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Original Article

Thermodynamic analysis of solar powered trigeneration arrangement for cooling, power and drinking water generation

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Abstract

Solar-driven trigeneration system is a most sustainable energy production technique. It produces valuable energy in the forms of heating, cooling, and power generation. Therefore, it meets the energy demands of a residential complex or of small-scale industries. This paper presents a solar-driven trigeneration system for power, cooling, and freshwater generation through a unit of humidification dehumidification desalination under various thermodynamic criteria. The trigeneration system consists of a parabolic trough collector, a storage tank, an organic Rankine cycle for power generation, a vapor absorption refrigeration system for producing a cooling effect, and a humidification and dehumidification desalination unit for producing fresh water. The average work output for the R-123 fluid was 2866.6 kJ, whereas for R-134a it was 2883.275 kJ. The present study had an average production of freshwater of about 157 kg per day from the proposed trigeneration system.

Keywords: solar energy, parabolic trough collector, trigeneration, desalination, organic rankine cycle

1. Introduction

One of the key problems of energy producers is establishing a more energy-efficient system with nearly zero greenhouse gas emissions. In today's energy systems, efficiency and sustainability are critical ideas. Cogeneration and trigeneration systems maximize energy utilization while lowering emissions in the energy systems. The combined cooling heating and power (CCHP) is a potentially efficient technique. It's a sort of plant operation in which power, heating, and cooling are all generated from a single source of energy. The waste heat from the plant is utilized to provide heating and cooling energy in a trigeneration facility.

To meet the sustainability goals of maximum resource use and low emissions, various renewable energy sources can be successfully integrated with trigeneration systems. Trigeneration facilities can be powered by a variety of energy sources. Solar energy is regarded a most promising source of energy. It is a free renewable energy source that emits no greenhouse gases. The number of power plants that run entirely or partially on solar energy has risen dramatically in the recent years.

Many research studies discuss trigeneration systems driven by solar concentration systems and various renewable energy sources. A hybrid trigeneration system based on renewable energy sources was proposed by Usón *et al.*, (2019). The system generates energy, sanitary hot water, and desalted fresh water for a single-family home by combining photovoltaic/thermal collectors, an evacuated tube collector, and a wind turbine. The authors reported the exergy efficiency of the trigeneration system of 7.76%, which includes 6.68 due to electricity, 0.33 due to freshwater, and 0.75 due to sanitary hot water. Praveen Kumar, Saravanan, and Coronasa (2018) studied a low-temperature-driven polygeneration system based on renewable energy resources for single-stage absorption combined power cooling and purified water generation. They performed a comparative study of the system for estimating outputs at different cooling water conditions and evaluated the effect of expander efficiency on the system outputs and performance.

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Wang, and Yang (2017) studied a solar and conventional energy based hybrid thermal-powered plant to produce hot water, cooling, and electrical power for hotel applications. Tora, and El-Halwagi (2011) and Al-Sulaiman, Hamdullahpur, and Dincer (2012) studied the integration of solar energy with the trigeneration plant; the study concluded that there are energetic benefits to the hybrid arrangement. Zhang, Li, Liu, Zeng, and Zhang (2016) studied a hybrid solar-biomass trigeneration system for generating electricity, hot, and chilled water. India is the fourth-largest power-consuming country globally, and it is about to see a growth of 6%. Trigeneration technology is emerging as one of the most reliable energy supply options in developing countries like India. India's manufacturing sectors are banking on this trigeneration technology to reduce their energy expenditure (Shukla *et al.*, 2020).

The most significant advantage of a trigeneration system based on solar energy is that it optimally manages heat production from solar concentration techniques. The solar concentration in the trigeneration arrangement is supported by a linear Fresnel reflector and a parabolic trough collector, which help us achieve high temperatures around 400°C, enough to drive the trigeneration system. Thus, multigeneration units have considerable environmental and economic benefits compared to conventional sources of energy (Khan, Shukla, Sharma, Phanden, & Mishra, 2021).

The organic Rankine cycle (ORC) operates on the same thermodynamic principle as the Rankine cycle, and the only difference is that an organic fluid is used instead of water or steam. Because the ORC can function with low, medium, and high temperature heat sources, it is a popular choice among waste heat recovery technologies. It also has a high level of flexibility and compatibility with waste heat. Gupta, Tiwari, and Said (2022) reviewed the solar organic Rankine cycle and its poly-generation applications to provide various useful energy outputs, including electricity, heating, cooling, drying, desalination, and hydrogen. The organic Rankine cycle is used in solar parabolic trough technology instead of the usual steam Rankine cycle since it is capable of power generation at lower capacities and at a lower collector temperature (Hussain, Sharma, & Shukla, 2021). A parabolic trough collector is used as the solar concentration technique. Parabolic trough solar collectors are used in more than 90% of solar concentration methods. Radiation from the Sun is concentrated and then converted into thermal energy of the heat transfer fluid. Heat transfer fluid in the parabolic trough collector is used to transport thermal energy for power generation (Khandelwal, Sharma, Singh, & Kumar Shukla, 2021). Various factors such as temperature, density, and specific heat capacity have been considered in selecting the heat transfer fluid. The HTF fluid should have a maximum bearable temperature, after which it decomposes due to the high heat generated. It must also be environment friendly and have low explosivity.

The humidification – dehumidification technology is a highly efficient and decentralized water generating approach based on the natural rain cycle. The significant advantages of this technology are that it produces water by operating on a common heat source or industrial waste heat. The essential components of this water generation technique are humidifier, dehumidifier, and heat source. In the humidifier, the air is brought in contact with saltwater and gets humidified. In the dehumidifier, the water vapor is made to condense, and thus fresh water is generated (Kumar, Shukla, Sharma, & Nandan, 2021). He *et al.*, (2019) performed a thermo-economic study of industrial waste heat powered trigeneration system, to fulfill the demand both for power and freshwater by employing ORC and humidification dehumidification desalination unit. The authors reported 13.1 kW as the net output power using isobutane as the working fluid in ORC, and 208 $kg \cdot h^{-1}$ water production rate through humidification dehumidification.

A comprehensive literature survey shows an opportunity to enhance the solar-assisted system efficiency by utilizing the low temperature exhaust heat for getting useful energy outputs in terms of cooling and fresh drinking water. Therefore, the present paper aims to perform thermodynamic modeling and simulation of the solar-assisted tri-generation system for power production through ORC running on two different fluids, getting cooling effect from VARS along with the freshwater generation through HDH. The proposed system uses a vapor absorption refrigeration technique for producing the cooling effect. Vapor absorption refrigeration systems work on low-grade energy sources like solar or industrial waste heat. Ammonia water is used as a refrigerant in the system. The present paper evaluates a solar-driven Trigeneration system with two working fluids R-134a and R-123, at different working temperatures. Turbine work of both fluids has been calculated, and a comparison is presented. The coefficient of performance of the vapor absorption system is analyzed over a range of evaporator temperatures. The productivity of freshwater is calculated for a range of humidifier temperatures.

2. System Description

Figure 1 depicts the solar-powered trigeneration system for combined power, cooling, and water generation. In this system, the primary energy source is solar energy which is concentrated by a parabolic trough collector and transferred by heat transfer fluid Therminol VP-1. Therminol VP-1 is a synthetic ultra-high temperature heat transfer fluid that was developed to meet the demanding requirements of vapor phase and liquid phase systems. It has thermal stability and low viscosity for efficient, dependable, and consistent performance over a wide temperature range from 12° to 400°C (54° to 750°F). The heat storage tank is used to maintain a reserve supply of energy. The organic Rankine cycle extracts the stored energy using a medium temperature vapor turbine as a prime mover, the main power generating unit. The waste heat from the turbine is utilized in the humidification dehumidification desalination unit for producing fresh water. The HTF fluid leaving from the heat recovery vapor generator supplies thermal energy to the vapor absorption refrigeration cycle using ammonia water pair as a working fluid for the cooling effect (Kshitiz Sajwan, Sharma, & Shukla, 2021). The advantage of the organic Rankine cycle is that it operates on a low grade heat supply; similarly, the VARS cycle has been used to produce a cooling effect with the help of low quality heat energy.

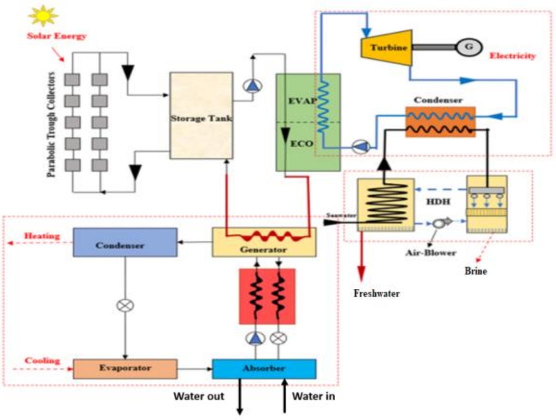


Figure 1. Schematic of solar-powered trigeneration arrangement for cooling, power, and drinking water generation

3. Technical Feasibility and Weather Data

The performance of the solar trigeneration system is influenced by the location of the trigeneration unit and weather conditions. The proposed trigeneration system was designed considering the weather data for Delhi NCR, as this region has got enough solar energy for the functioning of the solar trigeneration system.

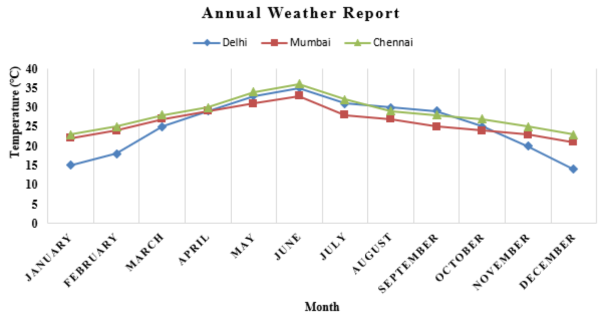


Figure 2. The average monthly temperatures of the three main cities of India

Delhi lies 226 m above sea level. The climate in Delhi is referred to as a local steppe climate. The temperature here averages 25.1°C, and the annual rainfall is 740 mm.

4. Working Fluids

The present system involves three working fluids: the heat transfer fluid; and the other two are organic fluids for the organic Rankine cycle. Heat transfer fluid is used for transferring the heat energy to the power generation unit. The HTF should have a sufficiently high evaporation temperature and a low freezing point so that no freezing protection is required if the temperature of the solar field falls. HTF should also have a maximum bearable temperature before it decomposes due to the high heat generated. HTF should also be environmentally friendly and of low explosivity. Table 1 (a) shows the properties of Therminol VP-1, which is used as HTF in the present study.

Table 1. Properties of (a) Therminol VP-1, (b) and of the ORC Fluids (Mwesigye & Meyer, 2018); (Liu *et al.*, 2019) (Tora & El-Halwagi, 2011) (Wang & Yang, 2017)

(a)

Parameter	Value
Appearance	Clear, water-white liquid
Composition	Biphenyl/Diphenyl oxide
Maximum temperature	400 °C
Normal boiling point	257 °C
Crystallizing point	12 °C
Average molecular weight	166

(b)

Parameters	R-123	R-134a
Environmental classification	HCFC	HFC
Chemical name	Dichlorotrifluoroethane	Tetrafluoroethane
Molecular weight	152.9	102.03
Boiling point	27.8	-26.06
Critical temperature	183.7	101.8
Critical point density (kg/m^3)	550	511
Constant pressure specific heat of liquid @ 25 °C (kJ/kgK)	1.0196	1.425
Constant pressure specific heat of vapour @ 25 °C (kJ/kgK)	0.6953	0.851
Global warming potential	77	1430
Ozone depletion potential	0.02	0

Two organic fluids, R-123 and R-134a, were used for the ORC. The selection of organic fluids is very crucial for the efficient function of ORC. Various factors such as heat source temperature, thermodynamic properties of liquid such as enthalpy, boiling point, molecular mass, viscosity, chemical reactivity, ozone depletion potential, global warming potential, etc., are considered during the fluid selection for the organic Rankine cycle. The properties of ORC fluids chosen in the present work are shown in Table 1 (b).

5. Methodology and Thermodynamic Modelling

The methodology of the present analysis is to develop a mathematical model of the proposed solar-powered trigeneration arrangement for cooling, power, and drinking water generation, based on steady state mass and energy balances of each component system, and to generate the computer code in C++ programming language for a parametric investigation. The input parameters for the parametric analysis are shown in Table 2. The important equations for this modeling are described below.

Table 2. Input parameters (Hussain, Sharma, & Shukla, 2021); (Shukla, Sharma, Sharma, & Nandan, 2019); (Cihan & Kavasogullari, 2017); (Kalogirou, 2014)

Parameter	Value
Solar field area	100 m^2
Maximum operating temperature	400 °C
Storage volume tank	4m^3
Tank thermal loss coefficient	0.5 Wm^{-2}K^{-1}
Working fluid	Therminol VP-1
Ambient temperature	25°C
Turbine inlet temperature	300°C, 310°C, 320°C
Humidifier temperature	50°C, 60°C, 70°C

5.1 Parabolic solar trough collector

The modeling of parabolic solar collectors was based on the equation derived by (Kalogirou, 2014). The thermal efficiency of this system is given by

$$\eta_c = \frac{Q_u}{A_a G_B} \quad (1)$$

The required power supplied by the concentrator is formulated as:

$$Q_u = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in}) \quad (2)$$

The required power is also formulated as:

$$Q_u = F_R [G_B \eta_0 A_a - A_r U_L (T_{in} - T_{amb})] \quad (3)$$

F_R is given by:

$$F_R = \frac{\dot{m}_{nf} Cp_{nf}}{A_r U_L} [1 - \exp\left(-\frac{U_L \acute{F} A_r}{\dot{m}_{nf} Cp_{nf}}\right)] \quad (4)$$

The area of a receiver is:

$$A_r = \pi D_{r,o} L \quad (5)$$

The efficiency aspect of the collector is:

$$\acute{F} = \frac{\frac{1}{U_L}}{\frac{1}{U_L} + \frac{D_{r,0}}{h_{fi} D_{r,i}} + (\frac{D_{r,0}}{2k_r} ln \frac{D_{r,0}}{D_{r,i}})} = \frac{U_0}{U_L} \quad (6)$$

The total heat loss factor in the collector is:

$$U_L = \left[\frac{A_r}{A_g (h_w + h_{r,c-a})} + \frac{1}{h_{r,r-c}}\right]^{-1} \quad (7)$$

For several PTSCs, say N of them, the overall accessible solar-powered irradiation is:

$$Q_{sol} = A_a G_B N \quad (8)$$

The overall efficiency of the collector is:

$$\eta_{oc} = \frac{F_R}{N}\left[\eta_0 - U_L \left(\frac{T_i - T_{amb}}{G_B \frac{A_a}{A_r}}\right)\right] \quad (9)$$

5.2 Organic rankine cycle

Based on the heat and mass balances, the efficiency of the ORC is as follows:

$$\eta_{oc} = \frac{F_R}{N}\left[\eta_0 - U_L \left(\frac{T_i - T_{amb}}{G_B \frac{A_a}{A_r}}\right)\right] \quad (10)$$

Turbine work and pump work are:

$$W_T = \dot{m}_{cycle} (h_4 - h_5) \quad (11)$$

$$W_P = \dot{m}_{cycle} (h_1 - h_2) \quad (12)$$

Heat entering the ORC evaporator is:

$$Q_{in} = \dot{m}_{cycle} (h_4 - h_2) \quad (13)$$

The heat coming out from the ORC system is:

$$Q_{out} = \dot{m}_{cycle} (h_5 - h_1) \quad (14)$$

5.3 Humidification dehumidification system

The feed of seawater is heated in the ORC condenser, and then it is sprinkled into the humidifier where it comes into contact of air. The temperature and humidity ratio of air are increased, while the seawater is concentrated. The heat and mass balance of the HDH system is given below:

$$\dot{m}_f = \dot{m}_d + \dot{m}_b \quad (15)$$

$$\sum \dot{m}_{in} h_{in} = \sum \dot{m}_{out} h_{out} \quad (16)$$

$$Q_{HDHcooling} = \dot{m}_{HDHcooling} \Delta h_{HDH\ cooling} \quad (17)$$

$$RR = \frac{\dot{m}_d}{\dot{m}_f} \quad (18)$$

The Gain Output Ratio is:

$$GOR = \frac{\dot{m}_d h_{fg}}{Q_{in}} \quad (19)$$

5.4 Vapor absorption refrigeration system

In the present study ammonia water-based vapor absorption system is used to produce the cooling effect. The COP of the VARS system is calculated as follows.

$$COP_{cooling} = \frac{Q_{eva}}{Q_{gen}} \quad (20)$$

$$\eta_{ex,cooling} = \frac{\dot{Q}_{eva}(1 - \frac{T_{amb}}{T_{eva}})}{\dot{Q}_g(1 - \frac{T_{amb}}{T_{gen}})} \tag{21}$$

$$\eta_{ex,heating} = \frac{\dot{Q}_{cond}\left(1 - \frac{T_{amb}}{T_{cond}}\right) + \dot{Q}_{abs}(1 - \frac{T_{amb}}{T_{abs}})}{\dot{Q}_g(1 - \frac{T_{amb}}{T_{gen}})} \tag{22}$$

6. Results and Discussion

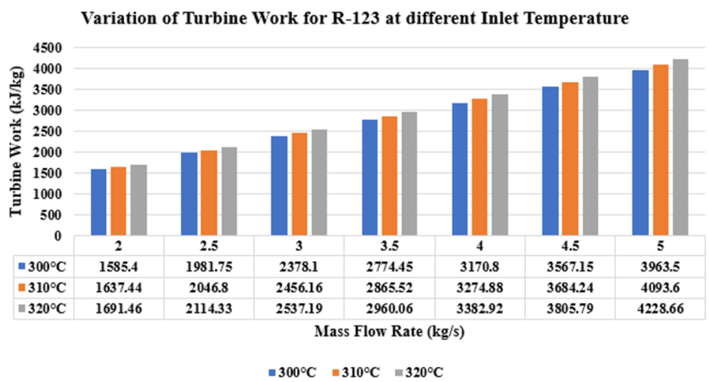
Based on the thermodynamic modeling of the proposed trigeneration system, computer code in C++ was developed for a parametric investigation. The performance of the proposed solar-driven trigeneration system was investigated for varied parameters from indicators, such as work output of the turbine, the productivity of the freshwater, gain output ratio of the HDH, and the COP of the VARS system. The parameters of the trigeneration system were investigated for two working fluids, R-123 and R-134a. The working temperature was varied for all the components, and the performances were evaluated.

In Figure 3 (a), the results for R-123 fluid at different inlet turbine temperatures are shown. The mass flow rate of heat transfer fluid was varied from 2 kg/s to 5 kg/s. The turbine outlet temperature has been fixed at 50°C. As the turbine inlet temperature increased, the turbine's work increased. This increment occurs because of the working fluid enthalpy increment at the inlet of the ORC. At a fixed inlet temperature of an ORC Turbine, on increasing the mass flow rate the energy content of the working fluid increases, which yields more specific work out of the plant. The maximum work obtained was 4,228.66 kJ/kg at 320°C and 5 kg/s mass flow rate. The average work obtained for R-123 at the fixed outlet temperature of 50°C was 2,866.62 kJ/kg.

In Figure 3 (b), the turbine outlet temperature has been varied, and the inlet temperature of the turbine was fixed to 300°C. The mass flowrate of heat transfer fluid has been varied from 2 kg/s to 5 kg/s. There is a decrease in turbine work as the turbine outlet temperature increases. The reason behind this is a reduction in the enthalpy difference between the inlet and outlet states of the ORC's turbine. On increasing the mass flow rate of an ORC turbine at a given input temperature, the working fluid's energy content rises, leading to more work from the cycle. The maximum work obtained at 50 °C was 3,963.5 kJ/kg. The average turbine work received when the inlet temperature was fixed at 300°C was 2,689.79 kJ/kg.

In figure (4 a), an analysis of R-134a at different turbine inlet temperatures has been done. The outlet temperature was fixed at 50°C. The mass flow rate was the same for both of the working fluids. The turbine work increased with an increase in the turbine inlet temperature. This increment occurs because of the enthalpy increase at the inlet of the ORC. The maximum work output of 4,173.81 kJ/kg was obtained at 320°C. On increasing the mass flowrate of the working fluid at an ORC turbine with a given input temperature, the energy content of the fluid rises, resulting in more output of work from the plant. The average work by R-134a at a fixed outlet temperature of 50°C was 2,884.38 kJ/kg.

(a)



(b)

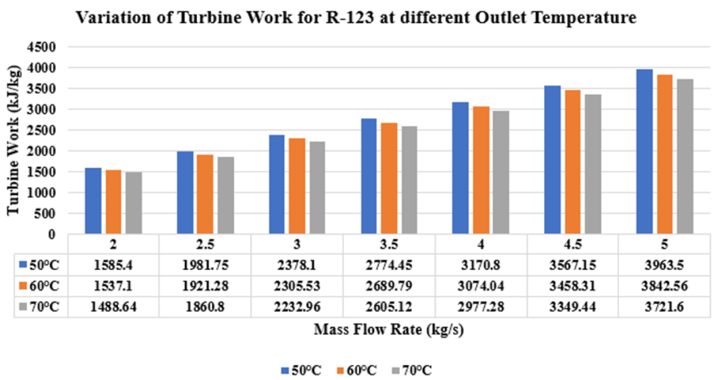


Figure 3. Variation of turbine work for R123 at different (a) inlet temperatures, and (b) outlet temperatures

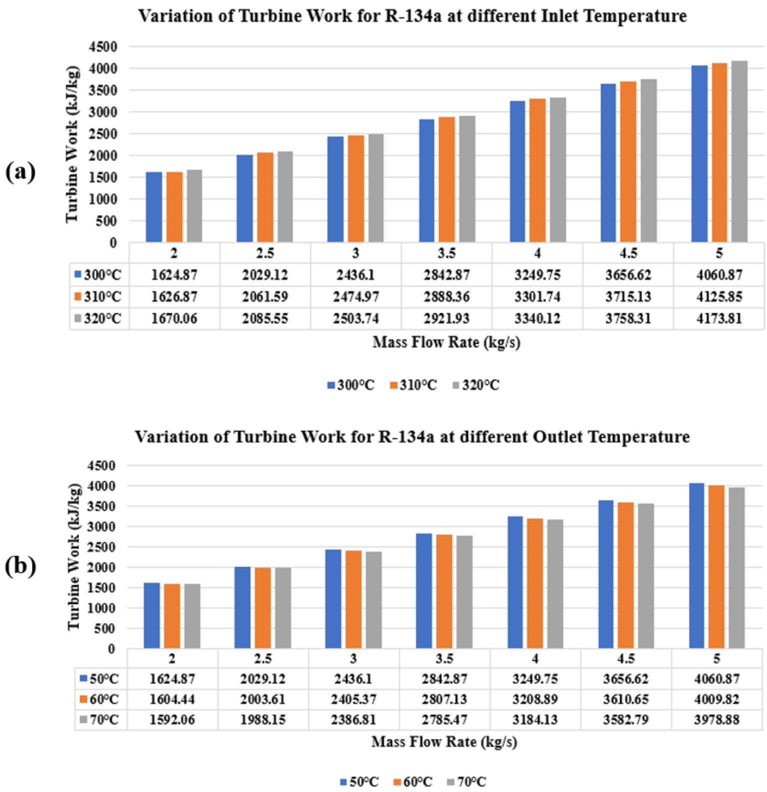


Figure 4. Variation of turbine work for R134a at different (a) inlet temperatures, and (b) outlet temperatures

In Figure (4 b), the inlet turbine temperature has been fixed at 300 °C. The outlet turbine temperature varies, and the mass flow rate is the same as in previous conditions. The work output decreased due to a decrease in the enthalpy difference between the inlet and outlet states of the ORC's turbine. The maximum work obtained was 4,060.87 kJ/kg. The average work obtained with a fixed inlet temperature of 300 °C was 2,811.82 kJ/kg. Both of the working fluids have been analyzed at the same range of temperatures. Input temperature was varied from 300 °C to 320 °C while the outlet temperature varied from 60 °C to 70 °C. Higher work output was obtained with R-134a fluid than with R-123 for temperatures ranging from 300 °C to 320 °C. With the increase in output temperature, there was a decrease in the work output for both fluids. This decline was steeper with R-123 than with R-134a.

The average work output for the R-123 fluid was 2,866.62 kJ/k, whereas for R-134a it was 2,884.38 kJ/kg. So, per the work output calculations of the organic Rankine cycle, R-134a was the better and more suitable working fluid for our proposed trigeneration system.

In Figure 5, the productivity of fresh water at varied mass ratios and at different humidifier temperatures is shown. The productivity of freshwater is proportional to the inlet temperature of the humidifier. As the humidifier inlet temperature increases, the amount of moisture available for condensation also increases, which improves the productivity of freshwater generation. Based on the numerical simulation of the HDH system, the productivity of freshwater increased with increased humidifier temperature. A maximum of 238

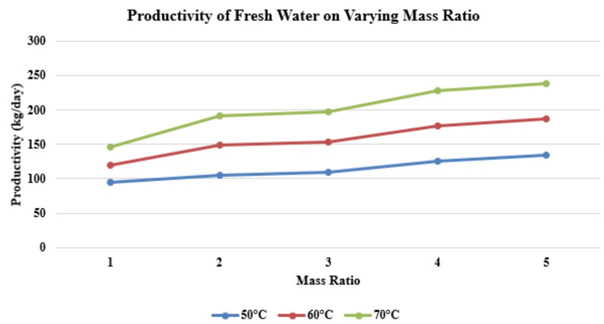


Figure 5. Production of fresh water on varying the mass ratio

kg of fresh water per day was obtained from the proposed trigeneration system. The average productivity was 157 kg per day.

In Figure 6, the variation of the gain output ratio over a range of temperatures is shown. The gain output ratio is directly proportional to the inlet temperature of the humidifier. As the humidifier inlet temperature increases, the amount of moisture available for the condensation also increases, which improves freshwater production and yields a higher gain output ratio. The maximum value of the gain output ratio was 0.7 at 70°C.

In Figure (7 a), the variation of COP with generator temperature is analyzed. As the generator temperature increases, there is a marginal increase in the COP. After a certain temperature, the coefficient of performance increases

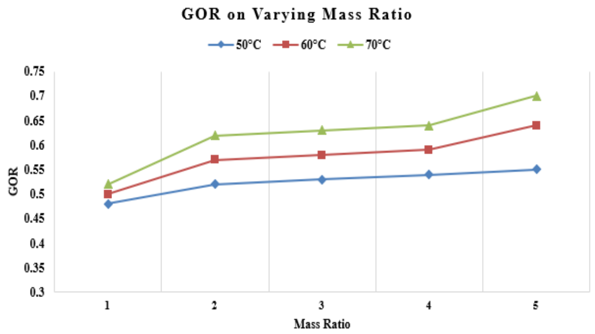


Figure 6. Variation of GOR with mass ratio

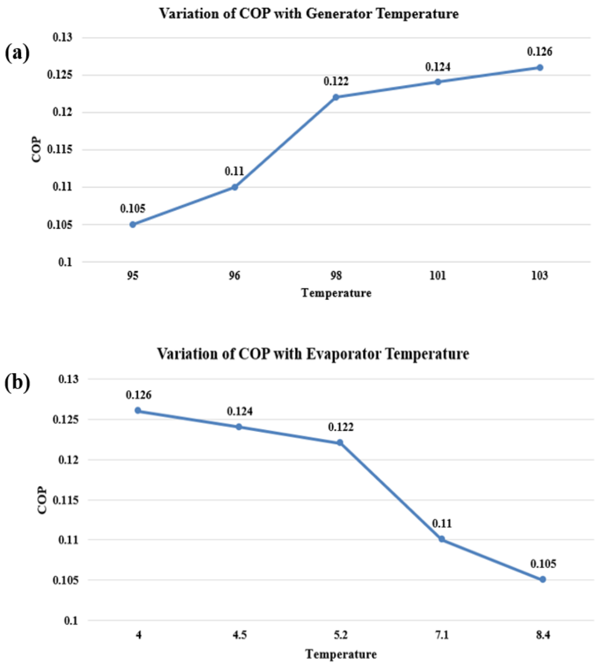


Figure 7. Variation of COP with (a) generator temperature, and (b) evaporator temperature

because the high temperature difference will lead to an increase in generator load.

Figure (7 b) demonstrates the variation of COP with evaporator temperature. As the evaporator temperature decreases, the system's performance decreases because the evaporator load has a negative impact on the system performance. It is seen in Figure 8 that as the effectiveness of the heat exchanger rises, the COP of the system increases; this is because the heat exchanger helps in increasing the working of the refrigeration system and exchanges heat from hot to cold fluid, which leads to an increased temperature of the cold fluid before entering the generator. Hence, the heat input requirement is very low in the generator, so the COP of the system increases. The coefficient of performance increases with an increase in the effectiveness of the heat exchanger. The heat exchanger is used to exchange the heat from hot fluid to cold fluid, which increases the temperature of cold fluid before entering the generator, so less heat is required in the generator. Hence, the COP increases.

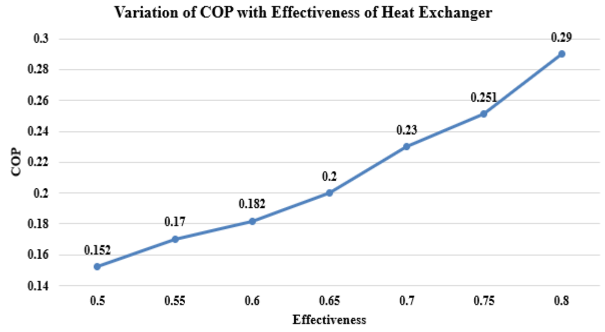


Figure 8. Variation of COP with the effectiveness of heat exchanger

8. Validation

The current ORC results and trends are consistent with what Hussain Sharma and Shukla (2021) described. The findings of freshwater productivity through the HDH system are consistent with the findings provided by Kumar *et al.* (2021). The current outcomes for the combination of solar-powered ORC, HDH, and vapor absorption hybrid systems are comparable to those described in the literature. The present study extends the understanding of the integration of ORC, HDH, and vapor absorption hybrid systems to simultaneous power, cooling, and purified water generation.

9. Conclusions

The present solar-powered trigeneration system provides electricity, freshwater, and cooling effect simultaneously. Based on a thermodynamic analysis of the trigeneration system, the following conclusions have been drawn:

- The performance of the solar-powered trigeneration system is sensitive to the temperature of the working fluid. The inlet and outlet temperatures affect the overall work output of the system.
- The average work output for the R-123 fluid was 2,866.6 kJ, whereas for R-134a it was 2,883.275 kJ. So per the work output calculations of the organic Rankine cycle, R-134a is the better choice for working fluid than R-123.
- The average productivity of freshwater was 157 kg per day from the proposed system.
- Variation of COP of VARS system with generator and evaporator temperatures and heat exchanger effectiveness were also analyzed. The average COP was 0.1174 with varying generator temperature, while for the heat exchanger the average COP was 0.210.

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