MXene incorporated nanofluids for energy conversion performance augmentation of a concentrated photovoltaic/thermal solar collector

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Abstract

This research work introduces emerging two-dimensional MXene (Ti_3C_2) and Therminol®55 oil-based mono and hybrid nanofluids for concentrated photovoltaic/thermal (CPV/T) solar systems. This study focuses on the experimental formulation, characterization of properties, and performance evaluation of the nanofluid-based CPV/T system. Thermo-physical (conductivity, viscosity, and rheology), optical (UV-vis and FT-IR), and stability (Zeta potential and TGA) properties of the formulated nanofluids are characterized at 0.025-0.125 wt.% concentrations of dispersed particles using experimental analysis. By suspending the nanomaterials photo-thermal energy conversion is improved considerably, up to 85.98%. The thermal conductivity of pure oil is increased by adding Ti_3C_2 and CuO nanomaterials. The highest enhancements of up to 84.55 and 80.03% are observed for the TH-55/Ti_3C_2 and TH-55/Ti_3C_2+CuO nanofluids, respectively. Furthermore, dynamic viscosity decreased dramatically over the temperature range investigated (25-105°C), and the nanofluid exhibited dominant Newtonian flow behavior as viscosity remained nearly constant up to a shear rate of $100 s^{-1}$. Numerical simulations of the experimentally evaluated nanofluids are performed to evaluate the effect on a CPV/T collector using a three-dimensional transient model. The numerical analysis revealed significant improvements in thermal and electrical energy conversion performance, as well as cooling effects. At a concentrated solar irradiance of 5000

W/m^2 and an optimal flow rate of 3 liters/min, the highest thermal and electrical energy conversion efficiency enhancements are found to be 12.8 and 2%, respectively.

Keywords: Nanofluid, Thermal-optical Properties, Stability, MXene, Therminol®55, CPV/T Solar Collector.

Nomenclature

A_c	Area of collector (m^2)	*Subscripts*	
c_p	Specific heat (J/kg.K)	*amb*	Ambient
FF	Field factor	*bf*	Base fluid
G	Solar radiation intensity (W/m^2)	*el*	Electrical
h	Convective heat transfer coefficient (W/m^2.K)	*in*	Inlet
I_{sc}	Short circuit current (A)	*out*	Outlet
V_{oc}	Open circuit voltage (V)	*s*	Solid particle
k_{bf}	Thermal conductivity of base fluid (W/m.K)	*th*	Thermal
k_{nf}	Thermal conductivity of nanofluid (W/m.K)	*el*	Electrical
k_s	Thermal conductivity of nanoparticle (W/m.K)	*nf*	Nanofluids
P_{el}	Electrical power output (W)	*Abbreviations*	
P_{th}	Thermal output (W)	NF	Nanofluid
T	Temperature (K)	TH-55	Therminol®55
A	Absorptivity	FTIR	Fourier-transform infrared spectroscopy
Greeks		SEM	Scanning electron microscopy
ζ	Zeta potential, mV	FTIR	Fourier-transform infrared spectroscopy
σ	Stefan Boltzmann Constant W/(m^2.K^4)	TGA	Thermogravimetric analysis
ρ	Density, kg/m^3	UV-Vis	Ultraviolet–visible spectroscopy
η	Efficiency	EVA	Ethylene Vinyl Acetate
Φ	Nanoparticle weight fraction	PV/T	Photovoltaic thermal
		SI	Solar irradiance
		LPM	Litter per minute

1. Introduction

Inadequate renewable energy supplies have turned into a sophisticated obstacle to meeting the world’s ever-growing energy demand. The depletion of carbon-based fossil fuel supplies and their ongoing threat to the environment are compelling researchers to seek renewable energy sources that will be sufficient to meet potential energy needs. Given that energy demand will continue to rise in the future, one way to mitigate energy shortages is to increase reliance on sustainable renewable energy sources such as solar energy. It is one of the most convenient, pollutant-free, clean, and abundantly available energy resources [1]. As a result, numerous experimental and systematic studies are being conducted to develop renewable solar-based energy conversion systems for thermal and electrical applications. Solar collector technologies such as concentrated photovoltaic/thermal (CPV/T) allow us to capture and transform solar irradiation, resulting in increased thermal and electrical energy production. Additionally, the CPV/T solar system needs fewer PV cell surface areas due to the concentrated optical design, and construction and maintenance costs are low as well. The hybrid CPV/T device is a low-emission technology that is commonly used in industrial and residential applications [2]. A CPV/T is a hybrid device that combines a concentrated photovoltaic (CPV) panel with a thermal collector to provide a potential cooling effect. It is an advanced variant of a traditional CPV collector that does not include a cooling unit, which results in a rise in cell temperature at higher irradiation intensities and a decrease in device performance [3]. In CPV/T, the collector's effective concentrating device concentrates incoming solar irradiation onto the photovoltaic panel's surface. Solar irradiance then rapidly heats the photovoltaic cells by producing a high heat flux [4]. As concentrated solar radiation strikes the surface of the CPV/T system's solar cell integrated PV plate, approximately 40% of the incident solar energy is absorbed and converted to electrical energy by the PV unit, while the remaining heat can be transferred to the collector's working fluid in the thermal cooling unit [5]. In comparison to traditional CPV, non-concentrating hybrid PV/T, and standalone PV devices, hybrid CPV/T collectors produce more electrical power and thermal energy simultaneously [6]. However, the inefficiency of common heat transfer fluids (HTFs) in converting thermal energy to heat limits the cooling and overall efficiency of the PV/T system, thus limiting the output of CPV/T [7]. Therefore, to augment the energy efficiency of solar collectors, such as PV/T and CPV/T, traditional HTF should be replaced with a working fluid that possesses efficient thermal energy conversion properties.

In this framework, due to their superior optical, thermal, and chemical properties, nanofluids (NFs) can be considered a possible substitute for conventional HTF in solar energy technologies [8]. Said, et al. [9] investigated the efficiency and cooling effects of traditional fluids and nanofluids in hybrid PV/T systems. After reviewing a large number of studies, they concluded that NFs could be utilized to significantly boost the cooling power and efficiency of the device. Bellos, et al. [10] reviewed the implementation of NFs on concentrating solar systems, including CPV/T, PV/T, compound parabolic collector (CPC), evacuated tube collector (ETC) and so on. They reported significant benefits from using NFs in the solar system rather than conventional HTFs. NFs/nano-colloids are highly engineered dispersions of solid nanomaterials with a nanoscale (<100 nm) in a liquid base fluid. Due to the advanced properties of dispersed nanoparticles, stable NFs exhibit exceptional photo-thermal properties in comparison to base fluids (BFs) [11]. In an experimental investigation, Qu, et al. [12] examined the photo-thermal energy transformation characteristics of aqueous/CuO+MWCNT NFs for solar energy harvesting applications. The NFs exhibited significant absorption properties and attained a 14.1°C higher temperature compared to the base fluid. Furthermore, NFs showed advanced optical behavior in response to incoming solar irradiation at low particle loading. Karami, et al. [13] examined the effects of CuO NFs based on ethylene glycol and water on a direct absorption solar collector (DASC) for domestic water heating at different NP volume fractions. They reported a growth in collector efficiency of up to 17% because of the NF's promising properties. Despite numerous studies establishing the specific properties of NFs on a theoretical and experimental level, the long-term stability of suspended NPs is the primary impediment to their commercial production in the industrial energy sector. Furthermore, several factors influence NF stability, including base fluids, NPs (concentration, size, and geometry), temperature, inter-molecular/chemical interactions, and so on [14, 15].

Recent experimental/numerical studies on solar energy conversion technology have drawn attention to the potency of NFs in enhancing performance in a variety of concentrating [16] and non-concentrating solar systems by utilizing them as working fluids [17]. Nonetheless, only a few studies on the implementation of NF-based hybrid PV/T or CPV/T devices at concentrated irradiance have been conducted. Han, et al. [18] examined the performance augmentation of a hybrid PV/T collector employing the propylene glycol-based Ag/$CoSO_4$ NF optical filter. They observed that inclusion of the optical filter leads to excellent absorbance, transmittance, and an increment in overall photo-thermal conversion efficiency. Hemmat Esfe, et al. [19] evaluated the effectiveness of NF-based collectors by analyzing a wide range of literature that used pure fluids and NF as the working fluid in hybrid PV/T collectors. They discovered that NF-based systems outperform conventional fluids in terms of electrical efficiency (EE), PV panel cooling, and thermal efficiency (TE). In a Multiphysics simulation of the hybrid CPV/T collector using the full coupling method, Ju, et al. [20] showed that the Therminol®VP-1 based indium tin oxide (ITO) NF filter achieved significantly higher powers and efficiencies along with excellent absorption characteristics than that of the BF. Huaxu, et al. [21] carried out a cost-effective outdoor experimental investigation with an NF-based spectral splitting CPV/T system. The study discovered that the CPV/T system had 47% enhanced photo-thermal efficiency along with 3.8% higher energy conversion efficiency than a conventional CPV collector at a very cheap cost relative to Au, Ag and polypyrene NPs. An, et al. [22] performed an experimental analysis on energy efficiency of hybrid CPV/T collector using Oleylamine-Cu_9S_5 NF. They reported 17.9% improved thermal efficiency relative to without NF filtration, along with significant EE of the hybrid CPV/T collector.

Due to their superior properties, nanomaterials dispersed in colloidal suspensions provide the remarkable development of unique thermal and optical properties of NFs. Different types of materials are extensively examined in the literature, including metal/metal oxides (Cu, Si, Ti, CuO, Al_2O_3, SiO_2, TiO_2 and so on), carbon-based nanotubes (CNT) and two-dimensional (2D) graphene NPs [23]. Among a wide range of NPs, carbon-based 2D materials [24] and CNTs exhibit greater effectiveness because of their larger surface area and chemical structure relative to non-carbon-based particles [25]. Recent investigations with NF suspensions, due to the superior characteristics of emerging advanced 2D nanomaterials have attracted unprecedented attention. MXenes are the latest discovery in the innovative two-dimensional family, invented back in 2011 by Naguib, et al. [26]. MXenes exhibit remarkable mechanical strength [27] and an unique multilayered chemical structure [28] accompanied by distinct thermal [29], optical [30], photo-thermal [31], electrical [32] and magnetic properties [33] relative to conventional nanomaterials. MXenes are comprised of transition metal carbides, nitrides and carbonitrides. MXenes are produced from three-dimensional $M_{n+1}AX_n$ (M stands for transition metals, A represents group-A element, X denotes carbon or/and nitrogen and n = 1, 2 or 3) phase employing selective etching method to eliminate 'A' layers [34]. Over 70 MAX phases have been identified so far, and a large portion of them are converted to MXenes through etching approaches. The MXenes are being studied extensively due to their remarkable properties, and a few of them are being used in applications such as, but not limited to, energy storage and conversion systems [35]. Pang, et al. [36] comprehensively reviewed advances with MXene-based studies on energy conversion and storage applications, including their mechanical, thermo-chemical, and optical properties.

In the present study, we experimentally formulated Therminol®55 oil-based mono and hybrid NFs dispersing synthesized 2D Ti_3C_2 nanosheets and spherical CuO nanoparticles for the first time to date. Prepared NF samples are characterized to evaluate their thermo-physical, optical, and chemical properties. Thermal conductivity, specific heat capacity, viscosity, UV-Vis, TGA, FT-IR and stability analysis are carried out to assess the potency of the NF for hybrid

CPV/T solar systems. The prepared NF's improved thermo-optical properties (i.e., thermal conductivity and solar absorbance) indicate its potential application in a hybrid CPV/T system. The thermal conductivity of the NFs is augmented with the addition of nanomaterials and elevated temperatures for both variants. In addition, the dynamic viscosity of the NFs decreased radically at elevated temperatures, which makes the nanofluid particularly suitable for high temperature applications like the CPV/T solar collector. In the numerical part of this work, performance (thermal, electrical, and cooling) of the nanofluid-based hybrid CPV/T system is reported as new findings and compared with the base fluid operated system. By adding Ti_3C_2 and CuO nanomaterials, the highest thermo-optical, thermal, and electrical energy conversion efficiencies are augmented by 85.98, 13 and 2.8%, respectively.

2. Methodology

2.1. Materials

To experimentally formulate the NF for solar thermal application, medium temperature range industry-standard synthetic Therminol®55 (TH-55) oil was purchased from EASTMAN and used as pure base fluid. Emerging two-dimensional MXene nanoflakes are synthesized from the three-dimensional MAX phase and used as NP to prepare the fluid. Specific characteristics of TH-55 are provided in **Table 1**. CuO nanoparticles are used to prepare hybrid NF. The particles purchased from US Research Nanomaterials. The specifications of synthesized MXene and purchased CuO particles are depicted in **Table 2**.

2.2. Formulation of TH-55/Ti_3C_2 and TH-55/Ti_3C_2+CuO nanofluids

The synthesis of Ti_3C_2 nanosheets from its three-dimensional MAX phase is performed using the same method reported in our previous research [37]. TH-55/Ti_3C_2 NF samples are prepared experimentally in two steps at three different particle loadings (0.025, 0.075, and 0.125 wt.%) of synthesized Ti_3C_2 nanoflakes. The two-step method is suitable in terms of commercial aspects and industrial large-scale production of NF. The Schematic of MXene synthesis and nanofluid is presented in **Figure S1** (See supplementary material). In the first step, the estimated amount of synthesized two-dimensional Ti_3C_2 nanosheets is dispersed into pure TH-55 as weight fractions. To make the suspension homogenous, several mechanical stabilization techniques are employed in the second step of the formulation process. Immediately after the addition of solid particles into the oil, all the samples are stirred with a magnetic stirrer for about 30 to 60 minutes at 700 to 900 rpm and 80°C. For further stabilization, NFs are sonicated at a high frequency (1200 W, 20 kHz) utilizing an ultrasonic homogenizer (FS-1200N) for 30 minutes. To ensure effective stabilization, the sonication is carried out at a temperature of around 80°C. This technique provides a uniform dispersion of MXene nanosheets in the base fluid by distributing the particles evenly throughout the suspension. Hybrid TH-55/Ti_3C_2+CuO nanofluids are formulated similarly using the same method and dispersing Ti_3C_2+CuO nanocomposite in powder form at a weight ratio of 1:1 into pure TH-55 oil at the same three particle loadings as solo NF. The same stabilization techniques are used after the addition of particles to produce stable dispersion of particles in hybrid NFs as described for solo NFs in the above.

2.3. Morphology, optical and chemical structure characterization

Nanofluid samples are characterized by employing several instruments for optical, chemical and morphological investigation. The surface morphology of Ti_3C_2 flakes was inspected using TESCAN-VEGA3, a Scanning Electron Microscope (SEM). The equipment can provide high resolution SEM imaging for coated metal samples under a stable electron beam using a LaB_6 filament. Magnified SEM images of synthesized Ti_3C_2 nanosheets illustrate the particles' distinct thin multi-layered structure in **Figure 1**(a-b). Thin layered nanosheets of Ti_3C_2 have been found to be more stable and transparent than two-dimensional graphene nanomaterials Zhou, et al. [38]. The amount of $Ti_3C_2T_X$ flakes synthesized is dependent on the etching conditions and etchant used Shen, et al. [39]. Additionally, HF-etched Ti_3C_2 exhibits a characteristic accordion-like morphology with a less compact structure between the layers than other etching methods [40]. The obtained results, which include $Ti_3C_2T_X$ flakes from SEM images, demonstrate the efficient conversion of two-dimensional Ti_3C_2 from three-dimensional MAX-phase ($Ti_3C_2T_x$). The spherical structure of the CuO nanoparticles is also identified in **Figure 1**(c-d). FESEM and HRTEM analysis are used to further investigate the morphology of the Ti_3C_2 nanostructure [41]. The FESEM images (**Figure S2**, a-b) confirms the thin multi-layered flake-like structure of the Ti_3C_2. In addition, high-resolution HRTEM images (**Figure S2**, c-d) represent a typical Ti_3C_2 nanosheet which is incredibly thin and flexible. A hexagonal based crystal is exposed with the analogous atomic configuration relative to original MAX-phase ($Ti_3C_2T_x$) in the grain boundaries [42] (as depicted in **Figure S2**, d). Hence, HRTEM and FESEM images provide more compelling evidence for the material's transformation from three-dimension to two-dimension.

Fourier transform infrared spectroscopy (FT-IR) is conducted to identify the existing chemical functional groups and observe the chemical composition in the suspension of Therminol®55 with Ti_3C_2 and CuO nanoparticles. The experiment was performed using a high-performance

Spectrum-Two^{TM} FT-IR spectrometer from Perkin Elmer. The instrument can measure at the highest resolution of 0.5 cm^{-1} for spectral range of 350 to 8300 cm^{-1} using single channel $LiTaO_3$ detector. Transmittance and chemical compositions of TH-55/Ti_3C_2 and TH-55/Ti_3C_2+CuO NFs are examined utilizing the FT-IR for the wavenumber range of 450 to 4000 cm^{-1} at 0.2 cm/s scanning speed. Lambda 750 (Parkin Elmer) is employed to accomplish absorbance characteristic of the formulated NFs using a monochromatic light source of 860 nm. All samples are measured at room temperature for 200 to 800 nm wavelengths at a scanning speed of 266.75 nm/min. Suspension stability of the NFs is examined by using an electrophoresis technique to measure the electrophoretic mobility of dispersed particles in terms of Zeta potential. Anton Paar's LITESIZER 500 is operated to conduct the assessment using dynamic, electrophoretic, and static light scattering techniques. It offers good measurement accuracy for samples with a size range of 3.8 nm to 100 µm. All the equipment is calibrated before assessing the NF samples, and protocols were repeated several times to ensure consistent precision of the measurements.

2.4. Characterization of thermal conductivity and viscosity

To obtain the thermal conductivity (TC) of TH-55/Ti_3C_2 and TH-55/Ti_3C_2+CuO NFs, TEMPOS (form Meter Group USA) is operated from 30 to 70 °C temperature. This equipment functions under the transient hot wire method and is supplied with several sensors and a digital controller with a DB-15 connector. In the present experiment with the NFs, the KS-3 sensor (1.3 mm diameter × 60 mm length) is utilized as it is particularly suitable to assess TC in the range of 0.02 to 2 W/m.K. TEMPOS can keep the heat constant from the source and offers excellent accuracy in the measurements with an uncertainty of $\leq \pm 10\%$. A temperature stable water-bath (MEMMERT, WNB22) is integrated during the experiment, and temperature can be controlled using a knob to measure conductivities at each temperature. Before measuring the conductivities of the NF samples, the equipment is calibrated with glycerin samples provided by the suppliers. In this approach, a certain temperature is set to the water-bath and the sample are placed into the water-bath using jigs. The KS-3 needle sensor is placed inside the sample vertically and connected with the analyzer via a USB cable.

The viscosity characteristics of pure Therminol®55 oil and the solo and hybrid NFs are studied using the MCR-92 Rheometer from Anton Paar. The measurements are conducted with respect to a temperature scale of 20 to 105°C and shear-rate from 30 to 100 s^{-1}. The instrument offers very good accuracy (precision: ±1%) for a wide range of viscosity from -40 to 400 °C. The device is calibrated with water before performing the test with oil samples. 60 ml of each sample is required to measure viscosity with MCR-92.

2.4.1. Specific heat capacity

Due to measurement facility limitations, the c_p of the TH-55/Ti_3C_2 and TH-55/Ti_3C_2+CuO NFs is measured using the correlations widely used in reported studies [43] as follows:

$$(\rho c_p)_{nf} = \varphi(\rho c_p)_{np} + (1-\varphi)(\rho c_p)_{bf} \qquad (1)$$

Where, $(c_p)_{np}$, $(c_p)_{bf}$ and $(c_p)_{nf}$ are the specific heat capacity (in J/kg. K) of nanomaterials, base fluid and formulated nanofluid, respectively.

The c_p of Ti_3C_2 nanomaterial is experimentally determined and correlated as follows [41]:

$$(c_p)_{np} = -0.001T_{nf}^2 + 3.4T_{nf} + 604.5 \qquad (2)$$

Where, T_{nf} is evaluated in °C.

Since the concentrations of the Ti_3C_2 nanoparticles is very low, the density of the TH-55/Ti_3C_2 is presumed to be constant and equal to the density of pure Therminol®55. Indeed, the effect of nanoparticle loading on the nanofluid's density can be significant at high loading values. Without considering the effect of density-shift due to the nanoparticle loadings, the specific heat of the TH-55/Ti_3C_2 nanofluid is measured as follows.

$$(c_p)_{nf} \cong (c_p)_{np}(1-\varphi)(c_p)_{bf} \qquad (3)$$

Similar approach is followed to calculate the c_p of the hybrid NF.

The density (ρ_{nf}) of the nanofluid is considered to be constant, and the properties were obtained from Eq. 4 [44]:

$$\rho_{nf} = (1-\phi)\rho_{bf} + \phi\rho_s \qquad (4)$$

2.5. Application of TH-55/Ti_3C_2 and TH-55/Ti_3C_2-CuO nanofluids on CPV/T solar system

In a concentrated photovoltaic/thermal (CPV/T) system, Fresnel lenses are used to concentrate the sunlight on each of the solar cells of a poly-crystalline-silicon PV module. Researchers used a variety of active and passive techniques to reduce the temperature rise of photovoltaic module cells. Some of them used nanofluid as a coolant at the back of the photovoltaic panel to reduce the heat and thus boost electrical and thermal efficiency. This section conducts a numerical analysis of the newly produced TH-55/MXene-based nanofluid and its hybrid variant TH-55/MXene+CuO in the CPV/T system. The proposed work utilizes a CPV/T system to compare the performance of mono and hybrid Therminol®55-based nanofluids to that of base fluid alone, numerically. The problem under investigation is presented in **Figure 2**. This investigation considers a large photovoltaic module with 72 polycrystalline silicon cells (each cell has an area of 0.024 m^2). In India, the average solar radiation is 1000 W/m^2. To achieve solar irradiation of up to 5000 W/m^2, each lens must have a surface area of 5×0.024 m^2, taking the total surface area of the 72 lenses to 72×0.122 m^2. The computational domain for numerical simulation is the total area of the solar cells (1.73 m^2). **Table 3** summarizes the physical properties of the PVT module's various layers.

2.5.1 Numerical modelling of CPV/T solar system

The solar collector under investigation is a 300-watt photovoltaic module made up of four layers: a photovoltaic solar cell, EVA (Encapsulated vinyl acetate) on both sides of the photovoltaic cell, and a tedlar plate. A serpentine copper tubing heat exchanger is placed underneath the photovoltaic module (**Figure 2**). The PV cells, EVA, and tedlar layers are each 0.3mm, 0.5mm, and 0.1mm thick. The remaining specifications are identical to those of the photovoltaic plate, i.e. (1955mm x 982mm). The three-dimensional (3D) numerical analysis is carried out using the Finite Element Method-based Multiphysics Software COMSOL. COMSOL's CFD and heat transfer modules are used to determine the CPV/T system's output parameters. In this study, 3D transient model is preferred because the flow pattern is 3D in real cases. Moreover, the 3D simulations show the interaction of individual components with their surroundings. The nanofluid flow is presumed to be constant, three-dimensional, incompressible, and laminar. The transmissivity of EVA is assumed to be approximately 100%, dust's effect on the absorptivity of the PV surface is assumed to be negligible, and temperature variation along the module's thickness is assumed to be zero. Additionally, it is assumed that the base fluid contains a homogeneous mixture of nanoparticles (i.e., no particle sedimentation). In this study, TH-55/Ti_3C_2 and hybrid variant TH-55/Ti_3C_2+CuO based nanofluids with varying nanoparticle concentration are used. Thermal conductivity, which is proportional to the weight fraction at various temperatures, is fitted to a third order polynomial using regression analysis and then incorporated into the COMSOL through a user defined function (UDF).

Regression analysis of experimental data is used to model temperature dependence on the viscosity of TH-55/Ti_3C_2 and hybrid variant of TH-55/Ti_3C_2+CuO nanofluids. Like thermal conductivity, the viscosity correlations are integrated into COMSOL's CFD environment through the UDF and used for simulation purposes. For solid domain in the PV/T device, heat conduction equations are used to account for heat transfer. Heat transmission from the surface of the photovoltaic panel to the flow channel is established using the heat conduction equation shown below in Eq.5 (a-d) [51].

$$\rho_c\delta_c C_{pc}\frac{dT_c}{dt} = \alpha_p G - E_e - h_{panel-ted}\left(T_{penal} - T_{ted}\right) + k_c\delta_c\left(\frac{\partial^2 T_c}{\partial x^2} + \frac{\partial^2 T_c}{\partial y^2} + \frac{\partial^2 T_c}{\partial z^2}\right) \qquad \text{(5-a)}$$

It reflects the heat transfer between the photovoltaic panel and the tedlar plate. Other thermal energy equations for additional layers can be written similarly. Here, α_p represents the panel's absorptivity, G is the irradiance, E_e is the electrical energy output and $h_{panel-ted}$is the heat transfer coefficient between PV module and tedlar plate. Correspondingly, other heat transfer coefficients between the layers are specified in Eq. 5-b, 5-c and 5-d. Specifications of the CPV/T collector are listed in **Table 3**.

From tedlar to serpentine tubing:

$$\rho_{td}\delta_{td}C_{ptd}\frac{dT_{td}}{dt} = -h_{penal-ted}\left(T_p - T_{td}\right) - h_{ted-tubing}\left(T_{ted} - T_{tubing}\right) + k_{td}\delta_{td}\left(\frac{\partial^2 T_{td}}{\partial x^2} + \frac{\partial^2 T_{td}}{\partial y^2} + \frac{\partial^2 T_{td}}{\partial z^2}\right) \qquad \text{(5-b)}$$

From serpentine tubing to nanofluid:

$$\rho_{tb}\delta_{tb}PdyC_{ptb}\frac{dT_{tb}}{dt} = -h_{ted-tubing}\left(T_{ted} - T_{tubing}\right) - h_{tubing-nf}Pdy\left(T_{tubing} - T_{nf}\right) + k_{tb}\delta_{tb}\left(\frac{\partial^2 T_{tb}}{\partial x^2} + \frac{\partial^2 T_{tb}}{\partial y^2} + \frac{\partial^2 T_{tb}}{\partial z^2}\right) \qquad \text{(5-c)}$$

Where P is the periphery of the tube. For working fluid in serpentine channel:

$$\rho_f A_f dy C_f\frac{dT_f}{dt} = h_{tubing-nf}Pdy\left(T_{tubing} - T_{nf}\right) \qquad \text{(5-d)}$$

Moreover, Eqs.6-8 describes the mass and momentum and energy equations for transient laminar fluid flow. For flow in the collector, the coupled heat transfer equation is used, as both conduction and convection are considered for the nanofluids in Eq.6-8.

Continuity:

$$\frac{\partial\rho_f}{\partial t} + \nabla.\left(\rho_f V_f\right) = 0 \qquad (6)$$

Momentum:

$$\rho_f\left(\frac{\partial V_f}{\partial t} + \left(V_f.\nabla\right)V_f\right) = -\nabla P + \nabla.\left(\mu_f \nabla V_f\right) \qquad (7)$$

Energy:

$$\rho_f C_{Pf}\frac{\partial T_f}{\partial t} + \rho_f C_{Pf} V_f.\nabla T_f = \nabla.\left(k_f \nabla T_f\right) \qquad (8)$$

The Nusselt number (Nu) for different flow regime between fluid and tube can be expressed as Eq.9 [45]:

$$\mathrm{Re} < 2300,\ \mathrm{Nu}=4.364 \text{ and } \mathrm{Re} > 2300,\ Nu = 0.0234Re^{0.8}Pr^{0.4} \qquad (9)$$

In equation 12, Reynolds number (Re) and Prandtl Number (Pr) can be calculated using Eq.10 and 11 [45]:

$$Pr = \mu_f{}^{C_{pf}}/k_f \tag{10}$$

$$Re = \rho_f v_f{}^{D}/\mu_f \tag{11}$$

The electrical modelling of the PV cell is developed using MATLAB/Simulink using the model of single PV cell.

The output electrical output and thermal energy are calculated by equation 12 & 13:

$$P_{el} = V_{oc} * I_{sc} * FF \tag{12}$$

$$P_{th} = \dot{m} C_p (T_{out} - T_{in}) \tag{13}$$

here, $\dot{m}$ is the mass flow rate of the nanofluid.

Eq. 14 and 15 determine the electrical and thermal efficiency, respectively.

$$\eta_{el} = \frac{P_{el}}{G * A_c} \tag{14}$$

$$\eta_{th} = \frac{P_{th}}{G * A_c} \tag{15}$$

2.5.2. Boundary Conditions

Proper boundary conditions were used throughout the domain in accordance with the physics of the problem. The boundary condition that is applied across the top and bottom layers of the photovoltaic module is represented by Eq. 16:

$$-n.q = h_c (T_{amb} - T_s) \tag{16}$$

Where **n** is the surface normal and T_{amb} and T_s are the surrounding environment and surface temperatures, correspondingly. For the fluid domain, the inlet boundary condition is specified as velocity of the inlet along x-axis i.e, $u=U_o$, $v=0$, $w=0$ and $T=T_o$, for solid boundaries no-slip condition is used ($u=v=w=0$), however, at the outlet, zero pressure boundary condition is used ($p=0$). For solid-fluid interface heat flux continuity at the interface is used as equation 17:

$$\left(\frac{\partial T_s}{\partial n}\right)_f = \frac{k_s}{k_f}\left(\frac{\partial T_s}{\partial n}\right)_s \tag{17}$$

Adiabatic boundary condition is applied for the solid walls of the device. Furthermore, the bottommost plate of the solar PV/T collector remains isolated (see **Figure S3**).

2.5.3. Meshing and Grid Independency

The PVT module was meshed in COMSOL Multiphysics® using the built-in physics-controlled mesh sequence setting shown in **Figure 3**(a-c). It consists of tetrahedral and triangular mesh elements at the sub-domain and at the boundary, respectively. The number of mesh elements increases at each boundary so that the heat transfer and flow fields can be resolved accurately. For grid independency simulation at 1000 W/m^2 and a mass flow rate of 3LPM is performed using water as a coolant with different mesh size (from coarser to finer) shown in **Table 4**. The initial layer thickness is set to 1/50 of the element's size at that boundary. The meshing along the thickness of the collector and diameter of the tube is presented in **Figure 3**(b-c) [46]. It was observed that there was no further change in panel temperature and outlet fluid temperature values after mesh no.5. Thus, mesh no.5 is selected for simulation purpose. The solution method of the governing equations using COMSOL Multiphysics modelling package is shown in **FigureS4**.

2.5.4. Validation

The results of the solar cell temperature at an irradiation intensity of 1000 W/m^2 and several flow rates (0.5 to 4 LPM) were obtained from the present numerical model, validated with Nasrin, et al. [47]. **Table 5** expresses this validation and provides a very good accord with the experimental findings.

3. Results and discussion

3.1. FT-IR analysis

Figure 4 represents FT-IR spectra of TH-55 and TH-55/Ti_3C_2 NF at 0.025-0.125 wt.% particle loadings of Ti_3C_2 to assess existing chemical bonds in the fluids. The study is performed for each sample from 450 to 4000 cm^{-1} wavenumber at room temperature. Both solo and hybrid NFs depicted similar profile of the spectrums with no major deviation in the absorption peaks as particles are suspended in identical base fluid for both types of nanofluid. The indistinguishable spectrums are observed with both oil and the NF samples which convey indication of no chemical reaction between the fluids and particles except physical interactions. Samylingam, et al. [46] have attained similar outcomes by investing palm oil as base fluid as well as adding solid particles at different concentrations. They reported a chemically unique FT-IR spectrum for each of the individual fluids. Therefore, the present optical results with TH-55/Ti_3C_2 NFs confirm that the fluids are consistent in terms of chemical interactions.

Several absorption peaks are noticed from the mixture of TH-55 oil and nanomaterial in the spectra absorbing IR bands. Key absorption peaks were observed in the spectrums at wavenumbers of 2923 cm^{-1}, 2856 cm^{-1}, 1459 cm^{-1}, 1376 cm^{-1}, 825 cm^{-1} and 701 cm^{-1}. The corresponding peaks at 2923 cm^{-1} and 1459 cm^{-1} revealed the presence of CH_3 and CH_2 stretching bond in the synthetic oil chain of TH-55 respectively [46]. The bands at 1459 cm^{-1}

and 1376 cm^{-1} are identified as C=C and C=O stretches of the carbon skeleton due to dominance of the oil in the mixture [48]. The peaks at low-frequency of 701 cm^{-1} is attributed to C-H bending vibration of the suspension [46]. No discrepancy is observed in terms of deviation of absorption peaks changes in FT-IR spectrum profiles among the oil and NFs. The spectrums of samples with different concentrations of Ti_3C_2 flakes are undistinguishable due to excellent chemical stability and consistency of the dispersion. The conclusive results imply that the formulated NFs are chemically stable.

3.2. UV-vis absorbance assessment

Ti_3C_2 and CuO nanoparticles are suspended into TH-55 to advance the absorption aptitude of the fluids so that it can improve the efficiency and cooling capacity of the hybrid CPV/T system. The optical absorption characteristics of formulated TH-55/Ti_3C_2 and TH-55/Ti_3C_2+CuO NFs are examined by analyzing UV-vis spectrums presented in **Figure S5**. The analysis was performed with TH-55 and several concentrations (0.025, 0.075 and 0.125 wt.%) of Ti_3C_2 and hybrid Ti_3C_2+CuO particles for a wavelength range of 200 to 800 nm as it contains over 80% of total solar radiation emitted from the sun. According to the law of Beer-Lambert ($A = log_{10}\frac{I_0}{I}\alpha C$, where I and I_0 is the intensity of the incident and transmitted light, respectively), the absorption property of fluid will be amplified due to addition of particles into it and absorbance should be improved with increasing weight loadings of particles dispersed into the fluid [49]. **Figure S5** exhibits absorption of TH-55/Ti_3C_2 and TH-55/Ti_3C_2+CuO NFs intensified notably at different peaks and in visible wavelength scale relative to pure TH-55. Absorbance enhanced rapidly at 200-250 nm and observed high light absorbance up to 450 nm wavelength. At higher wavelength (450-800 nm), absorbance remained steady for all the fluids. Nevertheless, absorbance of NF samples remained greater than Therminol®55 oil. Gulzar, et al. [50] observed analogous trend investigating several Therminol®55 based NFs.

The obtained average increments in absorbance for TH-55/Ti_3C_2 NF at 0.025, 0.075 and 0.125 wt.% are 37.23, 61.72 and 80.16% respectively. For the hybrid NFs, the percentage augmentations are similar, being 32.75, 66.55 and 85.98% at the same weight loadings as solo NFs. The intermolecular homogeneousness among TH-55, Ti_3C_2 and CuO as well as the two dimensional structure of Ti_3C_2 nanoflakes with larger surface area lead to advanced light-to-heat (photo-thermal) energy conversion of the NFs [46]. The results from the UV-vis analysis suggest superior absorption capability of the formulated NFs and undoubtedly validates their potential implementation on direct absorption solar collectors, for instance, hybrid CPV/T solar system. MXenes are reported to have better absorption capability compared to conventional carbon nanotube based materials due to its distinct layered structure. Li, et al. [51] reported enhanced photo-thermal energy conversion efficiency of layered Ti_3C_2 nanomaterial. Wang, et al. [31] observed that MXene based NF exhibits 4.34% higher photo-thermal energy conversion efficiency relative to Graphene at 20 ppm.

3.3. Stability of TH-55 with nanoparticles

The homogeneous of the suspension or the nanofluid's long-term stability is a critical precondition for industrial applications. In general, the instability of nanofluid is caused by several attraction and repulsion forces acting at the solid-fluid interface of the suspension. When attraction forces dominate, the nanoparticles tend to form clusters and degrade the homogeneity and thermo-optical properties of the suspension. Zeta potential (ζ) analysis is an effective way to determine the dispersion stability of nanomaterials in a fluid medium. In this method, the electrical potential difference (i.e. Zeta potential, ζ) is measured in mV at the electric double layer (EDL) formed at the solid-fluid interface of the suspension [52]. Higher values of ζ implies higher mobility i.e., dispersion stability of the particles in the fluid medium. The ζ value beyond ±60 mV represents excellent stability of suspension whereas, values below ±15 mV indicates unstable or poor dispersion of nanoparticles in the mixture [53].

The suspension stability of prepared NFs is characterized by varying particle wt.% (0-0.125) and temperature (25 and 80°C). The obtained ζ results (depicted in **Figure 5**) suggest good stability of the formulated fluids, particularly for mono TH-55/Ti_3C_2 NF at 0.025wt.%. It is also clear that the addition of more particles (0.075 and 0.125wt.%) deteriorates dispersion homogeneity as ζ drops due to formation of clusters in the suspensions. Nevertheless, NF samples with single NPs are found to be more stable than hybrid ones. On the 4th day of preparation, absolute ζ value of 79.39, 64.83, 44.17 mV and 54.36, 41.74, 27.29 mV are measured for TH-55/Ti_3C_2 and TH-55/Ti_3C_2+CuO NFs, respectively. In terms of temperature, NFs are observed to be more stable at high temperatures than the lower ones. At 80℃, both mono and hybrid NFs exhibited absolute ζ value above 30 mV, while comparatively lower ζ is noted at 25℃ for all three wt.%. This is due to particle addition movement (i.e., Brownian motion), which results in a decrease in Van der Waals attraction potential at higher temperatures. Other studies examining oil-based NFs confirm the associated effects of particle loading and temperature on stability [37, 48].

3.4. *Thermal conductivity of TH-55 with nanoparticles*

Figure 6 depicts experimental results on the thermal conductivity (TC) variation of TH-55/Ti_3C_2 and hybrid TH-55/Ti_3C_2-CuO NFs at 0.025-0.125 wt.% nanoparticle concentration against increasing temperature (30 to 70 °C). The TC values of the NFs are measured experimentally within a standard deviation of less than ±0.0025. The addition of Ti_3C_2 and CuO particles into the base fluid provides a significant improvement in the TC of the fluids. Furthermore, as temperature was raised, TC of the NFs was observed to improve, whereas TC of the TH-55 oil alone deteriorated. **Figure 6(a-b)** depicts the percentage linear increment of TC for formulated NFs with the inclusion of nanoparticles as well at increasing temperatures. The enhancement is calculated using the equation $\left(\frac{k_{nf} - k_{bf}}{k_{bf}}\right) \times 100$ where, k_{nf} is TC of NF and k_{bf} is TC of base fluid TH-55. At 70°C, the maximum augmentations in TC obtained by suspending the particles are 84.55% and 80.03% for TH-55/Ti_3C_2 and hybrid TH-55/Ti_3C_2-CuO NFs, respectively. The remarkable improvement of TC for all the NFs is due to the distinct thin two-dimensional layered structure of Ti_3C_2 flakes, their high surface area to volume ratio, stable dispersion, and movement of the suspended particles into the TH-55 [54]. In the case of hybrid NF, TC increases are attributed to the incorporation of highly heat conductive Ti_3C_2 and CuO nanomaterials into pure oil, as well as intermolecular movements among the particles and their large conductive surface area [55]. Added particle wt.% is observed to have a noteworthy impact on TC as higher wt.% yields more conductivity of the NFs. However, the addition of nanomaterial showed better TC augmentation at lower wt.% with hybrid NF, being 18.16% and 25.88% at 0.025 wt.% and 30°C for sole and hybrid NFs, respectively. Thus, it is evident that the dispersed solid concentration of the particles offers an effective heat transport aptitude in comparison with pure base fluid.

TC and heat transfer characteristics of NF are a function of temperature variation of the system. The phenomenon of TC improvement with increasing temperature is associated with particle Brownian motion and kinetic energy, which increases heat transport through dispersed nanomaterials [56, 57]. As Brownian motion intensifies at higher temperatures, it enables heat to be transported more efficiently from one particle to another utilizing large surface area of Ti_3C_2 nanoflakes and spherical CuO particles. Furthermore, tinny Ti_3C_2 flakes with negligible thickness (<10 nm) are able to randomly move with high energy within the oil medium [58]. For TH-55 oil with the highest weight concentration (0.125 wt.%) of Ti_3C_2 flakes, TC is intensified by 4-8% for each 10°C rise in NF temperature. TC of the NFs intensified more at higher temperatures due to effective Brownian movement at elevated temperatures. A similar trend is noticed for hybrid loading of Ti_3C_2 and CuO nanoparticles in thermal oil except at 0.125 wt.% conductivity values of hybrid NF are lower relative to that of solo NF samples. The outcomes can be ascribed to extra-large surface area of Ti_3C_2 particles, aggregation of particles at higher loadings and different size and shape of two types of particles dispersed together into the oil. Similar findings are reported by Yu, et al. [59] analyzing NF formulated from ethylene glycol and two-dimensional graphene nanosheets. It is important to note that the inherent TC of Ti_3C_2 is much lower than graphene. However, due to stable dispersion and compatibility with solvents, it can offer potential TC in suspension. As intensified TC of working fluid can produce enhanced thermal performance of the system, the formulated NFs can be potential HTFs to utilize in thermal systems like CPV/T systems.

From the obtained results, it is evident to state that the impact of wt.% is dominant over the effect of increasing temperatures on TC of the prepared NFs. Several previous studies with oil-based NF and Ti_3C_2 particles have yielded results that are consistent with those obtained in this experiment. [60] investigated colloidal conductivity of ethylene glycol (EG) based multi-layered and single layered Ti_3C_2 nanofluid. They reported that adding Ti_3C_2 sheets produced the highest 64.9% augmented TC relative to EG. Samylingam, et al. [46] experimentally estimated TC of palm oil-based NFs adding 0.01 to 0.2 wt.% Ti_3C_2 nanomaterials for temperature range of 25-70 °C. Their results revealed that the NF obtained a 68.5% increment in TC compared to palm oil.

3.5. Dynamic viscosity of TH-55 with nanoparticles

Dynamic viscosity (μ) is one of the key properties of NF, which is defined by the resistance force that causes fluid deformation in the reverse path of flow. It has a substantial effect on heat transfer by convection in fluids during the application of fluids on thermal systems. This is mainly due to its impact system's pumping power. Lower μ of working fluids results in less pumping power being required to operate solar thermal systems [61]. The μ of synthesized NFs is measured at considered concentrations (0-0.125wt.%) over a range of temperature (25-105°C) and shear-rate (0-100s^{-1}). The μ of TH-55 varies with the addition of Ti_3C_2 and Ti_3C_2+CuO nanocomposite, increasing with inclusion of solid nanomaterials and decreasing with rising temperatures (**Figure 7**). However, the growth is marginal in contrast to the significant decrease in all concentrations at higher temperatures. The drop in μ is due to weaker intermolecular interaction (i.e., adhesion forces) between the fluid and solid materials and higher molecular movement at elevated temperatures. Among the NF samples, 0.025 wt.% of

NP loading resulted in the lowest μ of 1.75 and 2.64 mPa.s at 105°C, while 0.125 wt.% resulted in the highest μ of 5.71 and 6.31 mPa.s for mono and hybrid NFs, respectively.

Rheology is the study of flow behavior of fluids streaming against applied tensions. To characterize the rheological behavior of experimentally formulated NFs, variation in μ of the NFs is observed for corresponding value of shear-rate at constant temperature of 25 and 50℃ (**Figure 8**). The results suggest that Newtonian flow characteristic is dominant in TH-55/Ti_3C_2 and hybrid TH-55/Ti_3C_2+CuO NFs as μ remained constant over the range of shear-rate (0-100s^{-1}) except little fluctuation at very low of shear-rates up to 20s^{-1}. Furthermore, the rheological property remained constant regardless of temperature variation. Newtonian shear behavior of the NFs is a result of spindle rotation and decorated fluid molecules. Hence, further increment in shear-rate will not alter the μ of the fluids. The obtained results are in accord with other oil-based NFs reported at similar operating conditions [62, 63]. Since these NFs exhibit prominently low μ and Newtonian flow characteristics at elevated operating temperatures, these mono and hybrid NFs can be an efficient working fluid in the CPV/T solar system.

3.6. Performance assessment of hybrid CPV/T system

3.6.1. Temperature of the PV panel

To keep the PV component temperature within the acceptable range, this study used two nanofluid-based coolants. The effects of various operational parameters on cell efficiency were investigated under the influence of five effective suns on a tightly packed concentrated photovoltaic/thermal device. Simulations were performed at 1000-5000 W/m^2 and with varying nanomaterial concentrations and flowrates. The temperature distribution among different layers (PV cell, EVA, tedlar and back plate) of the PV pane at 5000 and 1000 W/m^2 is presented in **Figure S6**. The obtained temperature distribution data show that temperature of the layers is significantly higher at highest solar irradiance intensity (5000 W/m^2) than that of lowest irradiance (1000 W/m^2). It was observed that the of PV cell temperature becomes highest compared to EVA, tedlar and back plate layers of the system. Tedlar temperature is lower than PV cell and adjacent EVA layer due to the cooling effect of the heat exchanger connected to the back plate.

Figure S7 shows temperature contours of the PV surface and fluid flow through the serpentine tubes of the thermal collector at a flow rate of 3 LPM and different solar irradiance (1000 and 5000 W/m^2). It is noticed from the obtained contours that the average surface temperature of the PV panel is much higher, about 60℃ at concentrated intensity of 5000 W/m^2 relative to

38°C at1000 W/m^2 using the nanofluids at 0.125 wt.%. This is due to the fact that high solar irradiation is captured on the panel at higher irradiation intensity. In addition, the temperature augmentation of the PV panel is uniform as the radiation rises (shown in **Figure 9**).

The temperature of the cooling nanofluid increases as it passes through the serpentine thermal collector tubes and absorbs heat from the tedlar layer to reduce the surface temperature of the PV panel connected above it. The captured heat transfers through the solid layers and nanofluid via conduction and convection heat transfer mechanisms, respectively. **Figure S8** represents the temperature contours of the outlet of the cooling nanofluids at a flow rate of 3 LPM and concentration of 0.125 wt.%. It is observed that the maximum outlet temperature for the nanofluid is about 32°C higher at 5000 W/m^2.

Figure 9 (a-b) reveals that the average cell temperature values of the PV panel drop with rising inlet fluid volume flow rate from 0.5 to 4 LPM at an irradiation level of 5000 W/m^2, and at an inlet fluid temperature of 30°C. As the inlet fluid flow rate increases, more heat is removed from the PV unit by convection, which decreases the temperature. It is obtained that the cell median temperature declines rapidly with increasing flow rates of the fluids. For Therminol®55, at the flow rate of 0.5 LPM and average cell temperature of 91°C, the temperature reduces steadily as the flow rate extends upward to 3 LPM. Following that, at a flow rate of 4 LPM, it decreases slightly, but the pumping capacity is increased. Hence, for this CPV/T collector, the optimized volume flow rate of cooling fluid is 3 LPM. This trend is same for both mono and hybrid nanofluids. However, more temperature reduction is achieved in mono nanofluid at the same concentrations of nanoparticle (0.025-0.125 wt.%). It was noticed that the average solar cell temperature drops from 81 to 51°C for TH-55/Ti_3C_2 at 0.125 wt.% and from 79 to 56°C for TH-55/Ti_3C_2 at the same concentration. **Figure 9**(c-d) depicts the cell temperature variation with solar irradiance. Cell temperature rises reasonably with an increase in irradiance intensity from 1000 to 5000 W/m^2 for every nanofluid sample for both mono as well as hybrid nanofluid. It was observed that for each 100 W/m^2 rise in intensity, the average cell temperature enhances by 0.85°C for Therminol®55 as cooling fluid. However, in the case of mono TH-55/Ti_3C_2 nanofluid (0.125 wt.%), it dropped to 0.55°C. The similar rate, 0.57°C per 100 W/m^2, is observed in the case of hybrid TH-55/Ti_3C_2+CuO nanofluid at 0.125wt.%. This clearly reveals that the formulated nanofluids are performing better as cooling fluid relative to TH-55. We have observed Nasrin, et al. [64] showed an increase of 0.9°C for each 100 W/m^2 growth in irradiance intensity.

3.8.2. Electrical efficiency

The electrical output of the concentrated PV/T system varies between 1000 and 5000 W/m^2 and 0.5 and 4 LPM, respectively, against solar irradiance and volume flow rate (presented in **Figure 10**(a-d)). The electrical efficiency of PV panel increases with flowrate. However, the increment was not remarkable when the flow rate enhanced from 0.5 to 4 LPM for each nanofluid sample at a fixed irradiance of 5000 W/m^2. Thus, an inlet fluid flow rate of no more than 3 LPM is advantageous for the cooling system of the PV/T module. The maximum efficiencies recorded for nanofluids at maximum fraction (0.125 wt.%) are 12.8 and 12.6% at a flowrate of 4 LPM for TH-55/Ti_3C_2 and TH-55/Ti_3C_2+CuO nanofluids, respectively. Due to rising inlet volume flow of nanofluid, the cell's average temperature is reduced (as shown in **Figure 9**). Consequently, the PV/T module's current declines slightly with an evident increase in PV/T voltage which, in turn, improves the output power and electrical efficiency. **Figure 10**(c-d) confirms the variation of electrical efficiency with irradiance level. Here, the flowrate is fixed at 3 LPM and irradiance is varied up to 5000 W/m^2. The electrical efficiency decreases with rising irradiation level. The electrical efficiency depreciates from 12 to 9.7% due to increasing solar radiation for Therminol®55, from 14.1 to 12.5% for TH-55/Ti_3C_2 (0.125 wt.%), from 14 to 12.4% for TH-55/Ti_3C_2+CuO (0.125 wt.%). Nasrin, et al. [65] revealed that the electrical efficiency for Water/Ag nanofluid in PVT system at 5000 W/m^2 and 3 LPM was 12.5%. This clearly indicates that the formulated nanofluids perform more effectively.

3.8.3. Thermal efficiency

The thermal energy efficiency increases with rising volume flow rate of the cooling fluid at a constant solar intensity of 5000 W/m^2 is presented in **Figure 11**(a-b). An escalation in flow rate from 0.5 to 4 LPM augments the convective heat transfer coefficient of the working fluids. As a result, more heat is transferred at higher velocities under a given temperature difference, increasing energy efficiency. The efficiency intensifies from 58 to 65% for Therminol®55, from 71 to 78% for TH-55/Ti_3C_2 (0.125 wt.%) and 70 to 77% for TH-55/Ti_3C_2+CuO (0.125 wt.%). The rate of growth in energy efficiency decreases as solar irradiance increases from 1000 to 5000 W/m^2, because increasing the solar intensity increases the overall amount of receiving energy from the CPV/T system (depicted in **Figure 11** (c-d)). The thermal efficiency of the CPV/T collector decreases from 87 to 77% for TH-55/Ti_3C_2 (0.125 wt.%) and from 86 to 76% for TH-55/Ti_3C_2+CuO (0.125 wt.%). Nasrin, et al. [64] stated a 0.3% abatement of thermal energy efficiency at each 100 W/m^2 growth of irradiation. In this study, using the nanofluids, 0.25% reduction rate is found for per each 100 W/m^2 increment of irradiation.

3.8.4. Efficiency comparison

Figure 12 (a-b), a comparison of electrical and thermal efficiency of mono and hybrid nanofluid at maximum volume fraction and at a flowrate of 3 LPM with varying irradiation level is presented. It is clear from the **Figure 12** that the mono nanofluid is performing well in comparison to hybrid one, but variation among the performance is very little. So, we can conclude that TH-55/Ti_3C_2 operated CPV/T system is better, and it is not necessary to make it hybrid one by adding CuO in Ti_3C_2.

4. Conclusions

In this research, mono (TH-55/Ti_3C_2) and hybrid (TH-55/Ti_3C_2+CuO) nanofluids are prepared using experimentally synthesized emerging two-dimensional MXene (Ti_3C_2) nanomaterial and spherical CuO nanoparticles. Significant results are obtained in terms of thermal conductivity, solar absorbance, and stability behavior of the nanofluids. In the simulation-based application part of this work, we numerically evaluated the effectiveness of the synthesized nanofluids as cooling fluids on a concentrated PV/T system under transient conditions. The investigation is performed considering various nanomaterial loadings (0.025-0.125 wt.%), solar irradiations (1000-5000 W/m^2), flow rates (0.5-4 LPM) and particles to evaluate cooling, electrical and thermal efficiency. The major experimental and numerical findings of this work are drawn in the following points:

- The morphological characterization of the synthesized Ti_3C_2 nanosheets demonstrates that the MAX-phase structure was successfully transformed into the two-dimensional multi-layered structure. Zeta potential analysis discloses that the formulated nanofluids exhibit a very good level of suspension stability.
- UV-vis analysis confirms enhanced absorbance of the nanofluids. The photo-thermal energy conversion efficiency of TH-55 oil is increased by 80.16 and 85.98% by adding Ti_3C_2 and Ti_3C_2+CuO nanocomposite, respectively.
- The addition of nanomaterials to the base fluid increases thermal conductivity. At 0.125 wt.%, the maximum 84.55 and 80.03% increments are measured 70 ℃ for TH-55/Ti_3C_2 and hybrid TH-55/Ti_3C_2+CuO NFs, respectively. Furthermore, dynamic viscosity measurements showed a slight increase when adding the nanoparticles, but they dropped remarkably at elevated temperatures. Besides, the nanofluids behaved like Newtonian fluid.

- Application of the nanofluids in a CPV/T solar collector produced an improved cooling effect on the PV unit of the system as 25 and 24℃ temperature drops are achieved at 0.125 wt.% using mono and hybrid nanofluids, respectively.
- At 5000 W/m^2 solar irradiance, the highest thermal and electrical output enhancement of the formulated nanofluid-based CPV/T system is found to be 12.8% and 2% at an optimum flowrate of 3 LPM. Moreover, mono nanofluids performed marginally better relative to hybrid ones.

Future research could lead to the practical implementation of proposed nanofluids on CPV/T solar collectors by examining additional parameters, such as exergy analysis and estimation of the system's pumping power.

Competing interests

The authors declare that they have no financial or personal conflicts of interest that may seem to have affected the work reported in this article.

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Table 1**.** Characteristics of TH-55 base fluid.

Properties	**Observed values for therminol®55**
Dielectric constant (at 23°C)	2.23
Refractive index	1.48
Flash point	193°C
Thermal conductivity (at 30°C)	0.136 W/m.K
Dynamic viscosity (at 30°C)	25.2 mPa.s

Table 2**.** Specifications of dispersed nanoparticles used to formulate the nanofluids.

Particles	**Dimension**	**Morphology**	**Density (g/cm^3)**	**Purity**
MXene (Ti_3C_2)	1-10 µm × 1 nm	two-dimensional	--	99%
CuO	10 nm	spherical	6.4	99%

Table 3**.** Specifications and properties (thermal and optical) of the CPV/T system

Parameter	**Values**
PV Model No.	ELDORA VSP.72.AAA.03
Material	Polycrystalline silicon cell
Power	300 W
Dimensions	1955 × 982 × 36 mm
Weight of PV panel	20.5 kg
$h_{panel-tedlar}$	150 W/m^{2}K
$h_{tedler-tubing}$	77 W/m^{2}K
$h_{tubing-nanofluid}$	66 W/m^{2}K
A_{PV}	0.9
A_{tedlar}	0.5
$Emissivity_{PV}$	0.99
k_{EVA}	0.311 W/m.K
k_{PV}	148 W/m.K
k_{Tedlar}	0.15 W/m.K
$k_{thermalpaste}$	1.9 W/m.K
k_{tubes}	2700 W/m.K

Table 4. Grid independency test.

S. No.	**Mesh size (elements)**	**PV Temp. (℃)**	**Deviation (%)**	**Outlet Temp. (℃)**	**Deviation (%)**	**Solution Time (s)**
1	2.5×10^5	42.341	--	41.213	--	560
2	4×10^5	43.872	1.2%	40.751	1.13%	720
3	6×10^5	44.003	0.29%	40.254	1.23%	817
4	8×10^5	44.118	0.26%	39.104	2.94%	1115
5	1.5×10^6	45.200	2.3%	38.889	0.55%	1487
6	3.5×10^6	45.201	0.002%	38.801	0.22%	1815

Table 5. Validation of average cell Temperature.

Flowrate (LPM)	**Cell Temperature (℃)**		**Percentage error**
	Present Research	**Nasrin, et al. [47]**	
0.5	52.56	51.11	2.83%
1	49.85	48.04	3.70%
3	47.10	45.76	2.92%