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A Numerical Investigation of the Feasibility of a Concentrating Photovoltaic Thermal System based on Point-Focus Fresnel Lens

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Abstract **-** Concentrated Photovoltaic Thermal (CPVT) systems are a hybrid of concentrated photovoltaic (CPV) and photovoltaic thermal (PVT) systems that use optics such as lenses to concentrate a significant amount of sunlight onto photovoltaic surfaces to produce electrical and thermal energy simultaneously. The CPVT model equipped with MJPV (InGaP/InGaAs/Ge) solar cells, point-focus Fresnel lenses, heat sinks, and a cooling pipe has been numerically investigated. A numerical model was developed to investigate and evaluate the thermal and electrical performance of the proposed model under various input and output parameters. The inputs consisted of HTF flow rates, HTF inlet temperature, incident radiation, concentration ratio, and the optical efficiency of the Fresnel lens. In contrast, the outputs consisted of the HTF outlet temperature, MJPV cell temperature, and thermal and electrical efficiency. The results show that the highest thermal and electrical efficiencies occurred at a mass flow rate of 0.025 kg/s, and their values were 85.31% and 35.74%, respectively. The results also demonstrate that concentration ratio affects the electrical characteristics. Finally, the results indicated that CPVT is a promising renewable energy system and has an excellent possibility of being competitive with conventional power generation systems.

Keywords**:** hybrid concentrating photovoltaic/thermal CPVT; multi junction photovoltaic; point focus Fresnel lens

1. Introduction

Russia's invasion of Ukraine directly impacted the world's energy systems, making energy security the most pressing priority for many countries. The crucial question here is how this crisis will affect the environment. Will this mean a rush to exploit domestic fossil fuels and new suppliers of gas and oil, or a renewed race towards renewable energy? [1]. There are two possible answers to this question. The first is associated with massive amounts of emissions that lead to an increase in greenhouse gases causing an overall increase in the earth's atmospheric temperature. The second scenario considers renewable energy as a sustainable and emission-free source of energy. Although there are various renewable energy resources such as wind, solar, geothermal, hydropower, biomass, and so on, solar energy is the most plentiful source. The amount of solar energy that reaches the earth's surface in four hours is estimated to be greater than the amount of solar energy consumed by the entire world's population in one year [2]. Energy from solar radiation can be directly collected in two forms: solar electricity and solar thermal. In photovoltaic technology, solar radiation is converted into direct electrical energy, while in solar thermal technology, dissipative heat from solar radiation is utilized as thermal energy in useful applications.

The integration of these two techniques enables the exploitation of the most significant amount of solar radiation. This combination has led to a hybrid system called the Photovoltaic/Thermal System (PV/T). The PV cell integrates with the thermal collector, heat exchanger, or flow channel underneath the PV cells to simultaneously produce electrical and thermal energy. Large areas of conventional PV arrays are required to harness and produce usable energy. Concentrated solar radiation on PV cells is an effective method for reducing the area of PV receivers while harnessing the same amount of solar radiation; this technology is known as CPV. The main idea of the CPV is to replace the PV cell material with inexpensive concentrator optics that concentrate sunlight onto PV cells, enabling them to harness the same amount of solar radiation but with fewer PV receivers. The main problem with CPV is that it causes elevated PV surface temperature due to concentrated solar radiation requiring active cooling. On the other hand, the main problem with a hybrid PV/T system is the limited thermal energy produced. We can tackle these issues by presenting the concept of Concentrating Photovoltaic Thermal

System (CPVT). The excess heat generated in PV cells is harvested and converted into thermal energy in the CPVT system. Therefore, the PV cells maintain a moderate temperature.

The hybrid CPVT system is comprised of multijunction PV solar cells (MJPV) with significantly high efficiency [3], [4]. The MJPV absorbs a large part of the solar spectrum and is also known as a tandem, consisting of multiple material layers stacked on top of one another using gallium indium phosphide (GaInP), gallium arsenide (GaAs), and germanium (Ge). Each semiconductor utilizes a different wavelength range of the solar spectrum to generate electricity [5]. Over the last 30 years, MJPV has progressed tremendously. Since 1988, the efficiency of MJPV cells has increased by more than 200 %. In 2013 and 2014, the Fraunhofer Institute for Solar Energy Systems achieved the record for MJPV efficiency, with 44.7 % and 46 % for a quadruple-layer cell [6], [7]. Due to a shortage of producers in this field, MJPV solar cells are currently more expensive than single-junction PV cells. As the technology improves and production capacity expands, the cost of solar cells is likely to drop giving these cells a competitive advantage in the marketplace [8].

The CPVT is usually categorized into high and low concentrations. The high-concentration CPVT systems are divided into linear-focus and point-focus systems according to their concentration shape [9]. Further, in CPVT systems, the concentration ratio is a significant parameter, defined as the entrance aperture (area of the concentrator) divided by the exit aperture (area of the receiver).

The first prototype of CPVT was produced at Sandia National Laboratories. This early work identified most of the problems associated with concentration systems and provided satisfactory solutions to many of them [10]. Kribus et al. studied a miniature CPVT module's thermal and electrical performance. The overall efficiency was around 80%, whereas the electrical efficiency was about 20% [11]. A CPVT system's performance and economic feasibility study with single-effect absorption cooling was conducted by Mittelman et al. [12]. The results demonstrated that integrating power generation plants and solar cooling can be comparable to, and sometimes better than, the conventional alternative. To evaluate the thermal and electrical performance of different configurations of CPV/T systems, Renno and Petito [13] developed a mathematical model for domestic application. They used Fresnel lenses and parabolic mirrors as optical devices. The results revealed that since the fluid output temperature is about 90 °C, using an absorption heat pump with a CPV/T is possible. Ning et al. [14], [15] studied the performance of the HCPV/T system based on a point-focus Fresnel lens with triple-junction solar cells experimentally and numerically. The experimental results showed an electrical efficiency of 28%, a thermal efficiency of 54%, and a total system efficiency that could reach 80%. They find an excellent agreement when comparing the numerical results with experimental results.

This research introduces a preliminary numerical investigation of the feasibility of a hybrid CPVT system based on a point-focus Fresnel lens (PFFL) with MJPV. A numerical model was developed to evaluate the thermal and electrical performance of the CPVT system.

2. Description of the CPVT model

Figure 1, shows a schematic diagram of the CPVT model, consisting of 12 point-focus Fresnel lenses, 12 MJPV cells, 12 heat sinks, and a flow loop containing a 1/2-inch copper pipe. The area of the Fresnel lens is 280 x 280 mm^2, and the size of the solar cell is 10 x 10 mm^2. The design of the heat sinks works as adapters to provide a planar surface for MJPV mounting and a round contour on the backside for attachment to the pipe. Epoxy adhesive glue was used to paste the MJPV onto a copper heat sink.

3. Thermal and Electrical Analysis

The performance analysis of the CPVT model is based on an energy balance around the CPVT components. The energy balance includes the incident solar radiation, optical losses from the Fresnel lens, thermal losses from the CPVT, heat flow into the HTF, and electrical energy. Figure 2, shows a side view of the one-dimensional steady-state energy balance and boundary conditions for a longitudinal section of a single cell of the CPVT model. There are three kinds of heat transfer mechanisms: convection, conduction, and radiation. Some of this heat is transferred within the MJPV solid layers by conduction, with the remaining parts of the heat lost to the surrounding environment by convection and radiation [16].

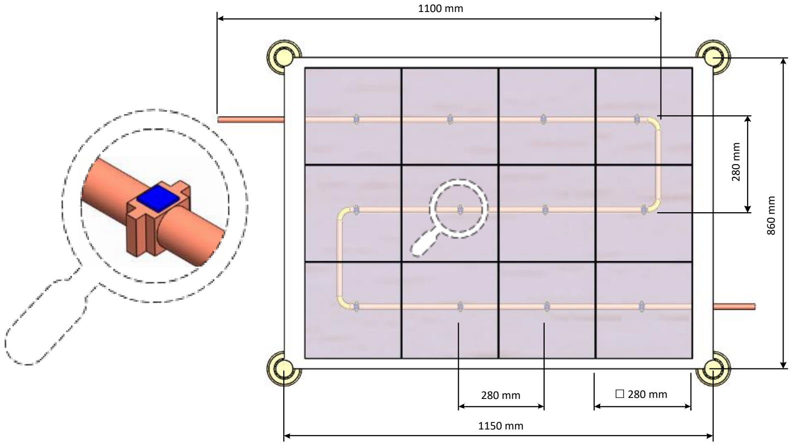


Fig. 1. The top-section view of the proposed CPVT model depicts PFFLs, the flow loop, heat sinks, and MJPVs.

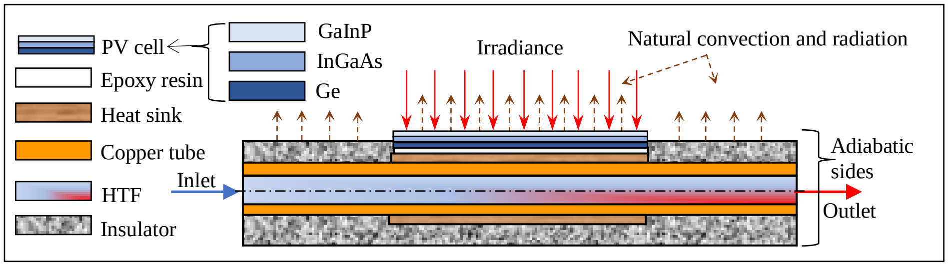


Fig. 2. Schematic description of CPVT assembly layers.

The maximum concentration ratio of the CPVT system is calculated as follows [17]:

$$\mathrm{CR} = \frac{\mathrm{A_{Fr}}}{\mathrm{A_C}} \times \eta_{\mathrm{opt}} \tag{1}$$

where A_{Fr} is the Fresnel lens area, A_c is the solar cell area, and η_{opt} is the optical efficiency of the concentrator system, and it is typically around 80%−90% [18]. The solar radiation flux Q_{in}, which reaches the MJPV cell, can be evaluated from the following relation:

$$\mathrm{Q_{in}} = \mathrm{q_{irr}} \times \mathrm{CR} \times \mathrm{A_C} \tag{2}$$

where q_{irr} is the solar radiation flux in (W/m^2). The solar radiation flux received by the MJPV cell is converted into electrical power and heat. The electrical power can be determined as follows:

$$\mathrm{P_{ele}} = \mathrm{Q_{in}} \times \eta_{\mathrm{sc}} \tag{3}$$

while the following equation can be used to calculate the amount of energy that converts to heat [19]:

$$\mathrm{Q_{heat}} = \mathrm{Q_{in}} \times (1 - \eta_{\mathrm{sc}}) \tag{4}$$

where η_{sc} is the cell's electrical efficiency of the MJPV and can be calculated as follows [20]:

$$\eta_{\mathrm{sc}} = \eta_{\mathrm{ref}}[1 - \beta_{\mathrm{ref}}(\mathrm{T_c} - \mathrm{T_{ref}})] \tag{5}$$

where η_{ref} is the cell's electrical efficiency at the solar cell reference temperature $\mathrm{T_{ref}}$, which is equal to the ambient temperature of 25 °C, $\mathrm{T_c}$ is the solar cell temperature, and the β_{ref} is the temperature coefficient of the MJPV solar cell. The values of η_{ref}, β_{ref} are usually provided by the manufacturer of the solar cell. The thermal energy Q_{th} absorbed by HTF is expressed as:

$$\mathrm{Q_{th}} = \dot{\mathrm{m}}\mathrm{C_p}(\mathrm{T_{out}} - \mathrm{T_{in}}) \tag{6}$$

where $\dot{\mathrm{m}}$, $\mathrm{C_p}$, $\mathrm{T_{in}}$, and $\mathrm{T_{out}}$ are mass flow rate, specific heat, inlet, and outlet temperatures of the HTF respectively. Hence, the thermal efficiency can be determined as follows:

$$\eta_{\mathrm{th}} = \frac{\mathrm{Q_{th}}}{\mathrm{Q_{in}}} \tag{7}$$

The electrical efficiency of the system can be calculated as follows:

$$\eta_{\mathrm{ele}} = \frac{\mathrm{P_{ele}}}{\mathrm{Q_{in}}} \tag{8}$$

The overall efficiency of the CPVT system can be calculated using the following equation:

$$\eta_{\mathrm{tot}} = \frac{\mathrm{P_{ele}} + \mathrm{Q_{th}}}{\mathrm{Q_{in}}} \tag{9}$$

4. Numerical Analysis

The heat transfer mechanism and thermal performance of the CPVT system were investigated using a numerical model, which included heat transfer from the MJPV to the HTF and the total heat losses to the surroundings. The simulation was carried out in Ansys Fluent 19.0 using computational fluid dynamics (CFD). A three-dimensional CPVT model was designed using Ansys Design Modeller. The numerical simulation is performed by applying the Ansys Fluent solver, which uses the Finite Volume Method (FVM) to discretize the governing equations of continuity, momentum, and energy. Furthermore, the energy and laminar flow models are used for this simulation. In addition, a hybrid unstructured tetrahedral and hexahedral mesh was employed in this simulation. The meshing was done using the Ansys Fluent Meshing tool to generate small elements to solve flow and energy equations for the CPVT model computationally. A mesh independence study was conducted, and six mesh independence tests were completed to obtain mesh-independent solutions and sustain credible results. The objective of these tests is to eliminate the influence of discretization, rounding, and iterative errors. The number of mesh elements ranges from 4.0 to 35.0 million, and the study was undertaken in terms of cell temperature. The results show that the cell temperature does not vary significantly with further increasing the grid elements. With these results, the number of mesh elements used in this study is sufficient for accuracy and simulation run time. Figure 3 depicts part of the side and isometric views of the meshed CPVT model.

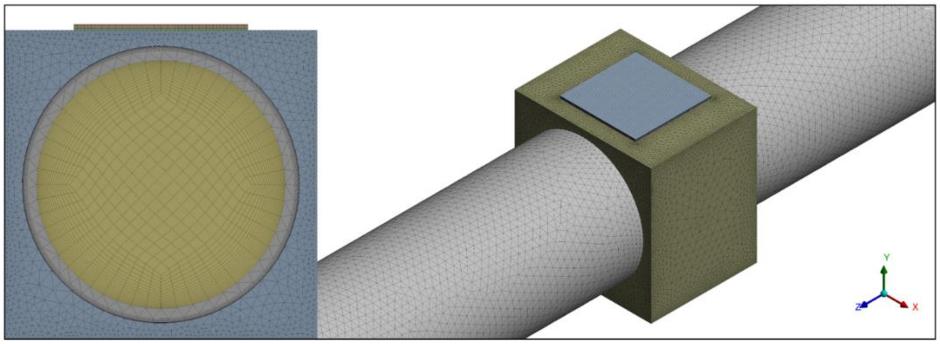


Fig. 3. Part of the side and isometric views of the meshed model.

5. Results and discussion

The present paper presents the preliminary numerical investigation feasibility of a hybrid CPVT system based on 12 point-focus Fresnel lens concentrators, 12 MJPV solar cells, 12 copper heat sinks, and a flow loop containing a 1/2-inch copper pipe. The performance of the CPVT system is investigated at different solar concentration ratios by using water as HTF at different mass flow rates within the laminar regime flow. Figure 4 describes the average pipe wall temperature of the CPVT model at different concentration ratios and mass flow rates. As we can see, the average wall temperature decreases significantly with an increased mass flow rate.

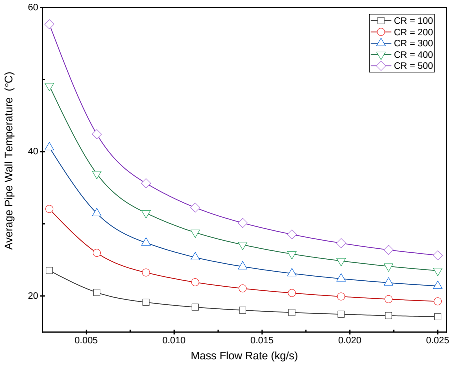
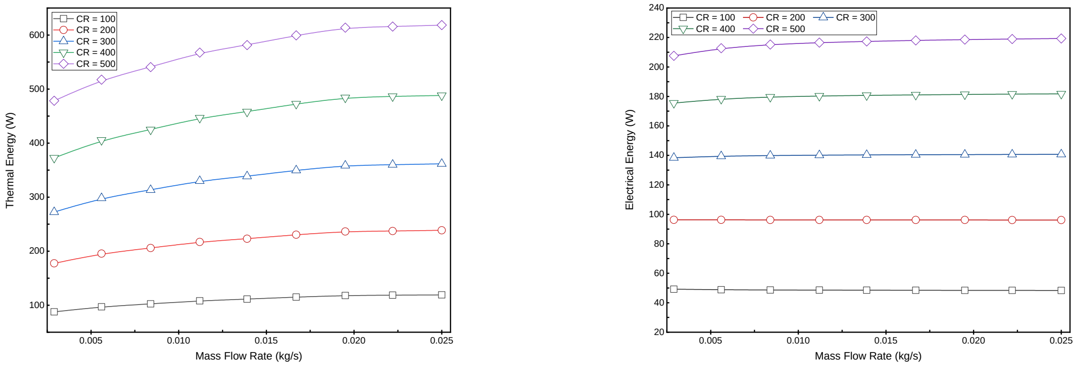


Fig. 4. Average pipe wall temperature with mass flow rate

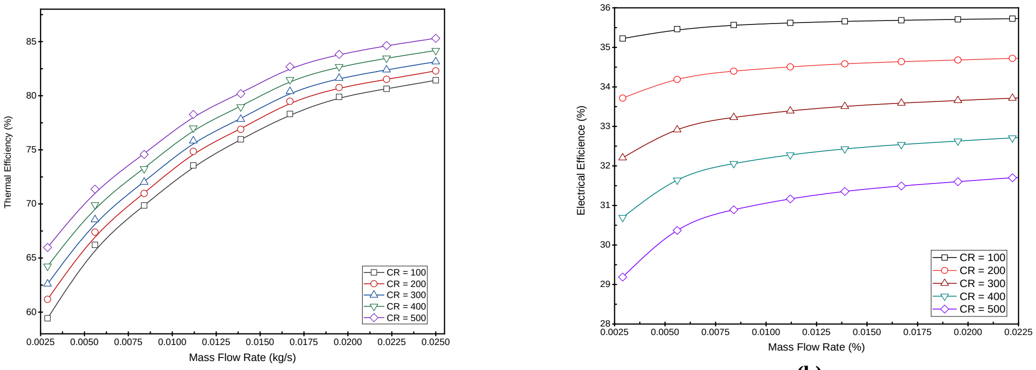
In addition, the average wall temperature at the lowest concentration ratio (CR = 100x) ranged from 17.13 ℃ to 23.53 ℃. On the other hand, the average wall temperature at the highest concentration (CR = 500x) varied from 25.63 ℃ to 57.67 ℃. These changes are due to the increase in the heat generated through the MJPV solar cell that is caused by the increased concentration of solar radiation intensity. Figures 5 (a) and (b) show the variation of the extracted thermal and electrical energy by the CPVT model under different concentration ratios. It is observed that the thermal and electrical power produced are synchronized with the evolution of the mass flow rate and concentration ratios. The maximum thermal and electrical energies were 618.5 W and 219.35 W, respectively. Besides, thermal and electrical energy occurred at a concentration ratio of 500x and a mass flow rate of 0.025 kg/s.



(a) **(b)**

Fig. 5. Variation of (a) the thermal energy and (b) the electrical energy of the CPVT model against increasing mass flow rate and concentration ratio.

Figures 6 (a) and (b) display the variation of thermal and electrical efficiencies of the CPVT model against increasing mass flow rate and concentration ratio. As we can show from both figures, an increase in mass flow rate results in a rise in the thermal and electrical efficiencies of the CPVT model. This indicates that the increase in mass flow rate results in a high amount of heat from the model. Therefore, the cell temperature decreases. The electrical efficiency is inversely connected to cell temperature. Consequently, the electrical efficiency is increased as cell temperature decreases. Moreover, it is observed from Figure 6 (b) that the increase in the concentration ratio results in an elevated cell temperature. Accordingly, the electrical efficiency decreases.



(a) **(b)**

Fig. 6. Variation of (a) the thermal efficiency energy and (b) the electrical efficiency of the CPVT model against increasing mass flow rate and concentration ratio.

Additionally, the highest thermal and electrical efficiencies occurred at a mass flow rate of 0.025 kg/s and their values were 85.31% and 35.74%, respectively.

Figure 7 depicts the I–V characteristic and P–V characteristic of the MJPV based on the numerical model for a single cell. The most common approach to evaluating the electrical characteristics of a CPVT system is to get its response curves, which give short-circuit current Isc, open-circuit voltage Voc, and maximum power output. The electrical output characteristics of the MJPV were drawn for different concentration ratios with a constant cell temperature of 25 °C. It is obvious that the changes in Isc with concentration ratios are more significant than the changes in Voc. Nevertheless, both of them increase with the concentration ratios. Further, figure 8 demonstrates the global temperature distribution of the CPVT model and the local temperature distribution of the outlet HTF at CR 100x and a mass flow rate of 0.0029 kg/s. It can be seen that the highest temperatures for the CPVT model and outlet HTF were 55.79 °C and 28.09 °C, respectively. Also, it is observed from outlet HTF contours that the highest temperature distribution occurred near the wall since the flow regime was laminar.

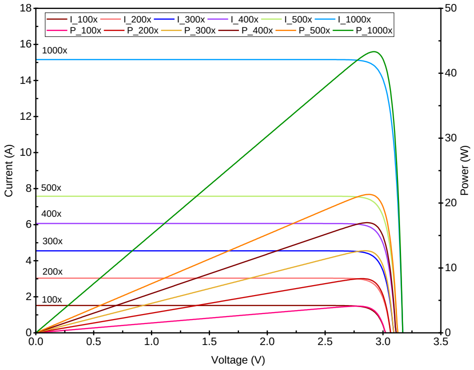


Fig. 7. I-V and P-V characteristics of MJPV in different concentration ratios at PV temperature of 25 °C.

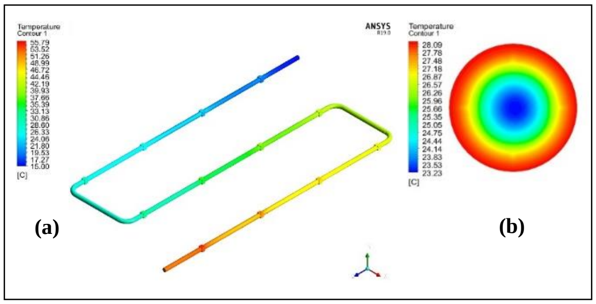


Fig. 8. Temperature contours at CR 100x and mass flow rate of 0.0029 kg/s, (a) Full CPVT model, (b) outlet temperature distribution.

6. Results validation

The objective of CFD model validation is to verify the accuracy and reliability of the CPVT model results. The designed CPVT model was compared with the experimental results at the same number of cells, geometry dimensions, material properties, and operating and boundary conditions [16]. Cell temperature is a significant parameter. Therefore, we chose it as a comparative element. Figure 9 compares cell temperature for both the CFD and the experiment. The maximum error between the experimental and CFD models was about 4.42%. In contrast, the minimum error was 1.54%, confirming that the results are satisfactory and agree well with the experiment results.

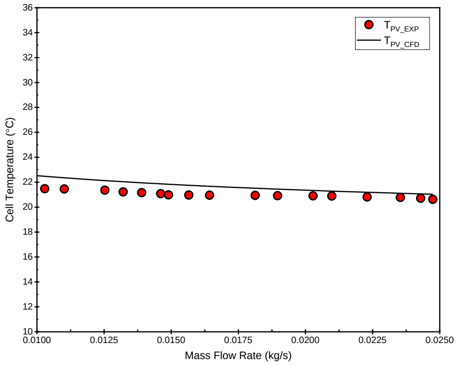


Fig. 9. Variation of the solar cell temperature for the CFD and the experiment.

7. Conclusion

Although CPVT technologies are one of the most attractive renewable energy technologies of the last decades, many challenges still need to be addressed. This paper proposes a CPVT model equipped with MJPV solar cells and point-focus

Fresnel lenses. The design is simple and reliable and can produce electricity and heat simultaneously. A numerical model was developed to investigate and evaluate the thermal and electrical performance of the proposed CPVT model under parameters such as HTF flow rates, HTF inlet temperature, MJPV cell temperature, incident radiation, concentration and the optical efficiency of the Fresnel lens. The electrical model was implemented using Matlab code. In the thermal simulation process, a three-dimensional steady-state heat transfer CPVT model was established according to solar radiation on the MJPVs. Based on the results, we conclude the following:

- For the effect of varying the mass flow rate of HTF on the average pipe wall temperature of the CPVT model, the results show the average wall temperature decreases significantly with an increased mass flow rate.
- For the changes in electrical and thermal efficiencies with the mass flow rates, the results demonstrate that an increase in mass flow rate results in a rise in the thermal and electrical efficiencies of the CPVT model. The highest thermal and electrical efficiencies occurred at a mass flow rate of 0.025 kg/s, and their values were 85.31% and 35.74%, respectively.
- For the effect of varying the concentration ratio on the electrical efficiency, the results indicate that the increase in the concentration ratio results in an elevated cell temperature. Accordingly, the electrical efficiency decreases.

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