Received October 4, 2019, accepted October 25, 2019, date of publication October 30, 2019, date of current version April 6, 2020.

Digital Object Identifier 10.1109/ACCESS.2019.2950384

A Review: Emphasizing the Nanofluids Use in PV/T Systems

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This work was supported by the Taylor's University under Flagship Grant TUFR/2017/001/01.

ABSTRACT Certainly, photovoltaics (PV) is regarded as one of the most reliable and competitive energy production alternatives due to a massive decline in prices. Coming years are expected to witness PV systems leading the renewable electricity capacity growth by surpassing 550 GW. However, the efficiency of the enormous number of PV modules being produced and installed remains poor due to overheating. PV systems that are cooled using liquid coolants, popularly known as photovoltaic-thermal (PV/T) is a promising solution, but the inherent thermal conductivity of the conventional coolants being used makes it less attractive. Besides the evolution of next-generation PV modules and efficient designs, a breakthrough was made when nanoparticles successfully dispersed in coolants that led to better heat transfer and energy conversion. In recent years, hybrid nanoparticle-based fluids have helped augment heat transfer through PV panels. In this review, we discussed the evolution of PV/T system; difficulties faced in improving thermal and electrical production, and explain how the design modifications and hybrid nanofluids contribute in enhancing the system performance. In terms of the PV/T efficiency, we specifically highlight the role of hybrid nanofluids and the struggles arise from design to operation through 10 big questions and some possible solutions are also suggested to overcome those issues.

INDEX TERMS Solar thermal, hybrid nanofluids, channel flow patterns, channel geometry, heat transfer, thermal conductivity.

I. INTRODUCTION

Energy is the backbone of the economy and development of every country in the world. In the last decade, photovoltaic has undoubtedly revolutionised the non-renewable energy sector with unparalleled growth [1]. One of the primary reasons for its impact is access to solar radiation amounting to 1.8×10^{14}kW in the form of heat and light hitting the planet earth. However, the overheating of PV modules causes a drop in its efficiency and remain a significant challenge for engineers and scientists. Recently, scientists bring a lot of awareness about the working principle of PV cells by conducting different levels of experiments that result in a change in energy efficiency. To date, many researchers assume the execution of PV technology is better in the location-specific solar resources, which results in better yield in efficiency and performance. However, the solar cell efficiency varies with the effect of solar radiation intensity, solar panel position, panel installation, and temperature, which acts a ubiquitous part in driving the energy output of the PV cell [2]. In solar panels, with an increase in temperature, there is a gradual decline in energy output, which is in agreement with the thermodynamic law. Besides, the decrease in the PV cell performance is not only limited to temperature but also other factors such as mobility of charges, life span of minority charge carriers, saturation current and cell working conditions, which reveals the actual mechanism of PV cells behind the transformation of heat into energy [3]. Typically, the PV cell can convert about 4-17% of incident sun rays into energy based on the operating conditions and PV cell type.

Moreover, the fact is that over half of the incoming sun rays subjected to transform into heat due to the bandgap energy of the semiconducting materials, where the conversion of electricity does not take place once the cell reaches its

The associate editor coordinating the review of this manuscript and approving it for publication was Arash Asrari.

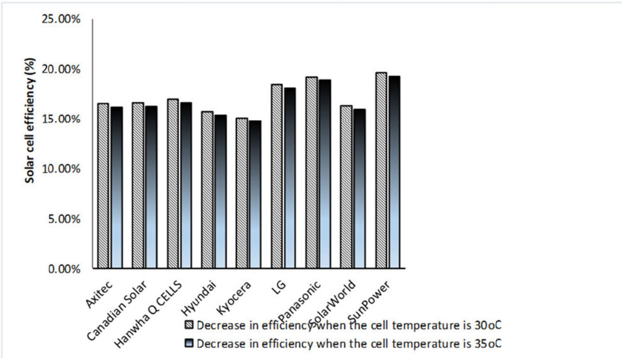

FIGURE 1. Change in solar cell efficiency with an increase in temperature.

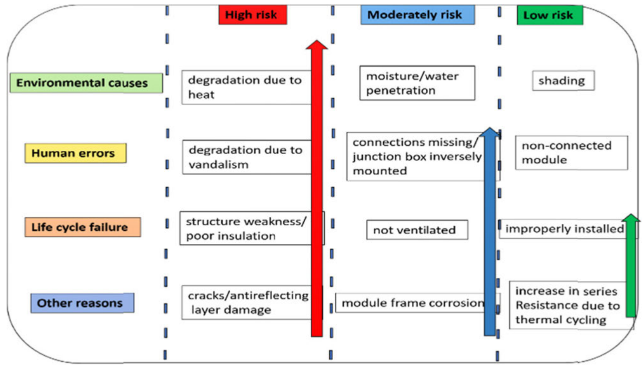

FIGURE 2. Different reasons that affect the performance of the PV module.

threshold photon energy. A thermal coefficient quantifies this loss, and this may vary from model to model depends on cell manufacturer. Generally, the testing of PV cells is conducted between the range of 15-35 °C to acquire maximum efficiency, and still, it can reach up to 65 °C, but the main concern is the productivity hindrance. The gradual decline in solar cell efficiency of different manufacturers compared with the rise of temperature represented in the **Fig.1**.

From the above Figure 1, it is observed that the cell efficiency drops by 15-20 with the rise in temperature. However, the decline in productivity will increase further with cell temperature at a higher temperature. The most critical parameter affected by temperature rise is the open-circuit voltage. The difference is percentage efficiency among various brands is due to a different intrinsic carrier concentration of semiconductor material used.

Nanofluids are the best possible solution to transfer the heat from the solar cell and helps to improve the performance of the system. Few studies that used different types of nanofluids to enhance the overall performance of the system discussed here. Elmir *et al.* [4] studied Al_2O_3-water nanofluids using numerical simulation by cooling the solar cell through forced convention. The results showed an increase in heat transfer up to 27% at low Reynolds number (Re=5) with the change in mass from 0.0% to 10% that causes increased cell performance. Teng *et al.* [5] investigated the effect of Al_2O_3-water nanofluid with different nanoparticle size, concentration on heat transfer at different temperatures and found that the smaller nanoparticle size shows good thermal conductivity. Interestingly, they observed that the heat transfer increases with the increase in temperature. Sundar *et al.* [6] found that the addition of Fe_3O_4 nanoparticles to water increased the convective heat transfer coefficient and friction factor. Duangthongsuk and Wongwises [7] reported that the TiO2-water-based nanofluids show an improvement of heat transfer coefficient from 6-11% with 0.2% volume of nanoparticles.

In this paper, we focus on different parameters that need to be considered to improve the efficiency and overall performance of the PV/T system. We through light on the nanofluids, PV/T system and reviewing all theoretical and experimental analysis of data that were mentioned in the literature. We also proposed some possible solutions to improve better efficiency and performance of the system and suggestions to work in the future.

II. REASONS THAT DOWNTURN THE CLEAN AND SURPASS ENERGY AMBITIONS OF PV MODULE

This section mainly elevates different reasons such as excess heating, failures caused due to external/internal factors and climatic changes that led to the downfall of the PV module and surpass the energy output.

Middle East countries especially, Saudi Arabia and Qatar are facing the highest solar radiation in the world, as these countries located near the Sun Belt. Solar energy's contribution to the world is endless and drastically increased the expansion of solar PV market globally, which meets the rising demands for electricity in developing countries [8]. However, many challenges left unanswered before the solar PV can establish its trademark for electricity generation in the world. During humid and hot conditions, the PV module may undergo stress, cell cracking and sometimes deformation of panel, cells. Rainy seasons and winter may form moisture or penetration of water inside the cell leads to short circuits, corrosion and increase in conductivity/resistance. Transportation, mishandling and human errors may cause cell cracking, packaging, installation and manufacturing.

The main reasons that are affecting the energy output of the PV module either by external and internal factors are delamination, back sheet adhesion loss, junction box failure, frame breakage, cell cracks, EVA discolouration, snail tracks, burn marks, potentially induced degradation and disconnected cell and string interconnect ribbons [9]. On the other side, these damages and defects caused by either environmental/physical factors, transportation failures, and manufacturer defects affect the performance. All the above parameters directly or indirectly interrelated to each other and show a considerable impact on the PV end result/performance. Based on the different reasons, the severity was scaled up under different categories were illustrated in **Fig. 2**.

Some of the possible solutions, we suggest is circulating the free air on installation types and gaps maintained under the panel to remove the heat that could increase solar deployment and enhance the energy output. Circulation of cooling water between the flow channels and panels will reduce the heat and improve the production also. The other simple way is using the light shaded/coloured materials for the panel fabrication to minimise heat absorption. Moreover, scientists are working continuously to overcome these challenges for better clean energy.

III. MILESTONES THAT PAVED THE WAY FOR THE EVOLUTION OF PV/T SYSTEMS

This section highlights the historical development of PV/T systems and the following paragraphs gives a brief description about various types of PV/T systems and different modifications introduced to improve the overall efficiency and performance of the system.

The combination of two different technologies, i.e., photovoltaics and thermal system into a single technology, known as PV/T that passed different obstacles and currently outspread its supremacy in the field of solar technology. The recent studies have shown various techniques to dissipate the heat from the photovoltaic modules. First time in the 1970s, researchers came with the evolution of PV/T, which was unfortunately restricted only to the discussion stage. A basic model of PV/T had made earlier to understand the fundamental elements and feasible studies. However, during the early 1990s, the research focus was diverted towards collector design and advancements to reduce the cost after the emerging of building an integrated model [10]. Scientists have shifted their attention on the evolution of new materials, designs, new strategies, testing and optimisation followed by an analysis of the system with the help of dynamic model and analytical tools from past one decade. The application of this technology is growing attractively in building integration PV/T systems [11]. Recently, the selection and deliberation of parameters such as thermal absorber design, choice of materials, manufacturing, coating techniques, testing, optimisation, safe and stable [10] propel the researchers in a better understanding of the technology and shaping it to satisfy the needs.

Several researchers conducted both experimental and theoretical analysis on the PV/T system performance with different modifications such as glazing [12]–[14], without glazing [15], channel arrangements [16], [17], environmental parameters [18] and optimisation of air channel depth [19], [20]. They found some impressive results, and few of them are discussing here.

Agrawal *et al.* reported air type transparent PV/T system throughout the year in India and the experimental studies cleared showed 1.8 years of the energy payback period for the system [13], [14]. Farshchimonfared *et al.* studied unglazed PV/T air collector to determine the channel duct and mass flow rates. The optimised PV/T air system showed that the energy required to operate the fans by the air duct delivery system was 23.4-27.2%. So, the energy needed to operate the fans must be taken into account while building the duct system for BIPVT [15]. Bambrook *et al.* conducted a study on PV/T unglazed, single-pass, open-loop type collector in Sydney and observed 28-55% of increasing thermal efficiency and 10.6% increasing electrical efficiency during early hours and 12.2% at midday with increasing air mass flow rate [12].

El-Amine Slimani *et al.* [16] investigated and compared four different configurations such as single photovoltaic module, a conventional air-PV/T, a glazed single pass PV/T and a translucent double pass PV/T to study the thermal and electrical performance of air type PV/T system. The daily average highest overall efficiency of 74% achieved by double pass PV/T. Ooshaksaraei *et al.* [17] designed four bifacial PV/T solar collector and conducted experimental studies at the steady-state condition. The results indicated that the second path parallel flow showed 51%-67% of highest total energy efficiency.

Alejandro del Amo *et al.* [18] designed air type PV/T system with and without fins and analysed the influence of environmental, dimensional and operational guidelines on the system performance. The results showed an increase in thermal efficiency and decrease in electrical efficiency with the help of glass covers. The parameters such as solar radiation intensity, the mass flow rate of air, and channel depth play a crucial role in the air type PV/T.

Singh *et al.* proposed a Genetic Algorithm method to analyse the enhancement in the efficiency of PV/T system optimisation. Factors such as length, depth of the channel, the velocity of air flowing into the channel, the thickness of the Tedlar and glass and the temperature of inlet fluid affecting the efficiency of the PV/T system. The results indicated that the 4.6% and 13.14% enhancement in the overall exergy and thermal efficiency noticed [19].

The above studies have shown the development of PV/T technology and their efforts to increase the efficiency of the system by considering several parameters. There is still more to explore and understand to develop a better and efficient system, which will open up further research gap to the next generation researchers.

Earlier studies showed that the usage of air and water extensively for the extraction of heat from PV modules and the technology has been progressed in the last three years. PV/T systems are classified into different categories based on their heat transfer techniques, absorber plate designs, and fluid flow systems used. Still, researchers are finding new possibilities to increase the system efficiency depending on their system design, configuration, working fluids and environmental and physical parameters that contribute/supports in improving the system performance either by externally or internally. The PVT technology still requires some amendments to improve its efficiency further, which will guide researchers to understand the development better soon. **Fig 3** below summarises various PVT system design, type, and parameters.

As the advancement of the technology, different PV/T systems with various modifications were introduced but still struggling to find a way to avoid degradation of PV cells and reuse/refurbish the used PV cells.

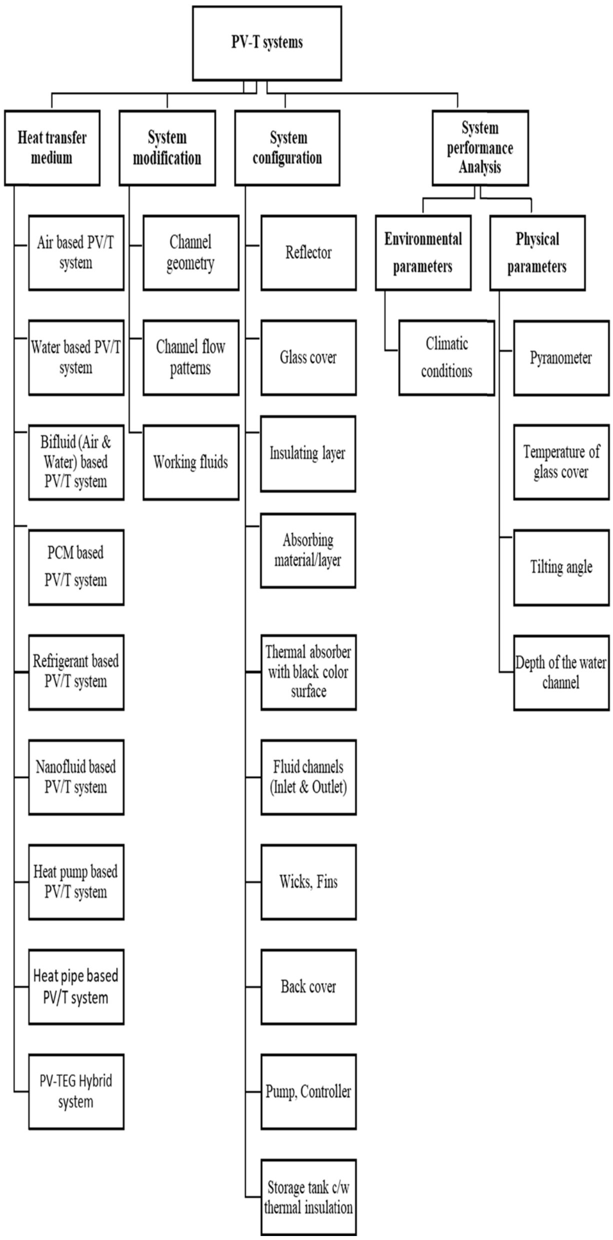

FIGURE 3. **Description of PV-T systems based on types, design, and parameters.**

IV. EFFECT OF HEAT EXCHANGER DESIGN ON THE PV/T SYSTEM EFFICIENCY

Since last few years, researchers have studied and developed novel techniques to enhance the thermal efficiency of the system.

Here, we critically address the issues of heat removal and increased heat transfer efficiency using different channel geometries and patterns that can protect the PV module from undesirable efficiency drop by cooling the PV surface temperature.

A. CHANNEL GEOMETRY

Channel geometry especially, channels of different sizes and cross-sectional shapes have a remarkable impact on the system efficiency by maintaining the solar cell temperature continually lower. The basic idea behind the implementation of channel geometry is to improve the availability of active area to heat transfer and reduce the thermal resistance. Generally, heat transfer enhancers have usually diminished the heat from the PV module using cooling agents such as fins, metal sheets, and wicks typically find in the middle/behind the panel. Fins are very simple in design and further divided based on their interaction with a single fluid tank or two different fluid tanks thermally. Moreover, it can be further categorised based on the surface attachment, roots in the heated/cooled walls and finally, they can be solid, porous and permeable [21], [22].

1) FINS

Fins are a kind of thin metallic strips that promotes the heat transfer rate from the panel surface to the fluid to improve the efficiency of the system [23]. Generally, fins are used when the conventional heat transfer coefficient is low. Sharma *et al.* [24] reported different types of fins with different shapes such as rectangular, triangular, cylindrical, trapezoidal, and parabolic. Velmurugan *et al.*, [25] described the attachment of fin to a simple one basin solar still with different materials such as black rubber, sand, pebble, sponge, and sand sponge of the same size to increase the productivity (**shown in Fig. 4a**). The data clearly showed an increase in yield of solar still is 73% for black rubber, 74% for sand, 71 % for pebble, 70% for the sponge, and 68% for a sand sponge for the fin. The increase in water temperature, solar intensity improves the productivity rate, whereas it decreases with wind velocity. Moreover, the fins acted as an extended surface. When sand is filled in between the fins, sand exhibited the highest productivity rate compared to other materials, which is due to the increase in water temperature to sensible heat of the sand. Jarimi *et al.* [26] examined a new kind of PV/T system containing two working fluids, which are experimentally validated using 2-D theoretical model. Moreover, to improve the performance of the system, two fins are set along the direction of airflow as presented in **Fig. 4b**. The results indicated that the collector energy-saving efficiency was about 58.1% for air and 62.31% for water as a working fluid. Bi-fluid in parallel approach at 0.0262 kg/s fixed airflow rate, and at 0.0017 kg/s lowest water flow rate, the working temperature of the PV cell was found to be 49.22 °C compared to 57.79 °C at similar lowest flow rate when performed under single water mode. Identically, under the bi-fluid way of operation when the water flow rate fixed at 0.0066 kg/s and 0.0074 kg/s lowest airflow rate, the average temperature of PV cell was found to be 51.42 °C and compared to 62.77 °C at similar lowest flow rate were recorded under single air mode.

Muhammad Zohri *et al.* developed a theoretical model to investigate the thermal and electrical efficiency of PV/T systems with and without fins. The results showed an increased thermal and electrical efficiency with fins compared to without fins [28]. Elsafi and Gandhidasan conducted

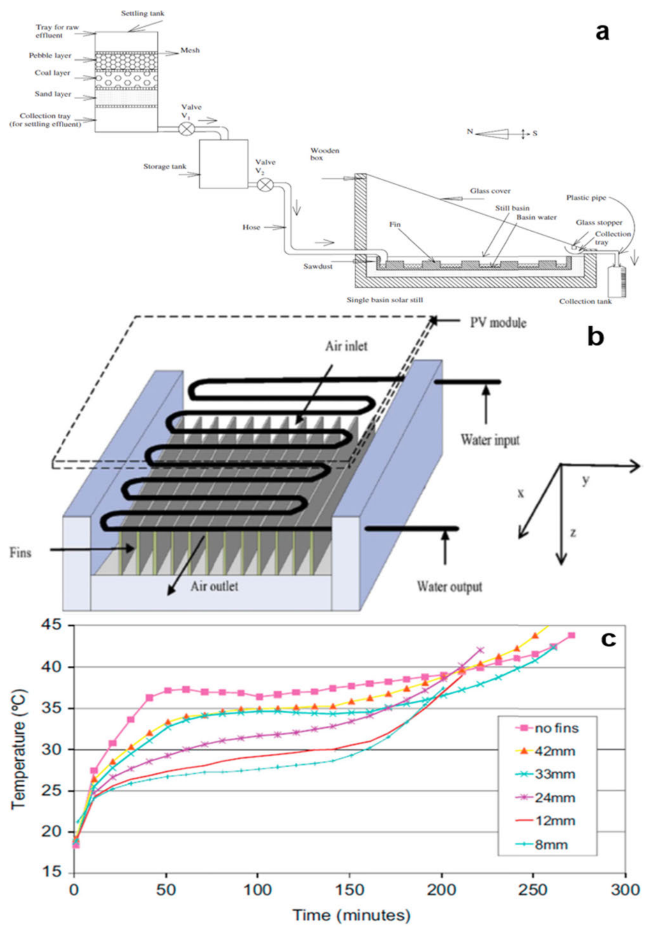

FIGURE 4. a) Pictorial representation of single basin solar still and experimental setup. b)Top view of bi-fluid PV-T collector [26] c) Fin height and spacing affecting the average surface temperature of PV panel [27].

comparative studies between double pass flat and compound parabolic concentrated PV/T systems with and without fins. The results showed an increased thermal and electrical gain of 3% and 8% for double pass flat and compound parabolic concentrated PV/T systems with fins compared to without fins [29].

Tonui and Tripanagnostopoulos [30], [31] designed a PV/T air system by inserting a fragile metal plate placed at the centre of the system at a very low cost to obtain higher overall efficiency. Furthermore, fins attached at the rear end of the panel plate, which helps to increase the heat transfer of the system.

Fin number, fin height, and fin thickness depend on different parameters such as outlet air temperature and pressure drop. Increase in fin number effects the outlet air temperature as well as the pressure drop that determines the system efficiency. More importantly, in the case of fin geometry, the orientation of the fin considered as a significant factor in improving the heat removal from the PV module. Huang *et al.* [27], described that the solar cell surface temperature greatly influenced by the fin height and fin spacing shown in Fig.3c. Till date, several numerical simulations and analytical studies performed on the use of different channel geometries, but still, only a few experimental works have reported [32], [33]. Therefore, there is a scope for the researchers to explore more on different channel geometries using empirical studies.

2) WICK TYPE

Wick type materials are usually porous and absorbing pads that commonly aid to remove the heat from the PV module and enhance cell efficiency. The sun rays hitting on the glass cover passes through and gets absorbed on to the wick surface. Several researchers worked on different wick type based solar still designs their results discussed below:

a: BASIN WICK TYPE SOLAR STILL

The fabrication of basin wick type solar still is straightforward, where the solar still placed inside a thermally insulated wooden box with a glass cover on top of it. In this type of solar still, jute and charcoal wick materials act as an absorber medium to enhance the productivity of the basin wick type solar still by removing the heat from PV module [34].

b: BASIN WICK TYPE SOLAR STILL

Simple construction and experimental setup (**Fig. 5a**) of floating wick type solar still was demonstrated by Al-Karaghouli and Minasian [35], which was potentially useful because of its high yield. The solar still was designed by blackened jute wick and aluminium black paper as a floating material. The floating wick type shows a higher output of 18% compared to the previous wick types during the hot summer season. This increased output is due to the sufficient water flux through the jute wick fibers. More importantly, the grooved shaped jute cloth helps to resolve the formation of salt scale on the basin of floating wick type solar still. Also, the capillary action of the jute fibers addresses the dryness issue of the wick during the sunny hours, which shows a good productivity rate as the black body has the highest heat-absorbing capacity compared to standard material.

c: MULTI-WICK TYPE OF SOLAR STILL

The construction of a multi-wick type of solar still is straightforward and requires less maintenance (**Fig. 5b**). The solar still is assembled using different materials such as evaporating wick, condensing wick and poly tetra fluoro ethylene (PTFE) net sandwiched, which has great potential due to its superior productivity [37]. Dhiman and Tiwari [38] concluded that the performance is improved by 10% due to the difference in heat transfer coefficient between the glass cover and water flowing on it and also the effect of water temperature in the still. Shukla and Sorayan [39] suggested that the change in internal heat transfer on the inner glass cover temperature was compatible with the experimental and theoretical data. They proposed analytical modelling to check the effect of water flowing over the glass cover of multi-wick type solar still.

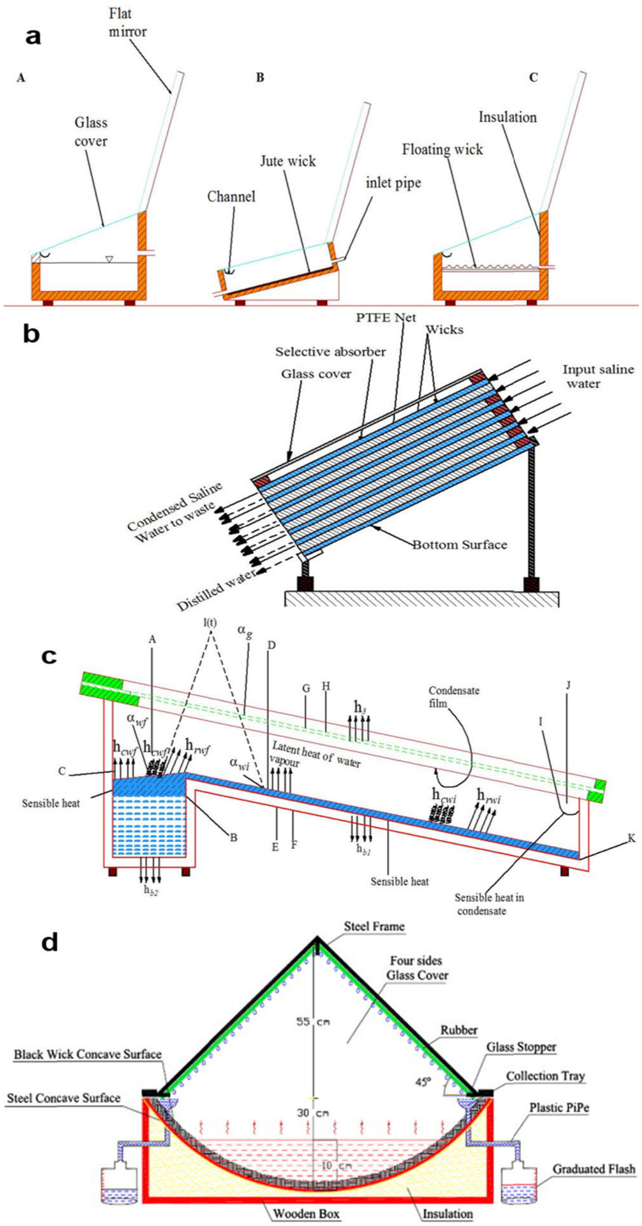

FIGURE 5. **Schematic representation of different wick types. a) Floating wick type still b) Multi-wick type solar still made of wick/PTFE net/wick layer units c) Side view of floating cum tilted wick type solar still d) Pictorial representation of concave wick type solar still [36].**

d: FLOATING CUM TILTED WICK TYPE SOLAR STILL

Janarthanan *et al.* [40] reported a novel and straightforward floating cum tilted wick type solar still construction (**Fig. 5c**). It consists of blackened jute and thermocol sheet as a wicking material. This shows an improved performance of the still due to the effect of water flowing over the glass cover, fast evaporation during sunny hours leads to a decrease in glass cover temperature and absorption capacity of jute wick surface. Other results also show a significant increase in the performance of single effect solar still by using different wick materials [41]. Mahdi *et al.* [42] reported that tilted wick materials could enhance the evaporation rate. It shows an increase of 53% daily efficiency of the wick-type solar still during sunny days in summer. There is a gradual decline in the still productivity due to the rise in salinity of the input saltwater.

e: CONCAVE WICK TYPE SOLAR STILL

Kabeel [36] proposed concave wick type solar still (**Fig. 5d**), where evaporation and condensation surface phenomenon was used to increase the performance of the still. The results indicate that the yield of concave wick type solar still increased by 4.1 L/m^2 with a maximum efficiency of 45% and an average efficiency of 30%. Hybrid PV/T systems are the combination of PV cell/module and solar collectors or solar stills. The advantage of using hybrid PV/T solar still or collector over the PV module is to increase the electrical efficiency and also boost the thermal demand per unit surface area by decreasing the cost and cleaning charges especially in the uncleaned areas such as desserts and seashores [43].

The above studies from different researchers highlight the mechanism of solar stills in increasing efficiency and technology with the integration of solar still/ collectors. Additionally, these solar still enhances the overall system efficiency by reducing the cell temperature and boost the thermal demand per unit surface area. Latest information related to channel geometry in different PV/T systems tabulated in **Table 1**. The improved designs and modifications in the PV/T system help to improve thermal efficiency.

Shiv Kumar and Aravind Tiwari fabricated hybrid PV/T solar still and tested under composite climate where DC pump was used to recirculate water between the collector to solar still. The results indicate that the electrical and overall thermal efficiency increased up to 20% compared to passive solar still [44].

Pounraj *et al.* [45] developed a hybrid PV/T active solar still and incorporated with solar PV powered Peltier system to improve the freshwater yield. The results showed that the hybrid solar PV/T still enhances efficiency by 30% compared to conventional passive still and higher efficiency of 38% than the conventional PV system.

B. CHANNEL PATTERNS

The flow distribution usually determined by the pressure loss related to the original path of the fluid, and it is quite natural that the fluid favours the low resistance path. The uniform distribution of fluid across the channels determined by minimising the pressure drop difference. So, it is very crucial to design the outlet flow and inlet flow to make any flow uniform, as its shape will decide how to flow gets distributed [58]. The PV-T system efficiency based on the flow distribution of the fluids through channel patterns [59]. The design optimisation of channel flow pattern is required for effective heat transfer from collector to heat transfer fluid that is possible with increasing heat transfer area to retention time. Naher *et al.* [60] introduced a new PV/T system with a pancaked shaped flow channel (**Fig. 6**). Thermal paste is used to attach the flow channel directly to the solar panel.

TABLE 1. Design of various flow patterns reported by the researchers.

Channel Geometry type	Result	Reference
PV/T based solar air heaters with and without fins	Fins help to reduce the PV module surface temperature from 82° to 66° C and showed excellent thermal and electric efficiency.	Kumar et al. [46]
Nano-fluid based PV/T system	Nano-fluid based PV/T system designed by fabricating spherical and helical channels, which shows the highest electrical performance of 20.57% for spherical and 37.67% for helical.	Karami & Rahimi [47]
Bifluid based PV/T system	PV/T system is the combination of air and water, which shows an electrical efficiency of 17% by experimental analysis.	Othman et al. [48]
Water type-based PV/T system	Unique design to investigate the PV/T system performance and achieved 80% maximum overall efficiency.	Nahar et al. [49]
Water type-based PV/T system	A hybrid PV/T system designed with absorber in parallel vertical tubes and an enclosure helps to achieve 12.7% of electrical and 36.32% of thermal efficiencies.	Hocine et al. [50]
Hybrid air-based PV/T system	An average of overall efficiencies of different PV systems developed by using a numerical model. The results showed 29.63% efficiency for PV-I, 51.02% efficiency for PV-II, 69.47% efficiency for PV-III, and 74% efficiency for PV-IV.	Slimani et al. [16]
Bifluid based PV/T system	A PV/T system was studied with the experimental validation of a theoretical method	Jarimi et al. [51]
PCM based PV/T system	The addition of nano-SiC to paraffin wax was used to design the Nano-PCM PV/T system to improve the system performance with 72% of higher thermal efficiency.	Waeli et.el. [52]
Heat-based PV/T system	A PV/T system was designed by nano-coated heat pipe plate, which reduced the cell temperature to 40°C and showed a maximum evaporative heat flux of 450 W/m^2.	Du[53]
Heat pipe/Heat pump-based PV/T system	Two different methods were used to optimize the performance study of heat pipe/heat pump system.	Chen et al. [54]
Heat pump-based PV/T system	A design was developed to optimize the ground source heat pump combined with a PV/T system.	Xia et al. [55]
Air type PV/T system	At 0.01 kg/s mass flow rate of air, it shows the average thermal efficiency of 26.68%, electric efficiency of 11.26% and overall thermal efficiency of 56.30%.	Tiwari et al. [56]
PV-TEG hybrid system	A selective absorber layer is placed between PV and TEG and found an increase in overall efficiency up to 13% with 6.2 °C temperature gradient between the TEG junctions.	Wang et al. [57]

The electric efficiency of the solar module enhanced by 2%, where the cell temperature decreases to 42°C with the suggested copper and aluminium flow channel. In this study, we can observe that the thermal paste helps to eliminate the air gaps between the PV panel and channel flow pattern to increase the heat transfer. Karami and Rahimi [47] studied increased heat transfer in a solar cell using Boehmite nanofluid. Different design of models namely, straight channel flow pattern and helical channel flow pattern (**Fig. 7**) used for cooling beneath the cell. The straight pattern contains 23 parallel rectangular channels whereas; helical is divided into four symmetrical patterns that show the better result

FIGURE 6. Design of pan-cake channel flow pattern.

obtained for average temperature and electrical efficiency of PV cells. It also proved that the straight channel shows a 39.70% drop in the average solar cell temperature with an electrical efficiency of about 20.57% for 0.1 wt% at a flow rate of 80 ml/min. In the case of the helical channel, it shows a decrease of 53.76% in the average solar cell temperature with 37.67% highest electric efficiency for 0.1 wt% at a flow rate of 80 ml/min. The data indicated that the decline in PV cell temperature for the straight channel is about 18.33 °C and 24.22 °C for helical channel reported better results for nanofluid when compared to water. We can observe that the helical channel pattern shows a higher reduction in solar cell temperature. This is due to more symmetrical patterns influence the flow rate, which resulted in higher heat absorption capacity from the PV cell and increased electrical efficiency.

Hussain *et al.* [63] introduced a hexagonal honeycomb-shaped flow channel pattern placed behind the PV/T panel horizontally into the channel to study the system performance. The hexagonal honeycomb channel designed by joining the five pieces of corrugated aluminium sheets together **(Fig. 7c)** and the primary purpose of this are to increase the system thermal efficiency. The system shows a thermal efficiency of 87% at an irradiance of 828 W/m^2 with a flow rate of 0.11 kg/s. In case of hexagonal flow pattern, the different ducts (square, rectangular and triangular) may affect the flow rate present inside the two-dimensional channels, which will slow down the flow rate resulting in the heat removal from the solar panel and increasing its efficiency.

Aste *et al.* [61] reported serpentine pipe and hard pipe channel flow patterns, **(Fig. 7d)** placed behind the PV cells to analyse the thermo-electrical performance of the system. They have restricted the boundary conditions to Nominal Operating Cell Temperature (NOCT), which acts as a reference to check the working behaviour of the module while in real terms. Yusof *et al.* [62] demonstrated the V-groove type of channel flow pattern, **(Fig. 7e)** made up of aluminium sheet with a thickness of 0.5 mm installed at the rare side of the solar panel. The system achieves a thermal efficiency of 71% at an irradiance of 828 W/m^2 with a flow rate of 0.11 kg/s. The experimental results suggest that the channel flow pattern plays a critical role to increase electric efficiency and to decrease the average solar module temperature as well. The design of different Channel flow patterns reported and represented in **Table 2**.

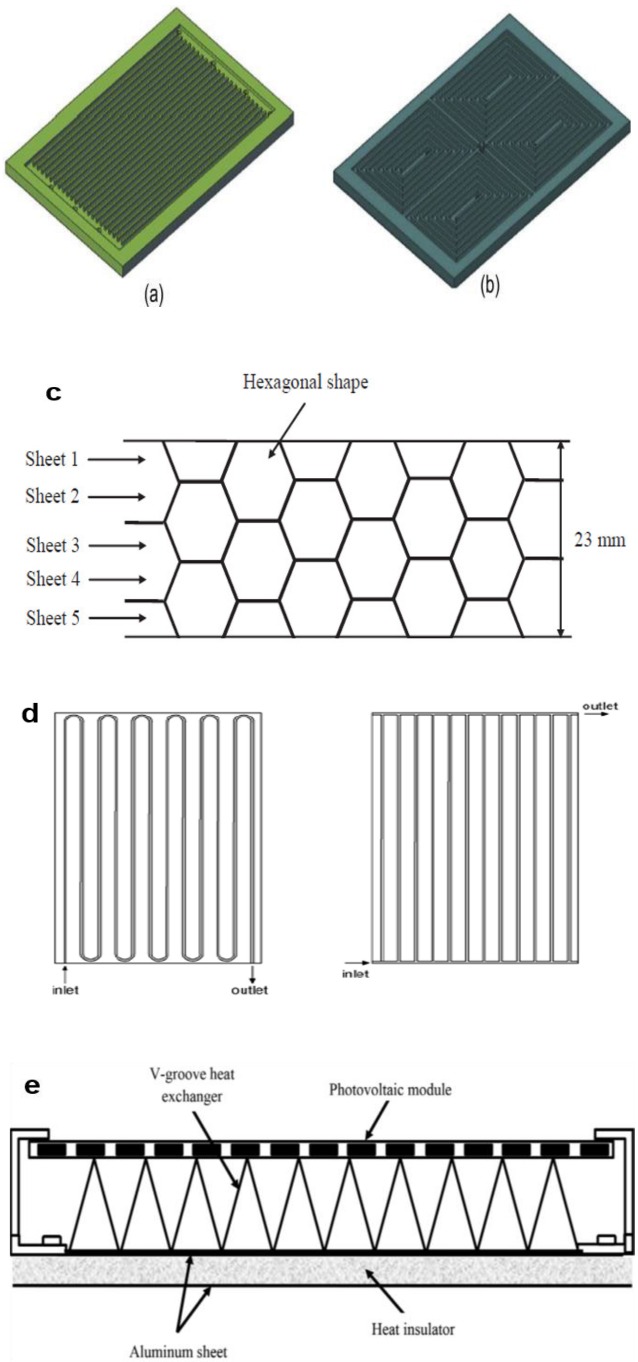

FIGURE 7. Channel flow design of a-e), a.) Straight b.) Helical [47] 7c) Design of Hexagonal honeycomb channel flow pattern (Hussain *et al.*, 2013) 7d) Design of serpentine pipe and hard pipe channel flow patterns [61]. 7e) Design of V-groove channel flow pattern [62].

Moreover, among all the channel flow patterns, we suggest that the honeycomb structure design is the best and showed an efficiency of 87% compared to the other type of designs. The main advantage of this pattern is non-uniform fluid flow at the entry of the honeycomb and the smooth walls inside the honeycomb restricts the coagulation of fluid in the tube or edges. This might be due to the complex structure designed by joining the five pieces of corrugated aluminium sheets together. The cross-sectional shapes of these honeycombs may be either square, circular, and regular hexagonal form or combination of all these. Computational fluid dynamics (CFD) helps to evaluate the effectiveness of honeycomb to reduce the swirl and turbulence level by studying the fluid flow simulation using the standard k-ε turbulence model.

More hybrid channel patterns have to be developed to maximise the efficiency and performance of the system.

TABLE 2. Design of various flow patterns reported by the researchers.

Flow patterns design	Flow rate	Thermal/electrical efficiency	Reference
Pan cake	0.0009-0.05 m/s	2%	Naher et al.[60]
Straight	80 ml/min	20.57%	Karami and Rahimi[47]
Helical	80 ml/min	37.67%	Karami and Rahimi[47]
Hexagonal honeycomb	0.11 kg/s	87%	Hussain et al.[63]
Serpentine and hard pipe	-	-	Aste et al.[61]
V-groove type	0.11 kg/s	71%	Yusof et al.[62]

V. IMPORTANCE OF NANOFLUIDS OVER CONVENTIONAL FLUIDS

The conventional fluids encounter difficulties in terms of poor thermal conductivity, which restrict their use in current heat transfer applications. Researchers come up with an alternative to overcome the defects of conventional nanofluids. This section explains how the use of nanofluid technology improved the PV/T system performance.

Generally, water, oil, and ethylene glycol are the most frequently used base fluids, which has an inherently limited heat transfer capability due to inferior thermal conductivity [64], [65]. The heat transfer capacity of conventional fluids increases with the addition of highly thermal conductive nano-sized particles into the base fluid [66]. The addition of nanomaterials to liquids is remarkably improving thermophysical and optical properties, including thermal conductivity, viscosity, oxidative stability, and specific heat capacity. Applied research involving metal cutting, heat exchangers, engine cooling, solar collectors, nuclear cooling, electronics cooling, etc., has uncovered tremendous commercialisation potential of nanofluids. Choi and Eastman coined the term '*nanofluid*,' which is the dispersion of nanometer-sized particles into the base fluid [67]. For the past few decades, scientists are focusing on nanofluids, which includes synthesis, characterisation, properties assessment, and applications of various combinations of nanoparticles in chosen base fluids [68]. Different types of nanoparticles such as metals (Cu, Ag, Au, Fe, Al, Ni), metal oxides (CuO, ZnO, Al_2O_3, MgO, SiO_2, TiO_2, ZrO_2, Fe_2O_3, Fe_3O_4), metal nitride (AlN, SiN), metal carbide (SiC), carbon materials (CNTs, SWCNTs, MWCNTs, Graphene, Graphite, Graphene Oxide, Diamond) are commonly used to improve the thermal conductivity, heat transfer properties and to achieve desired nanofluid stability. These metal and metal oxides synthesised using a one-step and two-step method. The best way for the production of metallic nanofluids is one-step, which can reduce the formation of agglomeration. The two-step method is systematic and useful for the development of nanofluids having metal oxide and carbon nanomaterials in it. This method uses ultrasonication, high shear homogenization, surfactants, and pH adjustment to achieve desired stability and restrain agglomeration.

The thermal conductivity of nanoparticles present in the nanofluids significantly relies on various characteristics such as type, size, shape, concentration, the stability of suspended nanoparticles, kind of base fluid, and the fluid temperature. [69], [70]. Homogenous nanoparticles dispersed in base fluids are well described and investigated before. Changwei Pang *et al.* [71] reported the suspension of Al_2O_3 (10-20 nm) and SiO_2 (40-50 nm) nanoparticles in pure methanol and at 293.15 K thermal conductivity was measured. The results indicated that at 0.5 vol%, Al_2O_3 and SiO_2 showed an enhancement of 10.74% and 14.29% over base fluid. O Manna *et al.* [72] reported the dispersion of 0-1 vol% Silicon carbide (SiC) nanoparticles in water-based nanofluids. The results indicated that at 0.1 vol% of nanoparticle thermal conductivity of nanofluid was raised to 12% and inverse dependence of conductivity on the particle size was prominent. KD2-Pro thermal analyzer used to measure the thermal conductivity of the fluids.

However, there are many drawbacks stated using single nanoparticle dispersion in the base fluids. The main concern was about the poor stability, clogging of nanofluids primarily through the passage of flow channels, which affects the performance of the thermal system under investigation. Additionally, the erosive/corrosive effect of nanoparticles on the walls of the flow channel influences the channel performance. The current research direction focuses on an alternate solution by utilising hybrid nanofluids due to their synergistic properties that potentially address the issues mentioned above. These hybrid nanofluids prepared by the suspension of hybrid nanoparticles into different conventional fluids applied for various application purposes.

Hybrid nanofluids have received considerable attention as a thermal/working fluid due to its excellent thermal properties. The conventional working fluids such as water, ethylene glycol, oil, ethylene/water mixtures are the most widely used fluids for the synthesis of hybrid nanofluids. The critical part during the synthesis of hybrid nanoparticles is maintaining the size (not >100 nm), which leads to the formation of stable hybrid nanofluids. However, based on the simulation, the practical use of nanofluids as a heat transfer fluid is only at the early research stage, and presently, people are focusing on understanding deeply about the changes introduced in the thermophysical properties and improving the heat transfer characteristics of fluids after the incorporation of nanoparticles. These nanofluids with synergistic properties used in cooling and heating systems. The heat extracted from the absorber plate transferred directly to the circulating fluid, which leads to an increase in efficiency and performance of the PV/T system. For cooling the photovoltaic panels, water, or air acts as a circulating fluid to increase the effectiveness of the solar cell [73], [74]. Moreover, to improve the cooling effect of the PV cell, the working fluids are now replaced with nanofluids due to their improved thermal behaviour. The effective thermal conductivity of nanofluids makes them a better substitute for base fluids to enhance system efficiency.

When compared to the existing nanoparticles, 2D materials performed better in all aspects and discussed in the next following section.

VI. HYBRID NANOFLUIDS APPLICATION IN PV/T

Stability remains a long-term puzzle that is still looking for answers, which can completely change the fate of hybrid nanofluids in practical applications. The main challenges and mechanisms related to hybrid nanofluid stability addressed here. Hybrid nanofluids are the most advanced engineered fluids, which improves the thermal conductivity of base fluids with the dispersion of various functional nanoparticles result in achieving excellent thermophysical properties and thus applied for a broad range of applications. To date, the poor dispersion stability of hybrid nanofluids considered as a long-term problem, which restricts their growth and practical applications in the research community. Several researchers made attempts and progress in improving the stability by implementing different techniques such as sonication, mechanical stirring, surface modifications, and by adding surfactants to address this issue, but still the dispersion challenges and the mechanisms by studying the forces that deployed between them remains debatable.

Dispersion Challenge and Mechanism: Hybrid nanofluids are complex in form, and after the synthesis, there are several parameters, challenges, and mechanisms need to be considered to make them stable. The most challenging part is the detection of microscopic forces, inter-particle forces, other surface modification agents and external factors (**Fig. 8 a-c**) that affects the kinetics and dispersion behaviour, which insist the formation of nanoparticle aggregation in the base fluid. The nanoparticle in the base fluid usually favours strong van der Waals forces of attraction; they attach and forms clumping because of size increment, and due to the density, a difference of gravity forces nanoparticles settle down [75]. Besides these forces, the inter-particle forces that act on the nanoparticle have played a crucial role in controlling the dispersion behaviour of nanofluid. In addition to this, nanomaterials with the large surface area such as rod-shaped, sheets comparatively to the spherical nanoparticles have a higher affinity to attract and form aggregates. In this case, the gravitational forces influence the dispersion behaviour relatively less than the Brownian forces before aggregation.

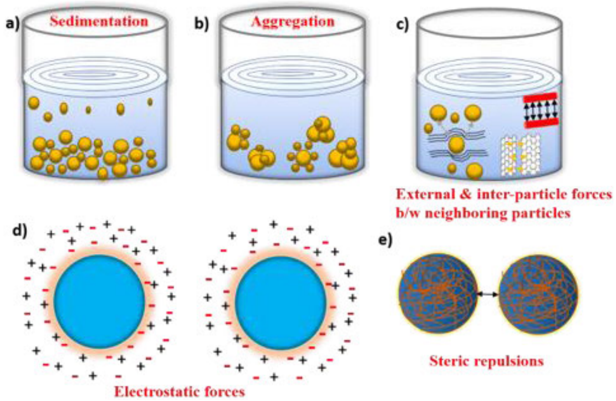

FIGURE 8. Schematic representation of nanofluid dispersion a) Density difference between nps and base fluid, the gravity force tends to sedimentation of nps, b) Various forces acting on the nps tends to aggregation, c) Forces acting on nps, interactions between neighbouring nps and interparticle distance between nanorods and sheets, d) Electrostatic forces, and e) Steric repulsions.

To obtain stable nanoparticles, the dispersion mechanism matters, and the complexity behind this mechanism have to understand. The first type of dispersion mechanism is electrostatic stabilisation (**Fig.8d**), where the repulsive forces between the nanoparticles with the same surface charges, either positive or negative, will encounter problems to produce stable nanoparticles. The main concern related to the mechanism is to neutralise the overall charges surrounded by the nanoparticles without affecting its structure or properties. This can be satisfied by using different approaches such as adsorption, the substitution of ions, disassociations of charges at the surface and depletion of electrons at the surface but the question is how efficiently it minimises the formation of aggregation. Moreover, Once, the aggregates are formed, it is challenging to redisperse it again. The second type of dispersion mechanism is steric stabilisation (**Fig.8e**), which applies to colloidal suspensions. The attachment of macromolecules/ polymer chain on the surface of the nanoparticle either by chemical bonding or by adsorption. The main problem with this stabilisation mechanism in water-based nanofluids is a narrow operating temperature range due to freezing and vaporisation of water. In case of oil-based nanofluids, it is a bit dominated by the formation of capping agents or polymer chains, but the reaction kinetics, morphology, size, and surface chemistry plays a critical role in the suspension of stable nanoparticles incompatibility with the base fluid [76].

For instance, carbon-based nanofluids, especially graphene oxide, graphene with their superior properties evolved as an efficient hybrid nanofluid, but the main challenging part is the formation of aggregation is easy because of their large surface area compared to other nanoparticles (Hamaker constant) and their structure (sheet). The other drawback with the multi-layered graphene sheets is the formation of strong inter-plane van der Waals attractions between the consecutive layers because of their large surface area, and importantly once the aggregation happens, the reaction cannot be altered. To overcome these issues, the surface modification of graphene sheets or addition of other surfactants favours to bind with other nanoparticles through non-covalent bonding (electrostatic, hydrophobic, and π-π interactions) and covalent bonding (OH, and COOH interactions). However, the concern is higher the volume of surfactant or surface modification on the sheet may damage the structure and function (thermal conductivity) of graphene, which leads to agglomeration. In point of practical applications, hybrid nanofluids tend to form agglomeration or even cause the degradation of nanofluids after reaching a specific temperature range. The other factor is the mixing process, which is a crucial element to attain stable dispersion but sometimes neglected.

Several researchers have reported different ways of enhancing the nanofluid stability by implementing distinct approaches such as addition of surfactants, surface modification techniques, and pH control.

Timofeeva *et al.* [77] studied the effect of surfactant on the silicon dioxide (SiO_2, 15 nm) nanoparticles dispersion behaviour in therminol 66 (TH66) to increase the heat transfer efficiency of base fluid. Different surfactants such as benzethonium chloride (BZC), benzalkonium chloride (BAC), and CTAB were used to improve the stability of the nanofluids. Nanofluids with BAC showed highest dispersion mechanism after 24h of visual appearance. However, the nanofluid without surfactant forms aggregation with larger size due to strong attraction between the nanoparticles. Finally, the nanofluids at higher temperature should not create any aggregation between the nanoparticles, where the thermal stability of the surfactant and the influence of nanoparticle properties onto the fluid is considered as a critical factor. Yang and Liu [78] prepared a stable SiO_2 functionalised with trimethoxysilanes (3-glycidoxylpropyl) in DI water-based nanofluids. These functionalised nanoparticles of 30 nm size and 10% wt show stability for 12 months. Moreover, these functionalized nanofluids showed better heat transfer coefficient than the conventional fluid (water) but no effect on heat flux. Modak *et al.* [79] investigated the influence of copper oxide (CuO) nanoparticles concentration on the heat transfer characteristics through experimental studies. They found an increase in Nusselt number by 14% and 90% with the (Cuo-water) nanofluid concentration of 0.15% vol and 0.60% vol. The optimal stability of the nanofluid is achieved at pH of 10.1 for a period of 60 h after the addition of sodium dodecyl sulfonate (SDS) surfactant.

Nanofluid based optical filters grabbed a lot of attention due to their properties such as heat transfer and thermal energy storage medium, especially in solar energy harvesting applications. The advantage of these nanofluid filters is to separate both PV and thermal systems, which can work at optimum temperature [80]. Hjerrild *et al.* [81] used hybrid (Ag-SiO_2/CNT) optical filters to improve the solar conversion efficiency in hybrid PV/T collector. The results showed an increase in optical efficiency by 58% for <$1L of nanofluid. An *et al.* [82] developed a concentrated PV/T collector with oleylamine based Cu_9S_5 nanofluid to test the spectral splitting filter. The results indicate an overall increase in efficiency by 34.2%, which is 17.9 times more than the system without the filter.

Authors suggest that the recent advancements in surface chemistry open a new route to understanding the dispersion mechanism of hybrid nanofluids and still researchers are working to find an effective way to tune their dispersion behaviour.

UV-Vis spectroscopy, Zeta potential, Sedimentation balance/ capturing and dispersion analyser centrifuge are some of the most widely used techniques to analyse the particle sedimentation and to analyse the nanofluid stability. Further, the mechanism of nanoparticles in enhancing the nanofluid thermal conductivity needs proper answers.

The possible solution to avoid such issues is either by sonication or using hydrothermal process, where metal oxide nanoparticles grow on the substrates (graphene sheet, carbon nanotubes, etc.). The production, function remains the same, and the formation of electrostatic or π-π interactions may also be possible.

VII. HOW DO THE 2D MATERIALS PERFORM COMPARED TO THE EXISTING NANOPARTICLES

2D materials, also known as ''wonder material,'' is commanding the nano-world because of their properties and constantly proving their potential in every aspect compared to the existing nanoparticles. These characteristics of 2D material dramatically affect the use of existing nanoparticles in practical applications, especially in heat transfer applications. The reason behind this might be a lack of potential, and these existing nanoparticles do not meet the researcher's expectations. The potential and domination of 2D materials over the existing materials highlighted here.

Recently, 2D nanomaterials are grabbing the attention of all researchers due to their physical, chemical properties and also because of their quantum size-effect [83], [84]. These fascinating materials include graphene (Gr), carbon nanotubes (CNTs), fullerenes (c60), transition metal dichalcogenides (TMDs), graphitic carbon nitride (g-C_3N_4), hexagonal boron nitride (h-BN), black phosphorous (BP), MXenes, Silicene, etc. transport heat, photons and charge carriers will be limited in the 2D plane, leading to prominent changes in the electrical and optical properties of the nanomaterials [85], [86]. These materials, due to their large surface area to volume ratio, they will exhibit better performance compared to the existing nanoparticles. In our review, we mainly concentrate on graphene nanomaterial and carbon nanotubes, their properties and applications as nanofluids in this section. Graphene hybrid nanofluids can be potentially studied and used as an efficient fluid in PV/T systems due to its advantages such as [87], [88]

(i) Easy to synthesis, (ii) Lower erosion, (iii) clumping, corrosion, (iv) Large surface area to volume ratio (1000 times larger), (v) High thermal conductivity (~5000 W m^{-1} K^{-1}), (vi) Increased heat transfer ability, (vii) Increased stability when compared to other existing nanoparticles (i.e., electrical), (viii) Mechanical and optical properties.

The above characteristics make these 2D nanomaterials perform better when compared to the existing materials. 2D nanomaterials especially, graphene due to its flexibility, lightweight, ultrathin, and conductive nature is highly recommended as a transparent conducting electrode, and as a Schottky barrier junction layer for silicon-based PV cells. Moreover, graphene is advancing as a transparent electrode in perovskite PV cells and other solar-based applications. 2D nanomaterials are progressing and emerging as ''tandem'' and ''hot carrier'' PV cells, and interestingly on-chip integrated designs of energy storage devices and energy harvesting applications. Comparatively, 2D nanomaterials are the potential candidates for satisfying the requirements and challenges for next-generation 2D photovoltaics at very less expenditure and high production rate [89]. Moreover, these conductive nanomaterials play a vital role in nanofluids to dissipate heat from the solar panel and attracting the interest of scientific communities than other nanoparticles.

Few examples were demonstrated to support the above statements.

Graphene-Based Hybrid Nanofluids: Recently, researchers are exploring different graphene-based hybrid nanofluids and different preparation techniques used, and dispersion of graphene-based hybrids into various base fluids such as water, oil, and ethylene glycol discussed under this section.

Aravind and Ramaprabhu [90] studied graphene/ MWCNTs/water hybrid nanofluids. Aravind and Ramaprabhu [91] reviewed graphene wrapped MWCNT composite for the preparation of water-based nanofluids by the solution-free green method. The results clearly showed an increase in thermal conductivity of 10.5% for graphene-MWCNT was more than the thermal conductivity of graphene 9.2% at 0.04% vol. The increased thermal conductivity was due to the formation of tightly bonded clusters, which can control the interface resistance due to higher thermal transport properties between them. Yarmand *et al.* [92] prepared ACG/EG, ethylene glycol-based hybrid nanofluids using pyrolysis and ball milling process and the results showed that the dispersion of 0.06% wt % ACG in EG increased the thermal conductivity by 6.47% at 40°C. In another study, Yarmand *et al.* [93] reported the Graphene nanoplatelets (GNP)/ Silver (Ag) hybrid nanofluids using a simple chemical process. The results indicated that 32.7% enhancement in Nusselt number and friction factor of 1.08 times with pumping penalty for 0.1% wt% at 17,500 Reynold number compared to distilled water. In both cases, graphene oxide was prepared from graphite flakes using Hummer's method and further reduced by chemical reduction. Zubir *et al.* [94] reported reduced Graphene Oxide (rGO) and formed hybrid complexes with other carbon sources such as Carbon Nanofibers (CNF), Multiwall Carbon Nanotubes (MWCNTs) and graphene nanoplatelets (GNPs) water-based hybrid nanofluids to improve the heat transfer process. The results clearly showed an increase in heat transfer with the use of hybrid nanomaterials compared to individual rGO.

Moreover, it indicated a 63% enhancement in heat transfer coefficient, and a 144% increase in Nu reported. Sundar *et al.* [95] studied Graphene Oxide (GO)/Cobalt Oxide (Co_3O_4) hybrid nanofluid by using in-situ method and chemical reaction. The data indicate an increase in thermal conductivity after the dispersion of hybrid nanomaterials in the base fluid, i.e., 19.14% for water and 11.85% for ethylene glycol at 0.2 vol% and 60°C temperature.

Water-based nanofluids and oil-based nanofluids have disadvantages such as polarity issues and narrow operating temperature range due to freezing and vaporisation of water. To overcome, these problems carbon-based hybrid nanofluids, mainly graphene nanomaterials are the best and most commonly used in recent times, particularly in the application of PV/T systems. This is due to their low density, high thermal conductivity, heat transfer ability, reduced erosion, corrosion, clogging in systems, solar thermal conversion capability and have been investigated as the fillers for thermal nanofluids [76], [88]. Due to their superior thermophysical properties and their fabrication process, graphene hybrid nanofluids have grabbed a lot of attention from all the researchers.

The above results clearly showed an improvement of thermal conductivity of hybrid nanoparticles over single nanoparticles. Interestingly, the combination of 2-D nanoparticles with metal oxides gives better results compared with other hybrids.

This study will give an overview of the 2D hybrid nanomaterials and their role as active enhancers in the conventional fluids to improve the thermal conductivity and efficiency of the PV/T systems. This enhancement might be due to the formation of bonding with the coexisting nanoparticles improves the thermal conductivity well, and this phenomenon is more observed between two carbon nanomaterials, where heat is transported easily from one carbon material to the other and reduce thermal resistance, which will increase PV/T system performance.

Moreover, the use of 2D nanomaterials and explore their properties, a thorough investigation is necessary to bring new applications in the field of PV/T related to heat transfer.

VIII. ANOMALIES AFFECTING THE HEAT TRANSFER

The primary factor that affects the heat transfer is the thermal conductivity of nanofluids. Besides, lack of consistency and the mechanisms behind this anomalous thermal conductivity changing the future of solar PV/T industry. The different mechanisms of heat transfer portrayed under this section.

A. NANOPARTICLE/LIQUID LAYER/INTERFACE

The development and significance of nanofluid properties mainly depend on the following key components: nanoparticle size, shape, concentration, and selection of nanomaterial. The well-known fact is that the nanomaterials such as graphene with high thermal conductivity will enhance the specific heat of the materials are advantageous for heat transfer applications. The surface-to-volume ratio is concise to nanoparticle size and importantly for smaller particles, the solid/liquid interface is more in the suspension, and the interfacial effect is stronger. Generally, the nanoparticle and fluid interactions expressed through interfacial thermal resistance called "Kapitza resistance," which increases as the interfaces function as a barrier flow and reduce the system thermal conductivity. The enhancement of one or more thermo-physical properties of designed fluids such as optical absorption and thermal conductivity termed as hybrid nanofluids. The dispersion of nanoparticles in the base fluids can transform the solar thermal area and used as direct solar absorbers due to their properties such as high thermal conductivity, enhance the heat transfer efficiency and optical properties. These solar absorbing nanomaterials in the suspension can convert solar to thermal energy. Besides, that several nanoparticles because of their superior properties in the aqueous solutions such as graphene due to its high light absorptance ability (**Fig. 9a**), gold by plasmonic effect have the efficiency in converting solar energy to steam.

B. BROWNIAN MOTION

The Brownian motion states that the movement of particles through a liquid where they collide with each other and transport heat energy from one to another resulted in increased thermal conductivity. Brownian motion plays a critical part in affecting the flow and heat transfer fluids. The general assumption is when the temperature rises, thermal conductivity also increases, but the fact behind this phenomenon was the smaller particles present in the nanofluid experience higher enhancement compared to bigger particles. So, when the temperature describes the overall kinetic energy of the particle, obviously the particle motion depends on the temperature [96]. This explains that the movement of particles depends on the particle size, so smaller the particle size higher the level of Brownian motion. Moreover, Brownian motion also represented by the particle diffusion coefficient D, stated by Stokes-Einstein formula:

$$D = \frac{K_B T}{3\pi \eta d} \tag{1}$$

where K_B indicates the Boltzmann constant, η indicates viscosity of the fluid, and d is the particle diameter. The effect of Brownian motion on the thermal conductivity outlined as the time scale of particle motion concerning heat diffusion in the liquid. Also, the movement of particles due to the Brownian motion was too slow in transporting the amount of heat through a nanofluid, and cannot be neglected [97], [98]. It stated that the Brownian motion is responsible for directing the thermal conductivity at the molecular or nanoscale level [99]. Furthermore, if the nanofluid to be an outstanding supplier of thermal conductivity, the Brownian motion would have to be a good effective heat transfer mechanism than the thermal diffusion in the fluid [100]. Hwang *et al.* [101] concluded when compared to the thermal diffusivity of base

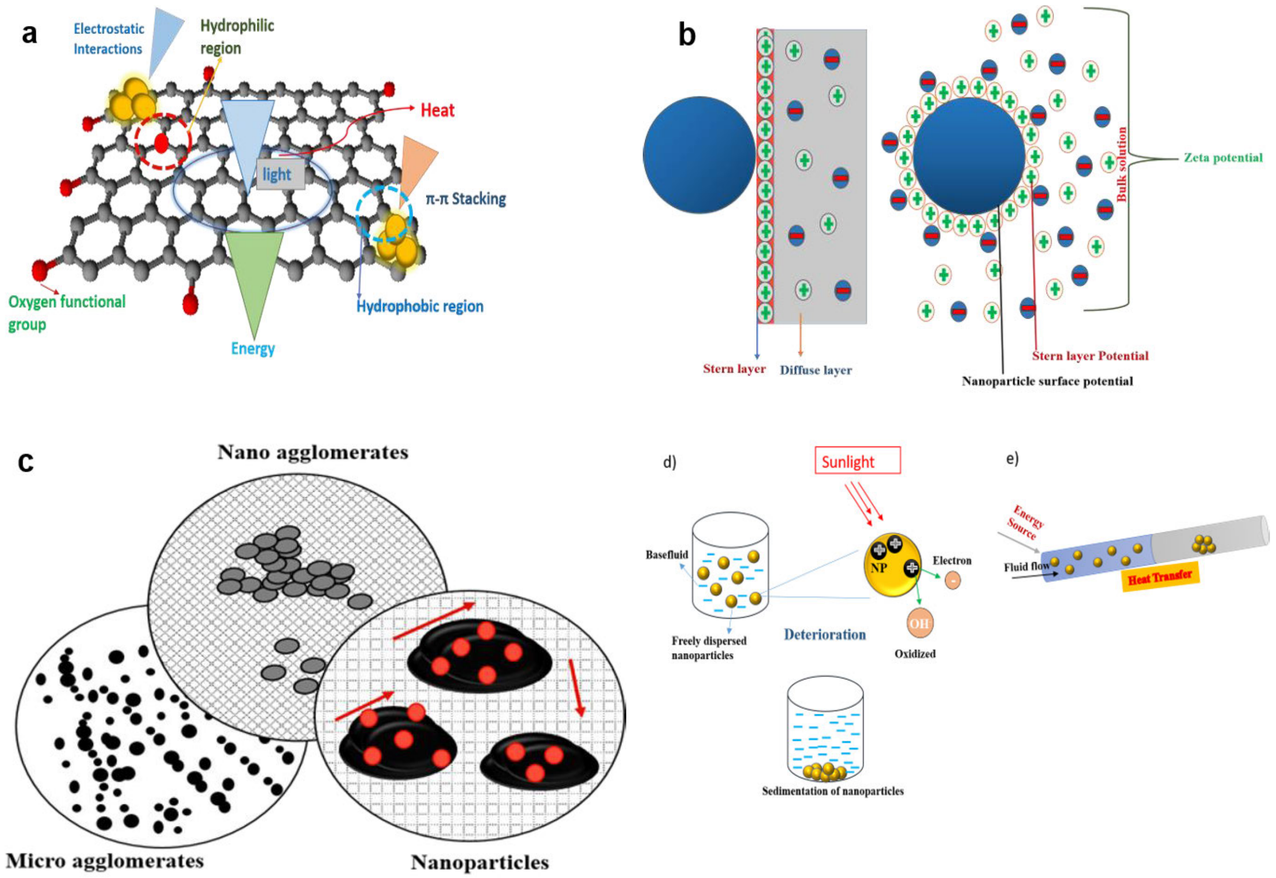

FIGURE 9. Pictorial representation of various mechanisms of thermal conductivity a) Graphene with high thermal conductivity and high light absorptance ability can act as efficient solar absorbers. The oxygen functions groups on the sheet play a vital role in the conversion of solar radiation into heat after the electrons jump from valence to conduction band. 9b) Interfacial interaction between nanoparticle surface charge and ions in the bulk solution. 9c) The nanoparticle, micro, and nanocluster formation and their behaviour under different conditions and their phenomenon behind nano-scale thermal transport. 9 d,e) Deterioration on heat transfer when d) nanoparticles are oxidised with base fluid, e) affects the channel flows of nanofluid.

fluids, the diffusion coefficients for nanoparticle, Brownian motion, and thermophoresis is negligible.

The single nanoparticles are moving freely through the base fluid, collide, and transport heat within the system. During the heat transfer of fluids, these nanoparticles may form clusters and can affect the heat transfer when compared to single nanoparticles, and these agglomerates change the thermal conductivity because of rich particle limited zones formation. This is due to the settling of clumping particles shows less thermal resistance to heat flow [102]. However, the suspended particles in the base fluid with a high dielectric constant are typically charged and prevented from joining due to electrostatic/repulsive forces. For example, if the carbon nanomaterials functionalized and dispersed in fluid; they develop a negative charge on the particle surface by ionisation method. When these functional nanoparticles dispersed in the fluid, the surface charge generated on the nanoparticles forms a repulsive force or van der Waals attraction that can dominate the potential barrier between them and overcome the aggregation to enhance the thermal conductivity (**Fig. 9b**).

C. AGGLOMERATION

Agglomeration is one of the potential issues, which shows an adverse effect on thermal conductivity enhancement. As the particle size increases, the rate of agglomeration increases leading to the formation of clusters, which result in low thermal conductivity enhancement and particle sedimentation. For the reduction of particle agglomeration, factors such as low volume concentration and small particle sizes need to consider for nanofluids. Also, the volume concentration of a cluster without the presence of other clusters volumes might be more significant than the physical amount of the particles [102], [103]. Heat can move more rapidly in such type of clusters, where the volumetric concentration of the particles within the group is higher than the volume of solid (**Fig 9c**). The thermal conductivity of aggregate, of course, less compared to the thermal conductivity of the nanoparticle. This is because the decrease in thermal conductivity of the aggregate relative to nanoparticle will not be considered unless the nanoparticle conductivity is good enough [100].

D. DETERIORATION

Deterioration of heat transfer performance is one of the significant problems, which can be predicted due to particle settling, particle agglomeration, and a surface deposition during boiling experiments [104]–[107]. Xue *et al.* [108] reported a deterioration of thermal performance when they used 1 vol% of carbon nanotubes in an aqueous solution instead of pure water in a closed thermosiphon. At higher particle concentration, the deterioration in thermal performance was high when compared with that at low particle concentrations. This is due to the dispersion of carbon nanotubes in the water, which cause a rise in increased surface tension. The addition of carbon nanotubes changes the solid-liquid-vapour interfacial properties, improve the boiling point mechanism and therefore, deteriorate the boiling heat transfer. Narayan et al. [107] described that deterioration could be determined or controlled by using surface conditions.

The deterioration of heat transfer may be happening due to two possible reasons. The initial cause is when the nanoparticles attain energy from an external source or sunlight they subjected to get oxidised with the base fluid, which results in settling of nanoparticles shown in **Fig. 9d**. The other case is the heat transfer of nanofluid through the channel may result in aggregation of nanoparticles is shown in **Fig. 9e**. Moreover, the heat flux and mass flow rate of nanofluid potentially considered as the main factor that controls the heat transfer deterioration.

IX. HEAT TRANSFER ENHANCEMENT USING NANOFLUIDS

A. HEAT TRANSFER ENHANCEMENT USING NANOFLUIDS

Most of the hybrid nanofluids studies used in heat transfer applications are widely investigated and experimentally performed. Most of the studies reported that the main parameters affecting the thermal conductivity improvement are due to the large surface area, variation in thermal boundaries, and particle rearrangements.

Baby and Ramprabhu [109] synthesised Ag-HEG dispersed in water-based hybrid, which shows an increment of ∼21% of heat transfer at 25 °C for 0.05 vol% compared to base fluids. The increase in heat transfer is due to the increased thermal conductivity of hybrid nanofluids, and other factors such as particle rearrangements, large surface area and also variation in thermal boundaries are even playing a critical role.

In another study, Baby and Ramprabhu [110] produced (fMWCNT/f-HEG)/water hybrid nanofluids. They found 289% increase in heat transfer for 0.01 vol% of hybrid nanofluids at 15,500 Reynolds number compared to the base fluid. Later, Baby and Ramaprabhu [111] reported Ag/MWCNT-HEG dispersed in ethylene glycol-based hybrid nanofluids. They observed ∼570% heat transfer coefficient improvement for 0.005 vol% with Re =250 at pipe inlet that is due to the high surface area of hybrid nanomaterials in the solution.

Ho *et al.* [112] studied Al_2O_3 and MEPCM nanoparticles based hybrid nanofluids and their cooling characteristics with different weights into a heated copper tube having $d_{in} = 0.0034$m (inner diameter), and the $d_{out} = 0.004$m (outer diameter). They have observed the hybrid nanofluids improvement on cooling efficacy was more significant compared to water, nanofluid alone, and pure PCM suspension.

Suresh *et al.* [113] synthesised 0.1 vol % of Al2O3-Cu dispersed in water-based hybrid nanofluids showed convective heat transfer and pressure drop through the circular tube under laminar flow. They observed an increase in heat transfer performance of hybrid nanofluids than the pure water. Moreover, the results indicated that the hybrid nanofluid cause additional penalty in pumping power than Al_2O_3/water and also preferred correlation for Nusselt number based on the experimental studies and friction factor of −3% and +5% with maximum deviations for Nusselt number:

$$Nu = 0.031(RePr)^{0.68}(1+\emptyset)^{95.73} \tag{2}$$

$$f = 26.44Re^{-0.8737}(1+\emptyset)^{156.23} \tag{3}$$

The equations (2), (3) are a function of Reynolds number, Prandtl number, and particle concentration.

In another study, Suresh *et al.* [114] prepared 0.1% Al2O3-Cu/water hybrid nanofluids and analysed their heat transfer feature and pressure drop passing through a copper tube under turbulent flow. They have reported that the hybrid nanofluid shows an increase in heat transfer up to 8.02% in the tube than water and higher friction factor compared to Al_2O_3/water. Selvakumar and Suresh [115] prepared 0.1 vol% of Al_2O_3-Cu dispersed in water-based hybrid nanofluids as a coolant for the thin-channelled copper heat sink. The results reported an increase in heat transfer 25% at 0.0178 kg/s mass flow rate than water and a volume flow rate of 0.02245 l/s, the pressure drop increased by 14.25%.

They developed a new correlation equation:

$$Nu = 0.03124Re^{0.2351}Pr^{0.7341}(1+\emptyset)^{145.61} \tag{4}$$

Sundar *et al.* [116] reported 0.1, 0.3 vol% of MWCNT-Fe_3O_4/water based hybrid nanofluids passing through a circular tube under turbulent flow. The hybrid nanofluids showed 31.1% increase in Nusselt number and friction factor of 1.18 times at 0.3% concentration compared to water at Re = 22,000. The factors such as Brownian motion, large surface area, thermo-physical properties affect the enhancement of Nusselt number. The authors proposed correlations for friction factor and Nusselt number based on experimental studies:

$$N = 0.0215Re^{0.8}Re^{0.5}(1+\emptyset)^{0.78} \tag{5}$$

$$f = 0.3108Re^{-0.245}(1+\emptyset)^{0.42} \tag{6}$$

The equations (5), (6) are as a function of Prandtl number, Renolds number and nanoparticle concentration with an average deviation for the Nusselt number is of 6.75% and for friction factor was 2.24%.

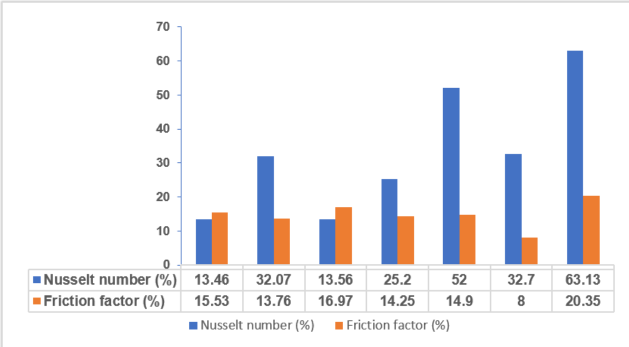

FIGURE 10. Comparative studies between friction factor % and Nusselt number % of hybrid nanofluids from different researchers.

Madhesh *et al.* [117] studied the rheology and heat transfer behaviour of Cu-TiO_2 hybrid nanofluids ranging from 0.1% to 2.0% volume concentration passing through tube-in-tube counter flow heat exchanger. The results showed 52% of heat transfer coefficient enhancement, 49% of Nusselt number, and overall heat transfer coefficient of 68% respectively at 1.0 vol% of hybrid nanofluids. Also, reported that the pressure drop of 14.9% and a friction factor of 1.7% of hybrid nanofluids at 2 vol%, which indicates a penalty in the pumping power. The increase in convective heat transfer and Nusselt number was due to the presence of increased thermal conductivity and reduced thermal resistance of Cu and TiO_2 nanoparticles in the nanofluid flowing on the surface wall of the inner tube.

They developed a new correlation for Nusselt number as a function of Reynolds number, Prandtl number, and nanoparticle concentration, with 17% average deviation.

$$Nu = 0.012RePr^{0.333}\text{Ø}^{0.032} \tag{7}$$

The experimental studies regarding the improvement of the heat transfer and the proposed correlations for the Nusselt number and friction factor of hybrid nanofluids are shown in **Fig. 10** and **Table 3**.

Experimental studies report the improvement in thermal performance of different heat exchangers after the usage of hybrid nanofluids as working fluids at various concentrations. The primary reasons for the advancement of thermal performance and thermal conductivity of hybrid nanofluids were due to Brownian motion, nanoparticle deposition, and reduction in the thickness of boundary layers. Several other factors such as thermophysical properties, a method of preparation, concentration, and type of surfactants used to stabilise the hybrid nanofluids and moreover, different ratios of nanoparticles play a significant role in affecting the results. Additionally, further improvement in the preparation process and standardised procedures for hybrid nanofluids is required.

TABLE 3. The impact of hybrid nanofluids on the heat transfer coefficient and friction factor enhancement.

Hybrid nanofluids	Flow conditions	Volume concentration	Nusselt number (%)	Friction factor (%)	Reference
Al_2O_3-Cu/water	700 ≤ Re ≤ 2,300	0.1 vol%	13.46%	15.53 %	[118]
Al_2O_3-Cu/water	10,000 ≤ Re ≤ 100,000	2 vol%	32.07%	13.76 %	[119]
Al_2O_3-Cu/water	700 ≤ Re ≤ 2,300	0.1 vol%	13.56%	16.97 %	[113]
Al_2O_3-Cu/water	2,576 ≤ Re ≤ 9,263	0.1 vol%	25.2%	14.25 %	[115]
MWCNT-Fe_3O_4/water	3,000 ≤ Re ≤ 22,000	0.1 - 0.3 vol%	31.10%	1.18 times	[116]
Cu-TiO_2/water	4,000 ≤ Re ≤ 8,000	0.1-0.2 vol%	52%/49%	14.9%	[117]
GNP-Ag/water	5,000 ≤ Re ≤ 17,500	0.1 vol%	32.70%	8%	[93]
Al_2O_3-graphene/water	200 ≤ Re ≤ 1,000	0.1 vol%	63.13%	20.35 %	[120]

B. COMPUTATIONAL STUDIES (RANS / LB)

The recent development and accessibility of high-performance computers, computational fluid dynamics (CFD) has become a robust tool for regulating different flow parameters in the studies and test in various scenarios [121]. From the past two decades, Lattice Boltzmann method (LBM) has grabbed much of the researcher's attention as an effective and efficient substitute for numerical simulations of fluid flows. The fluid flow is mainly affected by the collision and flowing of particles on the lattice node in LBM. LBM uses the simple approach in simulating the complex flow issues including multiphase, multicomponent flows, turbulent flow, particulate suspension, subsurface flows, and the flow parameters described at the micro and nano level as well [122], [123].

Nanofluids are the combination of liquid, and solid nanoparticles and their usage is a new route to enhance the heat transfer, especially scientists who are focusing on microflow due to their distinctive features [124]. Some of the studies focused on the flow behaviour and heat transfer of nanofluids in microchannels [125], [126]. Moreover, nanofluids also have exhibited suitable performance at macro scale due to their thermophysical properties [127], [128]. Some of the researchers in their studies reported the simulation of nanofluids in microchannels using LBM [129], [130]. LBM and RANS combination could be a suitable method in simulating turbulent flows, but rarely few people opting LBM for solving the RANS equation [123].

RANS models practically offer the best alternative for computing complex turbulent flow for industrial applications. Some of the frequently used or known turbulence models such as the Spalart-Allamaras (SA), the k – ε, and the k - ω models that affect the Boussinesq edd viscosity hypothesis use the RANS approach. The RANS simulation is helpful to answer the average Navier-Stokes equation and represent the Reynolds stress for analysing the flow filed, and root means square variable components. In most of the cases, the RANS simulation is applied to decrease the specifications of grid resolution and computational time remarkably under steady-state and in the two-dimensional state. The two-equation model was one of the most extensively used, out of all different turbulence models. Holmes *et al.* [131] found reasonably accurate results with the standard model, where he used a different one and two-equation models to simulate two rooms. Recently, Sajjadi *et al.* [123] used the Lattice Boltzmann computational approach in combination with standard and RNG model to investigate the simulation of particle deposition, dispersion, and turbulent airflow. The addition of two transport equations with increased LBM formulations helps to predict the probability distribution function of population k and ε. They concluded that the combination of LMB-RANS model showed the moderately valid interpretation of turbulent flows, particle deposition, and transportation at a reasonable computational cost. Khelifa *et al.* [132] used CFD model to analyse the hybrid solar collector to understand the heat transfer capabilities. They have used two different models, Ansys 14 and Fluent to study the relationship between fluid flow and heat transfer and PV cells and coolant. Yang Li and Jing studied 3D concentrated PV/T model using TRNSYS combined with CFD simulation to investigate the performance of the system. They found that the results are determined and depend on different evaluation factors, which changes with optimum operational conditions.

X. IMPACT OF HYBRID NANOFLUIDS IN PV/T SYSTEMS

A. EXERGY

In thermodynamics, the exergy is the amount of useful work done by engineering analysis of energy flows in industrial processes to improve the design and minimise the total energy usage. The PV/T system performance is balanced by calculating the exergy, exergy efficiency by considering the nature of different energy forms. The total exergy efficiency is calculated by:

$$\varepsilon_{total} = \varepsilon_{th} + \varepsilon_{ele} \tag{8}$$

The outcome of the exergetic performance of PV/T system favours the use of optical fibers, concentrators, and nanofluids. The exergetic performance of different PV/T systems compared with various studies and the results reported the exergy efficiency reply on multiple parameters such as solar radiations, ambient temperature [133]–[135], packing factor [17], [54], [136], length of the collector [136], nanofluid concentration [137], [138]. Mortazavi and Ameri [139] come up with an advanced new exergy method to recognise the additional part of exergy destruction by technical enhancements of a system using solar air collectors.

Few studies reported the influence of exergy and energy efficiencies on the PV/T system. Salem *et al.* [140] reported hybrid PV/T system with aluminium plate using straight and helical channels and found 11.1-13.5% exergy efficiency and 59.3-92% of energy efficiency of PV/T system. They also observed an increase in PV efficiency of 17.7-38.4% and thermal efficiency of 31.6-57.9%. Khanjari et al. [141] investigated a new hybrid PV/T system by numerical analysis using CFD. The results showed 15% exergy efficiency of PV/T, 55% thermal efficiency, 10-13.7% PV efficiency, and 90% of PV/T energy efficiency.

Till date, no one has studied advanced exergy method on PV/T systems, which opens a future direction for researchers to work on it.

B. ENTROPY

The performance of any thermodynamic system can be defined by thermodynamic performance only. Several studies have supported the irreversible analysis of various systems and revealed that the entropy generation is a powerful tool to choose the process efficiency [142]. The measurement of entropy generation is due to several factors such as friction, mixing, chemical reaction, and heat transfer through a finite temperature difference [143]. Researchers have carried out numerous analysis on entropy generation and highlighted some of them here: (i) Channel size and type of flow distribution, nanoparticle volume concentration, and use of nanofluids help to decrease entropy generation and therefore system optimisation. (ii) Several models proposed to calculate the thermophysical properties of nanofluids might cause opposition to the prediction for entropy generation. (iii) Addition of nanoparticles may increase entropy generation while studying the viscous effects in microchannels. (iv) In general, it assumed that the supply of heat transfer is dominant to entropy generation when using nanofluids in the flow system, which results in a noticeable decrease of entropy generation due to a uniform temperature.

Bejan concluded entropy generation for forced convective heat transfer for various geometries by deriving an equation [144], [145]. Ratts and Raut [146] proposed entropy generation for fixed heat transfer and mass flow rate at an optimum Re. The rate of entropy generation theory was well studied and reported by different researchers to date, and it can relate to comparing the performance of different systems.

C. PUMPING POWER

The enhancement of heat transfer coefficient and thermal conductivity is more likely with nanofluids compared with base fluids. The main concern is viscosity; once the nanoparticles suspended into the base fluid, there is a possibility to increase viscosity which requires high pumping effect to allow the fluid inside the system [147]. The increase in viscosity subjected to enhance of friction factor and thus responsible for high pumping power. Pumping power is a function of the heat transferred and the particle volume concentration. Moreover, the friction factor affects the pressure drop, and pressure drop calculation is proportional to pumping power. As the increase in nanocomposite volume concentration causes the rise of hybrid nanofluid friction factor and pressure drop due to density gradients and viscous forces. The formation of nano-agglomerates and re-framing of hybrid nanocomposites with primary nanoparticles increase the viscosity of hybrid nanofluids. The heat transfer enhancement using pin fins, which shows better overall performance by considering higher pressure losses through fin array [148], [149].

Sparrow *et al.* [150], [151] and Metzger *et al.* [152] reported the use of cylindrical pin fin in the inline and staggered configurations to study the heat transfer behaviour. The results showed 100% larger heat transfer coefficient when using pin fin surface than the end wall.

Madhesh *et al.* [153] prepared Cu-TiO_2/water at different nanoparticle volume fractions and experimentally evaluated the changes in the friction factor and pressure drop. When compared to mono fluids and base fluids, the pressure drop and friction factor of hybrid nanofluids are high. The addition of hybrid nanoparticles initiated high wall shear, which increases the wall shear rate with volume fraction.

D. EFFECT OF THE INCLINATION ANGLE

The amount of heat transferred from hybrid nanofluid to water coolant depends on the temperature difference of inlet and outlet fluid flow, specific heat, and total mass flow rate of nanofluid considered. The effect of inclination angle reply on various other parameters such as 1.) Heat transfer rate, 2.) The evaporation heat transfer coefficient 3.) The condensation heat transfer coefficient and 4.) The total thermal resistance of two-phase closed thermophyson (TPCT).

The transfer rate can be affected by the inclination angle due to the pressure difference drove by the hydrostatic head of liquid is zero, positive or negative and also other aspects such as tube length, fluid density, acceleration from gravity force and the inclination angle of the TPCT to the horizontal axis [154]. The evaporation heat transfer coefficient of nanofluids or water depends on the nanoparticle concentration level and the inclination angle (maximum evaporation at 60°C).

The condensation heat transfer coefficient of nanofluids or water depends on the heat transfer rate, nanoparticle concentration level and inclination angle (maximum condensation at 30°C) and for constant inclination angle, the condensation heat transfer coefficient for nanofluids is more at lower working temperatures and low at higher operating temperatures. The total thermal resistance of TPCT influenced by nanoparticle concentration level and inclination angles.

E. HEAT TRANSFER

Heat transfer also defined as the exchange of heat flow from solid to liquid interface between the nanofluid and the system surface, where the particles colloid randomly with each other in the base fluid at the nano-scale level. Heat transfer relies mostly on heat transfer area of the heat exchanger, and the main concern is about the undesirable size increase of the thermal system. Heat transfer coefficient is another factor, which influences the heat transfer and geometric parameters of heat exchangers such as pitch, tube diameter, and tube alignment play a critical part in effecting the heat transfer coefficient [155]. Moreover, it depends on a few other parameters, such as heat capacity, thermal conductivity, viscosity, density, and surface tension if a phase change is involved [156].

XI. CRITICAL CHALLENGES IN USING HYBRID NANOFLUIDS

Challenges of Hybrid Nanofluids: The consequences of the hybrid nanofluids more or less addressed in the above sections that can provide excellent results. However, there are still some challenges that need to bring into the bigger picture:

Stability is the most challenging part that not only affects the performance of the system but also turns the excellent outcomes into a miserable one. The formation of clusters mainly affects the thermal conductivity and performance. The main reason to look into stability is that the issue that desires to study on pH, a different combination of nanoparticles, base fluid types, and different mixer techniques such as magnetic stirrer, ultrasonicator, and its effect on pumping power as well. Therefore, stability is the catalyst, which activated many complications for the researchers. For example, if we consider MWCNTs, which is hydrophobic does not disperse in the water at any of the pH values but the involvement of CTAB surfactant can form a stable MWCNTs solution. Moreover, the surface modification and incompatibility with the base fluid is also needed to take into consideration. The stabilisation effect and modified functional/oxygen functional groups on the surface/plane would restrict the heat transfer between the nanoparticles. These can affect the surface chemistry of the particle in the mixture, which can increase the suspension of nanoparticles in the fluid. Besides, the addition of surfactants sometimes results in a change of surface properties that reduce the surface tension of the nanofluid and will show an adverse effect on thermo-physical properties. The main disadvantage of adding an excess quantity of additives to nanofluids can disturb the stability, viscosity, and thermal conductivity. Researchers must focus on the prior mentioned factors to form a good dispersion of nanoparticles for further studies.

Recently, the hybrid nanofluids due to its increased thermal properties progressed well in heat transfer devices. However, the suspension of two different individual nanomaterials may increase the viscosity, which is vital to increase the pressure drop and pumping effect when compared to single nanoparticle suspension in fluid flow applications. Also, the production cost is another big challenge for the fabrication of nanofluids that includes different production techniques of nanoparticle synthesis and base fluid dispersion. The synthesis process involves the preparation of hybrid nanofluids and the apparatus used for these processes are highly advanced and high-cost. In spite of producing highly stable nanofluids using the one-step method, still researchers need to face challenges such as sophisticated equipment cost, the abysmal production rate of nanofluids, and cost of raw materials also need to be accounted. In the case of the two-step process, the synthesis of nanofluids in bulk quantity for commercial purpose by preventing the nanoparticle synthesis. However, the main concerns such as the equipment cost employed for the suspension of a nanoparticle-like magnetic stirrer, ultrasonication, and probe sonicator hinder this process on top of increased nanoparticles cost [157].

Finally, there is a need to have a deep understanding behind the physics of heat transfer in nanofluids and various parameters controlling the behaviour of nanofluids to considered.

The hybrid nanofluids are absolutely a new kind of nanofluids, and still, they are at the beginning phase of investigation and evolution as far as the industrial sector concerned. It is a fact that the use of different hybrid nanofluids for the same application with a better result. However, the hybrid nanofluids applications in the direction of research are restricted to very few because of their thermophysical properties [158]–[161]. Although, few studies stated that the effect of hybrid nanofluids was not up to the mark when compared to single nanofluids may be due to the lack of synergistic effect or proper bonding [162]. The use of hybrid nanofluids has been proposed for solar thermal collector [163], micropower generator [164], grinding [165], heat exchanger[166], solar energy [167], heat sink [168]. There is gradual progress in the improvement of heat transfer have reported for hybrid nanoparticle-based hybrid nanofluids [90]–[111], and development of their performance in various applications anticipated.

XII. CONCLUSION

The nanofluid technology in PV/T systems has tremendously increased to meet the industrial standards, and rise in investments to scale down the designs that can perform better and earn more profits with the use of new hybrid nanoparticles is still limited to research. The hybrid nanofluids emerged as a new kind of thermal fluids on which a lot of scope and job have to be done before implementing them into practice or practical applications. This work highlights the current research and development of nanofluids at different levels from lab scale to industrial scale with significant research output. Currently, many industries are looking for a novel technology, which has a maximum efficiency to produce highest electrical production, especially in cooling and heat removal disputes in the PV/T system. Several works are reported on the preparation of nanofluids but fail to achieve stable nanofluids. Some of them suggested the dispersion of single nanoparticle in the base fluid, but their properties still did not satisfy the desired requirement. Now, scientists come up with hybrid nanoparticle with synergistic properties performing well compared to the mono particles. When these nanofluids flow through the channels, different factors such as Brownian motion, the effect of nanoparticle agglomeration, deterioration, the impact of time on thermal conductivity and other factors come into play, which potentially affects the hybrid nanofluid performance in a PV/T system.

A detailed study to test the stability of nanofluids relies on many factors such as the addition of surfactants, preparation process, selection of nanomaterials, selection of base fluid, the dispersion of nanoparticles, and nanofluid cost may be demanding. A lot of research progressed on developing different solar cell technologies but still scientists struggling to find a suitable way to enhance the efficiency and performance of the PV cells at a large scale. Also, there is a need to focus more on channel geometry, flow patterns, flow distribution, and maintenance cost of PV cells, which is a never-ending research topic.

Additionally, new channel geometry and flow pattern configurations have to be investigated to improve the heat transfer between the solar module and hybrid nanofluids. The hexagonal honeycomb channel shows 87% of thermal efficiency compared to other types of channel geometry. Prediction of flow distribution of different hybrid nanofluids through different flow patterns using computational and simulation studies need to consider. The hybrid nanofluids show increased thermal conductivity, which can be determined by nanoparticle concentration and operating temperature. Moreover, the carbon-based hybrid nanofluids indicated highest enhancement in heat transfer coefficient of 63%, and a 144% increase in Nu reported than other type of hybrids. In addition, (fMWCNT/f-HEG)/water hybrid nanofluids showed 289% increase in heat transfer for 0.01 vol% of hybrid nanofluids at 15,500 Reynolds number compared to the base fluid. A detailed review is required to address the fundamental cause behind the specific changes in heat transfer and thermal conductivity features of hybrid nanofluids. Further investigation is crucial for deep understanding mechanism subjected to an increase of heat transfer through hybrid nanofluids in real-time/life applications.

Besides, an economic analysis of any PV/T system should consider the time value of money for the design selection. The increase/decrease in price of parameters such as maintenance cost, parts warranty, and reduction of the electrical performance of the system is a part of economic analysis. The most important aspect is the payback period was expected to be lesser than the life span of the PV panel and estimated to be less than 14.5 years. This study emphasises that the use of PV/T technologies with different modifications/designs and material selection helps to improve the energy-saving cost and attain preferable discount payback period. The solar technology and hybrid nanofluid technology benefits for low-carbon, economic, eco-friendly, and non-fossil fuel electricity generation, which shows a considerable impact on the environment by controlling the emission of harmful gases and depletion of non-renewable resources. In the long term, implementing the hybrid nanofluid technology enhance the efficiency and overall performance of the PV/T system by reducing the total cost of the system. Finally, the hybrid nanofluid technology consists of both economic and environmental profit by improving efficiency and decreasing the greenhouse gases emission.

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