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A Recent Jet Impingement PVT Collector Technique Developed (Reversed Circular Flow Jet Impingement): Energy and Exergy Analysis

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ABSTRACT

When subjected to solar irradiance, the upsurge in photovoltaic (PV) module temperature has constrained the photovoltaic thermal (PVT) technology's ability to generate electrical power, thereby affecting its overall PVT efficiency. Jet impingement has proven to be a viable method in improving a PVT collector's efficiency. This research functions as an extension to the existing established reversed circular flow jet impingement (RCFJI) PVT collector. The present study performed an in-house study to investigate the energy and exergy characteristics of the RCFJI PVT collector outlet configuration. The RCFJI outlet hole was configured into five distinct design settings: one hole (1h), two holes (2h), three holes (3h), four holes (4h), and five holes (5h). The experiment was executed with a uniform irradiance level of 900 W/m^2 and flow rate varying from 0.01-0.14 kg/s. As a result, the peak photovoltaic and thermal efficiency achieved using the 1h configuration was 11.09% and 63.2% at 0.14 kg/s. Particularly, the 1h configuration yielded an overall PVT efficiency of 72.35%. The study noted that the optimal flow rate was 0.06 kg/s, leading to the highest exergy of 12.32%. In a nutshell, increasing the RCFJI outlet numbers does not favourably impact the energy efficiency of the RCFJI PVT collector. The significance of this study contributes to the understanding of outlet configuration effects on the RCFJI performance.

Keywords: Jet impingement; photovoltaic thermal; energy analysis; exergy analysis; solar collector

INTRODUCTION

Owing to the prevailing worldwide issues presented by the threat of global warming, an imperative investigation to produce reliable and economically viable renewable energy sources has increased. The aforementioned endeavor possesses the ability to alleviate the inherent limitations related to conventional energy supplies (Coldrick et al. 2023). Based on forecasts, it is anticipated that the projected amount of electricity production generated from renewable sources would reach 4800 GW by the conclusion of 2027, signifying a notable increase of 67% compared to the amount generated in 2019 (Mokhtar et al. 2019; Nawab et al. 2022). The increasing demand for energy and adverse environmental issues related to conventional energy has motivated experts to pursue alternative renewable energy solutions. These initiatives are not just dedicated to electricity production but also encompass the advancement of hybrid technologies, such as photovoltaic thermal (PVT) (Çiftçi et al. 2021). In light of the rising concern regarding energy and sustainability, a notable worldwide focus on the progress and implementation of renewable sources has emerged (Fu et al. 2021). The adoption of renewable sources presents an assortment of advantages, including lowering greenhouse gases and efficient management of conventional energy (Mansir 2023). The rapid expansion of alternative energy sources, play a vital part in reducing the dependence on conventional sources and facilitating the shift towards sustainable practice (Ezugwu et al. 2022; Zheng et al. 2023). Solar energy holds the potential to fulfill the demands for both electricity and thermal energy owing to its widespread availability (Barthwal & Rakshit 2023). PVT technology is capable of converting generating both electrical power and heat energy (Lee et al. 2023; Yang & Harun 2022). PVT technologies have been acknowledged as a compelling technology for energy generation (Monjezi et al. 2020; Mustapha et al. 2018).

Despite the variety of perks offered by PVT technology, it possesses a primary constraint (Ibrahim et al. 2011). The technology itself is susceptible to a constraint in which the photovoltaic (PV) module perceives an upsurge in temperature due to exposure to solar radiation (Aziz et al. 2023; Imad et al. 2023; Ishak et al. 2023). An upsurge in the PV module's temperature indirectly diminishes its productivity to produce electrical energy, thus impacting its overall PVT efficiency. In conjunction with this, incorporating a cooling method within a PVT system has a key part in increasing its overall efficiency (Anwer B. Al-Aasam et al. 2023; Anwer Basim. Al-Aasam et al. 2023; Kazem et al. 2020). A substantial studies have been initiated to explore cooling techniques to regulate PVT performance (Chandrasekar & Senthilkumar 2021). The fundamental purpose of those research focus on lowering the operating temperature of the module which then improves the PVT performance (Al-waeli et al. 2018). Past studies have shown that jet impingement is one of the many potential cooling approaches that may be used to boost the efficiency of the PVT. This technique functions by facilitating a more efficient heat transfer (Abou-Ziyan et al. 2020). Because of its variety of applications, jet impingement has been the subject of a significant amount of research (Wai et al. 2022).

The first jet impingement technique was initially proposed by Choudhury & Garg (1991). The initial jet impingement technique implements the jet plate technique. The findings indicate a statistically significant enchantment in the PVT efficiency spanning between 20-27%. In turn, jet impingement method's capability for achieving a high heat transfer has garnered significant attention in the realm of scholarly Rashidi et al. (2019), Ishak et al. (2023a) and Ewe et al. (2021) conducted an extensive review of existing jet impingement methods applied in solar applications. The review points out a range of jet impingement techniques in solar technology, such as single-pass collectors, double-pass collectors, concentrated collectors, and jet configurations utilizing jet plates and jet nozzles. Yet, the review revealed a scarcity of research and an inadequate number of research pertaining to jet impingement in PVT applications (Ekkad & Singh 2021; Ewe et al. 2021; Ishak, et al. 2023a; Kumar et al. 2022; Vengadesan & Senthil 2020). Nevertheless, the review stated that the most established approach is the utilization of the jet plate technique present by Ewe et al. (2021), resulting in a notable PVT efficiency of 61.78%.

In 2023, a new approach known as the reversed circular flow jet impingement (RCFJI) PVT collector was introduced by Ishak et al. (2023b). An overall PVT efficiency of 72.3% achieved by the novel approach contributes to the current state of knowledge by introducing a unique method to enhance a PVT collector's efficiency. However, the RCFJI outlet configuration was never mentioned in the previous study. This research functions as an extension to the existing established RCFJI method. The present study carried out an in-house study with the aim of examining the energy and exergy characteristics of the RCFJI outlet configuration, which leads to the highest performance. The fundamental concept of the RCFJI PVT collector is illustrated in Fig. 1. The RCFJI is mounted beneath a PV module. Air will be facilitated through the RCFJI air inlet. The airflow pressure inside the cup increases, consequently discharging the air through the 0.003 m RCFJI outlet hole at high pressure, causing impinging effects to the PV module.

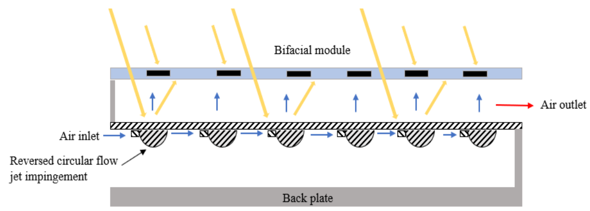

FIGURE. 1 Fundamental concept of the RCFJI PVT

METHODOLOGY

An in-house study was carried out with the aim of examining the PVT collector 's energy as well as the exergy characteristics utilizing the RCFJI. The RCFJI cup measured 0.04m (diameter) and 0.02m (depth) and was positioned at 0.113m (spanwise) and 0.126m (streamwise) (Ishak et al. 2023b). The RCFJI outlet hole was configured into five distinct configurations: one hole (1h), two holes (2h), three holes (3h), four holes (4h), and five holes (5h), as depicted in Fig.2. Each hole's which is part of the RCFJI producing the impinging effects measures 0.003m (diameter). The RCFJI configuration was varied to identify the best RCFJI outlet configuration, leading to the highest performance. Incoming air is routed by a 0.006m hose hooked to the RCFJI air intake. As air enters the RCFJI, the airflow inside the cup will be compressed. The compressed air inside the cup will forcefully leave the cup at high velocity through the 0.003m holes, impinging the PV module. The Bifacial PV module specification is presented in Table 1.

A solar simulator was employed to replicate the solar intensity, as seen in Fig. 3. 18 type-K thermocouples linked to a data recorder were deployed around the PVT collector to record the temperature changes. The experiment process was executed in compliance with a framework developed based on recent studies (Moshery et al. 2021; Ooshaksaraei et al. 2017). The incoming air is supplied using an air compressor and was regulated to a desirable flow rate, monitored using an anemometer. The simulator intensity is tuned to 900W/m^2 irradiance, which is subsequently determined using a pyranometer. The temperature measurement was recorded at intervals of 1 second for approximately 40 minutes. After roughly 35-45 minutes, the PVT collector's temperatures stabilized with no fluctuation observed. At this state, the module's voltage and current were recorded using an I-V analyzer. The PVT collector is left to cool for an hour before commencing a new set of parameters.

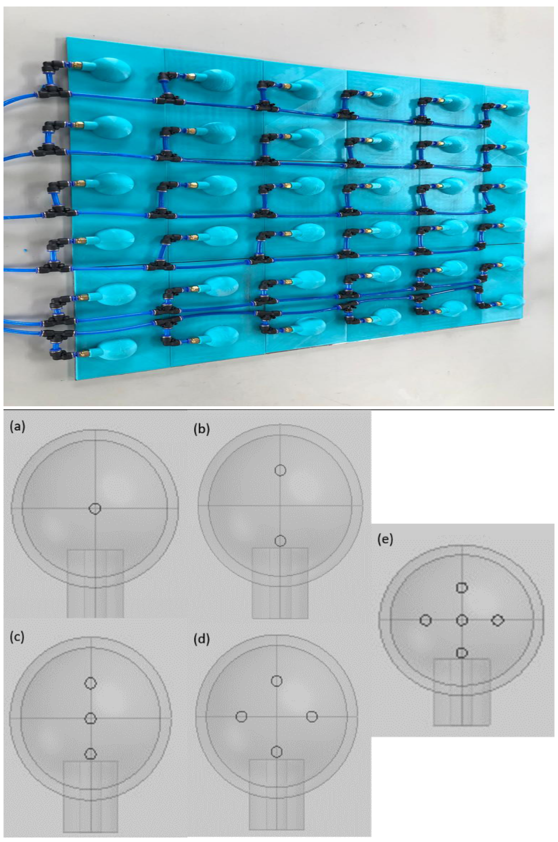

FIGURE. 2 Sample of assembled RCFJI (Top) and RCFJI outlet configuration (Bottom): (a) 1 hole (1h), (b) 2 holes (2h), (c) three holes (3h), (d) four holes (4h), and (d) five holes (5h)

FIGURE. 3 In-house experiment setup using a solar simulator

TABLE 1. Bifacial module characteristic

Parameters	Value
Packing Factor	0.66
Rated maximum power	60 w
Voltage at maximum power	17.4 V
Current at maximum power	3.5 A
Open circuit voltage	22.1 V
Short circuit current	3.71 A

ENERGY ANALYSIS

A comprehensive energy efficiency study was executed on the five distinct RCFJI outlet configurations. The variables and corresponding values utilized is indicated in Table 2.

PHOTOVOLTAIC EFFICIENCY

The expression for photovoltaic efficiency, abbreviated as η_{PV}, is specified by:

$$\eta_{PV} = \frac{Pmax}{(I \times Ac)} \quad (1)$$

The determination of maximum power point, Pmax, is measured using an I-V analyzer. However, theoretically, the Pmax of the module can be defined as (Ewe et al. 2022):

$$P_{max} = IA_c\alpha_{PV}P(\eta_{PVfront}) + IA_c\tau_i(1-P)n_r\alpha_{PV}P(\eta_{PVrear}) \quad (2)$$

And the module cell's efficiencies are defined as (Ewe et al. 2022):

$$\eta_{pvfront} = \eta_{pvrear} = \eta_{ref}[1 - \beta\left(T_{pv} - T_{ref}\right) \quad (3)$$

THERMAL EFFICIENCY

The thermal efficiency, abbreviated as η_{TH}, can be calculated using (Ewe et al. 2022):

$$\eta_{thermal} = \frac{Qu}{(I \times Ac)} \quad (4)$$

The beneficial heat gained is defined as:

$$Qu = \dot{m}C_p(T_o - T_i) \quad (5)$$

The specific heat capacity can be calculated using:

$$C_p = 1.0057 + 0.000066\,(T - 300) \quad (6)$$

ACCUMULATIVE PVT EFFICIENCY

The accumulative PVT efficiency of the RCFJI PVT collector is specified as:

$$\eta_{PVT} = \eta_{PV} \times \eta_{Th} \quad (7)$$

EXERGY ANALYSIS

The 2nd law of thermodynamics was applied to analyze the five distinct RCFJI outlet configurations. The intentional exergy analysis is used to emphasize the necessity of evaluating energy loss to get the optimum efficiency.

PHOTOVOLTAIC EXERGY

The photovoltaic exergy of the PVT collector, abbreviated as Ex_{PV}, is specified as (Ewe et al. 2022):

$$Ex_{PV} = P_{max}\left[1 - \left(\frac{4}{3}\right)\left(\left(\frac{T_a}{T_s}\right) + \left(\frac{1}{3}\right)\left(\frac{T_a}{T_s}\right)^4\right)\right] \quad (8)$$

Where the temperature of the sky is defined as (Moshery et al. 2021):

$$T_s = 0.0552(T_a^{1.5}) \quad (9)$$

THERMAL EXERGY

The thermal exergy, abbreviated as Ex_{TH}, is specified as (Ewe et al. 2022):

$$Ex_{TH} = Qu \times \left(1 - \frac{T_a}{T_{out}}\right) \quad (10)$$

EXERGY OUTPUT

The exergy output is specified as (Tripathi et al. 2016):

$$Ex_{output} = Ex_{PV} + Ex_{TH} \quad (11)$$

EXERGY INPUT

The exergy input is specified as (Ewe et al. 2022):

$$Ex_{input} = A_c \times I \times \left[1 - \left(\frac{4}{3}\right) + \left(\left(\frac{T_a}{T_s}\right) + \left(\frac{1}{3}\right)\left(\frac{T_a}{T_s}\right)^4\right)\right] \quad (12)$$

OVERALL EXERGY EFFICIENCY

The overall exergy efficiency is specified as (Ewe et al. 2022):

$$n_{exergy} = \frac{Ex_{output}}{Ex_{input}} \times 100\% \quad (13)$$

MEASUREMENT UNCERTAINTY

The measurement uncertainty allows the assessment of measuring device inaccuracy and precession of data. The measurement uncertainty was performed on each measuring device to identify the uncertainty in measurement. The measurement uncertainty associated with was found to be below than 1.5%, as indicated in Table 3. Therefore, the data gathered through the experiment is seen as dependable and precise. The mathematical representation of uncertainty is specified as the following Equation (Ooshaksaraei et al. 2017):

$$u = \frac{s}{\sqrt{n}} \quad (14)$$

The standard deviation, denoted as s, is defined as (Ooshaksaraei et al. 2017):

$$s = \sqrt{\frac{\sum_i^n (x_i - \bar{x})^2}{n-1}} \quad (15)$$

The abbreviation is defined as the average value: x, measurement reading: x̄ and sets of data: n. Each measuring device reading was collected 10 times for the data sets, n.

TABLE 2. Variables and values

Variables	Value
Mass flow rate, ṁ	0.1 – 0.14 kg/s
Width of collector, W	0.684 m
Length of collector, L	0.705 m
Duct depth, d	0.025 m
Solar irradiance, I (W/m^2)	900
Area of collector, Ac	0.48 m^2
Temperature ambient, Ta	30 ºC
Absorptivity of PV cell, α_{pv}	0.91
Packing factor, P	0.66
Heat transfer coefficient, h	9 W/(m^2.K)
External temperature, T_{ext}	30 ºC
The transmittance of Lamination, τ_1	0.85
The reflectivity of the jet plate, n_R	0.7
Electrical efficiency at reference condition, n_{ref}	0.16
Temperature Coefficient, β	0.0045 K^{-1}
The temperature at reference condition, T_{ref}	303.15 K

TABLE 3. Uncertainty of the measuring device

Equipment	Parameters	Unit	Uncertainty (%)
I-V Analyzer	Current/Voltage	I/V	± 0.64%
Data Recorder	Temperature	°C	± 0.98 °C
Thermocouple	Temperature	°C	± 0.11 °C
Pyranometer	Irradiance	W/m^2	± 1.32%
Anemometer	Air velocity	m/s	± 1.44%

RESULT AND DISCUSSION

ENERGY ANALYSIS

The analysis and presentation of the photovoltaic efficiency for the five different RCFJI outlet configurations is portrayed in Fig. 4. Based on the empirical observations, it was found that configuration 1h presented the lowest PV temperature from all configurations. From the observation, increasing the number of RCFJI outlet holes does not positively affect the PV temperature due to the inadequate force and sluggishness of airflow emanating from the outlet holes. Thus, the impinging effects decrease, which leads to a lower heat transfer. However, increasing the flow rate provides a better heat transfer which cools down the PV temperature. The recorded temperature for the 1h, 2h, 3h, 4h, and 5h spans between 43.90-54.69 ºC, 45.48-54.72 ºC, 47.05-54.74 ºC, 48.29-54.79 ºC, and 48.87-54.77 ºC, respectively. As observed in the photovoltaic efficiency trend, the flow rate positively correlates with rising photovoltaic efficiency. The observed phenomenon can be ascribed to the enhanced heat transfer, which lowers the

PV temperature. When the PV temperature decreases, the photovoltaic efficiency improves. Therefore, configuration 1h has the highest photovoltaic efficiency of 11.09% at 0.14 kg/s. Meanwhile, the peak photovoltaic efficiency for the 2h, 3h, 4h, and 5h was 11.01%, 10.93%, 10.86%, and 10.83%.

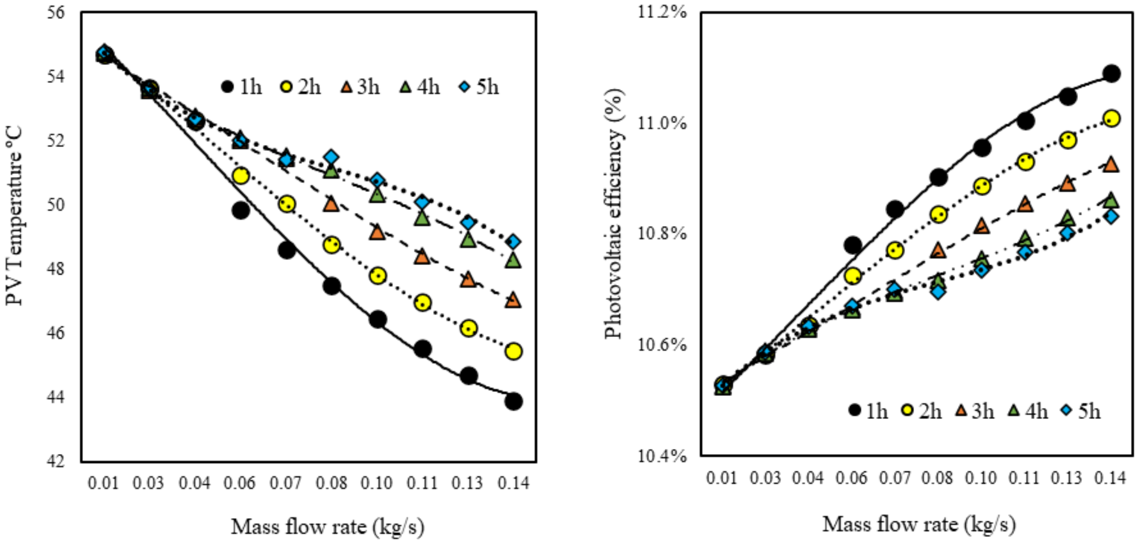

FIGURE. 4 PV temperature (top) and photovoltaic efficiency (bottom) of the five distinct RCFJI outlet configurations.

Figure 5 represents the PVT collector outlet temperature and thermal efficiency of the five different RCFJI outlet configurations. According to the data collection, the PVT outlet temperature drops at a higher flow rate. The highest PVT outlet temperature observed was using the 1h configuration with an outlet temperature of 34.37-42.22 ºC. The PVT collector outlet temperature for the 2h, 3h, 4h, and 5h was 33.26-41.96 ºC, 32.15-41.70 ºC, 31.18-41.33 ºC, and 10.53-10.83 ºC. Based on Equation (4), the thermal efficiency has a positive association with the collector's outlet temperature. Higher outlet temperature leads to more beneficial heat gain being produced, hence increasing the thermal efficiency. Another factor influencing to enhancing the thermal efficiency is the flow rate. Higher flow rate helps to improve the air circulation inside the PVT collector. Peak thermal efficiency was attained using 1h configuration with a thermal efficiency of 63.2%. In contrast, the maximum thermal efficiency for the 2h, 3h, 4h, and 5h was 62.1%, 60.98%, 60.01% and 59.57%. The lowest thermal efficiency was observed by using the 5h configuration.

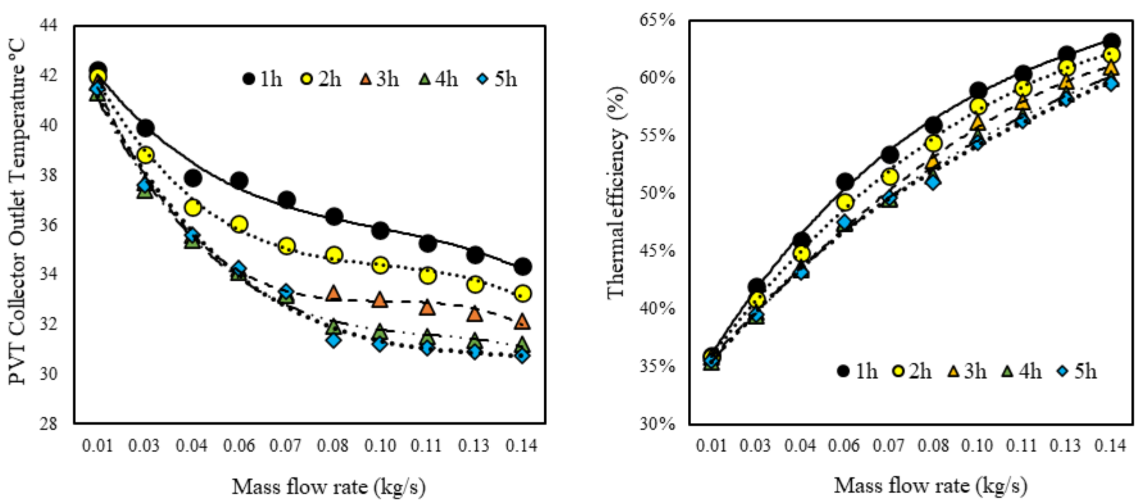

FIGURE. 5 PVT collector outlet temperature (top) and thermal efficiency (bottom) of the five distinct RCFJI outlet configurations

EXERGY ANALYSIS

Thermodynamic 2nd law was applied to evaluate the exergy performance and energy loss to achieve optimum efficiency. As demonstrated in Fig. 6, higher flow rate led to a surge in photovoltaic exergy for all configurations because raising the flow rate aids in boosting heat transfer and cooling the PV temperature. The 1h configuration produces the most photovoltaic exergy of 47.27 W at 0.14 kg/s. This is primarily due to the fact that configuration 1h presents the lowest PV temperature compared to the others. Lower PV temperatures encourage better photovoltaic efficiency, allowing for higher solar energy produced. At 0.14 kg/s, the photovoltaic exergy value for the 2h, 3h, 4h, and 5h was 46.92 W, 46.57 W, 46.30 W, and 46.17 W. Overall, the photovoltaic exergy for the 1h, 2h, 3h, 4h, and 5h spans between 42.39-47.27 W, 42.38-46.92 W, 42.38-46.57 W, 42.37-46.30 W, and 42.37-46.17 W.

In conjunction with thermal exergy, higher flow rate results in a reduction in the thermal exergy value across all five configurations, as illustrated in Fig. 6. The data gathered indicate that configuration 1h has the best thermal exergy, whereas configuration 5h yields the least thermal exergy. The dissipation of energy caused by the cooling effect from the RCFJI, which lowers the PV temperature is the reason of the thermal exergy drop. Notably, there is an enhancement in both heat transfer and airflow within the PVT collector at higher flow rate. Consequently, the PVT collector's temperature experiences a more rapid decrease, leading to the expulsion of hot air through the PVT collector's outlet. Nevertheless, the RCFJI outlet configuration which yielded the best thermal exergy was the 1h configuration with 9.67 W. Meanwhile, the most significant thermal exergy for the 2h, 3h, 4h, and 5h was 8.63 W, 7.59 W, 6.32 W, and 6.42 W.

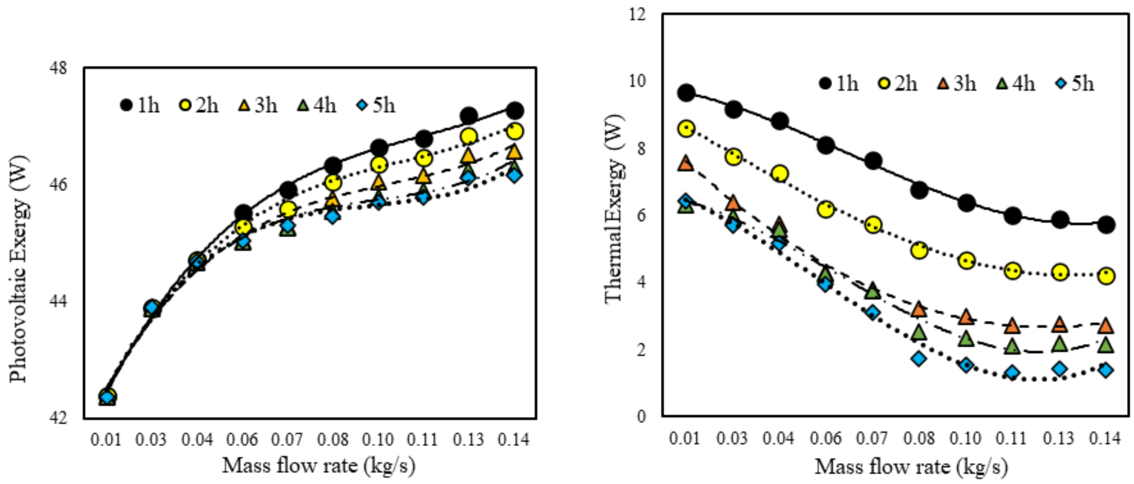

FIGURE. 6 Photovoltaic (top) and thermal exergy (bottom) of the five distinct RCFJI outlet configurations.

COMPARATIVE ANALYSIS OF ENERGY AND EXERGY PERFORMANCE

Figure 7 illustrates a comparative analysis of the photovoltaic energy and photovoltaic exergy using the highest energy performance configuration, which is configuration 1h. When examining the relationship between the photovoltaic energy and photovoltaic exergy for configuration 1h, it is evident that an augmentation in the photovoltaic energy and exergy is notable at higher flow rate. The utilization of the 1h configuration is significant as it facilitates heat transfer and cooling the PV temperature, thus leading to an increase in photovoltaic energy efficiency. Furthermore, a higher flow rate contributes to a corresponding elevation in the photovoltaic exergy, indicating that more energy is used effectively. The photovoltaic energy and exergy for the 1h outlet configuration spans between 45.49 to 47.91 W and 42.39 to 47.27 W. The findings of the analysis demonstrated a consistent pattern to a study by Ewe et al. (2022) and Ooshaksaraei (2015).

Meanwhile, for the thermal energy and exergy comparatives, the outcome demonstrates that there is an inverse relationship between thermal energy and exergy when the flow rate rises, demonstrated in Fig. 7. The decline in thermal exergy can be associated with the cooling effects of the RCFJI, which effectively decreases the temperature of the PVT collector. The thermal exergy for the 1h configuration exhibited a 151.51 to 272.97 W range, while the thermal exergy ranged between 5.73 to 9.67 W. The consistency of the aforementioned findings is similar to the past studies established by Chauhan et al. (2018) and Ewe et al. (2022).

Figure 8 presents the overall PVT efficiency and overall exergy efficiency of the RCFJI outlet configurations. According to the data presented, configuration 1h exhibits a photovoltaic efficiency of 11.09% and a thermal efficiency of 63.2% under an irradiance of 900 W/m^2 with 0.14 kg/s. The corresponding values sum up the highest overall PVT efficiency with 74.28% compared to other configurations. Subsequently, the 2h, 3h, 4h, and 5h configurations had a maximum overall PVT efficiency of 73.09%, 71.91%, 70.87%, and 70.40%, at 0.14 kg/s. Based on the empirical observations, it was determined that increasing the number of RCFJI outlets does not have a positive effect on the RCFJI performance. When the RCFJI outlet number increases, the air inside the RCFJI cup becomes less compressed, making the air discharge from the RCFJI sluggish and producing weaker impinging forces. The impinging effects are the main contribution to heat transfer augmentation. From the observation, a higher mass flow rate is also preferable for a better overall PVT efficiency.

However, experimental findings demonstrate a positive upward trend from 0.01 kg/s to 0.06 kg/s. The exergy efficiency reached its peak performance at 0.06 kg/s and eventually decreased as more flow rate is introduced. The observed phenomenon is caused by the energy loss and exergy destruction. Hence, the optimum flow rate for the highest exergy efficiency is 0.06 kg/s for all RCFJI outlet configurations. At this point, the maximum exergy efficiency reading was 12.64% by using a 1h outlet configuration. Conversely, the least exergy efficiency is seen when employing a 5h configuration with an efficiency of 12.32%. The 1h outlet configuration demonstrates the best exergy efficiency as more photovoltaic and thermal energy is utilized.

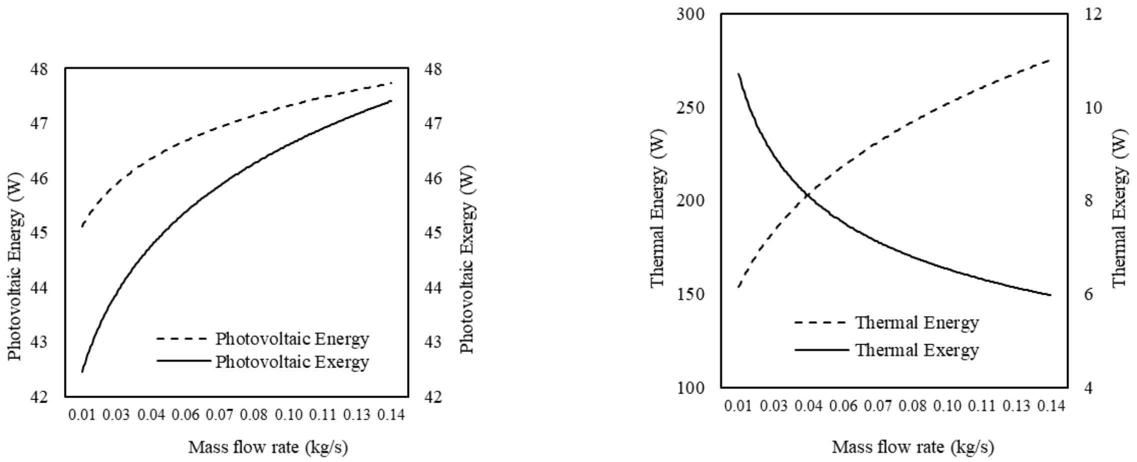

FIGURE. 7 Comparative of the photovoltaic energy and exergy (top) and the thermal energy and exergy (bottom) of the 1h RCFJI outlet configuration

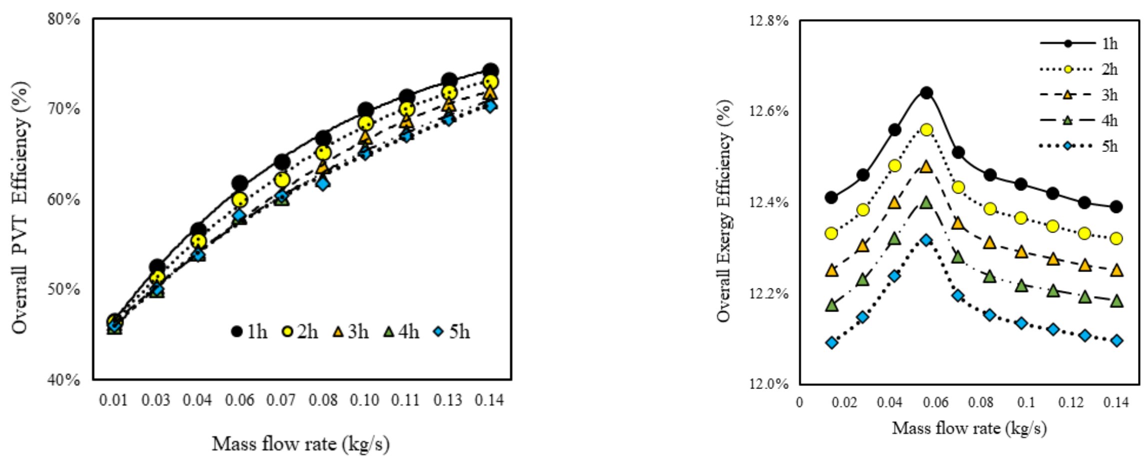

FIGURE. 8 Comparative of the overall PVT efficiency (top) and overall exergy efficiency (bottom) of the RCFJI outlet configurations

CONCLUSION

The study involved conducting in-house experiments on five different RCFJI outlet configurations to determine the optimal RCFJI outlet configuration leading to the best performance. As a summary of the findings, configuration 1h exhibited the best photovoltaic efficiency in comparison to other configurations. The maximal photovoltaic efficiency achieved using the 1h configuration was 11.09% at 0.14 kg/s. Meanwhile, the peak photovoltaic efficiency observed for the 2h, 3h, 4h, and 5h was 11.01%, 10.93%, 10.86%, and 10.83%. In the context of thermal efficiency, the peak performance recorded by the 1h configuration was 63.2%, while the thermal efficiency for the 2h, 3h, 4h, and 5h was 62.1%, 60.98%, 60.01%, and 59.57%. In general, configuration 1h attains the most significant overall PVT efficiency of 72.35% at 0.14 kg/s compared to the other configurations. The findings imply that increasing the RCFJI outlet numbers has no favorable impact on the energy performance. The main reason for the attribute is due to the insufficient pressure and sluggishness of airflow emitted through the RCFJI outlet, which reduces the impinging effects.

In regards to the thermal exergy, the peak photovoltaic exergy was 47.27 W using the 1h configuration, while the least recorded photovoltaic exergy was 46.17 W using the 5h configuration. As for the thermal exergy, the maximum value observed was 9.67 W using the 1h configuration, whilst the lowest thermal exergy was 6.42 W, employing the 5h configuration. According to the analysis, the optimum mass flow rate was 0.06 kg/s, which leads to the highest exergy efficiency. At this point, the peak exergy performance for the 1h configuration is 12.32%. Ensuring an effective operation of the RCFJI PVT collector necessitates the attainment of optimal flow rate, hence enhancing exergy performance. Furthermore, an enhancement of exergy efficiency has the desirable to reduce the required input energy and enables more energy to be effectively produced. In a nutshell, increasing the RCFJI outlet numbers does not contribute to enhancing the PVT performance. In addition, a higher flow rate is desirable for higher energy performance. However, based on the exergy analysis, the most optimal flow rate is 0.06 kg/s. Basically this technology can be applied in off-grid solar system which best suits in rural area. The capability of producing both electrical and thermal energy can provide a good energy solution for farming. For instance, drying purpose of agriculture. The proposed design has a significance increase in the PVT collector performance.

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DECLARATION OF COMPETING INTEREST

None.

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