed on using Regenerative Rankine cycle.
- Addition of nanoparticles such as Ag, Al_2O_3, CuO and TiO_2 in the heat capture loop lead to an increase in overall heat transfer coefficient which lead to an increase in heat transfer to the working fluid by up to 50%.

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• The efficiency of the basic Rankine cycle was found to be 16.3% for n-Pentane, 14.9% for n-Hexane, 13.83% for n-Butane and 9.82% for R134a.

• Highest efficiency of 27.96% was obtained for 6% volume concentration of Al2O3 in Dowtherm used in the heat capture loop with n-pentane as the working fluid employing regeneration used in the power generation loop.

The study primarily dealt with a theoretical analysis of a Rankine cycle. While the initial results obtained using Nano fluids for improved heat transfer looks promising, experimental verification of the results obtained through the simulation will improve our understanding of the Solar Organic Rankine system. Further, although the addition of nanoparticles aids in improving the heat transfer, the stability of the Nano fluid over long durations of time and exposure to high temperatures in a Solar Rankine system must be studied before it can be deemed reliable.

NOMENCLATURE

A	Cross sectional Area (m^2)
C_p	Specific heat (kJ/kg.K)
d1	inner diameter of the inner tube in heat exchanger (m)
d2	outer diameter of the inner tube in heat exchanger (m)
d3	inner diameter of the outer tube in heat exchanger (m)
d4	outer diameter of the outer tube in heat exchanger (m)
f	Friction factor
h	Heat transfer coefficient ($W/m^2.K$)
k	Thermal conductivity (W/m.K)
m	Mass flow (kg/hr)
Nu	Nusselt number
Pr	Prandtl number
Q	Heat (J)
Re	Reynolds number
T	Temperature (^oC)
U	Overall heat transfer coefficient ($W/m^2.K$)

Greek Letters

ρ	Density (kg/m^3)
μ	Dynamic Viscosity ($N.s/m^2$)
ϕ	Volume concentration of Nano particle

Subscripts

f	Base fluid
nf	Nano fluid
p	Nano particle

REFERENCES

1. Ministry of New and Renewable Energy, Government of India Annual Report, 2020-21, pp.15-44. [CrossRef]
2. Quoilin, S., Broek, M.V.D., Declaye, S., Dewallef, P., Lemort, V., “Techno-economic survey of Organic Rankine Cycle (ORC) systems, Journal of Renewable and Sustainable Energy Reviews, Vol.22, 2013, pp.168-186.
3. Jamal, N., “Comparative studies and analyses of working fluids for Organic Rankine Cycles – ORC”, KTH School of Industrial Engineering and Management, 2012.
4. Sylvain, Q., “Techno-economic survey of Organic Rankine Cycle (ORC) systems” Renewable and Sustainable Energy Reviews, Vol. 22, 2013, pp.168-186. [CrossRef]
5. Andrew, C.M., "Design & Optimization of Organic Rankine Cycle Solar-Thermal Power plants", Master Thesis, University of Wisconsin – Madison, 2006.
6. Cheng, E.C., Sanjayan V., Amer, N.D., “Solar Thermal Organic Rankine Cycle As A Renewable Energy Option”, Jurnal Mekanikal, Vol. 20, 2005, pp.68-77.
7. Freeman, J., Hellgardt, K., Markides, C.N., “An assessment of solar-powered organic Rankine cycle systems for combined heating and power in UK domestic applications”, Journal of Applied Energy, Vol.138, 2015, pp.605-620. [CrossRef]
8. Kyoung, H.K., “Effects of Superheating on Thermodynamic Performance of Organic Rankine Cycles”, World Academy of Science, Engineering and Technology, Vol. 2, 2011, pp.32-38.
9. Eastman, J.A., Choi, S.U.S., Li,S., Yu,W., Thompson,L.J., “Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles,” Applied Physics Letters, Vol. 78, (6), 2011, pp. 718–720. [CrossRef]
10. Xuan, Y., Qiang, L., “Heat transfer enhancement of nanofluids”, International Journal of Heat and Fluid Flow, Elsevier, Vol. 21, 2000, pp.58-64. [CrossRef]
11. Wen, D., Lin, G., Vafaei, S., Zhang, K., “Review of nanofluids for heat transfer applications”, Particuology, Elsevier, Vol. 7, 2009, pp-141-150. [CrossRef]
12. Keblinski, P., "Mechanisms of heat flow in suspensions of nano-sized particles (nanofluids)", International Journal of Heat and Mass Transfer, Vol. 45, 2002, pp. 855-863. [CrossRef]
13. Eastman, J.A., "Anomalously increased effective thermal conductivities of water based nano fluids containing copper nano-particles", Applied Physics Letters, Vol. 14, 2001, pp.121-125.
14. Singh, A.K., "Thermal conductivity of nano fluids", Defence Science Journal, Vol. 23, 2008, pp.345-369.
15. Sarit, K.D., "Temperature dependence of thermal conductivity enhancement for nano fluids", Journal of Heat Transfer, Vol. 15, 2003, pp.56-67.
16. Albadr, J., Satinder, T., Alasadi, M., “Heat transfer through heat exchanger using Al2O3 nanofluid at different concentrations”, Case Studies in Thermal Engineering, Vol. 1, 2013, pp. 38-44. [CrossRef]
17. Otanicar, T., “Nanofluid-Based Direct Absorption Solar Collector”, Journal Of Renewable and Sustainable Energy, Vol. 2, 2010, pp.109-118. [CrossRef]
18. Saadatfar, B., Fakhrai, R., Fransson, T., “Conceptual modeling of nanofluid ORC for solar thermal polygeneration”, Energy Procedia, Elsevier, Vol.57, 2013, pp.2696-2705. [CrossRef]
19. Xuan, Y., Roetzel, W., "Conceptions for heat transfer correlation of nanofluids", International Journal of Heat and Mass Transfer, Vol.43, 2000, pp. 3701–3707. [CrossRef]
20. Yu, W., Choi, S.U.S, "The role of interfacial layering in the enhancement of thermal conductivity of nanofluid: A renovated Maxwell model", Journal of Nanoparticles Researches, Vol.5, 2003, pp. 167-17. [CrossRef]
21. Duangthongsuk, W., Wongwises, S., "Heat transfer enhancement and pressure drop characteristics of TiO2–water nanofluid in a double-tube counter flow heat exchanger", International Journal of Heat and Mass Transfer, Vol.52, 2009, pp. 2059-2065. [CrossRef]
22. Bönnemann, H., “Mono disperse copper and silver nano colloids suitable for heat-conductive fluids,” Applied Organometallic Chemistry, Vol. 19, (6), 2005, pp. 768–773. [CrossRef]
23. Abdel, E., Tora, H., “Nanofluids as a cooling agent for Rankine power cycle”, 2nd International Conference on Energy systems and Technologies, Egypt, 18-21 Feb.2013.
24. Pak, B.C., Cho, Y.I., "Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles" Experimental Heat Transfer, Vol.11, 1998, pp. 151–170. [CrossRef]
25. Drew, D.A., Passman, S.L., "Theory of multi component fluids", Springer, Vol.3, 1999, pp. 156-162. [CrossRef]

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