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Experimental investigation of the usability of the rifled serpentine tube to improve energy and exergy performances of a nanofluid-based photovoltaic/thermal system

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Journal Pre-proof

1 **Experimental investigation of the usability of the rifled serpentine tube to**
2 **improve energy and exergy performances of a nanofluid-based**
3 **photovoltaic/thermal system**

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15 **Abstract**

16 This experimental study aims to energetically and exergetically compare the performance of a
17 PVT system with sheet-and-plain serpentine tube collector (base PVT system) with two cases
18 of modified PVT systems. The modified PVT systems are the replacements of plain
19 serpentine tube with rifled serpentine tube with 3 ribs (3-start rifled PVT system) and 6 ribs
20 (6-start rifled PVT system). The electrical parameter of the PV module without cooling is
21 compared with the three cases of the PVT system with cooling. The cooling fluid is
22 water/magnetite nanofluid. The effect of nanofluid flow rates (20-80 kg/hr) and nanoadditive
23 volume concentrations (0-2%) over the three cases of the PVT system is investigated to
24 propose a suitable combination of flow rate and NA concentration offering the best energetic
25 and exergetic performances. Thus, the 6-start rifled PVT system achieved a maximum of

26 22.5% and 3.8% higher overall energy efficiency, and 5.9%, and 1.9% higher overall exergy
27 efficiency than the base and 3-start rifled PVT systems at flow rate and concentration of 80
28 kg/hr and 2%. Finally, the electrical power generated by the base, 3-start rifled, and 6-start
29 rifled PVT systems achieved maximum enhancement of 27.5%, 29.5%, and 31.5% compare
30 to the PV module without cooling.

31

32 **Keywords:** PVT system; rifled serpentine tubes; nanofluid; concentrations; energy
33 efficiency; exergy efficiency.

34

35 **1. Introduction**

36 As reported by scientists, non-renewable energy sources will be exhausted by the end of the
37 22nd century [1]. Hence, significant attention is paid to renewable energy sources and
38 development of renewable energy systems. Solar energy is one such renewable energy source
39 that is extensively used to meet energy demand [2]. The conversion technologies of solar
40 energy have been assiduously investigated and noteworthy advances in recent decades have
41 been carried out in this area, including photovoltaic (PV), photochemical, photothermal, and
42 photovoltaic-thermal (PVT) systems as a third-generation solar systems. The defining feature
43 of all these collectors, that differentiates them from other solar systems, is perhaps the
44 cogeneration of heat and electricity [3]. PV system is one such kind of solar-based power
45 generation unit. In the PV system, the production of electricity is realized due to the falling of
46 sunlight on the semi conductive materials (silicon). These semi conductive silicon materials
47 are referred to as solar or PV cells in the field of PV technology [4]. The electricity
48 generation is the result of potential difference across the negative and positive poles that
49 actuates the flow of electrons. But, the exposed PV cells to the scorching heat from the sun
50 leads to a high PV module operating temperature. The high operating temperature of the PV

51 module deteriorates the PV electrical efficiency [5]. To overcome the demerit of the PV
52 module, the thermal collector was conceptualized in 1976 by Wolf [6] and termed as a
53 photovoltaic thermal (PVT) collector system. In a physical form, the PVT system has a
54 thermal collector placed below the PV module. The thermal collector has a fluid channel that
55 enables the fluid to flow through the back surface of the PV module and results in
56 withdrawing the unutilized heat present in the PV module's surface [7]. This heat withdrawal
57 leads to improved PV electrical efficiency and simultaneously provides thermal energy. The
58 thermal energy received is employed for low heat applications like industrial and domestic
59 applications [8].

60 Since the technological evolution of the PVT system, a never-ending attempt is in the process
61 to amplify its efficacy in terms of both thermal and electrical energies. Many pieces of
62 research have explored the possibilities of improving the overall efficiency of air and water-
63 based PVT systems by employing techniques such as optimization of design parameters [9-
64 10], inclusion of heat exchanger in flow channel [11-14], flow configurations [15,16],
65 glazing/unglazing [17, 18], etc. Apart from air, and water, some other conventional fluids are
66 used as coolants for the PVT system such as ethylene glycol and motor oil. These
67 conventional fluids are also termed as another significant parameter to withdraw heat from
68 the flow channel. Motor oil and ethylene glycol are associated with higher cost and lower
69 economic benefit. Nanofluids are a promising option as cooling fluids because they possess
70 superior thermal properties over ordinary fluids [20-24].

71 The suitability of a nanofluid as a cooling fluid in PVT systems has been explored by many
72 scientists in recent years. Yazdanifard et al. [25] tested the PVT system under the laminar and
73 turbulent flow for two different nanofluids. This work has shown that the addition of NAs
74 increases the overall efficiency which is more dominant for turbulent flow rather than laminar
75 flow. The investigation further indicated that for a turbulent flow, energy, and exergy

76 generated from the PVT system were higher for a higher NA diameter, while for laminar
77 flow, an opposite behavior was witnessed. Again, it was revealed that the aluminum oxide
78 (Al_2O_3) nanofluid has a higher efficiency than the titanium oxide (TiO_2) nanofluid.
79 Moradgholi et al. [26] reported an experimental study using methanol mixed Al_2O_3 nanofluid.
80 The study showed that the use of Al_2O_3 /methanol nanofluid decreases the PV module
81 temperature by 14.5°C which simultaneously generated 1.4 W higher power output. A sheet
82 and tube-based PVT system with Al_2O_3 /water, ZnO /water, and TiO_2 /water nanofluids were
83 numerically studied by Sardarabadi and Passandideh-Fard [27]. This research evidenced that
84 the thermal performance of the PVT system is better when it is operated with ZnO /water
85 nanofluid whereas the better electrical performance is imparted by the Al_2O_3 /water nanofluid.
86 Purohit et al. [28] numerically investigated a combination of water and alumina as a
87 nanofluid for the PVT system and compared with the water-based PVT system in terms of
88 working performance. They reported a 25% enhancement in overall working performance for
89 the nanofluid-based PVT system as compared to the water-based PVT system. However, this
90 study also revealed that at the same pumping power, this percentage enhancement falls to
91 13.8% for the water-based PVT system compared to the nanofluid-based PVT system. Al-
92 Waeli et al. [29] studied a nanofluid (SiC /water)-based PVT system. The prepared nanofluid
93 was introduced into the phase change material (PCM) tank to check its effect on the PV
94 module temperature. It was found that the PV module temperature reduced considerably.
95 Another concept of PCM was implemented by Hassan et al. [30] where a hybrid PCM based
96 nanofluid was used as a coolant for the PVT system. It was shown that the used nanofluid
97 enhances the system's electrical efficiency by 23.9% when compared with the water-based
98 PVT system. A techno-economic study was experimentally carried out by Al-Waeli et al.
99 [31] where a paraffin mixed nano- SiC nanofluid was made to pass through the backside of
100 the PV module. The study reported that this modification improved the electrical efficiency

101 from 7.1 to 13.7%, as well as provided 72% thermal efficiency. On the other hand, the
102 techno-economic section of the study suggested the payback period and electricity cost as 5-6
103 years and 0.125 \$/kWh. A new theoretical approach was established by Fudholi et al. [32] to
104 evaluate the performance of nanofluid-based PVT system. In this study, an aqueous
105 suspension of TiO_2 was utilized as NA for the nanofluid preparation. The findings reported a
106 13-25% augmentation in the energy efficiency of the PVT system due to the utilization of
107 NAs in comparison to pure water.

108 Exergy and entropy are the two important concepts in the thermodynamical systems, the
109 former shows the system's ability to execute useful work whilst the latter indicates the
110 system's inability to execute useful work [33]. The important concept of exergy is used in
111 nanofluid-based PVT system also by various researchers [34-38]. Sardarabadi et al. [34]
112 experimentally investigated the performance of nanofluid SiC/water nanofluid in PVT
113 system. The authors reported the exergy efficiency of pure water (19.36%) increased to
114 22.61% and 24.31% for 1 wt% and 3 wt% of SiC nanoparticles, respectively. Ag/water
115 nanofluid with 4 wt% in nanoparticle content was studied and compared with the traditional
116 PVT system by Aberoumand et al. [35]. They concluded that the PVT system's exergy
117 efficiency and electrical power was enhanced by 30% and 10%, respectively, with nanofluid
118 over the traditional PVT system. Another study to improve the PVT system's exergy
119 efficiency was performed by Hosseinzadeh et al. [36]. For this purpose, they used a
120 combination of nanofluid (ZnO/water) and PCM (paraffin wax), which resulted in an
121 attainment of 13.6% of overall exergy efficiency. With a similar objective of improving the
122 exergy performance, a microencapsulated PCM slurry was used as a cooling fluid by Yu et
123 al. [37]. In their study, the exergy performance was mapped with the variation of the melting
124 point and slurry concentration. It was found that the increase in melting point and slurry
125 concentration increased the exergy efficiency. Khanjari et al. [38] investigated a PVT system

126 with two different nanofluids, Ag/water and Al/water varying NA concentration. It was
127 shown that the higher NA concentration results in higher heat transfer properties for both
128 nanofluids. On the other hand, Ag/water nanofluid resulted in a better PVT system's exergy
129 efficiency as compared to the alumina/water nanofluid for the same NA concentration.
130 As reported before, some previous works have been conducted to evaluate and improve the
131 energy and exergy generation capacity of the nanofluid-based PVT systems. This is also the
132 objective of the present work to improve the energy and exergy performance of the traditional
133 nanofluid-based PVT system by replacing, in addition, the plain serpentine tube with a rifled
134 serpentine tube. To the best of our knowledge, the energy and exergy analysis of the PVT
135 system with a rifled serpentine tube collector has never been conducted in the past. The
136 effects of nanofluid flow rate (20-80 kg/hr), and NA volume concentration (0-2%) on the
137 energy and exergy performances of the modified PVT systems are studied and compared with
138 that of traditional system. A suitable combination of flow rate and NA concentration that
139 offers the best energetic and exergetic performances is identified.

140

141 **2. Experimental set-up**

142 The objective of this research is investigate three experimental cases of the PVT system
143 coupled with the use of nanofluids and evaluate the best option based on energy and exergy
144 analysis. The first case is the plain serpentine tube PVT system which is considered as the
145 base case. The other two PVT systems are the modifications of the base PVT system, which
146 is done by replacing a plain serpentine tube with a rifled serpentine tube with 3 ribs (3-start
147 rifled PVT system), and 6 ribs (6-start rifled PVT system).

148 The dimension considered for the serpentine tube is 8 mm in inner diameter and 2 mm in
149 thickness, and the collector is made of copper. The collector is positioned at the back of the
150 PV module by applying thermal grease while serpentine tubes are attached to the collector

151 surface with the help of soldering process. To reduce heat loss from the back surface of
152 collector, the serpentine tubes are insulated with stone wool. Both the height and width of
153 ribs used in the 3-start and 6-start rifled PVT system are 0.4 mm, while the rib pitch is 1 mm.
154 The schematic presentation of the considered PVT systems is illustrated in Fig. 1.

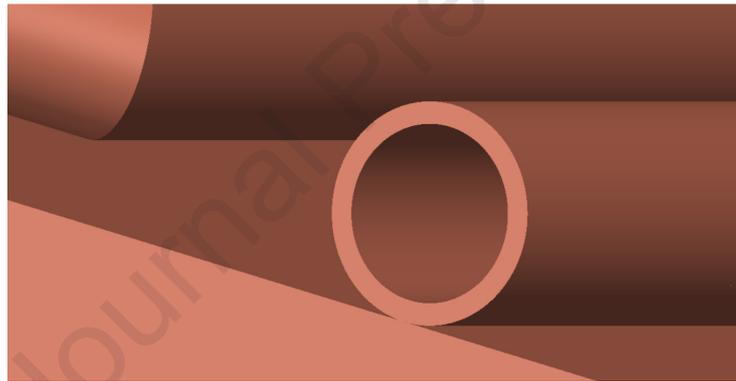
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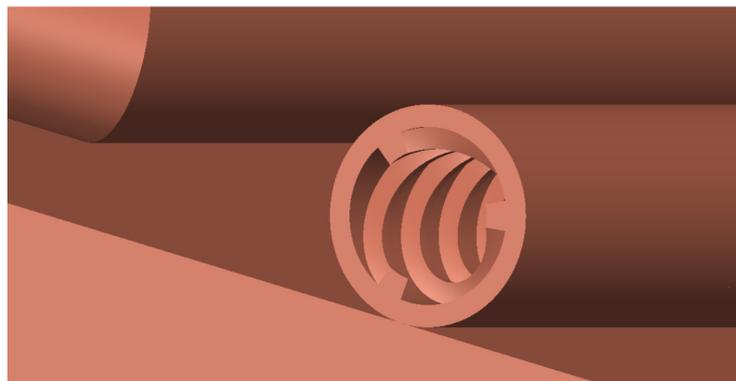
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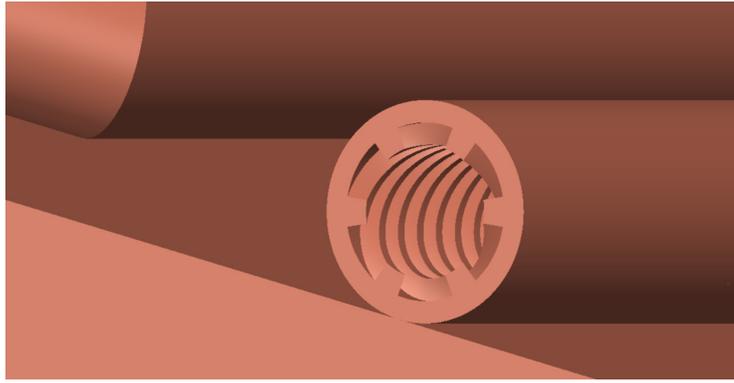
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161

(c)



(d)

162

163

164 **Fig. 1.** Schematic view of the (a) sheet-and-serpentine tube collector, (b) plain serpentine tube, (c) 3-
 165 start rifled serpentine tube and (d) 6-start rifled serpentine tube.

166

167 As mentioned above, the objective of this work is to compare three cases of the PVT system
 168 considering similar input conditions such as radiation intensity and ambient temperature. For
 169 such reason, a solar simulator is fabricated to perform the experimental investigation under
 170 the laboratory situations. The solar simulator consists of an aluminum box (1 nos.), DC fan (4
 171 nos.), 10 W LED lamps (4 nos.), 400 W reflector-sunlight-dysprosium-lamp (RSDL) also
 172 described as metal halide lamp (4 nos.), and an AC phase-cut dimmer (1 no.). The first
 173 objective is to achieve a similar radiation intensity ($126,582 \text{ lux} \approx 1000 \text{ W/m}^2$ [39]) and
 174 ambient temperature ($22 \text{ }^\circ\text{C}$) throughout the experiment which has been measured by a lux
 175 meter (BF06-Trotec-type) and a thermocouple (K-type). The PV module (Eco-Worthy type)
 176 used for the four cases has a dimension of $32 \text{ cm} \times 21.5 \text{ cm}$, a power weightage of 10 W and
 177 consists of 72 solar cells. A photograph and important specifications of the PV module are
 178 respectively given in Fig. 2(a) and Table 1. The temperature at 20 different locations over the
 179 PV module (shown in Fig. 2(b)) is also measured with the help of K type thermocouples. The
 180 temperature measurements are recorded by a datalogger (JUMO type). To calculate the
 181 electrical energy, the current and voltage imparted by the module during its functioning are
 182 measured by a multi-meter (LUTRUN-type). The working fluid used in the present

183 investigation is nanofluid, which requires a pump to push it from the inlet to the outlet of the
 184 serpentine tube. The pump operates on a DC source and has a head capacity of 3.5 m. The
 185 pump also facilitates different pumping speeds which is another requirement for the present
 186 investigation as various mass flow rates are used in the study. The pumping speed is
 187 measured by utilizing a rotary flow meter (M10000- Malema). The pressure drop caused by
 188 the nanofluid across the surfaces of the tubes at various flow rates is measured by a
 189 differential type pressure transmitter (3051CD-Rosemount). The circulation process of the
 190 nanofluid takes place in a closed cycle. The nanofluid is placed in a 2L capacity reservoir
 191 through which the nanofluid is pumped into the collector with the help of a tube and collects
 192 heat from the PV module. This cyclic process continues until steady conditions are achieved.
 193 Another criterion in the comparative analysis is to have a constant inlet temperature which is
 194 maintained throughout the trial and error method by passing the nanofluid through a plate
 195 type heat exchanger. The nanofluid, when passing through the heat exchanger, rejects its heat
 196 to a separate coolant (mixture of water and ethylene glycol) prepared through a constant
 197 temperature bath. The schematic diagram and real photograph of the utilized experimental
 198 setup are respectively shown in Fig. 3(a) and (b). Important specifications of the utilized
 199 equipment are also presented in Table 2.

200

201 **Table 1.** Technical characteristics of the studied PVT units in the current investigation [40].

PV solar cell (Under standard test conditions)	
Type	Mono-crystalline silicon
Nominal power output (W)	10
Maximum efficiency (%)	16
Number of cells	72
Fill factor	0.726

Dimensions (mm)	33×18×20
Weight (kg)	0.82
Short circuit current (A)	0.69
Open circuit voltage (V)	20.6
Temperature coefficient of power (%/°C)	-0.47
Temperature range (°C)	-40 to 80
Tempered glass thickness (mm)	3.2

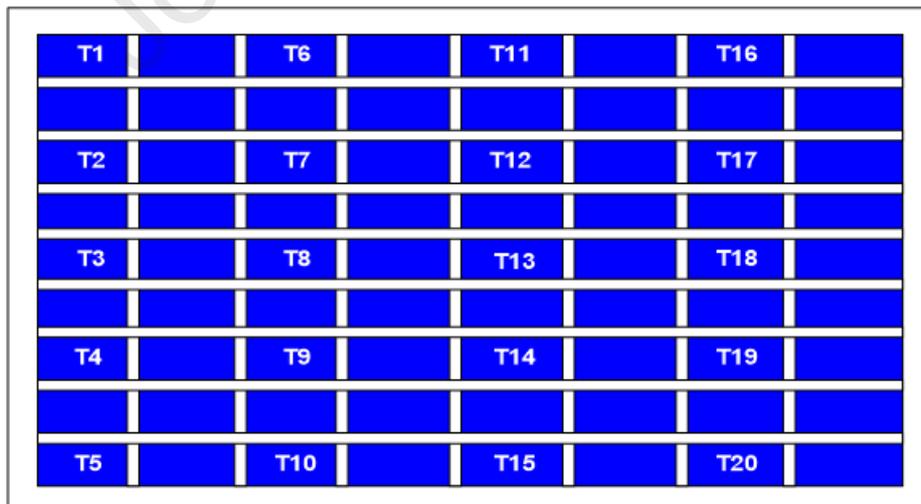
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(a)



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(b)

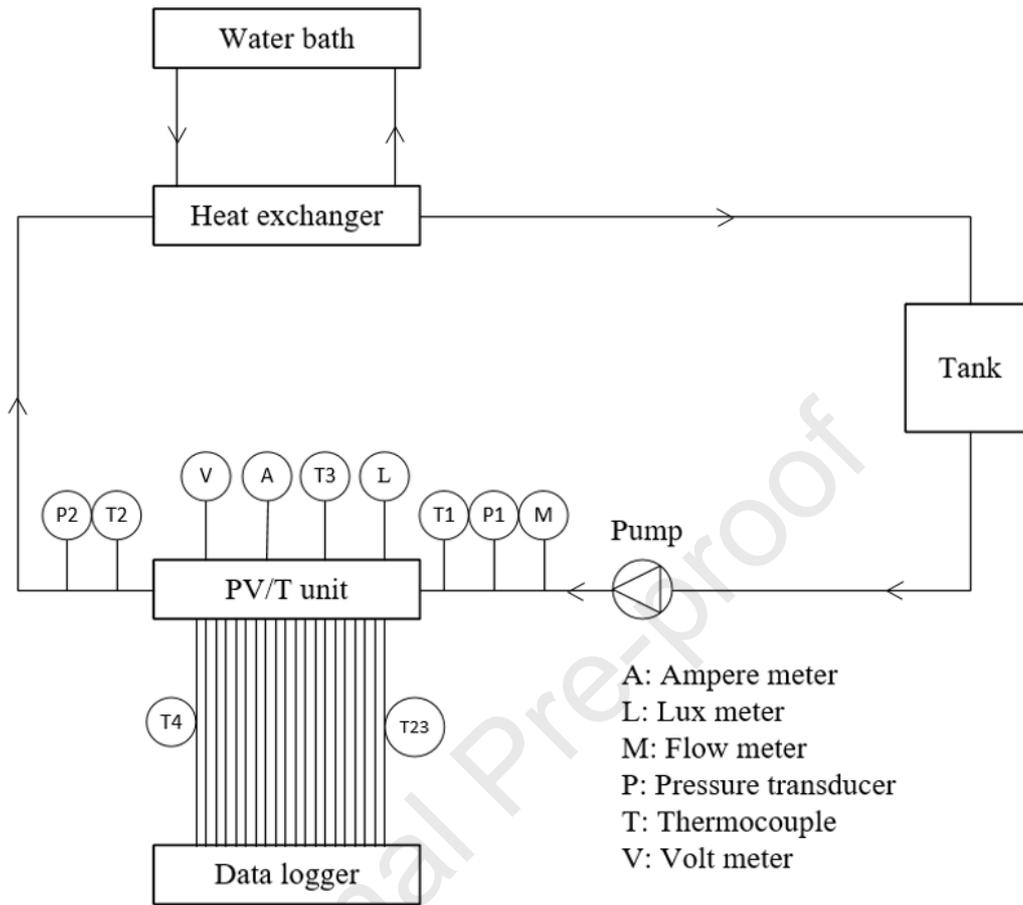
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Fig. 2. (a) A photograph of PV module and (b) placement of thermocouples at the front surface of the PV

208

module.

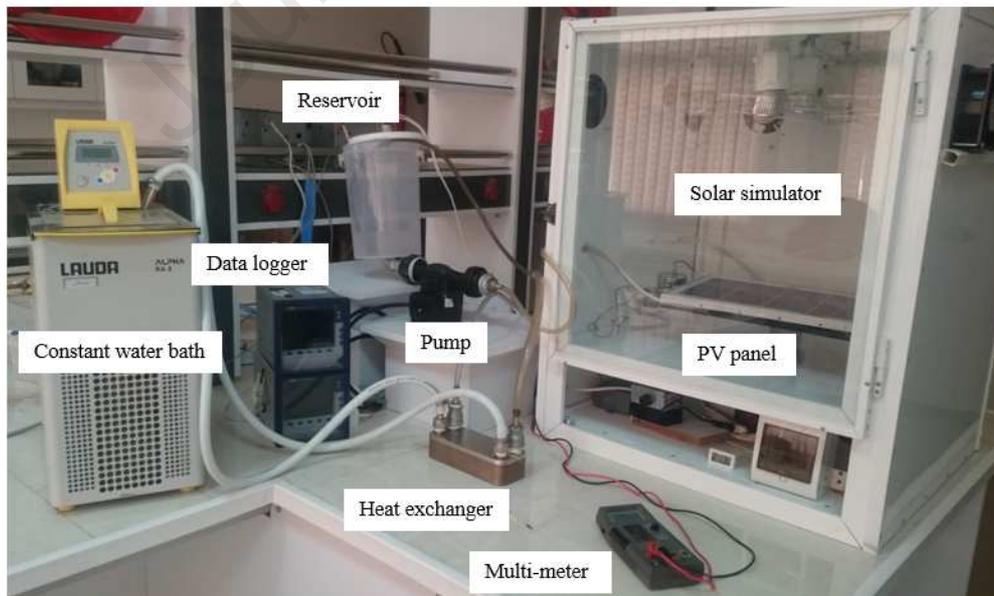
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210

211

(a)



212

213

(b)

214

Fig. 3. (a) Physical representation and (b) real photograph of the experimental setup [40].

215

216

Table 2. The specifications of instrument used in the experimental study [40].

Instrument	Model	Range	Precision (from manufacturer)
Luxmeter	TROTEC-BF06	0-40 klx	$\pm 5\% \pm 10$ lx
Thermometer	K-type	-200–1260 °C	$\pm 0.75\%$
Temperature sensor	TES-1327 K	-150-1260 °C	$\pm 0.1\%$ -1°C
Multimeter DC voltage	LUTURON-DW6060	0-600 V	$\pm 0.8\%$
Multimeter DC current	LUTURON-DW6060	0-10 A	$\pm 1\%$
Rotary flow meter	Malema-M10000	-0.1 to 225 Lit/min	$\pm 2\%$
Pressure transmitter	Rosemount 3051CD	0-2.07 MPa	$\pm 1\%$
Liquid density gravity meter	KEN-DA130N	0-2 g/cm ³	± 0.001 g/cm ³
Thermal properties analyzer	Decagon-KD2	0.02-4 W/m.K	$\pm 5\%$

217

218 3. Nanofluid preparation and its specification

219 The co-precipitation method is used to prepare the water/magnetite nanofluid [24] for the
 220 present experimental investigation. The different processes associated with the preparation of
 221 the water/magnetite nanofluid are:

- 222 1. Addition of 67.58 gm of FeCl₃.6H₂O in 100 ml of 2M hydrochloric (HCL) acid.
- 223 2. Addition of 39.76 gm of FeCl₂.4H₂O in 100 ml of 2M HCL acid.
- 224 3. The compositions obtained in the above processes 1 and 2 are mixed in a ratio of 4 to
 225 1 using a magnetic stirrer for 2 minutes at 100 RPM.
- 226 4. 50 mL of 0.7 M ammonia hydroxide under intense stirring is introduced dropwise to
 227 the solution obtained in process 3 for 10 min at 700 RPM.
- 228 5. The solution obtained in process 4 is placed over the permanent magnet with the help
 229 of a container. The permanent magnet discharged the magnetic NA and settled it into
 230 the bottom surface of the container.

231 6. The magnetic particles are added with 8 ml of 25% tetramethylammonium hydroxide
 232 and the final solution underwent a centrifugation process for 1 minute at 4000 RPM.

233 7. The magnetic NAs prepared in the previous step are sufficiently poured into pure
 234 water and the resulting solution is stirred using a magnetic stirrer for 30 min at 300
 235 RPM.

236 All the above-mentioned processes are also presented in a schematic representation in Fig. 4.

237 The stability of the prepared nanofluid samples was investigated using the fact that the
 238 instability of the fluid led to the deposition of NAs and, therefore, the change in nanofluid
 239 viscosity over time. Therefore, the nanofluid viscosity was measured every day for three
 240 weeks by means of a density gravity meter at temperature of 23 °C (liquid type, DA-130N,
 241 KEN Japan), and the results showed that the viscosity changes were negligible within three
 242 weeks. The necessary thermophysical properties of the prepared nanofluid are given in Table

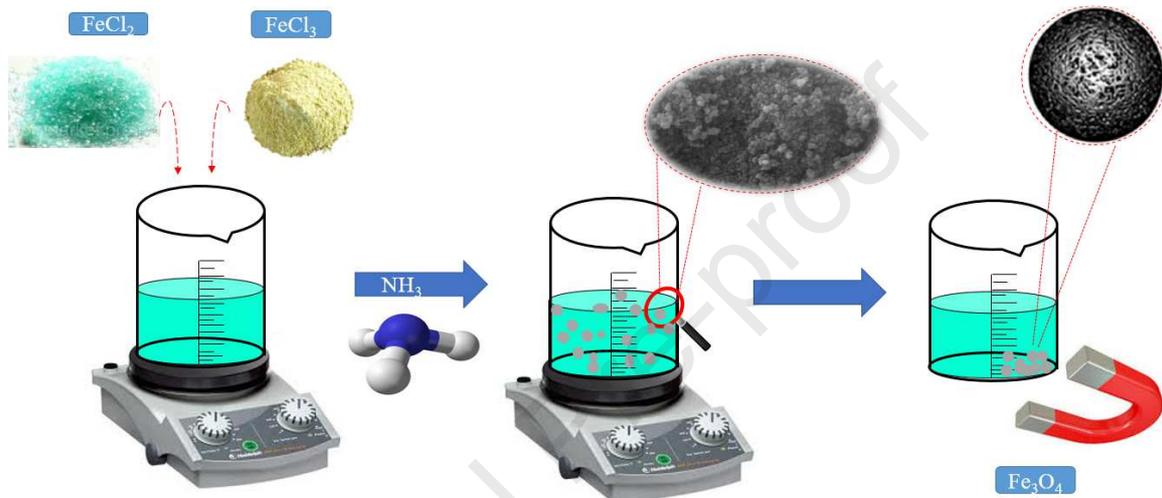
243 3. Thermal conductivity of NF was measured using a KD2-Pro thermal properties analyzer
 244 (Decagon devices, USA) that operates based on the transient hot wire technique. This device
 245 has a probe (KS-1) that must be placed in the solution for 90 seconds during the test. To be
 246 more precise, the thermal conductivity measurement was repeated 5 times at 20-minute
 247 intervals (to allow thermal stability), and the value reported in Table 3 is actually the average
 248 of the values obtained from the 5 experiments. To calibrate the device, the thermal
 249 conductivity of glycerol and water was measured at 20°C and the obtained values (0.274
 250 W/m.K for glycerol and 0.586 W/m.K for water) were compared with the values in a valid
 251 source (0.285 W/m.K for glycerol and 0.598 W/m.K for water) [41]. The difference between
 252 the experimental results and the values reported in the ref. [41] was less than 3.9%. In
 253 addition, the density (ρ_{nf}) and specific heat ($c_{p,nf}$) of nanofluid were computed using the
 254 following equations [42]:

$$\rho_{nf} = (1 - \varphi)\rho_w + \varphi\rho_p \quad (1)$$

$$c_{p,nf} = \frac{(1 - \varphi)\rho_w c_{p,w} + \varphi\rho_p c_{p,p}}{\rho_{nf}} \quad (2)$$

255 where φ is the NA volume concentration and the subscripts nf , w and p stands for the
 256 nanofluid, water and NA. The density and specific heat of magnetite NAs are respectively
 257 5200 kg/m^3 and 670 J/kg.K and the specific heat of water is 4179 J/kg.K [42].

258



259

260

Fig. 4. Various steps of the preparation of water/magnetite nanofluid [40].

261

262

Table 3. Thermophysical properties of the prepared nanofluid (aqueous magnetite).

NA concentration (%)	Heat capacity (J/kg.K)	Thermal conductivity (W/m.K)	Density (kg/m ³)
0	4179.0	0.610	997.10
0.5	4089.39	0.695	1018.11
1	4003.40	0.873	1039.13
1.5	3920.83	0.917	1060.14
2	3841.46	0.961	1081.16

263

264 4. Energy and exergy formulation

265 The concept of the PVT system was developed to receive thermal energy and electrical
 266 energy simultaneously. Keeping this in mind, the present study is aimed to improve the
 267 thermal and electrical performances of the traditional plain serpentine tube collector by some

268 design modifications as discussed in section 2. The detailed formulation of energy, exergy,
269 and electrical energy are presented in this section.

270 The thermal behavior of the PVT systems is characterized by its ability to produce total
271 thermal energy with respect to the total solar energy received. This process is termed as
272 thermal energy efficiency (η_{th}) of the PVT system [8]:

$$\eta_{th} = \frac{\dot{m}_{nf} c_{p,nf} (T_{nfo} - T_{nfi})}{I_{sol} A_{pvm}} \times 100 \quad (3)$$

273 where T_{nfi} , T_{nfo} , \dot{m}_{nf} and c_p respectively denote the inlet temperature, outlet temperature,
274 mass flow rate, and specific heat capacity of nanofluid. In addition, I_{sol} and A_{pvm} are the
275 striking radiation intensity and PV module area, respectively.

276 Similarly, the electrical behavior of the PVT system is characterized by its ability to produce
277 electrical energy with respect to the total solar energy received. This process can be termed as
278 electrical energy efficiency (η_{el}) of the PVT system [8]:

$$\eta_{el} = \frac{V_{pvm} I_{pvm} - \dot{E}_{elp}}{I_{sol} A_{pvm}} \times 100 \quad (4)$$

279 where I_{pvm} and V_{pvm} are respectively the output current and output voltage of the PV
280 module. \dot{E}_{elp} is the fluid pumping power which can be calculated as [43]:

$$\dot{E}_{elp} = \frac{\dot{m}_{nf} \Delta P}{\rho_{nf} \eta_p} \quad (5)$$

281 where ΔP and ρ_{nf} are the pressure drop and density of the nanofluid, respectively.
282 Additionally, η_p is known as pump efficiency (=75%).

283 Thermal energy is characterized as low-grade energy whereas electrical energy is
284 characterized as high-grade energy [8]. The conversion of electrical energy into thermal
285 energy is possible with an approximate efficiency of 100% while the opposite behavior is not
286 feasible. The PVT systems can be assessed and compared based on the overall energy
287 efficiency which can be determined as [44]:

$$\eta_{ovth} = \eta_{th} + \frac{\eta_{el}}{0.36} \quad (6)$$

288 where 0.36 is the conversion coefficient of a coal-based power plant [44].

289 Exergy is one of the important applications of the second-law of thermodynamics and
 290 is characterized as the maximum work theoretically possible from a thermodynamic system.
 291 Accordingly, the exergy efficiency of the PVT system is characterized by the percentage of
 292 the maximum theoretically possible output that can be achieved as an actual desired output
 293 [35]. Therefore, it is important to assess the overall exergy scenario of the PVT systems
 294 which is the summation of the thermal exergy efficiency and electrical exergy
 295 efficiency (η_{ellex}) [8]:

$$\eta_{ovex} = \eta_{thex} + \eta_{ellex} \quad (7)$$

296 where η_{thex} is thermal exergy efficiency which is defined as the ratio of thermal exergy gain
 297 from the PVT system to the exergy of sun radiation [35, 45]:

$$\eta_{thex} = \frac{\dot{m}_{nf} c_{p,nf} (T_{nfo} - T_{nfi}) \left[1 - \frac{T_{amb} + 273}{T_{nfo} + 273} \right]}{I_{sol} A_{pvm} \alpha_{PV} \left[1 - \frac{4}{3} \left(\frac{T_{amb}}{T_{sun} Y} \right) + \frac{1}{3} \left(\frac{T_{amb}}{T_{sun} Y} \right)^4 \right]} \times 100 \quad (8)$$

298 whereas η_{ellex} is the electrical exergy efficiency expressed as the ratio of the electrical power
 299 gain from the PVT system to the exergy of sun radiation [31, 45]:

$$\eta_{ellex} = \frac{V_{pvm} I_{pvm} - \dot{E}_{elp}}{I_{sol} A_{pvm} \alpha_{pv} \left[1 - \frac{4}{3} \left(\frac{T_{amb}}{T_{sun} Y} \right) + \frac{1}{3} \left(\frac{T_{amb}}{T_{sun} Y} \right)^4 \right]} \times 100 \quad (9)$$

300 where T_{amb} and T_{sun} are the ambient temperature and sun temperature, respectively ($\cong 5800$
 301 K). In addition, α_{pv} is the absorptivity of PV panel ($=0.9$) and Y is the interaction factor,
 302 which is determined as follows [45]:

$$Y = \left(\frac{f_s \varepsilon_s}{f_c \varepsilon_c} \alpha_{pv} \right)^{1/4} \quad (10)$$

303 where ε_s and ε_c are the dilution factors for incoming solar radiation and PV panel emitted
 304 radiation, respectively. In addition, f_c is the geometric factor for solar collector and f_c is the
 305 geometric factor for solar radiation defined as the ratio of concentration of solar collector (C)
 306 to the maximum concentration of solar radiation at level of earth orbit (C_{max}).

307

308 **5. Uncertainty analysis**

309 To assess the accurate findings of the experimental study, the uncertainty of the used
 310 instruments must be considered. In this study, uncertainty analysis is carried out via the
 311 method established by Moffat [46] which identifies the uncertainty of the dependent variable
 312 (D) as a function of the independent variables (d_1, d_2, \dots, d_n) as expressed below:

$$\delta D = \sqrt{\left(\frac{\partial D}{\partial d_1} \delta d_1\right)^2 + \left(\frac{\partial D}{\partial d_2} \delta d_2\right)^2 + \dots + \left(\frac{\partial D}{\partial d_n} \delta d_n\right)^2} \quad (11)$$

313 In the above equation, δ represents the parameter's uncertainty. The outcomes demonstrated
 314 that in all the experiments conducted in the current contribution, the uncertainty of the
 315 parameters was less than 5.21%, which is a justifiable value. The details of the uncertainty
 316 calculations are given in "Appendix A".

317

318 **6. Results and discussions**

319 The performance of the three cases of the PVT system has been experimentally investigated
 320 in this work. The three cases of the PVT system have been studied under indoor solar testing
 321 facilities for a range of nanofluid flow rates (20-80 kg/hr) and NA concentration (0-2%). The
 322 base, 3-start rifled, and 6-start rifled PVT systems are compared with each other in terms of
 323 thermal and electrical performances at the mentioned flow rates and NA concentrations. The
 324 thermal energy performance of the three cases is discussed in the first sub-section whereas
 325 the second subsection explains the thermal exergy performance. The third subsection details

326 the electrical energy performance of the experimental arrangements. Finally, the electrical
327 performance of the three cases under the cooling mode is also compared with those of the PV
328 module without cooling.

329

330 *6.1. Thermal energy and its related efficiency*

331 Fig. 5 displays the thermal energy output gained by the three cases of the PVT system under
332 the influence of the nanofluid flow rates and NA concentrations. It is witnessed that an
333 increase in the flow rate and NA concentration results in a corresponding increase in the
334 thermal energy output for all the three cases, i.e, the minimum thermal energy output has
335 been observed at a flow rate and NA concentration of 20 kg/hr and 0% whereas the maximum
336 value has been observed at 80 kg/hr and 2%. This is because the thermal energy gained by the
337 PVT system depends on the magnitude of the flow rate and outlet fluid temperature. The
338 increase in the flow rate directly influences the thermal energy gained by the PVT system
339 whereas an increase in the flow rate has a negative effect on the outlet fluid temperature
340 which results in a decrement of thermal energy gain. The effect of flow rates dominates the
341 effect of outlet fluid temperature and resulted in an enhancement of thermal energy output
342 with an increase in nanofluid flow rate (20-80 kg/hr). The reason for the enhancement in the
343 thermal energy output with the increase in NA concentration from 0-2% at a given flow rate
344 is due to the greater thermal conductivity of nanofluid at higher NA concentrations (see Table
345 3). The explained behavior of thermal energy output with the flow rates and NA
346 concentrations is quantified below.

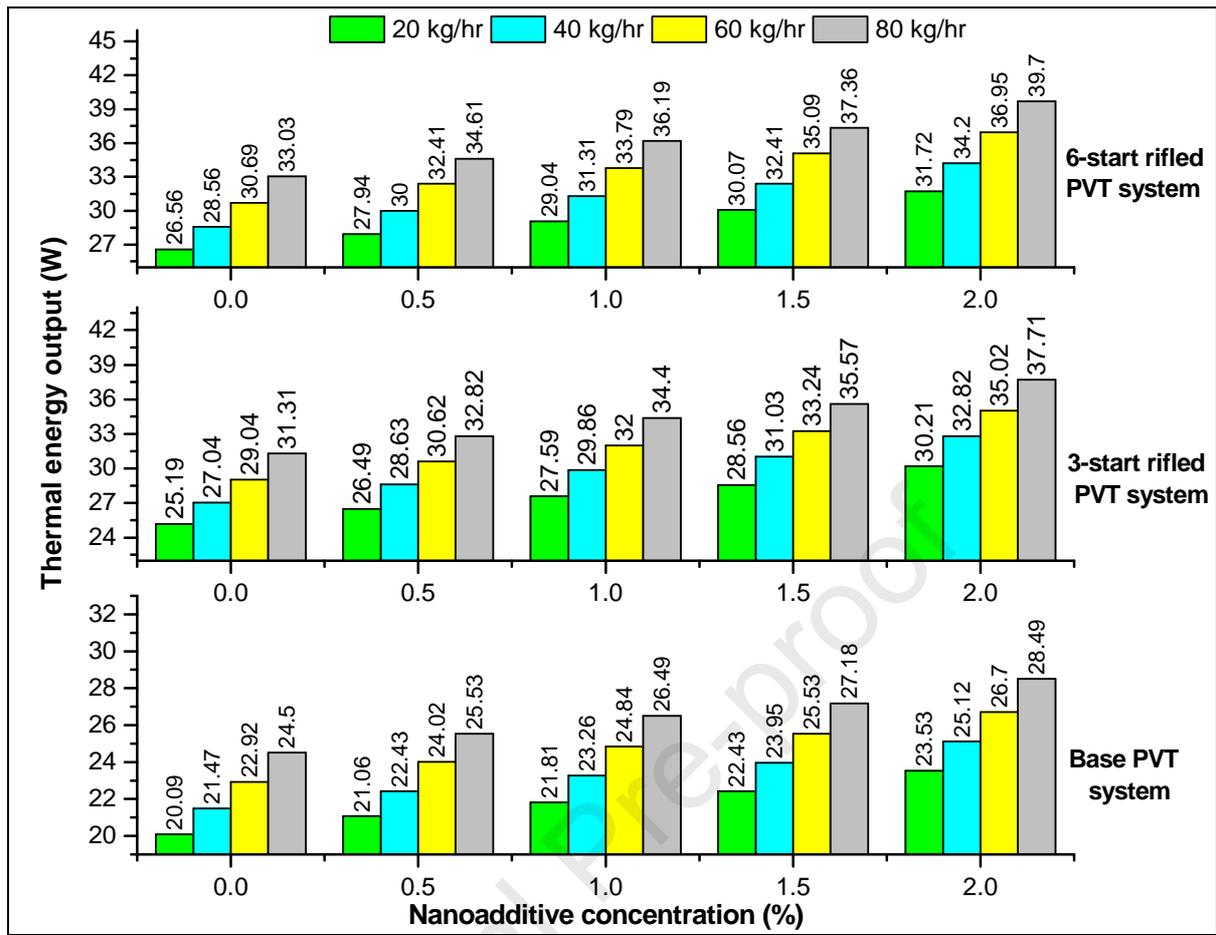
347 It is observed that for the base PVT system when the flow rate increased from 20-80 kg/hr at
348 a 0% NA concentration, the thermal energy output increased by 21.9%. At a similar
349 condition, this percentage improvement for the 3-start rifled, and 6-start rifled PVT systems
350 has been evaluated to 24.2% and 24.4% respectively. For a similar increment in the flow rate

351 (20-80 kg/hr), at a 2% NA concentration, the thermal energy output enhancement for the
352 base, 3-start rifled, and 6-start rifled PVT systems is 21%, 24.8%, and 25.2% respectively.
353 On the other hand, when NA concentration increased from 0-2% at a flow rate of 20 kg/hr,
354 the thermal energy output increased by 17.1%, 19.9%, and 19.4% for the base, 3-start rifled,
355 and 6-start rifled PVT system. For a similar increment in the NA concentration (0-2%), at a
356 flow rate of 80 kg/hr, the thermal energy output enhancement for the base, 3-start rifled, and
357 6-start rifled PVT systems reaches 16.3%, 20.4%, and 20.2% respectively.

358 The crux of this investigation is to also directly compare the three cases of the PVT system. It
359 is seen that the 6-start rifled PVT system has a higher thermal energy output as compared to
360 the 3-start rifled and base PVT systems at any combinations of flow rate and NA
361 concentration. It is seen that at a 2.0% and 80 kg/hr of NA concentration and flow rate, the 6-
362 start rifled PVT system has gained thermal energy output of 39.7 W against 28.49 W and,
363 37.71W of the base and 3-start rifled PVT system. The 6-start rifled PVT system has a 39.3%
364 and 5.3% higher thermal energy output than the base and 3-start rifled PVT systems at
365 maximum flow rate (2 kg/hr) and NA concentration (2%). It is seen that when the base PVT
366 system is modified into the 3-start rifled PVT system by adding 3 ribs, the thermal power
367 output enhanced. Similarly, when the 3-start rifled PVT system is modified into the 6-start
368 rifled PVT system by adding 6 rifled ribs, the thermal energy output further enhanced as
369 quantified in the above discussions.

370 Two factors can be considered as the reasons for this behavior: first, the rifled tube has a
371 higher heat transfer surface area compared to the plain tube, and secondly, due to the
372 centrifugal force, the rifled tube entails the fluid rotation and, in consequence, the mixing of
373 near-wall hot fluid with the cold fluid passing through the central region of the tube.

374



375
376

377 **Fig. 5.** Thermal energy output of the base, 3-start rifled, and 6-start rifled PVT systems at different
378 flow rates and NA concentrations.

379

380 Table 4 and Fig. 6 show respectively the thermal energy efficiency and overall energy
381 efficiency of the base, 3-start rifled, and 6-start rifled PVT systems for a range of nanofluid
382 flow rates (20-80 kg/hr) and NA concentrations (0-2%). It is seen that both parameters
383 increase with an increase in the flow rate and NA concentration. The minimum value of these
384 parameters has been achieved at a combination of the NA concentration and flow rate of 0%
385 and 20 kg/hr, while the maximum value is achieved at 2% and 80 kg/hr for all the three cases.
386 The reasons for an increase in the value of thermal energy efficiency and overall energy
387 efficiency with NA concentration and flow rate are similar to the case of thermal power.

388 In terms of quantitative value, it is evident from Table 4 and Fig. 6 that as the flow rate
389 increased from 20-80 kg/hr at a 0% NA concentration, the thermal energy efficiency of the
390 base, 3-start rifled, and 6-start rifled PVT system enhanced by 21.9%, 24.3%, and 24.4%,
391 while these values are 21%, 24.8%, and 25.2% at a 2% NA concentration for a similar range
392 of nanofluid flow rate. Again, the effect of increasing NA concentration at a given flow rate
393 has also been observed in terms of thermal energy efficiency. It is seen that as the NA
394 concentration increased from 0-2% at 20 kg/hr, the thermal energy efficiency of the base, 3-
395 start rifled, and 6-start rifled PVT systems improved by 17.1%, 19.9%, and 19.4%, while
396 these values are 16.3%, 20.4%, and 20.2% at the flow rate of 80 kg/hr for a similar range of
397 NA concentration. On the other hand, when the three cases are compared with each other, it
398 has been observed that the 6-start rifled PVT system achieved highest thermal energy
399 efficiency of 57.7% against 41.4%, and 54.8% of the base and 3-start rifled PVT systems at
400 the combination of maximum flow rate (80 kg/hr) and NA concentration (2%). This indicates
401 that the 6-start rifled PVT system has 39.4%, and 5.3% higher thermal energy efficiency than
402 the base and 3-start rifled PVT systems.

403 Coming to the overall energy efficiency behavior of the three cases of the PVT system, it has
404 been observed that the base, 3-start rifled, and 6-start rifled PVT systems achieved an overall
405 energy efficiency in the range of 64.66-78.04%, 72.66-92.08%, and 75.05-95.58% for the
406 range of flow rate (20-80 kg/hr) and NA concentration (0-2%). These ranges suggest that the
407 6-start rifled PVT system has generated 22.5% and 3.8% higher overall energy efficiency
408 when compared with the base, and 3-start rifled PVT system at a maximum flow rate (80
409 kg/hr) and NA concentration (2%). The reason for the dominance of the 6-start rifled PVT
410 system over the base, and 3-start rifled PVT system in terms of thermal energy and overall
411 energy efficiency is the same as explained for the case of thermal power.

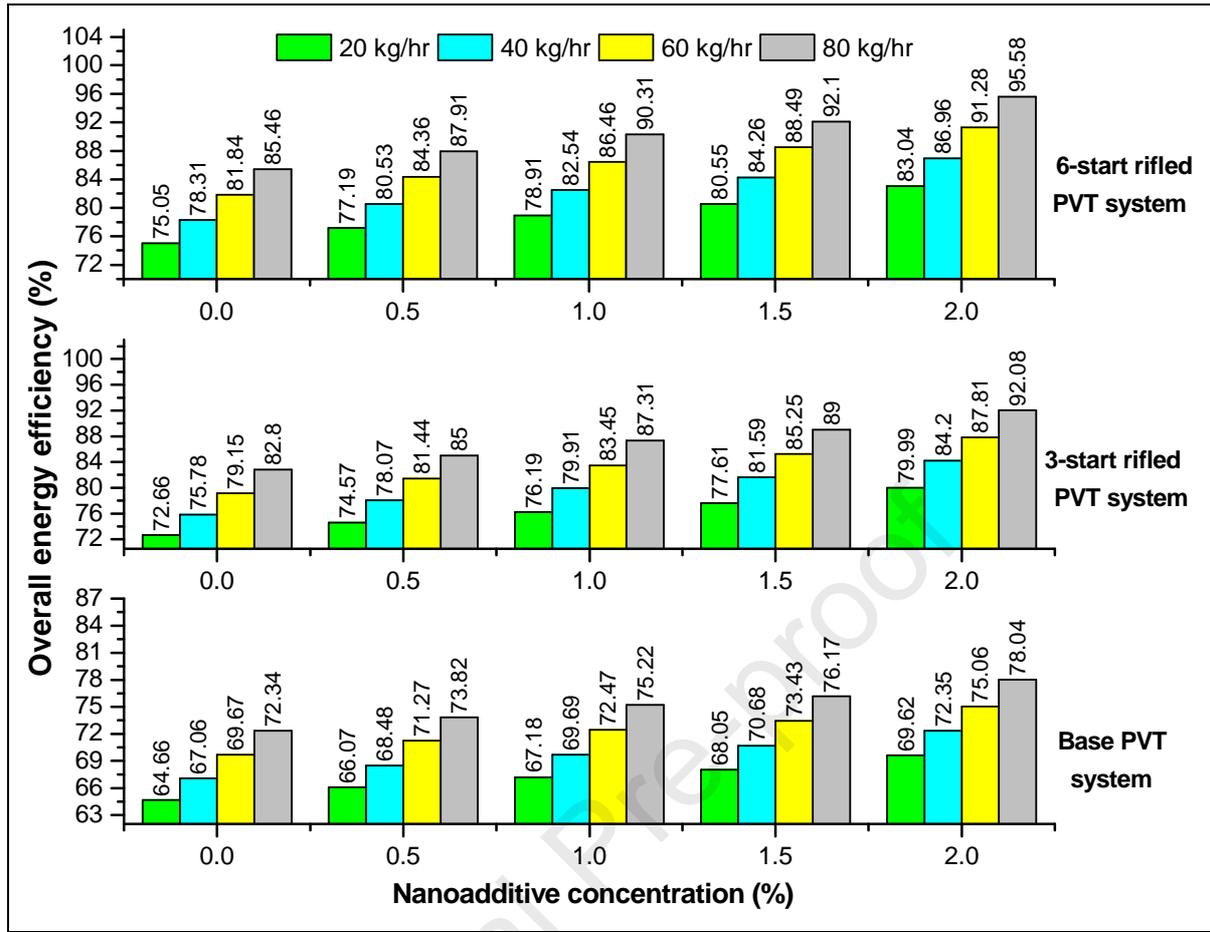
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413

Table 4. Thermal energy efficiency of the base, 3-start rifled, and 6-start rifled PVT systems at different flow rates and NA concentrations.

Mass flow rate (kg/hr) ↓	Base PVT system					3-start rifled PVT system					6-start rifled PVT system					
	NA concentrations (%) →	0.0	0.5	1	1.5	2.0	0.0	0.5	1	1.5	2.0	0.0	0.5	1	1.5	2.0
20		29.2	30.6	31.7	32.6	34.2	36.6	38.5	40.1	41.5	43.9	38.6	40.6	42.2	43.7	46.1
40		31.2	32.6	33.8	34.8	36.5	39.3	41.6	43.4	45.1	47.7	41.5	43.6	45.5	47.1	49.7
60		33.3	34.9	36.1	37.1	38.8	42.2	44.5	46.5	48.3	50.9	44.6	47.1	49.1	51	53.7
80		35.6	37.1	38.5	39.5	41.4	45.5	47.7	50.0	51.7	54.8	48.0	50.3	52.6	54.3	57.7

414



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417 **Fig. 6.** Overall energy efficiency of the base, 3-start rifled, and 6-start rifled PVT system at different
418 flow rates and NA concentrations.

419

420 6.2. Thermal exergy and its related efficiency

421 Figs. 7 and Table 5 display the thermal exergy output and thermal exergy efficiency gained
422 by the three cases of the PVT system under the influence of the nanofluid flow rates and NA
423 concentrations. It is shown that these three parameters for all the three cases increase with an
424 increase in flow rates (20-80 kg/hr) and NA concentrations (0-2%). The reason for an
425 increase in the value of these three parameters with an increase in the flow rate and NA
426 concentration is the same as explained in the sub-section 6.1. The minimum value of these
427 three parameters is achieved at a combination of NA concentration and flow rate of 0%, and
428 20 kg/hr, while the maximum is obtained for 2% and 80 kg/hr.

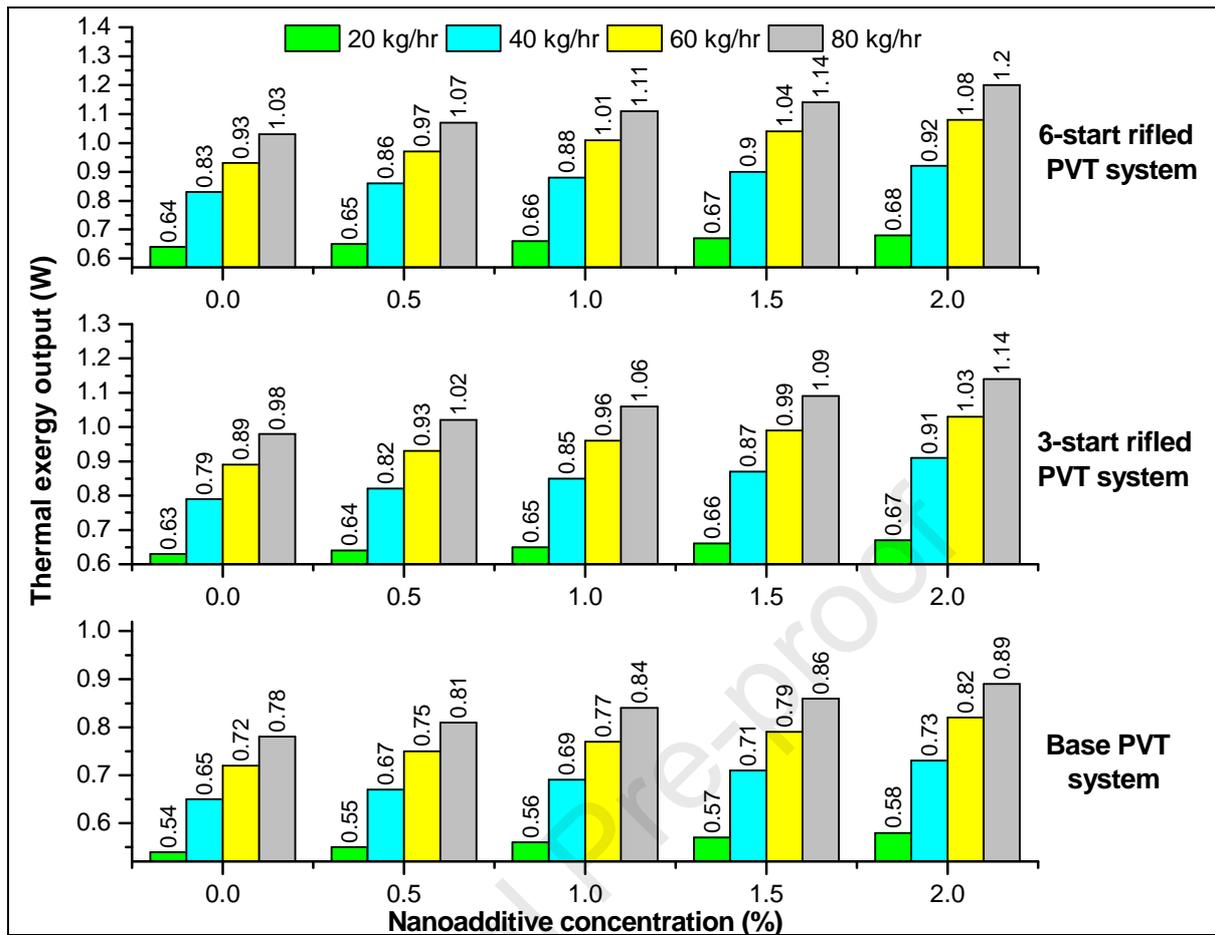
429 While observing the effect of increasing flow rate from 20-80 kg/hr at a given 0% NA
430 concentration, the thermal exergy output for the base, 3-start rifled, and 6-start rifled PVT
431 systems is enhanced by 44.4%, 55.5%, and 60.9% as shown in Fig. 7. On the other hand, at
432 2% NA concentration, these percentage enhancements are reported as 53.4%, 70.1%, and
433 76.5% under similar flow rate variations (20-80 kg/hr). Again, when the effect of increasing
434 NA concentration (0-2%) is observed at a given flow rate of 20 kg/hr, the thermal exergy
435 output for the base, 3-start rifled and 6-start rifled PVT systems is enhanced respectively by
436 7.4%, 6.3%, and 6.2%, while these corresponding enhancements at 80 kg/hr are observed to
437 be 14.1%, 16.3%, and 16.5%. Again, when these three cases are compared with each other, it
438 has been found that the 6-start rifled PVT system has gained a highest thermal exergy output
439 of 1.2 W against 0.89 W and 1.14 W of the base and 3-start rifled PVT systems at the
440 maximum flow rate and NA concentration of 80 kg/hr and 2%. It can be said that the 6-start
441 rifled PVT system has 34.8% and 5.3% higher thermal energy output than the base and 3-
442 start rifled PVT systems.

443 The effect of increasing flow rate at a given NA concentration and vice versa in terms of
444 thermal exergy efficiency is also evaluated in this investigation (Table 5). It is evidenced that
445 as the flow rate increased from 20-80 kg/hr at a given NA concentration of 0%, the thermal
446 exergy efficiency increased by 45.9%, 56.2%, and 60% for the base, 3-start rifled and 6-start
447 rifled PVT systems, respectively, whereas at 2% NA concentration, these percentage
448 enhancements are 53.6%, 72.3%, and 76.4%. Similarly, when NA concentration increased
449 from 0-2% at a given flow rate of 20 kg/hr, the thermal exergy efficiency increased by 8.7%,
450 6.2%, and 5.4% for the base, 3-start rifled and 6-start rifled PVT systems, whereas at 80
451 kg/hr, these percentage enhancements are reported as 14.5%, 17.2%, and 16.2%. The
452 comparison of the three cases shows that 6-start rifled PVT system has achieved thermal
453 exergy efficiency of 3.07% against 2.29% and 2.93% of the base and 3-start rifled PVT

454 systems at 80 kg/hr and 2% NA concentration, which means that the 6-start rifled PVT
455 system has 34%, and 4.7% higher thermal exergy efficiency than the base and 3-start rifled
456 PVT systems.

457 Fig. 8 displays the overall exergy efficiency achieved by three cases of the PVT system at
458 different flow rates and NA concentrations. The base, 3-start rifled, and 6-start rifled PVT
459 systems gained an overall exergy efficiency in the range of 25.99-27.71%, 26.63-28.82%, and
460 26.96-29.36% for the range of flow rate (20-80 kg/hr), and NA concentration (0-2%). The
461 ranges discussed with the help of the Fig. 8 is a clear representation of an increasing overall
462 exergy efficiency with the increase in flow rate and NA concentration for all the three cases.
463 These ranges also suggest that the 6-start rifled PVT system has the highest overall exergy
464 efficiency as compared to the other two configurations of the PVT system at any combination
465 of flow rate and NA concentration. It is seen that at 80 kg/hr of flow rate and 2% of NA
466 concentration, the 6-start rifled PVT system has generated 5.9%, and 1.9% higher overall
467 exergy efficiency than the base, and 3-start rifled PVT systems.

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471 **Fig. 7.** Thermal exergy output of the base, 3-start rifled, and 6-start rifled PVT systems at different
472 flow rates and NA concentrations.

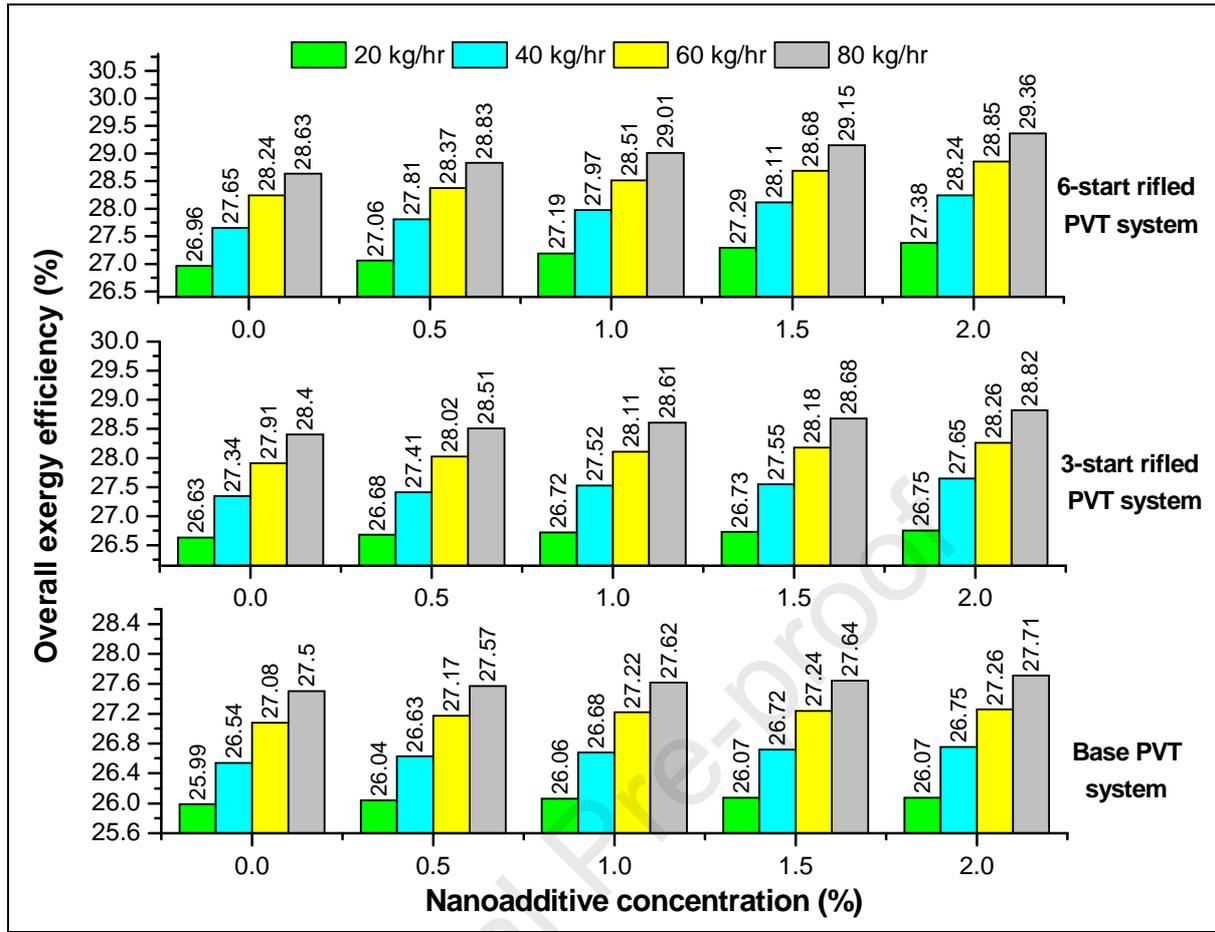
473

Table 5. Thermal exergy efficiency of the base, 3-start rifled, and 6-start rifled PVT systems at different flow rates and NA concentrations.

Mass flow rate ↓ (kg/hr)	Base PVT system					3-start rifled PVT system					6-start rifled PVT system				
	0.0	0.5	1	1.5	2.0	0.0	0.5	1	1.5	2.0	0.0	0.5	1	1.5	2.0
20	1.37	1.42	1.44	1.46	1.49	1.6	1.67	1.67	1.68	1.7	1.65	1.68	1.7	1.72	1.74
40	1.67	1.72	1.77	1.81	1.87	2.01	2.1	2.17	2.22	2.33	2.12	2.19	2.26	2.31	2.38
60	1.84	1.91	1.98	2.01	2.1	2.27	2.38	2.47	2.53	2.64	2.4	2.5	2.59	2.66	2.76
80	2	2.08	2.15	2.19	2.29	2.5	2.6	2.73	2.79	2.93	2.64	2.74	2.85	2.92	3.07

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478 **Fig. 8.** Overall exergy efficiency of the base, 3-start rifled, and 6-start rifled PVT systems at different
479 flow rates and NA concentration.

480

481 6.3. Electrical energy and its related efficiency

482 The concept of the PVT system was developed to reduce the operating temperature of the PV
483 module as the high value of the PV module temperature deteriorates its electrical efficiency.

484 So, in the present investigation, the temperature of the PV module and electrical power have

485 been initially observed without cooling it by nanofluid. Under this condition, the value of the

486 PV module temperature and electrical power have been observed as 346 K and 7.530 W. The

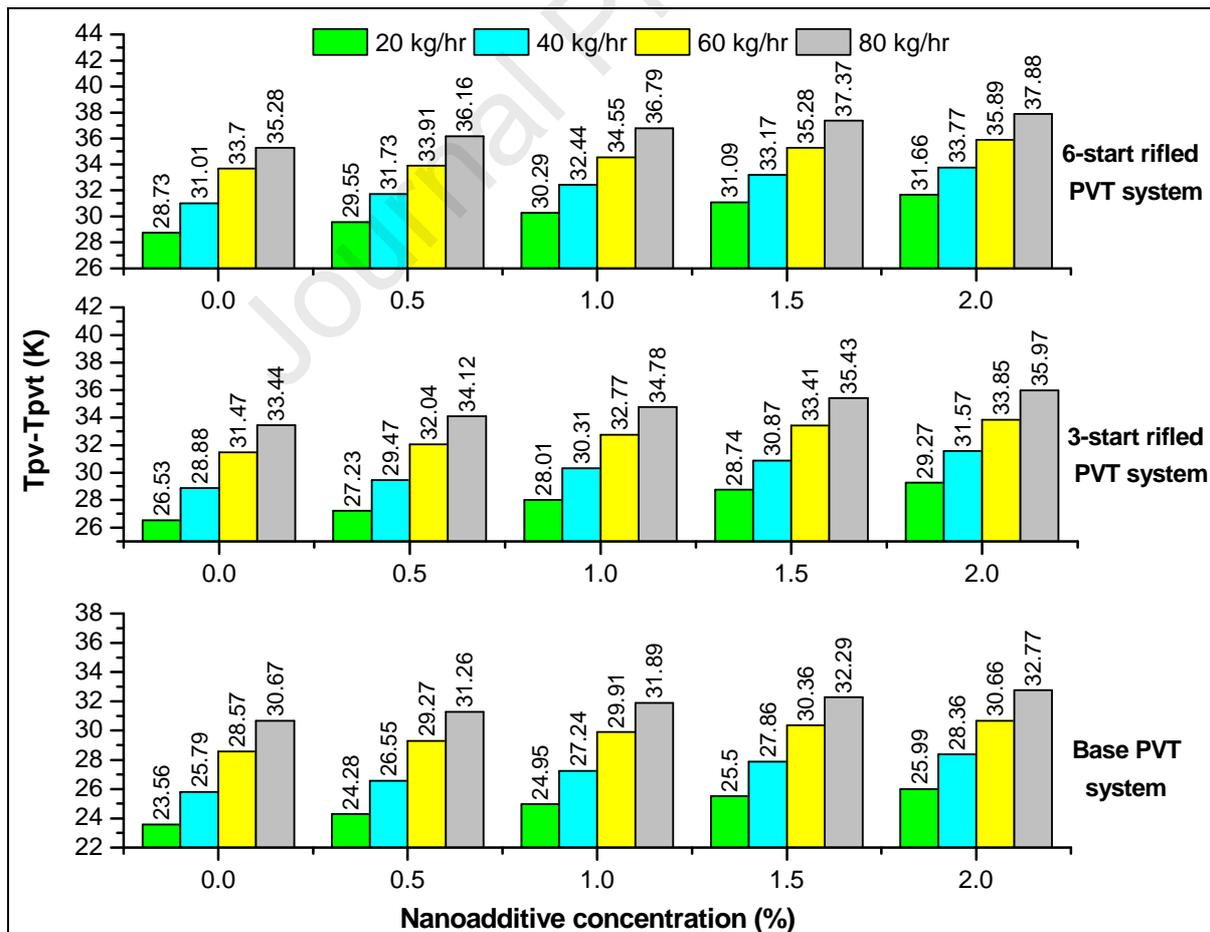
487 investigation has been further extended to monitor the difference of the PV module

488 temperature without cooling (T_{pv}) and the PV module temperature with cooling (T_{pvt}) for the

489 three cases of the PVT system as shown in Fig. 9. The value of $T_{pv}-T_{pvt}$ has been found in

490 the range of 23.56-32.77 K, 26.53-35.97 K, and 28.73-37.88K for the base, 3-start rifled, and
 491 6-start rifled PVT systems respectively when the flow rate increased from 20-80 kg/hr and
 492 NA concentration from 0-2%. It is seen that the $T_{pv}-T_{pvt}$ difference increases with the
 493 increase in flow rate and NA concentration for all the three cases. Fig. 9 further suggests that
 494 the maximum $T_{pv}-T_{pvt}$ difference has been observed at 80 kg/hr and 2% NA concentration
 495 for all three cases and the 6-start rifled PVT system has the $T_{pv}-T_{pvt}$ difference of 37.88 K
 496 which is 15.6%, and 5.3% higher than the base and 3-start rifled PVT systems, respectively.
 497 The reason for the higher $T_{pv}-T_{pvt}$ difference for the 6-start rifled PVT system over the base
 498 and 3-start rifled PVT systems is due to the efficient heat transfer from the back of the PV
 499 module due to the 6 rifled ribs.

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503 **Fig. 9.** $T_{pv}-T_{pvt}$ difference of the base, 3-start rifled, and 6-start rifled PVT systems at different flow
504 rates and NA concentrations.

505

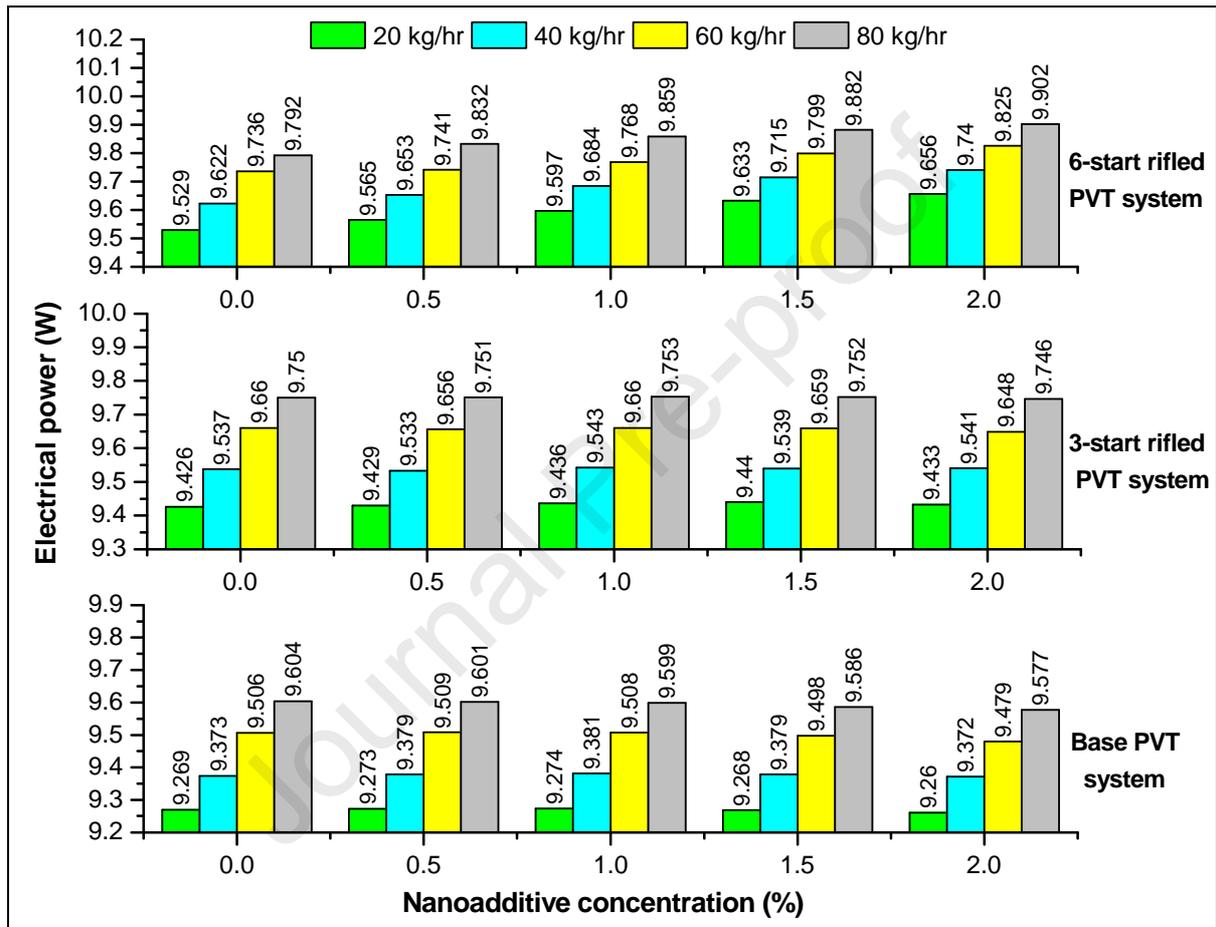
506 Fig. 10 and Tables 13 and 14 display the electrical power, electrical energy efficiency, and
507 electrical exergy efficiency achieved by the three cases of the PVT system under the
508 influence of the increasing flow rate and NA concentration. It has been observed that these
509 three parameters increase with an increase in the flow rate (20-80 kg/hr) at any given NA
510 concentration. When the flow rate increased from 20-80 kg/hr at 0% NA concentration, the
511 electrical power for the base, 3-start rifled and 6-start rifled PVT systems increased by 3.6%,
512 3.4%, and 2.8%, whereas at 2% NA concentration, these percentage enhancements are 3.4%,
513 3.3%, and 2.5%. The similar percentage enhancements are achieved in terms of the electrical
514 energy efficiency and electrical exergy efficiency for the three cases at 0% and 2% NA
515 concentration as the flow rate is increased from 20-80 kg/hr. The reason for the increase in
516 the electrical efficiency at a given NA concentration when the flow rate is increased from 20-
517 80 kg/hr is the higher efficient heat transfer. However, the behavior of the electrical
518 parameters is not consistent when the utilized three cases are compared with each other as the
519 NA concentration is increased from 0-2% at a given flow rate. This is because when the NA
520 concentration increases, both viscosity and thermal conductivity of the nanofluid increases
521 [24]. The increase in the viscosity results in high-pressure drop which causes high power
522 consumption. On the other side, the increase in the thermal conductivity improves the PV
523 cooling capacity and therefore increases the electrical power capacity of the PVT system. So,
524 it is seen that for the base case when the NA concentration increased from 0-2% at 20 kg/hr,
525 the electrical power, electrical energy efficiency, and electrical exergy efficiency decrease by
526 0.1%, whereas at 80 kg/hr, these parameters reduce by 0.3% because of higher power
527 consumption at 2% NA concentration compared to at 0% NA concentration, which

528 outweighed the significance of higher conductivity. However, for the 3-start rifled PVT
529 system, it has been observed that as the NA concentration increased from 0-2% at 20 kg/hr,
530 the electrical power, electrical energy efficiency, and electrical exergy efficiency increased
531 by 0.07% because of a better conductivity capacity of the nanofluid coupled with the effect of
532 3-start rifled ribs that resulted in a high electrical power from the PV module that
533 outperformed the problem of power consumption. However, these three parameters for the 3-
534 start rifled PVT system are decreased by 0.04% at 80 kg/hr because of the same reason as
535 explained for the base PVT system. In the case of the 6-start rifled PVT system, the electrical
536 power, electrical energy efficiency, and electrical exergy efficiency are increased by 1.3% at
537 20 kg/hr, and 1.1% at 80 kg/hr, as the NA concentration is increased from 0-2%. This is due
538 to the fact that the nanofluid coupled with the 6-start rifled ribs results in a better PV cooling
539 and hence a better electrical behavior.

540 Finally, this investigation shows that the maximum electrical power, electrical energy
541 efficiency, and electrical exergy efficiency achieved in the case of base PVT system is 9.604
542 W, 13.958%, and 25.498% at 0% NA concentration, whereas the counterpart values for the 3-
543 start rifled PVT system are 9.753 W, 14.175%, and 25.498% at a 1% NA concentration, and
544 for the 6-start rifled PVT system are 9.902 W, 14.398%, and 26.291% at a 2% NA
545 concentration. All these maximum values for the three cases have been achieved at the flow
546 rate of 80 kg/hr. This shows that the 6-start rifled PVT system has generated 3.1%, and 1.5%
547 higher electrical power compared with the maximum value achieved by the base and 3-start
548 rifled PVT systems. A similar percentage enhancement has been observed for the 6-start
549 rifled PVT system over the base and 3-start rifled PVT system in terms of electrical energy
550 efficiency and electrical exergy efficiency.

551 The main objective of the PVT system is to enhance the electrical performance of the PV
552 module. So, at the beginning of the study, the electrical power generated by the PV module

553 without cooling was observed and recorded as 7.530 W, and in the end, it is compared with
 554 the maximum electrical power generated by the three cases with cooling. So, the base, 3-start
 555 rifled, and 6-start rifled PVT system showed the percentage enhancement of 27.5%, 29.5%,
 556 and 31.5% of electrical power when compared with the PV module without cooling.
 557



558
 559

560 **Fig. 10.** Electrical power of the base, 3-start rifled, and 6-start rifled PVT systems at different flow
 561 rates and NA concentrations.

562

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Table 6. Electrical energy efficiency of the base, 3-start rifled, and 6-start rifled PVT systems at different flow rates and NA concentrations.

Mass flow rate (kg/hr) ↓	Base PVT system					3-start rifled PVT system					6-start rifled PVT system				
	0.0	0.5	1	1.5	2.0	0.0	0.5	1	1.5	2.0	0.0	0.5	1	1.5	2.0
20	13.471	13.477	13.478	13.470	13.458	13.700	13.703	13.713	13.719	13.710	13.850	13.903	13.949	14.001	14.035
40	13.623	13.631	13.634	13.632	13.620	13.860	13.855	13.870	13.863	13.867	13.985	14.030	14.075	14.121	14.157
60	13.816	13.820	13.819	13.804	13.777	14.039	14.033	14.039	14.038	14.022	14.152	14.158	14.197	14.243	14.280
80	13.958	13.953	13.951	13.932	13.919	14.171	14.173	14.175	14.174	14.165	14.233	14.291	14.329	14.364	14.393

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Table 7. Electrical exergy efficiency of the base, 3-start rifled, and 6-start rifled PVT systems at different flow rates and NA concentrations.

Mass flow rate ↓ (kg/hr)	Base PVT system					3-start rifled PVT system					6-start rifled PVT system				
	0.0	0.5	1	1.5	2.0	0.0	0.5	1	1.5	2.0	0.0	0.5	1	1.5	2.0
20	24.609	24.619	24.623	24.607	24.585	25.027	25.034	25.052	25.026	25.047	25.298	25.395	25.481	25.576	25.637
40	24.887	24.901	24.908	24.902	24.882	25.321	25.312	25.338	25.326	25.333	25.547	25.628	25.71	25.795	25.861
60	25.239	25.246	25.246	25.217	25.168	25.647	25.635	25.647	25.645	25.616	25.85	25.862	25.934	26.017	26.085
80	25.498	25.489	25.487	25.451	25.428	25.887	25.89	25.894	25.892	25.876	26	26.104	26.175	26.237	26.291

569

570 7. Conclusions

571 In the present experimental investigation, three cases of the PVT system were investigated for
572 various nanofluid flowrates and NA concentrations. These three cases are base PVT system,
573 3-start rifled PVT system, and 6-start rifled PVT system. It has been found that the increase
574 in the flow rate and NA concentration from 20-80 kg/hr, and 0-2% increases the thermal
575 performance of all three cases of the PVT system. Further, it has been found that the 6-start
576 rifled PVT system has achieved a maximum of 22.5%, and 3.8% higher overall energy
577 efficiency, and 5.9%, and 1.9% higher overall exergy efficiency than the base and 3-start
578 rifled PVT system, respectively. In terms of electrical performance, the base and 3-start
579 rifled PVT system, has achieved maximum performance at 0% and 1% NA concentrations at
580 the flow rate of 80 kg/hr, whereas for the 6-start rifled PVT system, the maximum electrical
581 performance has been achieved at 2% NA concentration and the flow rate of 80 kg/hr.
582 Further, it has been concluded that the 6-start rifled PVT system has achieved 3.1% and 1.5%
583 higher electrical power as compared with the base and 3-start rifled PVT systems. It is further
584 found that the 6-start rifled PVT systems has achieved 31.5% higher electrical power with
585 respect to the PV module without cooling as compared to its counterparts.

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593 Appendix A: Details of uncertainty analysis

594 - Pumping power:

$$\overline{\dot{E}_{elp}} = f(\overline{\dot{m}_{nf}}, \overline{\Delta p}, \overline{\rho_{nf}}, \overline{\eta_p})$$

$$u_{\dot{E}_{elp}} = f(u_{\dot{m}_{nf}}, u_{\Delta p}, u_{\rho_{nf}}, u_{\eta_p}) = \sqrt{\left(\frac{\delta \dot{E}_{elp}}{\delta \dot{m}_{nf}} u_{\dot{m}_{nf}}\right)^2 + \left(\frac{\delta \dot{E}_{elp}}{\delta \Delta p} u_{\Delta p}\right)^2 + \left(\frac{\delta \dot{E}_{elp}}{\delta \rho_{nf}} u_{\rho_{nf}}\right)^2 + \left(\frac{\delta \dot{E}_{elp}}{\delta \eta_p} u_{\eta_p}\right)^2}$$

$$\frac{u_{\dot{E}_{elp}}}{\dot{E}_{elp}} = \sqrt{\left(\frac{u_{\dot{m}_{nf}}}{\dot{m}_{nf}}\right)^2 + \left(\frac{u_{\Delta p}}{\Delta p}\right)^2 + \left(\frac{u_{\rho_{nf}}}{\rho_{nf}}\right)^2 + \left(\frac{u_{\eta_p}}{\eta_p}\right)^2} = 3.0\%$$

595

596 - Electrical energy efficiency:

$$\overline{\eta_{el}} = f(\overline{V_{pvm}}, \overline{I_{pvm}}, \overline{\dot{E}_{elp}}, \overline{I_{sol}}, \overline{A_{pvm}})$$

$$u_{\eta_{el}} = f(u_{V_{pvm}}, u_{I_{pvm}}, u_{\dot{E}_{elp}}, u_{I_{sol}}, u_{A_{pvm}}) = \sqrt{\left(\frac{\delta \eta_{el}}{\delta V_{pvm}} u_{V_{pvm}}\right)^2 + \left(\frac{\delta \eta_{el}}{\delta I_{pvm}} u_{I_{pvm}}\right)^2 + \left(\frac{\delta \eta_{el}}{\delta \dot{E}_{elp}} u_{\dot{E}_{elp}}\right)^2 + \left(\frac{\delta \eta_{el}}{\delta I_{sol}} u_{I_{sol}}\right)^2 + \left(\frac{\delta \eta_{el}}{\delta A_{pvm}} u_{A_{pvm}}\right)^2}$$

$$\frac{u_{\eta_{el}}}{\eta_{el}} = \frac{100}{I_{sol} A_{pvm} \eta_{el}} \sqrt{\left(I_{pvm} u_{V_{pvm}}\right)^2 + \left(V_{pvm} u_{I_{pvm}}\right)^2 + \left(-u_{\dot{E}_{elp}}\right)^2 + \left(\frac{\dot{E}_{elp} - V_{pvm} I_{pvm}}{I_{sol}} u_{I_{sol}}\right)^2 + \left(\frac{\dot{E}_{elp} - V_{pvm} I_{pvm}}{A_{pvm}} u_{A_{pvm}}\right)^2} = 5.19\%$$

597

598 - Thermal energy efficiency:

$$\overline{\eta_{th}} = f(\overline{\dot{m}_{nf}}, \overline{c_{p,nf}}, \overline{T_{nfo}}, \overline{T_{nfi}}, \overline{I_{sol}}, \overline{A_{pvm}})$$

$$u_{\eta_{th}} = f(u_{\dot{m}_{nf}}, u_{c_{p,nf}}, u_{T_{nfo}}, u_{T_{nfi}}, u_{I_{sol}}, u_{A_{pvm}})$$

$$= \sqrt{\left(\frac{\delta \eta_{th}}{\delta \dot{m}_{nf}} u_{\dot{m}_{nf}}\right)^2 + \left(\frac{\delta \eta_{th}}{\delta c_{p,nf}} u_{c_{p,nf}}\right)^2 + \left(\frac{\delta \eta_{th}}{\delta T_{nfo}} u_{T_{nfo}}\right)^2 + \left(\frac{\delta \eta_{th}}{\delta T_{nfi}} u_{T_{nfi}}\right)^2 + \left(\frac{\delta \eta_{th}}{\delta I_{sol}} u_{I_{sol}}\right)^2 + \left(\frac{\delta \eta_{th}}{\delta A_{pvm}} u_{A_{pvm}}\right)^2}$$

$$\frac{u_{\eta_{th}}}{\eta_{th}} = \sqrt{\left(\frac{u_{\dot{m}_{nf}}}{\dot{m}_{nf}}\right)^2 + \left(\frac{u_{c_{p,nf}}}{c_{p,nf}}\right)^2 + \left(\frac{u_{T_{nfo}}}{T_{nfo} - T_{nfi}}\right)^2 + \left(\frac{u_{T_{nfi}}}{T_{nfo} - T_{nfi}}\right)^2 + \left(\frac{u_{I_{sol}}}{I_{sol}}\right)^2 + \left(\frac{u_{A_{pvm}}}{A_{pvm}}\right)^2} = 4.43\%$$

599

600 - Electrical exergy efficiency:

$$\overline{\eta_{elex}} = f(\overline{V_{pvm}}, \overline{I_{pvm}}, \overline{\dot{E}_{elp}}, \overline{I_{sol}}, \overline{A_{pvm}}, \overline{T_{amb}})$$

$$u_{\eta_{elex}} = f(u_{V_{pvm}}, u_{I_{pvm}}, u_{\dot{E}_{elp}}, u_{I_{sol}}, u_{A_{pvm}}, u_{T_{amb}})$$

$$= \sqrt{\left(\frac{\delta \eta_{elex}}{\delta V_{pvm}} u_{V_{pvm}}\right)^2 + \left(\frac{\delta \eta_{elex}}{\delta I_{pvm}} u_{I_{pvm}}\right)^2 + \left(\frac{\delta \eta_{elex}}{\delta \dot{E}_{elp}} u_{\dot{E}_{elp}}\right)^2 + \left(\frac{\delta \eta_{elex}}{\delta I_{sol}} u_{I_{sol}}\right)^2 + \left(\frac{\delta \eta_{elex}}{\delta A_{pvm}} u_{A_{pvm}}\right)^2 + \left(\frac{\delta \eta_{elex}}{\delta T_{amb}} u_{T_{amb}}\right)^2}$$

$$\frac{u_{\eta_{elx}}}{\eta_{elx}} =$$

$$\frac{100}{I_{sol} A_{pvm} \eta_{el} \left[1 - \frac{4}{3} \left(\frac{T_{amb}}{T_{sun}} \right) + \frac{1}{3} \left(\frac{T_{amb}}{T_{sun}} \right)^4 \right]} \sqrt{\left(I_{pvm} u_{V_{pvm}} \right)^2 + \left(V_{pvm} u_{I_{pvm}} \right)^2 + \left(-u_{\dot{E}_{elp}} \right)^2 + \left(\frac{\dot{E}_{elp} - V_{pvm} I_{pvm}}{I_{sol}} u_{I_{sol}} \right)^2 + \left(\frac{\dot{E}_{elp} - V_{pvm} I_{pvm}}{A_{pvm}} u_{A_{pvm}} \right)^2 + \left[\left(\frac{-4T_{sun}^3 + 12T_{amb}^3}{3T_{sun}^4} \right) u_{T_{amb}} \right]^2}$$

$$= 5.21\%$$

601

602 - Thermal exergy efficiency:

$$\overline{\eta_{thex}} = f(\overline{\dot{m}_{nf}}, \overline{c_{p,nf}}, \overline{T_{nfo}}, \overline{T_{nfi}}, \overline{I_{sol}}, \overline{A_{pvm}}, \overline{T_{amb}})$$

$$u_{\eta_{thex}} = f(u_{\dot{m}_{nf}}, u_{c_{p,nf}}, u_{T_{nfo}}, u_{T_{nfi}}, u_{I_{sol}}, u_{A_{pvm}}, u_{T_{amb}})$$

$$= \sqrt{\left(\frac{\delta \eta_{thex}}{\delta \dot{m}_{nf}} u_{\dot{m}_{nf}} \right)^2 + \left(\frac{\delta \eta_{thex}}{\delta c_{p,nf}} u_{c_{p,nf}} \right)^2 + \left(\frac{\delta \eta_{thex}}{\delta T_{nfo}} u_{T_{nfo}} \right)^2 + \left(\frac{\delta \eta_{thex}}{\delta T_{nfi}} u_{T_{nfi}} \right)^2 + \left(\frac{\delta \eta_{thex}}{\delta I_{sol}} u_{I_{sol}} \right)^2 + \left(\frac{\delta \eta_{thex}}{\delta A_{pvm}} u_{A_{pvm}} \right)^2 + \left(\frac{\delta \eta_{thex}}{\delta T_{amb}} u_{T_{amb}} \right)^2}$$

$$\frac{u_{\eta_{thex}}}{\eta_{thex}} = \sqrt{\left(\frac{u_{\dot{m}_{nf}}}{\dot{m}_{nf}} \right)^2 + \left(\frac{u_{c_{p,nf}}}{c_{p,nf}} \right)^2 + \left(\frac{u_{T_{nfo}}}{T_{nfo} - T_{nfi}} \right)^2 + \left(\frac{u_{T_{nfi}}}{T_{nfo} - T_{nfi}} \right)^2 + \left(\frac{u_{I_{sol}}}{I_{sol}} \right)^2 + \left(\frac{u_{A_{pvm}}}{A_{pvm}} \right)^2 + \left(\frac{\delta \eta_{thex}}{\delta T_{amb}} \frac{u_{T_{amb}}}{\eta_{thex}} \right)^2} = 4.67\%$$

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Highlights:

- Energetic and exergetic performances of a nanofluid-based PVT unit are assessed.
- The unit is equipped with a sheet-and-rifled serpentine tube collector.
- Aqueous suspension of magnetite nanoparticles is considered as coolant.
- Energetic and exergetic performances of the unit intensify with boosting φ and \dot{m}_{nf} .
- Overall energy and exergy efficiencies of rifled PVT unit is better than base unit.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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