ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc. THESIS

Hacı Mehmet KILIÇ

NUMERICAL INVESTIGATION OF USING NANOFLUID COOLANT IN PVT SYSTEM

DEPARTMENT OF MECHANICAL ENGINEERING

ADANA-2022

ABSTRACT

MSc. THESIS

NUMERICAL INVESTIGATION OF USING NANOFLUID COOLANT IN PVT SYSTEM

Hacı Mehmet KILIÇ

ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF MECHANICAL ENGINEERING

Supervisor : Prof. Dr. Orhan BÜYÜKALACA
Year: 2022, Page: 97
Jury : Prof. Dr. Orhan BÜYÜKALACA
: Assoc. Prof. Dr. Göktürk Memduh ÖZKAN
: Assist. Prof. Dr. Kamil Neyfel ÇERÇİ

In this thesis, a numerical study of a photovoltaic thermal (PVT) system with nanofluid was conducted due to its increasing popularity as clean energy in recent years. The analyzed PVT collector consists of glass, top transparent ethylene vinyl acetate (EVA) layer, monocrystalline silicon solar cell, bottom transparent EVA layer, tedlar polyvinyl fluoride (tedlar) layer, thermal paste, copper absorber plate and copper tubes. The PVT collector was designed in 3D in order to investigate the effect of nanofluid use in the PVT system. Finite element method was used for numerical analysis. Studies in the literature were considered for the selection of the dimensions of the PV panel and the materials of the layers that consist of the PV panel. The layers that forms the photovoltaic panel were examined in detail in the analysis. Hexagonal Boron Nitride (hBN) material, which was not used as a part of the coolants in PVT systems before was used in this numerical study. First of all, the results obtained by the numerical analysis for hBN/water nanofluid and water were compared. Then, analyzes were performed for determining the effect of different hBN concentrations, flow rate and hBN nanoparticle diameter on the performance of the PVT system. Fluid outlet temperature, cell temperature, thermal, electrical and overall efficiency were determined for the PVT collector. The results show that the hBN/water nanofluid improves the performance of the PVT system.

Keywords: Photovoltaic Thermal System, Nanofluid, Hexagonal Boron Nitride, Finite Element Method, Numerical Analysis

ÖZ

YÜKSEK LİSANS TEZİ

PVT SİSTEMDE NANOAKIŞKAN SOĞUTMA KULLANIMININ SAYISAL İNCELENMESİ

Hacı Mehmet KILIÇ

ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ
MAKİNA MÜHENDİSLİĞİ ANABİLİM DALI

Danışman : Prof. Dr. Orhan BÜYÜKALACA
Year: 2022, Page: 97
Juri : Prof. Dr. Orhan BÜYÜKALACA
: Doç. Dr. Göktürk Memduh ÖZKAN
: Dr. Öğr. Üyesi Kamil Neyfel ÇERÇİ

Bu tez kapsamında, son yıllarda temiz enerji olarak artan popülaritesi nedeniyle nanoakışkanlı bir fotovoltaik termal (PVT) sistemin sayısal analizleri yapılmıştır. Ele alınan PVT kolektör cam, üstte şeffaf etilen vinil asetat (EVA) tabakası, monokristal silikon güneş pili, altta şeffaf EVA tabakası, tedlar polivinil florür (tedlar) tabakası, termal macun, bakır soğurucu plaka ve bakır borulardan oluşmaktadır. PVT kolektör, nanoakışkan kullanımının etkisini incelemek için 3 boyutlu olarak tasarlanmıştır. Sayısal analizler için sonlu elemanlar yöntemi kullanılmıştır. Fotovoltaik panelin boyutlarının ve paneldeki katmanların malzemelerinin seçiminde literatürdeki çalışmalar göz önünde bulundurulmuştur. Analizde fotovoltaik paneli oluşturan katmanlar detaylı olarak ele alınmıştır. Bu sayısal çalışmada daha önce PVT sistemlerinde soğutucu akışkanların bir parçası olarak kullanılmayan Altıgen Bor Nitrür (hBN) malzemesi kullanılmıştır. Analizlerde öncelikle hBN/su nanoakışkanı ve su karşılaştırılmıştır. Daha sonra farklı hBN konsantrasyonlarının, akış hızının ve hBN nanoparçacık çapının PVT sisteminin performansı üzerindeki etkileri incelenmiştir. PVT kolektör için nanoakışkanın çıkış sıcaklığı, hücre sıcaklığı, termal, elektriksel ve toplam verim parametreleri belirlenmiştir. Sonuçlar, hBN/su nanoakışkanının PVT sistemin performansını iyileştirdiğini göstermektedir.

Anahtar Kelimeler: Fotovoltaik Termal Sistem, Nanoakışkan, Altıgen Bor Nitrür, Sonlu Elemanlar Yöntemi, Sayısal Analiz

EXTANDED ABSTRACT

Technological applications in almost every sector such as industry, agriculture and domestic services are in great need for energy. The amount of energy required to meet the needs will increase further in the future as the time progresses. Increasing demand for energy with the increasing population causes a decrease in the available energy resources. Research predicts that fossil fuels that we use intensively now will be completely exhausted in the 22^{nd} century. Residual substances from fossil fuels burning for energy generation have played a major role in environmental pollution and climate change. Therefore, studies on renewable energy that does not cause any harm to nature have been the interest of many researchers from all over the world. Solar energy is one of the leading renewable energy sources. By using the heat and light provided by the sun, safe, clean and cheap energy can be obtained without harming the nature.

The photovoltaic thermal (PVT) system is an instrument designed that receives solar energy and converts this energy into both electrical and thermal energy. Efficiency of photovoltaic solar panel (PV), which produces electricity by absorbing sunlight, decreases over time as the temperature of the silicon cells that make up the PV increases. Therefore, in order for the PV not to decrease its electrical production over time, it must be cooled. The PVT system cools the PV with its cooling element. The PVT system not only prevents the decrease in electricity production by cooling the PV, but also shows a superior feature by producing thermal energy as well as electrical energy.

Different designs and innovative methods are proposed to obtain maximum efficiency from PVT systems. Nanofluid based PVT systems is a novel method developed to obtain higher efficiency from PVT system. In order to reduce the panel temperature in the PVT system, new generation of nanofluids have been developed as an alternative to the traditional fluids used as a coolant in the PVT systems.

Hexagonal Boron Nitride (hBN) material, which was not used as a part of the coolants in PVT systems before was used in this numerical study. Hexagonal Boron Nitride has the hexagonal form of boron nitride and belongs to the class of ceramic materials. It has a chemically stable structure and versatile properties such as high thermal conductivity. Therefore, hBN is a good candidate for heat transfer applications. Nanofluids consisting of hBN and water can be considered as a promising fluid for future thermal engineering applications with their stable properties and enhanced thermal performances.

The nanofluid properties are of fundamental importance in this study. For this reason, it was accepted that the nanoparticle forming the nanofluid and the molecules of the base fluid are in thermal equilibrium without shifting. Because of all these conditions, the nanofluid is considered to be single phase. The single step model is a very common model used to calculate the convective heat transfer of the nanofluid and is used to facilitate simulation.

The cooling fluid flow was assumed to be steady, incompressible, and uniform. Thermophysical properties of the PVT components were assumed to be constant. The sky was considered to be a black body with a temperature of sky. The solar panel used in the PVT system and the layers (materials) that make up the PV panel were taken from those commonly used in the literature. The thermophysical properties of layers in PVT collector used in this analysis are commonly accepted in the literature. These layers are tedlar layer, ethylene vinyl acetate (EVA) layer and silicon layer representing the silicon PV cells that generate electricity in PV panel. The thermal paste and the absorber plate are used to combine the PV module with the heat exchanger and form the PVT system. The PV panel includes a glass layer at the top.

In the numerical simulation, the inlet fluid velocity boundary condition was applied for the fluid entering the tube and the studied inlet fluid velocities were 0.08 m/s, 0.16 m/s and 0.24 m/s. The temperature of the fluid entering the tube was taken as constant at 25 °C. The ambient temperature was assumed to be the same as the water inlet temperature. The pressure outlet condition of the fluid from the tube was taken as 0 (zero) atm. The no slip condition was applied to the inner walls of the tube. Inward heat flux was applied on the PV panel. Heat losses occurred from the upper surface of the PVT collector by convection. The convection heat transfer coefficient from the upper surface of the PVT collector was taken as 20 W/m^2K. It was assumed that the side and bottom surfaces of the PVT collector are insulated very well. Therefore, the side and bottom surfaces of the PVT collector were assumed to be adiabatic (zero heat flux).

Water with an inlet velocity of 0.16 m/s was used as the fluid for the for the mesh independency test. For this test, the ambient air and inlet water temperature was 25 °C and the solar radiation was 1000 W/m^2. The outlet temperature of the cooling water and the surface temperature of the cell were compared for five different mesh sizes varying between 395431 and 1927871. The relative error in cell and outlet temperatures between 1469137 and 1927871 element sizes was found to be very small, being 0.029% and 0.010%, respectively. Therefore, the numerical studies were carried out with a mesh size of 1533133.

Numerical analyzes showed that hBN/water nanofluid with 2% concentration relative to water improves the performance parameters of the PVT system compared to water. It was found that adding 2% hBN to the water causes a very small increase in the temperature of the water leaving the collector, resulting in an increase of approximately 1.51% in the average thermal efficiency. When nanofluid was used, the cell temperature was on average 3.27% lower than water, but the electrical efficiency was 0.11% higher, when nanofluid was used. The overall efficiency of hBN/water nanofluid was obtained greater than water. Also, the outlet temperature of the fluid, thermal efficiency and PV panel surface temperature increased with the increase of radiation from 200 W/m^2 to 1200 W/m^2, while the electrical efficiency decreased for both fluids.

Considering the effect of the concentration of hBN in water the fluid outlet temperature, thermal efficiency, electrical efficiency, and overall efficiency increased with increasing concentration from 0% to 8%. Cell temperature decreased with increasing concentration.

Increasing the inlet fluid velocity of the hBN/water nanofluid from 0.08 m/s to 0.24 m/s caused a decrease in fluid outlet temperature and PV panel temperature, but an increase in thermal, electrical, and overall efficiency. It was seen that the highest cell temperature was reached when fluid velocity was the minimum, but the lowest cell temperature was obtained with maximum velocity. The minimum and maximum values obtained for the outlet temperatures of the fluid are similar to those obtained for PV panel temperature.

Reducing hBN diameter from 0.75 nm to 0.25 nm, there was a slight increase in all performance parameters except for PV panel temperature. There was a slight increase in the PV panel temperature. The maximum cell temperature was obtained with 0.75 nm hBN diameter. It can be concluded that in the 0.25 nm to 0.75 nm diameter range, the effect of nanoparticle size is insignificant for the considered performance parameters of the PVT system.

In the numerical analysis, different parameters were examined to increase the performance of PVT system by using hBN nanoparticles. It was proven that the new nanofluid formed by adding hBN nanoparticles, which were not used in PVT systems before, to the base fluid water, increases slightly the efficiency of the PVT system. However, an experimental investigation was not carried out in this study. Therefore, the effect of the hBN/water nanofluid on the PVT system performance should be tested in real climatic conditions. Moreover, the effect of mixing hBN with other thermal oils on the performance of PVT can be studied both numerically and experimentally. In addition, the serial, parallel or serial/parallel connection of PVT collectors to each other should also be investigation.

GENİŞLETİLMİŞ ÖZET

Sanayi, tarım ve konutlar gibi hemen her sektörde teknolojik uygulamalar enerjiye büyük ihtiyaç duymaktadır. İhtiyaçların karşılanması için gereken enerji miktarı gün geçtikçe artmaktadır. Artan nüfusla birlikte artan enerji talebi, mevcut enerji kaynaklarının azalmasına neden olmaktadır. Araştırmalar, günümüzde yoğun olarak kullandığımız fosil yakıtların 22. yüzyılda tamamen tükeneceğini öngörmektedir. Enerji üretimi için yanan fosil yakıtlardan kaynaklanan artık maddeler, çevre kirliliği ve iklim değişikliğinde önemli bir rol oynamaktadır. Bu nedenle doğaya zarar vermeyen yenilenebilir enerji üzerine yapılan çalışmalar dünyanın her yerinden birçok araştırmacının ilgi odağı olmuştur. Güneş enerjisi, yenilenebilir enerji kaynaklarının başında gelmektedir. Güneşin sağladığı ısıl enerji ve ışık kullanılarak doğaya zarar vermeden güvenli, temiz ve ucuz enerji elde edilebilir.

Fotovoltaik termal (PVT) sistem, güneş enerjisini alan ve bu enerjiyi hem elektrik hem de termal enerjiye dönüştürmek üzere tasarlanmış bir cihazdır. Güneş ışığını emerek elektrik üreten fotovoltaik güneş panelinin (PV) verimi, PV'yi oluşturan silikon hücrelerin sıcaklığı arttıkça zamanla düşmektedir. Bu nedenle PV'nin zamanla elektrik üretimini düşürmemesi için soğutulması gerekir. PVT sistemi, soğutma elemanı ile PV'yi soğutur. PVT sistemi sadece PV'yi soğutarak elektrik üretiminin azalmasını engellemekle kalmaz, aynı zamanda elektrik enerjisinin yanı sıra termal enerji de üreterek üstün bir özellik gösterir.

PVT sistemlerinden maksimum verim elde etmek için farklı tasarımlar ve yenilikçi yöntemler önerilmektedir. Nanoakışkan tabanlı PVT sistemleri, PVT sistemden daha yüksek verim elde etmek için geliştirilmiş yeni bir yöntemdir. PVT sistemdeki panel sıcaklığının düşürülmesi için PVT kollektöründe soğutucu olarak kullanılan geleneksel akışkanlara alternatif yeni nesil nanoakışkanlar geliştirilmiştir.

Bu sayısal çalışmada daha önce PVT sistemlerinde soğutucu akışkanların bir parçası olarak kullanılmayan Altıgen Bor Nitrür (hBN) malzemesi kullanılmıştır. Altıgen Bor Nitrür, Bor Nitrür'ün altıgen formuna sahiptir ve seramik malzeme sınıfına aittir. Kimyasal olarak kararlı bir yapıya ve yüksek ısı iletkenliği gibi çok yönlü özelliklere sahiptir. Bu nedenle hBN, ısı transferi uygulamaları için iyi bir adaydır. Su ve hBN'den oluşan nanoakışkanlar, kararlı özellikleri ve gelişmiş termal performansları ile gelecekteki termal mühendislik uygulamaları için umut verici bir akışkan olarak kabul edilebilir.

Nanoakışkan özellikleri bu çalışmada temel öneme sahiptir. Bu nedenle nanoakışkanı oluşturan nanopartikül ile baz akışkanın moleküllerinin kayma olmaksızın termal dengede olduğu kabul edilmiştir. Tüm bu koşullar nedeniyle, nanoakışkan tek fazlı olarak kabul edilir. Tek adımlı model, nanoakışkanın taşınım ısı transferini hesaplamak için kullanılan çok yaygın bir modeldir ve simülasyonu kolaylaştırmak için kullanılır.

Soğutma akışının sabit, sıkıştırılamaz ve homojen olduğu varsayılmıştır. PVT'yi oluşturan bileşenlerinin termofiziksel özelliklerinin sabit olduğu varsayılmıştır. Gökyüzü, gökyüzü sıcaklığına sahip siyah bir cisim olarak kabul edilmiştir. PVT sistemde kullanılan güneş paneli ve PV paneli oluşturan katmanlar (malzemeler) literatürde yaygın olarak kullanılanlardan alınmıştır. Bu çalışmada kullanılan PVT kolektöründeki tabakaların termofiziksel özellikleri, literatürde yaygın olarak kabul edilmektedir. Bu katmanlar, tedlar katmanı, etilen vinil asetat (EVA) katmanı ve PV panelinde elektrik üreten silikon PV hücrelerini temsil eden silikon katmanıdır. Termal macun ve emici plaka, PV modülünü ısı eşanjörü ile birleştirmek ve PVT sistemini oluşturmak için kullanılmaktadır. PV paneli bir cam katman içermektedir.

Sayısal simülasyonda, kolektörün akışkan borusuna giren akışkan için giriş akışkan hızı sınır koşulu uygulanmış ve çalışılan giriş akışkan hızları 0.08 m/s, 0.16 m/s ve 0.24 m/s'dir. Boruya giren akışkanın sıcaklığı 25 °C'de sabit olarak alınmıştır. Ortam sıcaklığının su giriş sıcaklığı ile aynı olduğu varsayılmıştır.

Akışkanın borudan çıkış basıncı 0 (sıfır) atm olarak alınmıştır. Tüpün iç duvarlarına kaymama koşulu uygulanmamıştır. PV panel üzerine içeriye doğru ısı akısı uygulanmıştır. PVT kolektörünün üst yüzeyinden taşınım ve radyasyon yoluyla ısı kayıpları meydana gelmiştir. PVT kolektörün üst yüzeyinden gelen taşınım ile ısı transfer katsayısı 20 W/m^2K olarak alınmıştır. PVT kolektörün yan ve alt yüzeylerinin çok iyi yalıtıldığı varsayılmıştır. Bu nedenle, PVT kolektörün yan ve alt yüzeylerinin adyabatik (sıfır ısı akısı) olduğu varsayılmıştır.

Ağ bağımsızlığı testi için, akışkan olarak su kullanılmış olup, suyun giriş hızı 0.16 m/s, ortam havası ve giriş suyu sıcaklığı 25 °C ve güneş ışınımı 1000 W/m^2 alınmıştır. Soğutma suyunun çıkış sıcaklığı ve hücrenin yüzey sıcaklığı 395431 ile 1927871 arasında değişen beş farklı göz boyutu için karşılaştırılmıştır. 1469137 ve 1927871 eleman boyutları arasında hücre ve çıkış sıcaklıklarındaki nispi hata %0.029 ve 0.010% olmak üzere çok küçüktür. Bu nedenle sayısal çalışmalar, 1469137 ve 1927871 ağ boyutları arasında 1533133 ağ boyutunda gerçekleştirilmiştir.

Sayısal analizler, %2 konsantrasyona sahip hBN/su nanoakışkanının PVT kolektörünün performans parametrelerini suya göre iyileştirdiğini göstermiştir. Suya %2 hBN eklenmesinin kolektörden çıkan suyun sıcaklığında çok küçük bir artışa neden olduğu bulunmuştur. Nanoakışkan çıkış sıcaklığındaki artış, hBN/su nanoakışkanının ortalama termal verimliliğinde suya kıyasla %1.51'lik bir artışa neden olmuştur. Nanoakışkan kullanılması durumunda, PV panel sıcaklığı su kullanılmasına göre ortalama %3.27 daha düşüktü, ancak elektriksel verim %0.11 daha yüksek çıkmıştır. hBN/su nanoakışkanının genel verimliliği, sudan daha fazla elde edilmiştir. Ayrıca güneş ışınımının 200 W/m^2'den 1200 W/m^2'ye arttırılmasıyla akışkanın çıkış sıcaklığı, termal verim ve PV panel yüzey sıcaklığı artarken, her iki akışkan için elektriksel verim düşmüştür.

Sudaki hBN konsantrasyonunun etkisini incelemek için gerçekleştirilen sayısal analizlerde sıvı çıkış sıcaklığı, termal verim, elektriksel verim ve toplam verim, konsantrasyonun %0'dan %8'e artmasıyla artmıştır. Sudaki hBN konsantrasyonunun artması, PV panel sıcaklığının düşmesine neden olmuştur.

Su/hBN nanoakışkanının giriş hızının 0.08 m/s'den 0.24 m/s'ye çıkarılması, sıvı çıkış sıcaklığında ve PV panel sıcaklığında bir azalmaya, ancak termal, elektriksel ve genel verimlilikte bir artışa neden olmuştur. PV panelde en yüksek sıcaklığa akışkan hızı minimum iken ulaşıldığı, en düşük PV panel sıcaklığına ise maksimum hız ile ulaşıldığı görülmüştür. Akışkanın çıkış sıcaklıklarında elde edilen minimum ve maksimum değerler PV panel sıcaklığı ile benzerlik göstermektedir.

Nanoparçacık çapı 0.75 nm'den 0.25 nm'ye düşürüldüğünde, PV panel sıcaklığı dışındaki tüm performans parametrelerinde hafif bir artış olmaktadır. Öte yandan, PV panel sıcaklığında hafif bir artış gözlemlenmiştir. Ayrıca maksimum PV panel sıcaklığı 0.75 nm hBN çapı ile elde edilmiştir. 0.25 nm ila 0.75 nm çap aralığında, nanoparçacık boyutunun etkisinin PVT sistemin dikkate alınan performans parametreleri için önemsiz olduğu görülmüştür.

Tez kapsamında gerçekleştirilen sayısal analizlerde, hBN nanoparçacıkları kullanılarak PVT sistemin performansını artırmak için, birçok farklı parametre incelenmiştir. PVT sistemlerinde daha önce hiç kullanılmamış Altıgen Bor Nitrür nanoparçacıklarının baz akışkan olarak suya eklenmesiyle oluşturulan yeni nanoakışkanın, PVT sisteminin verimini suya göre arttırdığı kanıtlanmıştır. Ancak bu tez kapsamında deneysel bir araştırma yapılmamıştır. Bu nedenle, hBN/su nanoakışkanının PVT sistem üzerindeki etkisi gerçek iklim koşullarında gözlemlenmelidir. Ayrıca, hBN'nin diğer termal yağlarla karıştırılmasının PVT üzerindeki etkisi hem sayısal hem de deneysel olarak incelenebilir. Son olarak, PVT kolektörlerin birbirine seri, paralel veya seri/paralel bağlantıları da araştırılmalıdır.

ACKNOWLEDGEMENTS

Firstly, I would like to thank my supervisor Prof. Dr. Orhan BÜYÜKALACA for providing valuable research advice, continuous support, and his understanding during my thesis. The valuable information he provided during my master's education was a tremendous gain for me. I am also grateful to him for the systematic study and research behavior he thought me in science and the patient attitude he showed during this learning process.

I am grateful to Assoc. Prof. Dr. Göktürk Memduh ÖZKAN for his advices and contributions during my thesis work. It is an honor for me to have him as a committee member in my thesis.

I am truly grateful to Assist. Prof Dr. Kamil Neyfel ÇERÇİ for his valuable information and support, who made extraordinary contributions to the solution of the problems I encountered while continuing my thesis work. During my thesis study, I will never forget the technical and scientific support that he provided me to carry out my analysis.

I would like to thank Research Assistants Umutcan OLMUŞ and Yunus Emre GÜZELEL for their continuous support and motivation. Their interests and continuous supports during my master's education was very important to me. It is impossible for me to forget the support they provided in solving the problems I encountered during my education.

Finally, I would like to thank my family for their tremendous support and understanding which I will never forget for the rest of my life, during my master's education. The successful completion of this study has been thanks to their wonderful support.

CONTENTS **PAGE**

LIST OF FIGURES **PAGE**

LIST OF TABLES **PAGE**

LIST OF SYMBOLS

A : Area, $[m^2]$

c_p : Specific heat, [kJ/kg.K]

d_p : Nanoparticle diameter, [nm]

$\dot{E}$: Power, [W]

FF : Fill factor [-]

G_t : Solar radiation, $[W/m^2]$

I : Electric current, [A]

k : Thermal conductivity [W/m.K]

$\dot{m}$: Mass flow rate, [kg/s]

P : Pressure, [Pa]

PV : Photovoltaic

PVT : Photovoltaic Thermal

$\dot{Q}$: Heat transfer rate, [W]

T : Temperature, [^oC]

U : Overall heat transfer coefficient, [W/m^2K]

V : Velocity, [m/s]

α : Absorptivity [-]

β : Temperature coefficient, [0.0045 °C]

η : Efficiency [-]

κ_B : Boltzmann constant, [$1.381x10^{-23}$ J/K]

μ : Viscosity [Pa.s]

ρ : Density, [kg/m^3]

τ : Transmissivity [-]

u : Velocity, [m/s]

φ : Fraction [-]

amb : Ambient
bf : Base fluid
eff : Efficiency
in : Inlet
max : Maximum
min : Minimum
nf : Nanofluid
np : Nanoparticle
out : Outlet
t : Total
w : Water

1. INTRODUCTION

Technological applications in almost every sector such as industry, agriculture and domestic services are in great need for energy. The amount of energy required to meet the needs will increase further in the future as the time progresses. Increasing demand for energy with the increasing population causes a decrease in the available energy resources. Research predicts that fossil fuels that we use intensively now will be completely exhausted in the 22nd century (Esfe et al., 2020). Residual substances from fossil fuels burning for energy generation have played a major role in environmental pollution and climate change. Therefore, studies on renewable energy that does not cause any harm to nature have been the interest of many researchers from all over the world. Solar energy is one of the leading renewable energy sources. By using the heat and light provided by the sun, safe, clean and cheap energy can be obtained without harming the nature (Razali et al., 2019).

In order to reduce the effect of harmful gasses emitted into the atmosphere due to the burning of fossil fuels, there is an intense incentive for solar energy all over the world. The photovoltaic thermal (PVT) system is an instrument designed which receives solar energy and converts this energy into both electrical and thermal energy. Efficiency of photovoltaic solar panel (PV), which produces electricity by absorbing sunlight, decreases over time as the temperature of the silicon cells that make up the PV increases. Therefore, in order for the PV not to decrease its electrical production over time, it must be cooled. The PVT system cools the PV with its cooling element (Aste et al., 2017). The PVT system not only prevents the decrease in electricity production by cooling the PV, but also shows a superior feature by producing thermal energy as well as electrical energy.

Use of the PVT system provides environmental and economic benefits as it produces both electrical and thermal power. With these advantages, the PVT system is highly suitable for growth due to the worldwide concern for the environment and climate change, as well as, its cheapness. The main aim of many researchers studying PVT systems is to obtain the maximum efficiency that can be obtained from these systems. Previous studies focused on efficiency analyzes of the extensive use of air and water as working fluids for heat removal from PV modules. Therefore, PVT systems are divided into different classifications according to heat transfer techniques, absorber plate designs and flow systems of the fluid used and the fluid used in the system. In addition, new studies are carried out to increase the efficiency of the PVT system depending on environmental and physical parameters. PVT technology still needs improvement to further increase system efficiency (Vaka et al., 2019).

Different designs and innovative methods are proposed to obtain maximum efficiency from PVT systems. The photovoltaic panel is one of the main components of PVT system and it is used to convert sun lights into electricity production. The absorber plate as being other main component of PVT system is utilized to extract the heat from solar radiation and conveying it to the cooling fluid. The cooling fluid is generally water or air in the photovoltaic thermal system. Ethylene glycol, industrial oils and different refrigerants can also be used as coolant. Coolants are used to cool photovoltaic panels, and thus electrical efficiency of the solar cells increase. Moreover, nanofluid is a new generation heat transfer fluid that promises high thermal conductivity and raises the heat transfer rate if it is compared to conventional fluids (Sachit et al., 2018).

Photovoltaic thermal systems are compared to detached photovoltaic panels and solar collectors because they are a promising system. Researchers used nanofluids as coolants in PVT systems in order to use the incoming radiation efficiently, with the increase in studies in the field of nanotechnology. Many experiments are conducted on the use of nanofluids for cooling and heat absorption (Abdallah et al., 2019). Nanofluid is a fluid that has micro sized particles which is named nanoparticles. Nanofluids are composed of colloidal suspensions of nanoparticles in a base fluid. Nanoparticles utilized in nanofluids are typically made from metals, oxides or carbides by powder technology by crushing into micro dimensions. Experimental and numerical studies on the use of nanofluids in PVT technology have brought great innovations to this field. This area is relatively recent and the superior thermophysical properties of nanofluids will further raise efficiency of these kind of systems (Sachit et al., 2018). In this thesis a numerical study was carried out to raise efficiency of PVT system using a nanofluid.

In this thesis, the drawing of a PVT system, which also exists in the literature, was redesigned in 3D in order to observe the nanofluid effect in the PVT system. The solar panel used in the PVT system and the layers (materials) that make up the PV panel were taken from the commonly used in the literature. The thermophysical properties of layers in PVT collector used in this analysis are commonly accepted in the literature. These layers are tedlar layer, ethylene vinyl acetate (EVA) layer and silicon layer which represents silicon PV cells that generate electricity in PV panel. The thermal paste and the absorber plate are used to combine the PV module with the heat exchanger and form the PVT system. The PV panel includes a glass layer.

In the PVT system analyzed, water was used as the cooling base fluid. The thermophysical properties of water were evaluated at 25°C as it is commonly used in the literature. Base fluid is one of the basic components that make up the nanofluid. Another component for nanofluids is nanoparticles. Nanoparticles are added to improve the thermophysical properties of base fluids. Nanoparticle addition accomplished in various material structures, most of which are metals, metal oxides, nanotubes, carbides, nitrides and carbon materials. Hexagonal Boron Nitride (hBN) material, which was not used as a part of the coolants in PVT systems before was used in this numerical study. In the current literature on nanofluids containing hBN, the stability, thermal conductivity, rheological behavior and lubrication properties of the nanofluid have been emphasized. For this reason, hBN was chosen in this study, since there is a great deal of both experimental and numerical research with other known materials. The thermophysical properties of Hexagonal Boron Nitride accepted in the literature were used in this study.

Nanofluids are different substances from the thermophysical properties of the components that make them up. In order to calculate the thermophysical properties of the hBN water nanofluid, the existing equations in the literature were employed There are parameters that affect the thermal and electrical efficiency of PVT system. In this study, effect of nanoparticle volume fraction, nanofluid velocity, nanoparticle diameter and solar heat flux on the performance parameters of the PVT system was investigated.

2. PREVIOUS STUDIES

Comprehensive studies are carried out to increase thermal and electrical efficiency by using different fluids in PVT systems. Information about the design, simulation, modeling and testing of these systems has been brought to the literature as a result of the many studies of researchers. When these studies are investigated in detail, it can be concluded that many parameters can be effective on the PVT system performance (Khaled et al., 2010; Gong et al., 2018).

These parameters are separated into two main groups as the design of the cooling element of PVT system and the operational parameters of the PVT system. Important design parameters include photovoltaic cells type, working fluid type, wind speed, ambient temperature, cooling fluid temperature at the inlet of collector (coolant inlet temperature), and mass flow rate of cooling fluid. In order to find the optimum conditions of the PVT system, an examination of the operational parameters is required (Hosseinzadeh et al., 2018).

In general, PVT systems are classified into two main groups as conventional systems and novel systems. These two main groups are also divided into other subgroups according to their efficiency and usage purposes. Thanks to this classification, it has become easier to determine the intended use of PVT systems and to calculate their efficiency. The designs to be made are usually carried out within this framework. In addition to all these, this classification, which is followed in the studies on this subject in the literature, is an important starting point that determines the aims of the general PVT study as a guide. Many innovations on PVT and improvements of their efficiency bring the maximum benefit from solar energy. Therefore, the main purpose in PVT systems is to increase electrical and thermal efficiency as much as possible. It has been tried to get the maximum efficiency that can be obtained from the traditional systems and novel systems have been used to achieve more (Esfe et al., 2020). Figure 2.1 shows a comprehensive example of classification.

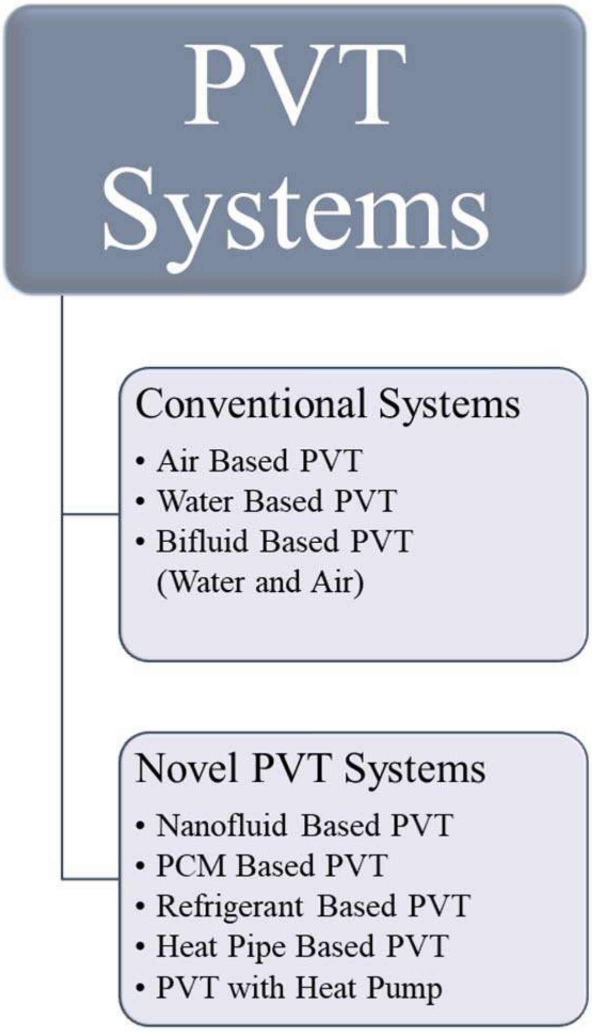

Figure 2.1. Classification of PVT systems (Sathe et al., 2017)

Studies carried out on conventional PVT systems show that air and water are widely utilized as the main heat transfer fluid and in addition to them, the combined use of both air and water fluid comes to the fore as a relatively newer traditional PVT system compared to water and air. Such systems are also called bifluid PVT systems in the literature.

In recent years, plenty of new thermal systems other than air and water have been developed to achieve the desired system outputs in the improvement studies. In novel PVT systems, the supplement of nanofluid, heat pipe, phase change materials and heat pump based thermal systems into PV systems is studied (Sathe et al., 2017). The aim of obtaining higher efficiency by using nanofluid in PVT systems is one of the most recent studies in this field. Very satisfactory results have been obtained in the studies carried out, and the obtained results have been taken as a reference point for new studies. This novel field has also taken its place in the literature as an effective part of a new technology.

2.1. PVT Systems with Nanofluid

Integrating nanofluids into photovoltaic thermal systems is a method that has been used for a little more than a quarter of a century. As a result of the fact that conventionally used fluids like water and air increase the efficiency in PVT systems, researchers started to look for different ways to further increase this efficiency. Since PVT systems are directly fed from the sun and generate electricity depending on the heat flux, the temperature on the panel and the solar silicon cells that produce electricity is quite high. Temperature in the solar cells of PVT systems increases over time and this leads to a reduction in efficiency of the system. Previous studies have shown that as a result of 1 °C increase in PV cell temperature in crystalline silicon cells, amorphous silicon cells and c-Si cells, the electrical efficiency decreases by 0.5%, 0.25% and 0.45%, respectively. In addition, thermal stress on PV cells can also damage the module if it continues for a long time (Maadi et al., 2017).

In order to decrease such solar cell temperatures in PVT systems, a significant increase in efficiency has effectively been achieved by adding nanoparticles, which have higher thermal conductivity than conventional liquid fluids. In order to increase thermal and electrical efficiency, a design of the heat exchanger employed to absorb heat from photovoltaic panel.

Choi and Eastman (1995) suggested that a new group of fluids could be created by addition of metallic nanoparticles into conventional fluids that perform heat transfer. The researchers carried out a theoretical study to investigate the thermal conductivity of the nanofluids obtained using copper nanophase materials. They estimated the potential advantages of the fluids and showed that one of the advantages of nanofluids would be impressive decrease in the pumping power of the heat exchanger. According to their study, while in conventional fluids it is necessary to increase the pumping power by 10 times to increase the heat transfer by 2 times, in a nanoparticle based fluid with 3 times the thermal conductivity of a conventional fluid, the heat transfer rate will be doubled without an increase in pumping power.

Elmir et al. (2012) carried out a numerical study to investigate the electrical performance of solar cells in the presence of nanofluids using single square absorber and PV panel. The researchers reported stated that the nanofluid they created by using different concentrations of Al_2O_3 nanoparticles and water base fluid increased the efficiency of solar cells. They also stated that the use of Newtonian nanofluids to improve heat transfer in forced convection is not very clear. The study revealed that the addition of nanoparticles to a basic fluid will not affect the structure of the flow, but the increase in the thermal conductivity of the mixture will increase the heat transfer rate. In the study, the effect of the Reynolds number on the flow pattern and heat characteristics was also investigated and it was found that for a given solid volume ratio, the heat transfer rate decreases with an increase in the Reynolds number after an optimum point. The local modified Nusselt number and the modified average Nusselt number was calculated to predict the increase in heat transfer. The modified average Nusselt number varied almost linearly with the change of the solid volume fraction. At a low Reynolds value (Re=5), the heat transfer rate was 27% greater when the concentration was changed from 0% to 10%.

Cui et al. (2012) experimentally investigated nanofluids with different mass fractions. They used MgO nanoparticles containing fluid to cool the solar cells of PV panel. They investigated the solar cell temperature, the inlet and outlet temperature difference of the fluid, and the output power of the solar cells in the PVT system. The study showed that the increase of both the particle volume fraction and the nanofluid film thickness resulted in a decrease in the output power of the solar cells in the PVT system. As a result, they revealed that the PVT system electrical efficiency is lower than that of the bare PV module, but the total energy conversion efficiency of the PVT system is higher. Figure 2.2 shows that the electrical output varies with solar irradiation and decreases with the mass ratio of nanoparticles.

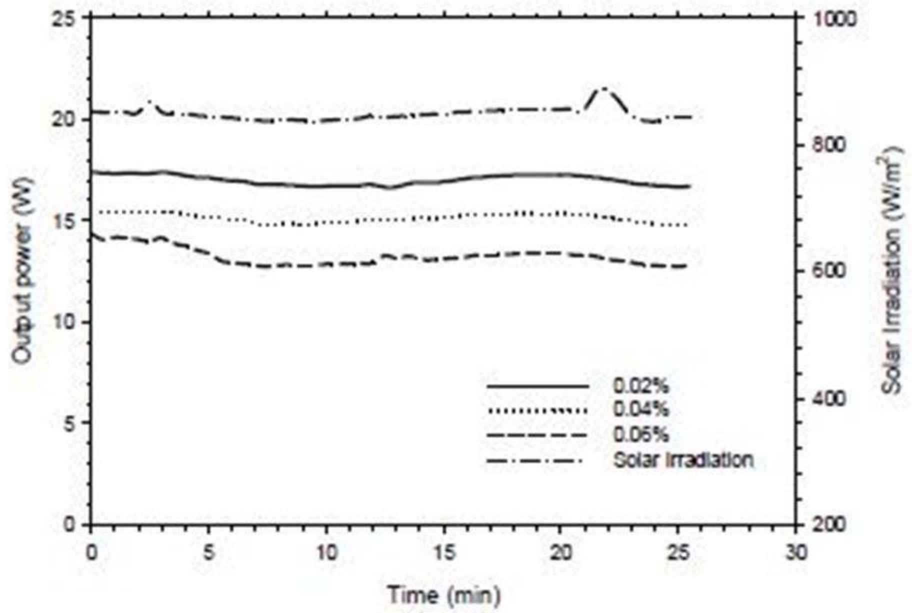

Figure 2.2. Variation of PVT system's output power with nanofluid mass fraction (Cui et al., 2012)

Chandrasekar et al. (2013) designed a PVT system with a cotton wick structure integrated behind the PV module. Thermal and electrical performance of the PV module was experimentally examined by using water, Al_2O_3/water nanofluid and CuO/water nanofluid. The thermal and electrical performance results obtained were compared with the results obtained from a PV system without cooling.

The maximum efficiency of the cooling system with water was 10.4% and the efficiency without the cooling system was 9%. It was found that when cooling with Al_2O_3/water and CuO/water nanofluids, the module efficiency was around 9.7% and 9.5%, respectively. Figure 2.3 shows the efficiency values under different conditions.

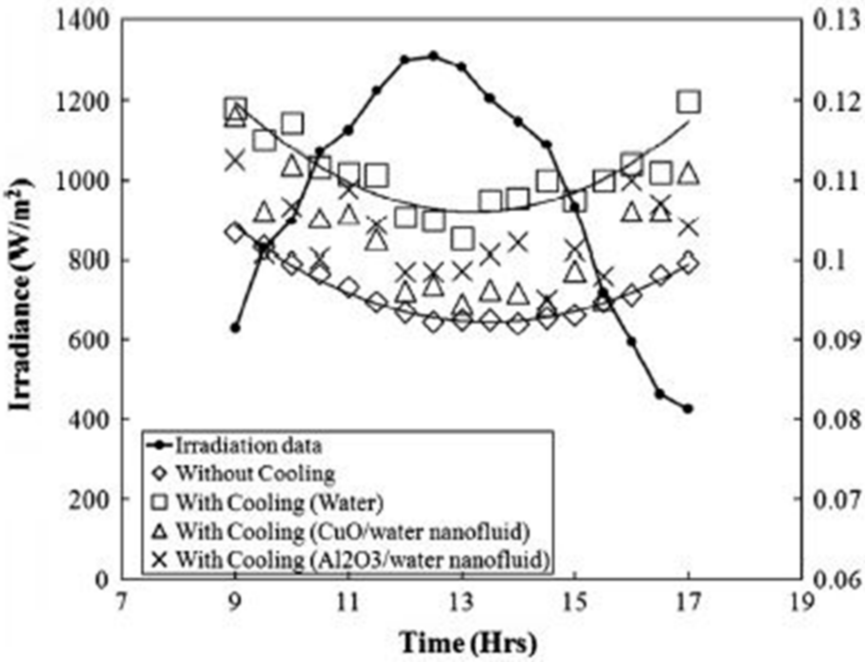

Figure 2.3. PV module efficiencies with different irradiances in a day (Chandrasekar et al., 2013)

Xu and Kleinstreuer (2014) revealed that electrical and total efficiency were increased by using nanofluids in PVT systems. They created a 2D model for thermal analysis and computational fluid dynamics simulations to evaluate individual subsystem and overall system efficiency. A new thermal conductivity model for nanofluids that has been validated with experimental datasets was used. They also evaluated electrical and thermal performances of the PVT system for various climatic conditions. The data showed that the use of nanofluids increases the electrical and overall efficiency of the system, especially when silicon solar cells are used. Figure 2.4 depicts the efficiency changes of the PVT system used by the researchers according to the cooling fluid.

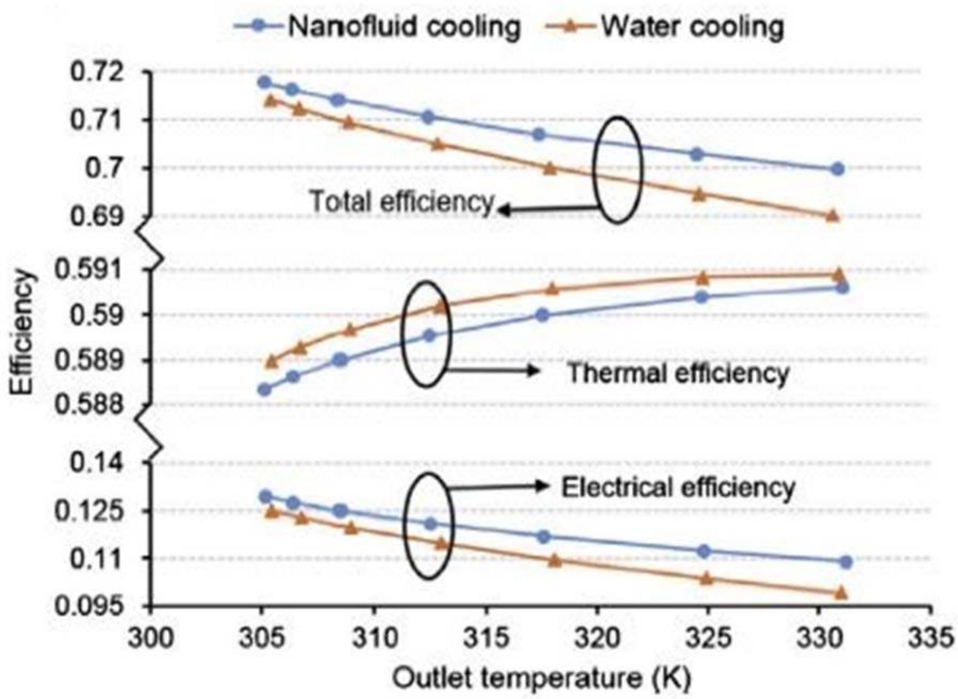

Figure 2.4. Efficiency of silicon solar cell (Xu and Kleinstreuer, 2014)

Sardarabadi et al. (2014) analyzed experimentally the effect of using nanofluid as coolant to examine the thermal and electrical efficiency of PVT system. Distilled water and SiO_2/water nanofluid at 1% and 3% by weight were used in the experiments. It was found that the total energy efficiency of the

SiO_2/water nanofluid at 1% (wt.) is 3.6% higher than pure water. The increase was 7.9% when the concentration is 3% (wt.). The researchers found that thermal efficiency of the PVT system increased 7.6% and 12.8%, respectively, for with 1% (wt.) and 3% (wt.) SiO_2/water nanofluids. In addition, the researchers compared the total exergy of the nanofluid and nanofluidless PVT system with that of the collectorless PV system. Figure 2.5 shows variation of total efficiency with flow rate for different cooling fluids.

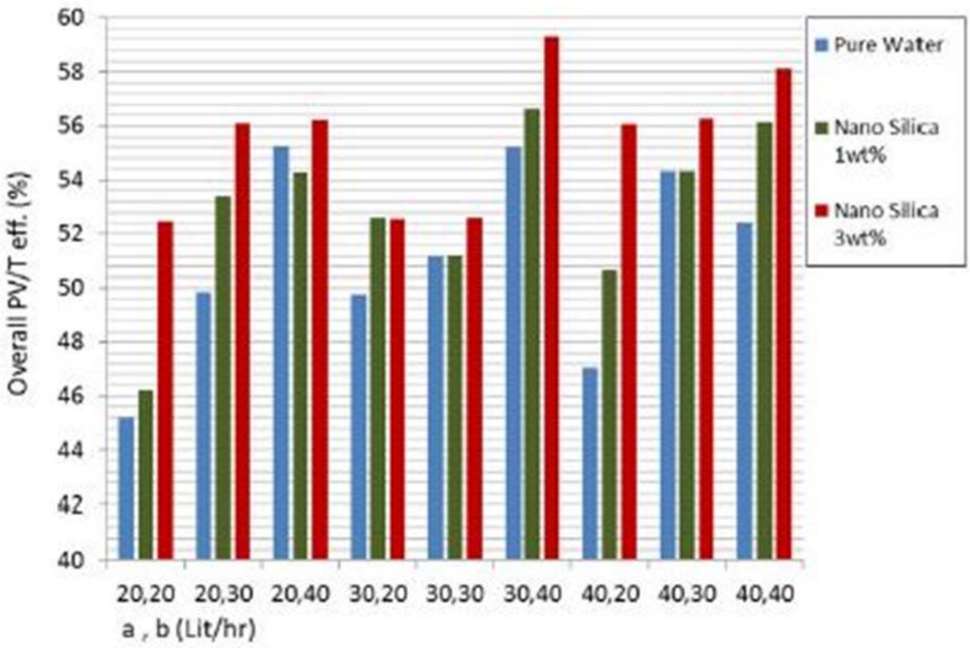

Figure 2.5. Efficiency of PVT system (Sardarabadi et al, 2014)

Karami and Rahimi (2014) investigated the cooling performance of PVT system with water based nanofluids including different concentrations of Boehmite nanoparticles. The results showed that the nanofluid performed better than water.

Jing et al. (2015) used SiO_2 nanoparticles in water fluid with different particle sizes. The sizes of SiO_2 nanoparticles in the nanofluid were confirmed as 5 nm, 10 nm, 25 nm and 50 nm by electron microscopy and light scattering technique. Mathematical analysis of the PVT system investigated was performed using CFD method. The results showed that a flow rate of 0.015 m/s, a particle size of 5 nm, and a nanoparticle volume ratio of 2% SiO_2 /water nanofluid were the optimal operating parameters in the formed PVT model. When the light concentration is 40 and the flow velocity is 0.015 m/s, the PV/T system has the highest exergetic efficiency.

Ghadiri et al. (2015) experimentally examined the effect of using nanofluid containing ferro nanoparticles on overall PVT system efficiency. The researchers conducted experiments by using a solar simulator under 2 constant solar radiation, 1100 W/m^2 and 600 W/m^2, and indoor conditions. The rheological and thermophysical properties of ferrofluids can change under an external magnetic field. They placed ferrofluids in the cooling section of PVT system in constant and variable magnetic fields. The results showed that total system efficiency increased by 45% when 3% (wt) ferrofluid was used. It was also found that when an alternating magnetic field with a frequency of 50 Hz was applied at the same conditions, the overall efficiency increased approximately 50% compared to distilled water. The results revealed an increase in yield compared to distilled water. The researchers also compared the total exergy of system output with and without ferrofluids. Adding a thermal collector to a PV system and utilizing 3% (wt.) ferrofluid under an alternating magnetic field, the total exergy could increase up to 48 W.

Michael et al. (2015) constructed a new photovoltaic thermal collector by integrating a copper sheet directly into the silicon cells. In this way, the researchers decreased the thermal resistance and increased the PVT system performance by utilizing the CuO/water nanofluid. It was observed from the experimental setup that the nanofluid provides an important raising in thermal performance compared to water. It was also noted that the use of a higher efficiency heat exchanger could further improve the PVT system electrical performance. The researchers obtained significant improvement in thermal efficiency by 44.90% and 45.76% in glazing and unglazing PV panel for CuO/water nanofluid (Figure 2.6). In addition the researchers found the highest electrical efficiency of the reference PV module to be 8.98% as shown in Figure 2.7. However, it was stated that the electrical efficiency due to the design of the experimental setup decreased over time.

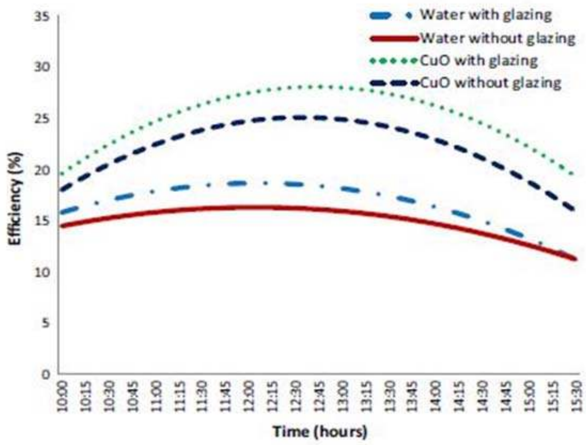

Figure 2.6. PVT thermal efficiency at different hours in a day (Michael et al., 2015)

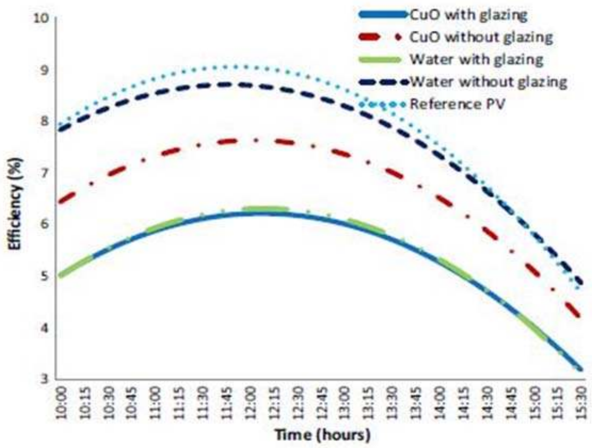

Figure 2.7. PVT electrical efficiency at different hours in a day (Michael et al., 2015)

Said et al. (2015) used a flat plate solar collector in their study and examined the use of TiO_2/water nanofluid to improve performance of the system. The nanoparticle volume fractions in the study were 0.1% and 0.3%. Mass flow rate of nanofluid varied ranging from 0.5 to 1.5 kg/min. Using a volume fraction of 0.1% and a flow rate of 0.5 kg/min increased energy efficiency by 76.6%. The maximum exergy efficiency was obtained as 16.9% for 0.1% volume fraction and 0.5 kg/min. According to the data, it was determined that the pressure drop and pumping power of the TiO_2/water nanofluid were very close to the base fluid for the volume fractions examined in the study.

Hassan et al. (2016) theoretically investigated the exergy of the operating cycle of three different configurations of the nanofluid based PVT hybrid system. The hybrid system performance was compared with a standard PV and PVT system. The researchers numerically examined the electrical and thermal performances of the solar collector. According to the exergy analysis, the PVT system with nanofluids showed better performance compared to a standard PV and PVT system.

Khanjari et al. (2016) performed a study to examine using the nanofluid effects on the PVT system performance. The coolants used in the simulations were pure water, Ag/water nanofluid and alumina/water nanofluid. The study simulated how the nanoparticle volumetric concentration and nanofluid inlet velocity effect the system efficiency. The researchers also applied second law analysis of the PVT in which only water was introduced as the coolant. Results showed that the efficiency of the system and the heat transfer coefficient increased when the nanoparticle volume fraction raised. The maximum increase percentage of heat transfer coefficient versus volume fraction was found %12 for Al/water nanofluid and %43 for Ag/water. When the inlet fluid velocity was increased, the heat transfer performance of the PVT system improved. To validate the results of the study, a comparison study was carried out with the experimental results in the literature. The results showed a good agreement with the literature.

Noghrehabadi et al (2016) experimentally analyzed the symmetrical square flat plate solar collector performance by using water as working fluid and SiO_2/water nanofluid with a mass fraction of 1% without surfactants. Experiments were performed at different flow rates ranging from 0.35 to 2.8 L/min according to ASHRAE Standard 93-86. The results revealed that SiO_2/water nanofluid improves the square flat plate solar collector efficiency compared to water. Increasing the incoming solar radiation had no significant effect on the efficiency of the collector when water was used as the coolant. However, when nanofluid was used, the collector efficiency increased with a very low slope with increasing incoming solar radiation. The increase in mass flow rate resulted in higher efficiency of square flat plate solar collector. Although this behavior was similar for both water and SiO_2/water nanofluid, the nanofluid was more efficient than water at higher flow rate.

Sardarabadi et al. (2016) experimentally and numerically analyzed the use of metal oxide/water nanofluid as cooling fluid in a PVT system. The nanoparticles were added to deionized water. The percentages of Aluminum oxide (Al_2O_3), Titanium oxide (TiO_2) and Zinc oxide (ZnO) nanoparticles in water were 0.2% by weight. Numerical and experimental results showed that TiO_2/water and ZnO/water nanofluids performed better in electrical efficiency compared to Al_2O_3/water nanofluids and deionized water. When the thermal performance of the system was evaluated, the ZnO/water nanofluid had the maximum thermal efficiency compared to deionized water and the other two nanofluids. The researchers also used numerical models to examine the effect of nanoparticle mass fraction ranging from 0.05 to 10% (wt) on the electrical and thermal performance of the PVT system. Results showed that ZnO/water nanofluid produced better thermal performance compared to other working fluids. Effect of ZnO nanoparticle mass fraction on PVT performance was also examined in the study and it was found that thermal performance of the PVT system largely depends on the mass fraction of nanoparticles. It was also found that the electrical efficiency slightly changed when the mass fraction of the nanoparticle in the liquid was changed.

Rejeb et al. (2016) conducted an experimental and numerical study to evaluate the performance of a PVT system by utilizing nanofluids. A two dimensional numerical model was developed to examine effects. The simulations were compared with the experimental results. The effect of integrating nanoparticles (Al_2O_3 and Cu) into various base fluids (pure water and ethylene glycol) at concentrations of 0.1%, 0.2% and 0.4% (wt) on electrical and thermal performance was also investigated. The result revealed that use of distilled water as the base fluid produced higher performance compared to ethylene glycol. The use of Cu/water nanofluid resulted in the maximum thermal and electrical efficiency compared to Cu/ethylene glycol, Al_2O_3/water and Al_2O_3/ethylene glycol.

Al Shamani et al. (2016) tested a PVT system with nanofluid containing dissimilar types of nanoparticles (SiO_2, TiO_2 and SiC). Using nanofluids increased the heat transfer characteristics of the system. The researchers designed, fabricated and tested the PVT collector under the climatic conditions of Malaysia. The PVT collector consisted of a specially designed rectangular tube absorber fitted under the photovoltaic module. In the study, the parameters considered were the average PV module temperature, the outlet temperature of the cooling fluids, the output power from the PVT, and electrical and thermal efficiency of PVT system. In addition to these parameters, the combined PVT power and efficiency were also determined. The maximum efficiency was obtained from SiC nanofluid among all nanofluids used in the study. The PV module efficiency and the fluid outlet temperature was obtained to be 13.52% and 53.16 °C, respectively. The experiments showed that, electrical, thermal and combined power of the PVT system was 115.7 W, 697.9 W and 813.6 W, respectively, with the corresponding efficiency was 13.52%, 68.21% and 81.73%, respectively. The researchers also determined the cost of the PVT system with nanofluid by calculating the life cycle cost.

Soltani et al. (2017) proposed a photovoltaic and thermoelectric system that uses a new nanofluid based cooling method. Five different cooling methods were experimentally investigated: natural cooling, forced air cooling, water cooling, SiO_2/water nanofluid cooling and Fe_3O_4/water nanofluid cooling. SiO_2/water nanofluid cooling provided the highest power and efficiency. Figure 2.8 represents the PV efficiency of five different circulating fluids in a day.

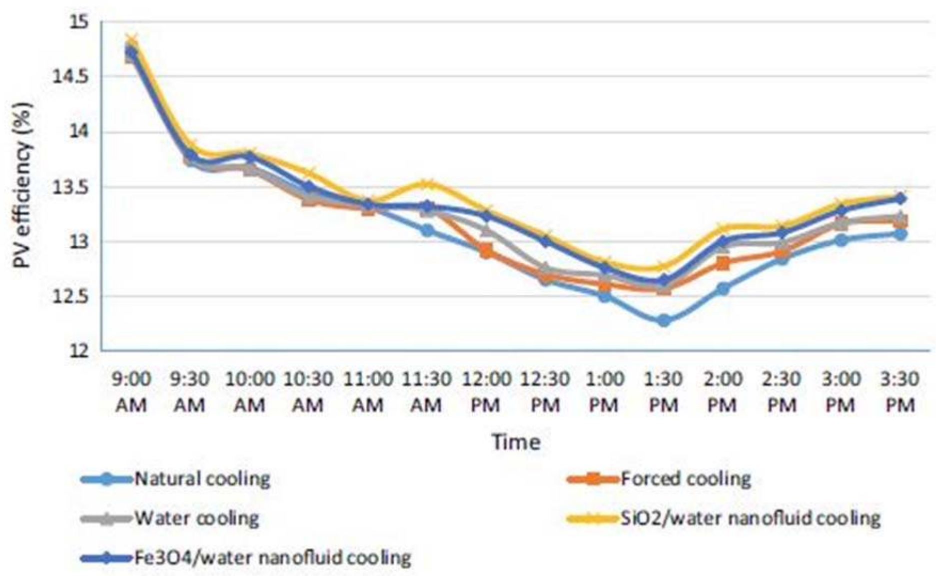

Figure 2.8. Variation of the efficiency of the PV cell during the day according to different cooling methods (Soltani et al., 2017)

Waeli et al. (2017) used water as the base fluid and added three different nanoparticles to the water. The study aimed to find the most efficient concentration and nanofluid for PVT system. The examined volume fractions were 0.5%, 1, 2, 3, and 4%, and the chosen nanoparticles were Al_2O_3, CuO, and SiC. Silicon carbide (SiC) nanoparticles had the maximum stability and the highest thermal conductivity compared to the other two nanoparticles. Copper oxide (CuO) nanofluid had higher thermal conductivity than aluminum oxide, but lower stability, although this material was found to be reliably stable compared to other studies.

Nasrin et al. (2018) performed an experimental study of PV module under controlled operating conditions. The researchers designed a new thermal collector in the study, and MWCNT/water nanofluid was used to improve the thermal performance of PVT. Active cooling for the PVT system was employed with the help of a centrifugal pump. A 3D numerical simulation with the finite element method was also performed within the study. Numerical results showed a good agreement with the experimental ones. In the experiments, it was found that the performance of the PV system was increased by 9.2% by using the water cooling system. When nanofluids were used in the numerical and experimental studies, a higher thermal performance of approximately 4% and 3.67%, respectively, was achieved compared to water. The researchers found the numerical and experimental total efficiency to be 89.2% and 87.65%, respectively, at 1000 W/m^2 irradiation with the nanofluid.

Aberoumand et al. (2018) utilized Ag/water nanofluid for cooling in the photovoltaic thermal (PVT) system and the effect of mass flow (i.e., laminar, transient and turbulent flow regimes) on efficiency was investigated. The results showed that increase in nanofluid concentration and the flow rate produce better system performance. When 4% (wt) nanofluid was used, the power output of the panel increased by 35% and 10%, respectively, compared to uncooled and water-cooled conditions. It was also found that the exergy efficiency of nanofluid cooling is 50% better than that uncooled condition.

Fayaz et al. (2018) utilized water and MWCNT/water nanofluid as coolant and performed a three dimensional numerical analysis of PVT system. The results of the numerical study were verified by experiments performed at mass flow rates of 30 to 120 L/h, constant solar radiation of 1000 W/m^2, inlet and ambient temperature of 32 °C and 25 °C, respectively. The increase in electrical efficiency of PV with nanofluid coolant at a flow rate of 120 L/h was found to be 10.72% and

12.25%, respectively, in the numerical and experimental studies. As a result of numerical and experimental studies, the researchers obtained a thermal energy increase of approximately 7.74 and 6.89 W per 10 L/h flow rate increase. Figure 2.9 shows the total efficiency of the system under different conditions.

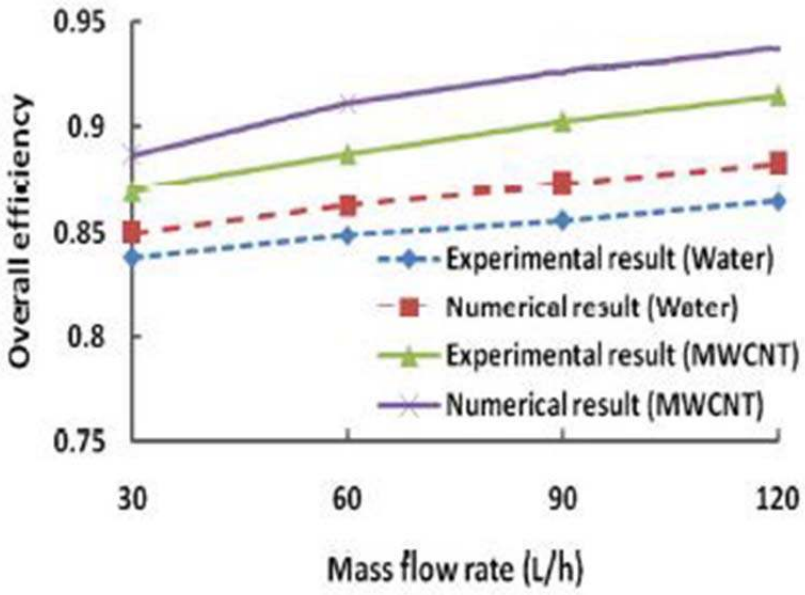

Figure 2.9. Overall efficiency (Fayaz et al., 2018)

Abdallah et al. (2019) conducted an experimental study on the use of nanofluids in photovoltaic thermal systems. The researchers set the circulation rate to be a constant 1.2 L/min and the effect of nanoparticle volume concentration ratio in fluid ranging from 0% to 0.3% was investigated. Multi Walled Carbon Nano Tubes (MWCNT) were used as nanoparticles in the research. When nanoparticles were added to the base fluid, a significant increase in the thermal properties of fluid was observed and as a result thermal and electrical efficiency of the system improved. The best system efficiency was obtained with 0.075% (by volume)

MWCNTs/water nanofluid. Figure 2.10 shows the effect of cooling fluid on the overall efficiency of the system.

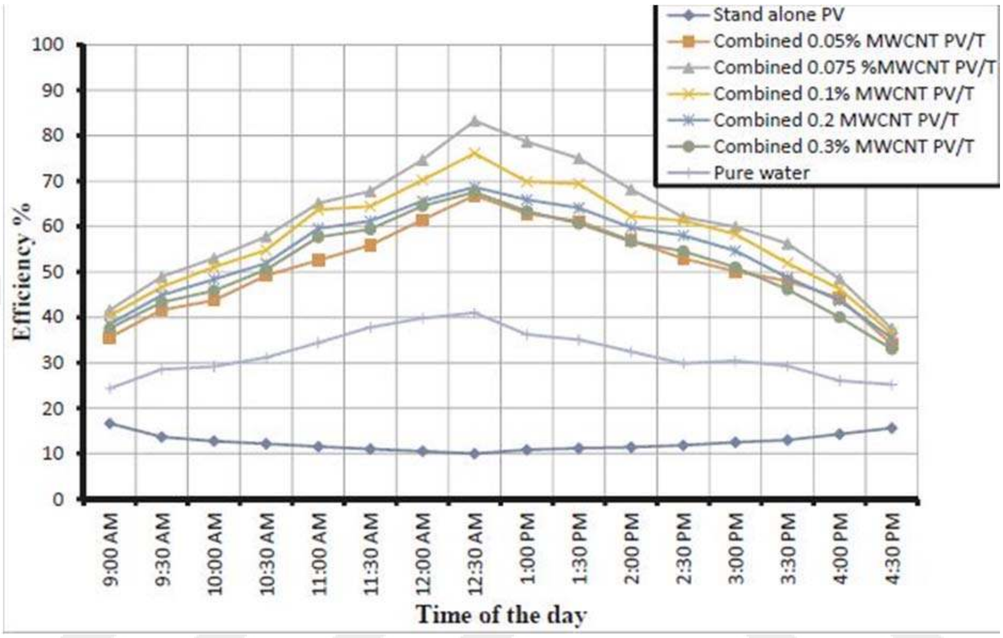

Figure 2.10. Overall efficiency (Abdallah et al., 2019)

Tong et al. (2019) investigated the performance of PVT system using water, Al_2O_3/water nanofluid and CuO/water nanofluid as coolants. The authors investigated energy efficiency, entropy production, exergy destruction and exergy efficiency under different conditions and compared them with each other. Highest efficiency was obtained when Al_2O_3/water nanofluid was used. In this case efficiency is 21.9% higher than water. The maximum exergy efficiency of PVT was provided with Al_2O_3/water nanofluid by using 1% (volume fraction). Figure 2.11 shows the efficiency improvement ratio for different cooling fluids.

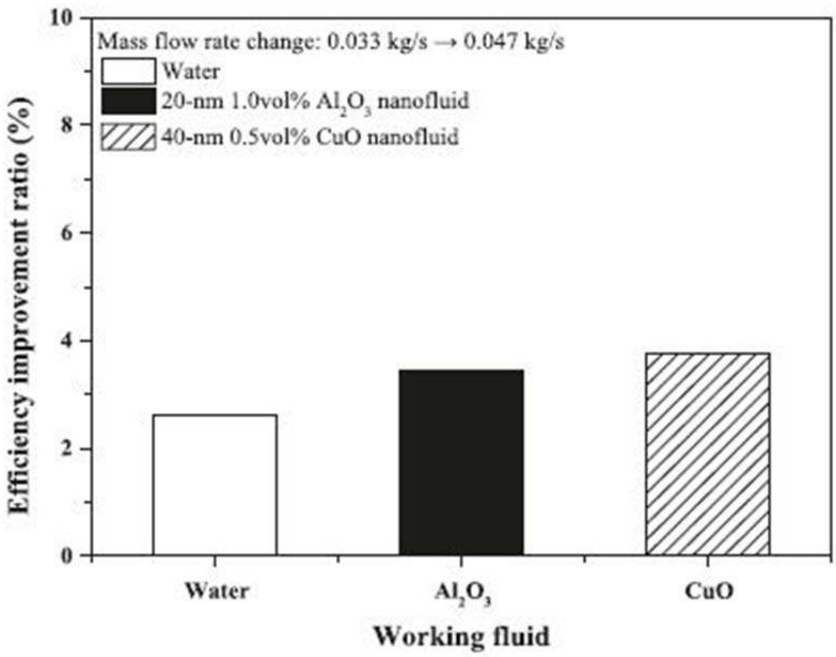

Figure 2.11. Efficiency improvement ratio for different coolants (Tong et al., 2019)

Sangeetha et al. (2021) experimentally investigated the effects of different nanofluids on the PVT system. Three different nanofluids, namely MWCNT/water, Al_2O_3/water and TiO_2/water at a constant volume of 0.3% (nanoparticle/base fluid) were used as cooling fluid to decrease the PV panel temperature. In order to evaluate the energy and exergy efficiency of the system, a parametric analysis was performed. The effect of mass flow rate of the nanofluids on the thermal efficiency and PV temperature was examined in the study.

When experimental results were analyzed, it was determined that using nanofluids as coolants in the system was highly effective on electrical output, thermal efficiency and total efficiency. MWCNT/water, Al_2O_3/water and TiO_2/water nanofluids provided 45%, 36%, and 25% increase in electrical power, respectively. Considering the electrical efficiency, it was found that there was an improvement of 47%, 33% and 27%., respectively. MWCNT/water nanofluid had excellent thermal conductivity and better physical properties than water, Al_2O_3/water nanofluid and TiO_2/water nanofluid. It was concluded that the efficiency of nanofluids in the system improved when the mass flow rate was increased.

As can be seen from the literature review presented above, the use of nanofluids in PVT systems has attracted the attention of many researchers. Although various nanofluids have been investigated to improve the thermal, electrical and overall efficiency of PVT collectors, Hexagonal Boron Nitride (hBN) has not been studied before. In this study, Hexagonal Boron Nitride (hBN) was tested first time as an alternative nanofluid coolant in a PVT system.

3. MATERIAL AND METHOD

3.1. PVT System

Photovoltaic panels produce electrical energy from the solar energy. It is essential to maintain the operating temperature of photovoltaic panels (Joshi et al., 2018). Rise in the temperature causes heating of the panels and electrical efficiency loss. In order to prevent to decrease of electrical efficiency, it is necessary to prevent overheating. Therefore, pipes or ducts are located to PV panels to prevent overheating. This structure constitutes the collector of the PVT. PVT systems convert sunlight into electrical energy and heat simultaneously via the collector in the system. Main components of a PVT collector are PV cells, channels, absorber plate and thermal insulation. Glass cover can be located above the PV cells. Adding glazing reduces heat loss, therefore thermal efficiency increases. On the other hand, when the PVT collector does not include glazing, electrical efficiency increases due to the higher solar radiation intensity. Figure 3.1 shows a general schematic representation of the PVT system (Laghari et al., 2020).

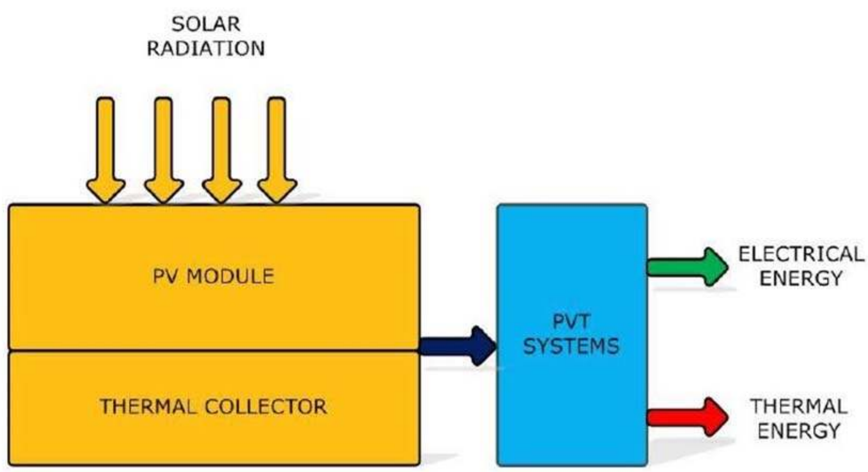

Figure 3.1. Schematic representation of PVT system (Laghari et al., 2020)

Air and water are used as working fluid in conventional PVT collectors. In air based PVT collectors, air can pass single or double configurations. Figure 3.2 and figure 3.3 show the single pass and double pass configurations of the air in the PVT collectors (Sathe et al., 2017).

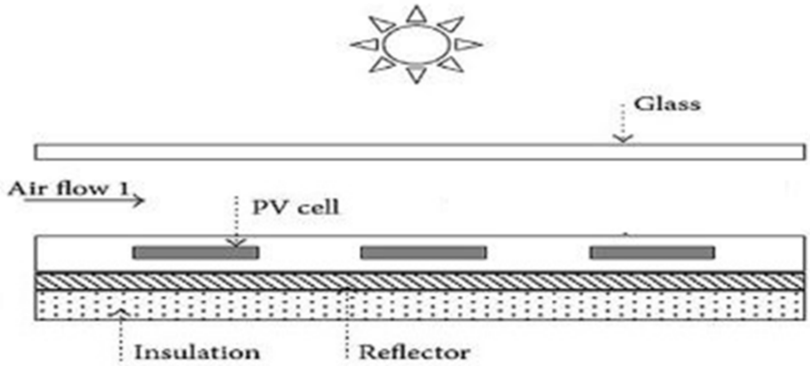

Figure 3.2. Schematic representation of single pass configuration (Sathe et al., 2017)

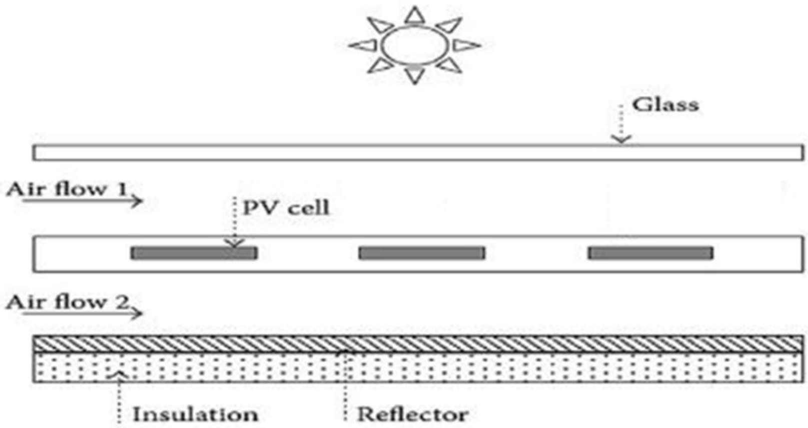

Figure 3.3. Schematic representation of double pass configuration (Sathe et al., 2017)

Although air-based PVT collectors are cheaper and less complex than water-based PVT collectors, they have some limitations such as low density, heat capacity and thermal conductivity. Thermal efficiency is higher in water-based PVT collectors due to higher heat capacity and thermal conductivity. Round tube and channel type absorbers are generally used in water-based PVT collectors. Additionally, there are also configurations where both air and water are used simultaneously in the collector of the PVT system. Figure 3.4 shows the classification of the different configurations in the collector of the PVT system (Mustapha et al., 2018).

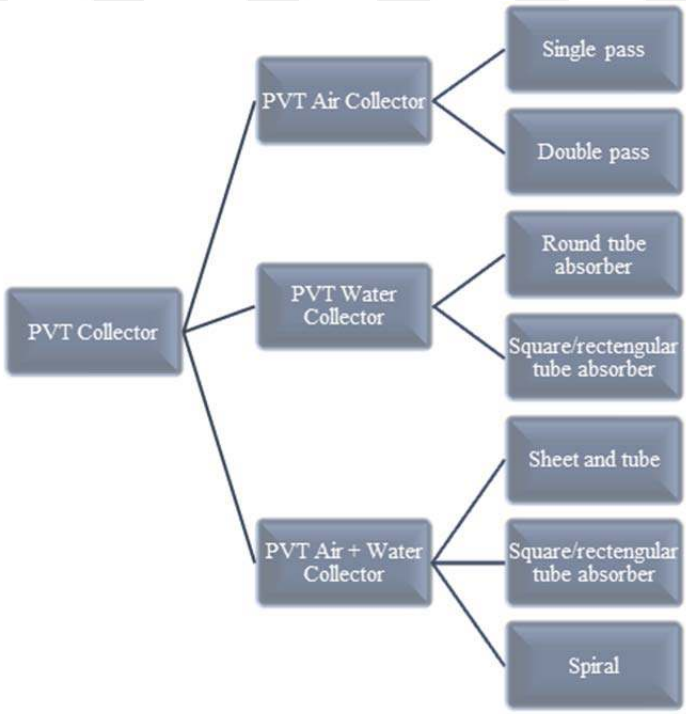

Figure 3.4. Classification of different configurations in the collector of PVT system (Mustapha et al., 2018)

The PVT collectors can also be classified based on system parameters such as absorber design, fluid flow (natural or forced circulation) and channel numbers.

Although many studies focused on the water and air-based PVT collectors, researches on nanofluid based PVT collectors have increased in recent years. Therefore, in this thesis, the analysis of nanofluid based PVT collector was carried out within the scope of novel PVT systems.

3.2. Nanofluid

Nanofluids are new generation fluids that are formed by adding nanoparticles smaller than 100 nm into them so as to improve the thermophysical properties of the base fluids used as conventional fluids. Liquids used as coolants in PVT systems such as water, ethylene glycol, propylene glycol and oils, known as conventional liquids, have low thermal conductivity. The nanoparticles suspended in these conventional liquids typically consist of metals, oxides, carbides or carbon nanotubes. Nanoparticles have small particle size and large specific surface area. Therefore, they have very good heat transfer characteristics due to their existing properties such as superior thermal conductivity, little clogging in the flow state, long-term stability and homogeneity (Sudha et al., 2018).

The thermophysical properties of nanofluids, which can be made suitable for different applications, can be further improved by means of nanoparticles of varying concentrations. In PVT systems, solar energy absorption can be maximized by changing the size, shape, material and volume ratio of nanoparticles in the fluid that cools the panel. Increasing the thermal conductivity of the nanofluid leads to an increase in the efficiency of heat transfer systems (Deshmuk et al., 2019). By adding different nanomaterials to different liquids with the contribution of materials science, nanofluids are used effectively in the automobile industry, biomedical applications, cooling of microchips, cooling of electronic and robotic systems, cooling of nuclear systems and machines used in machining. Besides all these, nanofluids also have some limitations. The price of nanoparticles and the complication of their suspension in liquid are two of them. In addition, choosing the appropriate nanoparticle together with the appropriate liquid for the desired nanofluid is an important effort. Due to the innovations that nanofluids bring to the world of science, research on them is further deepened.

3.2.1. Nanofluid Classification

Nanofluids are referred to in the literature as composite materials consisting of particles of a solid and a liquid. Nanofluids are generally classified according to the base fluid and additives added in the form of nanoparticles. A new nanofluid can also be created by using a base fluid with different properties and multiple nanoparticles. There are also examples for such new generation nanofluids in the literature. Figure 3.5 shows a representation of nanofluid classification (Singh and Kumar, 2021).

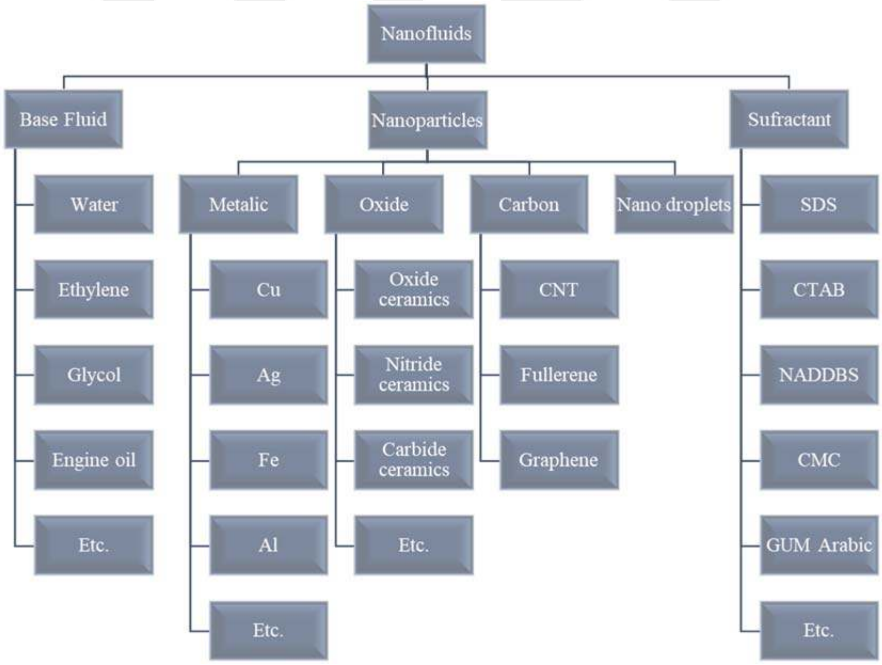

Figure 3.5. Nanofluid classification (Singh and Kumar, 2021)

3.2.2. Nanofluid Preparation

A nanofluid consists of nanoparticles, base liquid and additives homogeneously mixed. The method of mixing nanoparticles into the base liquid is divided into two main groups as single step and two step methods. Figure 3.6 shows a detailed classification for the nanofluid preparation.

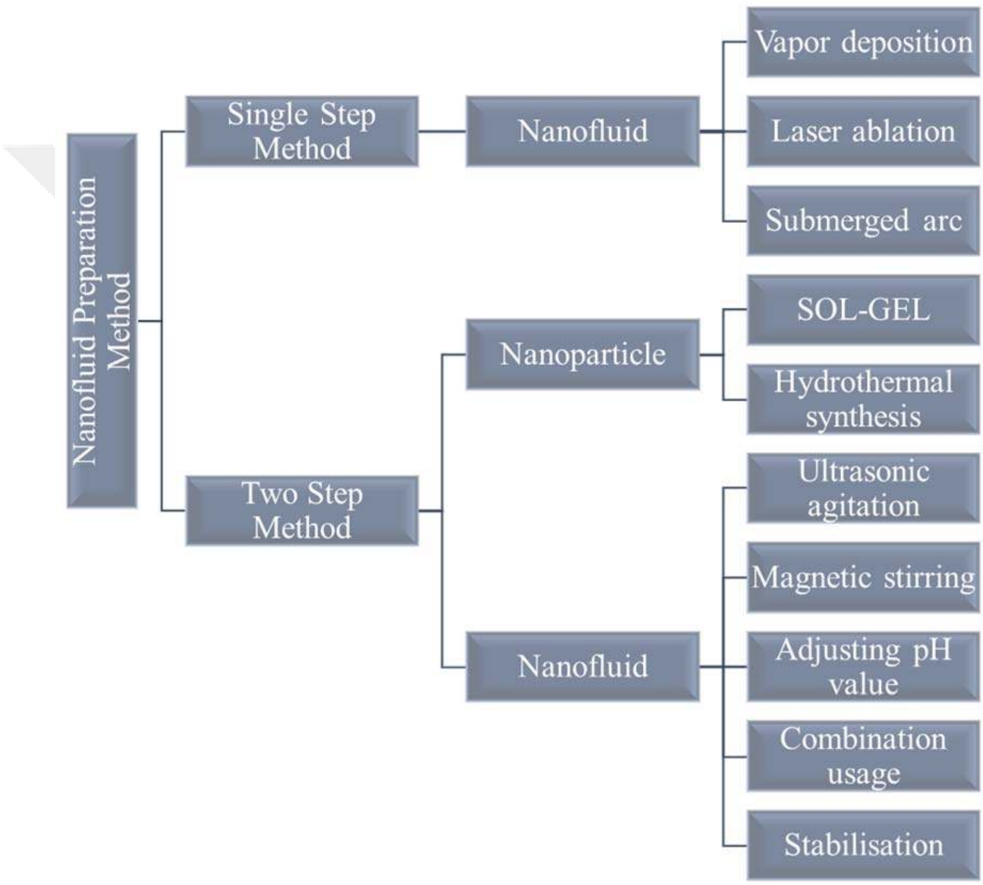

Figure 3.6. Classification of nanofluid preparation (Ali et al., 2018)

3.2.2.1. Single Step Method

Single step method refers to the preparation of nanofluids in one step. In this process, the main purpose is to make and disperse nanoparticles simultaneously in the base fluid. In this method, the drying, storage, transport and dispersal processes of nanoparticles are inhibited, therefore, the agglomeration of nanofluid is minimized and the stability of fluid is raised. This method also has some disadvantages. It is difficult to produce large amounts of nanofluids with this method, and cost of this method is also more expensive than the two step method. In this method, nanofluid is produced by vapor deposition, laser ablation technique and chemical reactions methods. Figure 3.7 is a demonstration of the single step method.

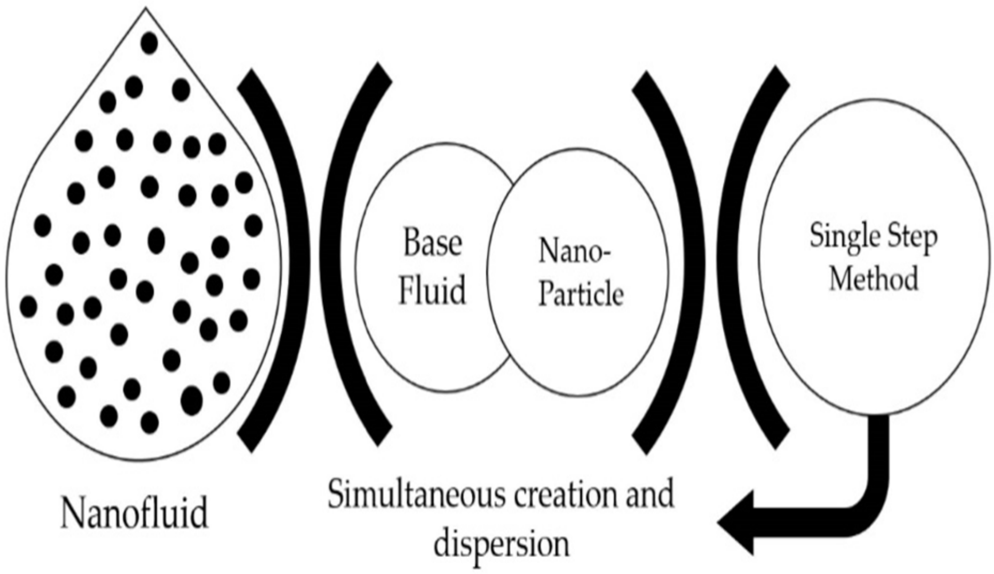

Figure 3.7. Single step method (Ali et al., 2018)

3.2.2.2. Two Step Method

Two step method consists of two steps. The first step of this method is the production of the nanoparticle to be used in the nanofluid by physical or chemical methods. In the second step, the materials produced as nanoparticles are dispersed into the liquid to be used as the base fluid to increase the stability of the nanofluid. Two step method is a widely used method for nanofluid production, and thus nanofluids can be produced on a very large scale. This method also has its own disadvantages. Drying, storage and transportation of nanoparticles are necessary in this method, in addition, it is difficult to prepare a stable nanofluid with this method. Figure 3.8 is an illustration of the two step method.

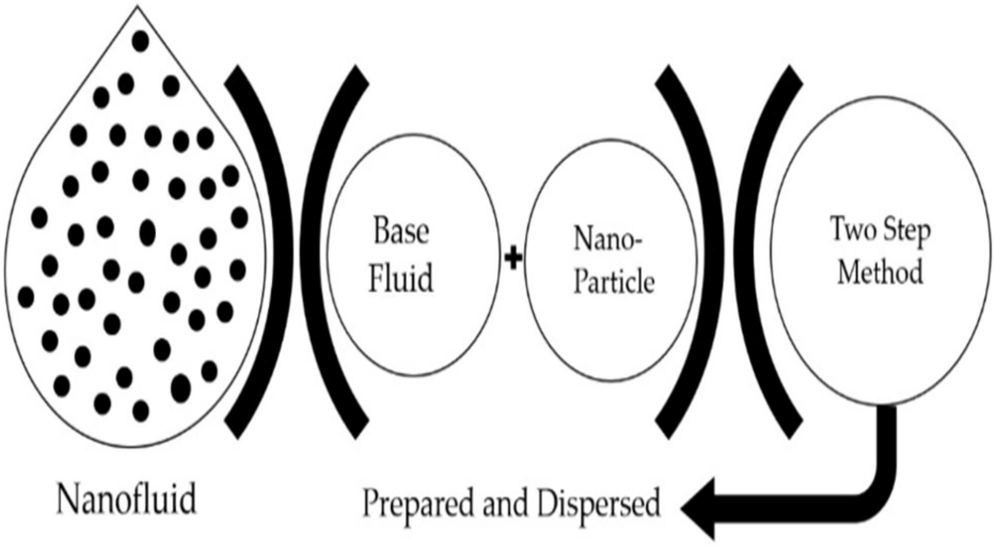

Figure 3.8. Two step method (Ali et al., 2018)

3.2.3. Nanofluid Properties

There are four basic properties of nanofluids used for heat transfer calculations in the literature. These are density, viscosity, specific heat and thermal conductivity. The results of experimental and numerical studies have shown that nanofluid properties play a very important role in the heat transfer mechanism. Therefore, all of these properties are taken into account in the creation of nanofluids.

3.2.3.1. Density

There are many studies on the density measurements for various nanofluids at varying temperatures in the literature. Since the data obtained through experimental studies produce inconsistent results, new studies are still needed on this subject (Said and Saidur, 2017). Density is an important thermophysical property and has a very important place to evaluate the heat transfer performance of nanofluids. Density directly affects Reynolds number, friction factor, pressure drop and Nusselt number. In addition, there are various studies that show that there are insufficient reports on the effect of density. The density of nanoparticles is higher than liquids. For this reason, if the volume concentration of nanoparticles in the fluid is increased, the density of the nanofluid also increases (Deshmuk et al., 2019).

Density of nanofluids is generally calculated with equation (3.1) presented by Pak and Cho (1998):

$$\rho_{nf} = (1 - \varphi)\rho_{bf} + \varphi\rho_{np} \tag{3.1}$$

Here, ρ is the density, φ is the volume concentration, “nf” is the nanofluid, “bf” is the base fluid and “np” is the nanoparticle. This equation is valid when a single nanoparticle and a fluid are present, as in this study.

3.2.3.2. Viscosity

Viscosity is the measure of tendency of a liquid to resist flow. In other words, it is the ratio of shear stress to shear rate. If the viscosity of a fluid does not change at different shear rates, this fluid is called Newtonian. However, if the fluid changes as a function of shear rate, the fluid is said to be non-Newtonian. Viscosity is the most important parameter in obtaining the convection heat transfer coefficient. Various mathematical models were developed to determine the viscosity of nanofluid. The first of these models is the viscosity model for solid spherical solids suspended in liquids as a function of volume, published by Einstein in 1906 and it was derived from linear hydrodynamic equations. However, it predicts the viscosity behavior of nanofluids with spherical solid particles and very low particle concentration in the liquid (Einstein, 1906). The model is:

$$\mu_{nf} = (1 + 2.5\,\varphi)\mu_{bf} \tag{3.2}$$

Brinkman (Brinkman, 1952), who improved Einstein's work by raising the limitation of the volume concentration of nanoparticles in Einstein's work, published a new formulation in 1952. This model proposed by Brinkman was more effective for nanoparticle volume fractions below 4% and was accepted in the literature (Mishra et al, 2014). The empirical equation of the Brinkman model is:

$$\mu_{nf} = \frac{\mu_{bf}}{(1-\varphi)^{2.5}} \tag{3.3}$$

Although the Brinkman equation improved Einstein's study, when it is applied to nanofluids, it fails due to a percentage error that raises as the nanoparticle diameter decreases. The Batchelor model is used for volumetric concentrations above 5%. It was derived by taking into account the effect of Brownian motion (Mishra et al, 2014). The Batchelor model is expressed by the following equation and is also used in this study:

$$\mu_{nf} = (1 + 2.5\,\varphi + 6.5\varphi^2)\mu_{bf} \tag{3.4}$$

3.2.3.3. Thermal Conductivity

Thermal conductivity means the rate at which a material transmits heat. It is an important property used to raise nanofluid efficiency in heat transfer. The researchers have carried out detailed research on thermal conductivity. Since the thermal conductivity of solids is higher than that of liquids and gases, the heat transfer rate in solids is also much higher than in liquids and gases. Therefore, nanofluids containing solid particles in nano size have a higher thermal conductivity than base fluids that do not contain any solids. There are some factors that affect thermal conductivity. These factors can be listed as nanoparticle type, volumetric concentration, different base fluids, temperature, particle size, pH, the effect of sonication, and the addition of a surfactant. Methods such as the transient hot wire method, thermal constants analyzer, steady-state parallel plate, and 3ω method are experimental methods used to measure the thermal conductivity of a material. Among all these methods, the thermal constants analyzer is generally used to analyze the thermal conductivity of nanofluids (Das, 2017).

Since solid nanoparticles added to the base fluid affect the thermal conductivity of the base fluid, the thermal conductivity of the nanofluid is also different from that of the base fluid. Maxwell's model (1881) entered the literature as the first model to determine the thermal conductivity of nanofluids. Maxwell's Model is adopted for nanofluids with randomly distributed, uniformly sized and non-interacting spherical particles. It is valid for homogeneously dispersed and low volume fraction liquid solid suspensions (Kumar et al., 2012). Maxwell's equation is:

$$k_{nf} = k_{bf} \frac{k_{np} + 2\,k_{bf} - 2\varphi(k_{bf} - k_{np})}{k_{np} + 2\,k_{bf} + \varphi(k_{bf} - k_{np})} \tag{3.5}$$

Xuan and Li (2003) modified Maxwell model by considering the effects of the Brownian motion and the aggregation of nanoparticles. The equation used in this study:

$$k_{nf} = k_{bf}\frac{k_{np}+2\,k_{bf}-2\varphi(k_{bf}-k_{np})}{k_{np}+2\,k_{bf}+\varphi(k_{bf}-k_{np})} + \left(\frac{\rho_{np}\,\varphi Cp_{bf}}{2k_{bf}}\sqrt{\frac{2\kappa_B T}{3\pi d_p \mu_{bf}}}\right) \tag{3.6}$$

3.2.3.4. Specific Heat

Every substance in nature has a certain thermal energy storage capacity. In order to increase the temperature of any substance, first of all, more energy must be given than the heat storage capacity of that substance. Therefore, specific heat refers to the energy storage capacity of materials. The specific heat of nanofluids can be increased or decreased according to the fluids that form them and the temperatures of those fluids. In addition, nanofluids can have higher or lower specific heat capacity, depending on the types and volume concentrations of nanoparticles. Obtaining accurate values of specific heat is essential for any study, as specific heat is used to calculate other important properties of a substance. Researchers use differential scanning calorimetry (DSC) and double hot wire to measure the specific heat of nanofluids (Deshmuk et al., 2019).

Pak and Cho (1998) developed a model based on a mixture of base fluid and particles:

$$C_{p_{nf}} = \varphi C_{p_{np}} + (1-\varphi)C_{p_{bf}} \tag{3.7}$$

The specific heat of many of the commonly used nanofluids decreases with the increase of the nanoparticle volume fractions. However, there are some inconsistent results in the literature about the effect of nanoparticle volume concentrations on the specific heat of nanofluids. When the same nanofluids are compared, nanofluids with high nanoparticle diameter have higher specific heat. In addition, the dispersants also have significant effects on the specific heat of nanofluids. The specific heat of nanofluids increase after addition of dispersant compared to base fluids (Shahrul et al., 2014).

The equation derived by Xuan and Roetzel (2000) assuming that the nanoparticle and the base fluid are in the same thermal equilibrium is widely used in the literature and was also used in this study:

$$C_{P_{nf}} = \frac{(1-\varphi)(\rho C_p)_{bf} + \varphi(\rho C_p)_{np}}{\rho_{nf}} \tag{3.8}$$

3.2.4. Base Fluid and Nanoparticle Properties Studied

The base fluid used in this study is water. The temperature dependent thermophysical properties of water were obtained using the curve fitting to the data of the ASHRAE Handbook. With these fits, the properties of the water in the PVT system can be calculated at different operating temperatures (Ebrahimnia Bajestan et al., 2016). These equations are given below for each property:

$$\rho_w = (-0.003T^2) + (1.505T) + 816.781 \tag{3.9}$$

$$\mu_w = 0.00002414 \times 10^{\frac{247.8}{T-140}} \tag{3.10}$$

$$k_w = (-7.843 \times 10^{-6}T^2) + (0.0062T) - 0.54 \tag{3.11}$$

$$c_{p_w} = (-0.0000463T^3) + (0.0552T^2) - (20.86T) + 6719.637 \tag{3.12}$$

Here, ρ_w [kg/m^3] is density, μ_w [Pa·s] is dynamic viscosity, k_w [W/m·K] is thermal conductivity, and c_{p_w} [J/kg·K] is specific heat capacity of water. T represent the temperature in K.

Hexagonal Boron Nitride the hexagonal form of boron nitride and belongs to the class of ceramic materials. It has a chemically stable structure and versatile properties such as high thermal conductivity. The thermal conductivity of

Hexagonal Boron Nitride (hBN) was taken as 400 ($Wm^{-1}K^{-1}$) and its specific heat is 740 ($Jkg^{-1}K^{-1}$) for calculations in this study (Yuan et al., 2019). The theoretically recorded density of Hexagonal Boron Nitride is 2290 (kgm^{-3}) and its molecular weight is 24.82 (Kostoglou et al., 2015). Table 1 shows the properties of Hexagonal Boron Nitride

Table 3.1. hBN Properties

Material	**Density (kgm^{-3})**	**T. Conduct. ($Wm^{-1}K^{-1}$)**	**Specific Heat ($Jkg^{-1}K^{-1}$)**
hBN	2290	400	740

3.3. Modeling and Simulation

3.3.1. Model Geometry

In this study performance analysis of hBN/water nanofluid in a PVT system was performed using COMSOL Multiphysics software. 3D drawing of the system was made using Solidworks software for numerical analysis. The configuration of the collector of PVT system used in numerical analysis consists of glass, top transparent ethylene vinyl acetate (EVA) layer, monocrystalline silicon solar cell, bottom transparent EVA layer, tedlar polyvinyl fluoride (tedlar) layer, thermal paste, copper absorber plate and copper tubes. The schematic view of the collector of PVT system is given in Figure 3.9.

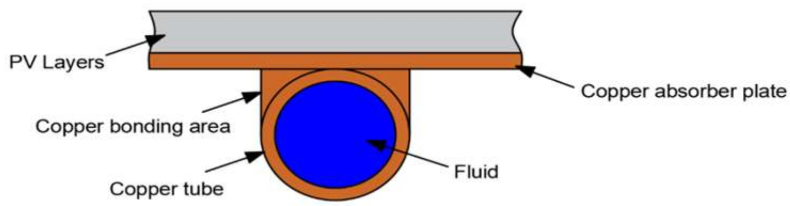

Figure 3.9. Schematic view of PVT collector with bonding area

The width and length of the PV panel were determined as 370 mm x 680 mm, considering the examples in the literature (Hosseinzadeh, 2018; Alous, 2019). The inner and outer diameter of water tube is 8 mm and 10 mm, respectively. Copper water pipes are bonded to the absorber plate using copper material as shown in figure 3.10.

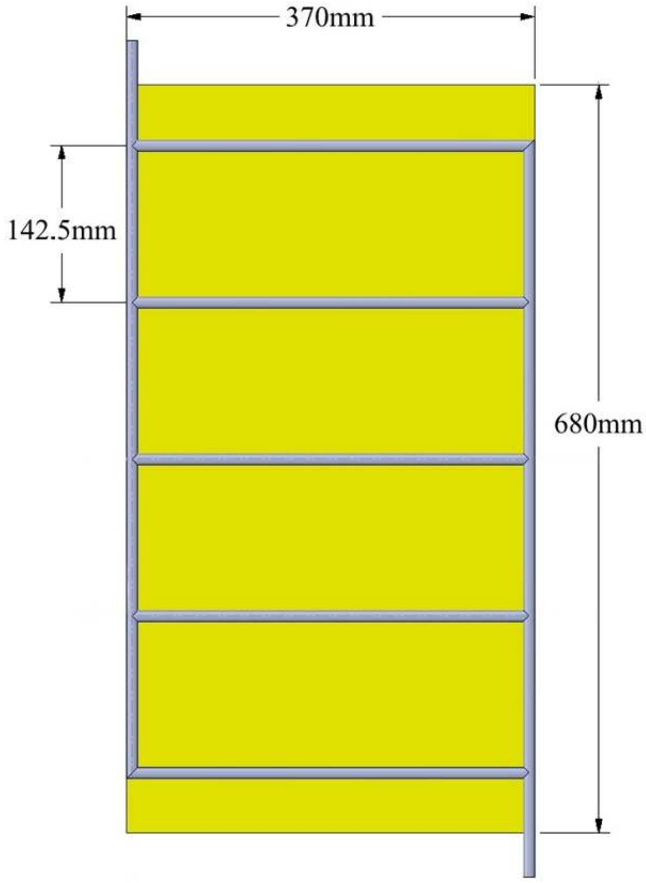

Figure 3.10. The bottom view of the PVT collector

Tables 3.2 and 3.3 present the thermophysical properties of the components used in the PVT collector, and the dimensions of the components for the numerical model.

Table 3.2. Thermophysical properties of the collector of PVT systems materials

Material	**ρ (kg/m³)**	**k (W/m.K)**	**c_p (J/kg.K)**
Glass	2500	1.8	500
EVA	960	0.35	2090
Monocrystalline silicon	2330	148	700
Tedlar	1200	0.20	1250
Thermal paste	2600	1.9	700
Copper absorber	8960	401	385

Table 3.3. Dimensions of the collector of PVT system components

Component	**Dimensions (mm)**
Glass	680 x 370 x 4
EVA	680 x 370 x 0.5
Total area of monocrystalline silicon	680 x 370 x 0.3
Tedlar	680 x 370 x 0.1
Thermal paste	680 x 370 x 0.3
Copper absorber	680 x 370 x 0.7
Inner diameter of copper tubes	8
Outer diameter of copper tubes	10

3.3.2. Numerical Procedure and Governing Equations

The finite element method was used for numerical analysis, and the COMSOL Multiphysics software was used for the finite element method within the scope of the thesis. The details of the dimensions of the collector of PVT system used in the numerical analysis were presented in the previous section. In the current study, numerical analyzes were carried out with the inlet fluid velocities of 0.08 m/s (Re=717), 0.16 m/s (Re=1434), and 0.24 m/s (Re=2151). Therefore, the flow regime is laminar since all inlet fluid velocities are below the critical Reynolds number (2300). The fluid flow is assumed to be incompressible, uniform, and steady state. Moreover, nonisothermal flows are selected for a multiphysics interfaces. It is supposed that the dispersion of nanoparticles is homogeneous in the base fluid. Other assumptions used in the numerical simulation of the PVT system in order to simplify the simulation process are as follows;

- The effect of dust on the glass cover on solar radiation is neglected.
- EVA is considered transparent and has 100% transmission efficiency.
- There is perfect contact between the components in the PVT system.
- The thermophysical properties of the PVT system components are constant.
- Sky temperature and ambient temperature were evaluated equally.
- The side and bottom surfaces of the collector of PVT system are considered to be completely insulated.

The heat conduction equation is used for heat transfer between solid surfaces in the PVT system. Therefore, the heat transfer from the PVT panel surface to the flow channel is solved by the heat conduction equation (Rubbi et al., 2020). The heat transfer between the solid pipe and the flowing fluid includes heat conduction and convection. Therefore, the conjugate heat transfer equation (Rubbi et al., 2020) is used for the flow in the collector.

The energy balance equation given in equations (3.13) and (3.14) expresses the Fourier heat conduction equation (Shen et al., 2021):

$$\left(\rho \times c_p\mu \times \nabla \mathrm{T}\right) + \nabla q = Q \tag{3.13}$$

$$-k \times \nabla T = q \quad (3.14)$$

Due to the fact that the cooling fluid is Newtonian and incompressible, the continuity and momentum equations for the cooling fluid are expressed in equations (3.15) and (3.16) (Shen et al., 2021):

$$\rho \times \nabla u = 0 \quad (3.15)$$

$$\rho(u \times \nabla)\mathrm{u} = \nabla\big(-\mathrm{pI} + \mu(\nabla \mathrm{u} + \nabla u^{T})\big) + F \quad (3.16)$$

Here, ρ is density (kg/m^3), c_p is specific heat capacity (J/kg.K), u is velocity (m/s), p is pressure (Pa), μ is viscosity of fluid (Pa·s), k is thermal conductivity of material, q is heat flux vector, T is temperature in Kelvin, F is volume force in Newton, I is moment of inertia (kgm^2) and ∇ is dimensionless differential operator.

3.3.3. Boundary Conditions

In the numerical simulation, the inlet fluid velocity boundary condition was applied for the fluid entering the tube and the studied inlet fluid velocities were 0.08 m/s, 0.16 m/s and 0.24 m/s. The temperature of the fluid entering the tube was taken as constant at 25 °C.

The ambient temperature was assumed to be the same as the water inlet temperature. The pressure outlet condition of the fluid from the tube was taken as 0 (zero) atm. The no slip condition was applied to the inner walls of the tube. Inward heat flux was applied on the PV panel. Heat losses occurred from the upper surface of the PVT collector. The convection heat transfer coefficient from the upper surface of the PVT collector was taken as 20 W/m^{2}K (Hu et al., 2019). It was assumed that the side and bottom surfaces of the PVT collector are insulated very well. Therefore, the side and bottom surfaces of the PVT collector were assumed to be adiabatic (zero heat flux). To perform the numerical analysis, the boundary conditions are expressed with the governing equations.

The solar radiation absorbed on the top surface of PVT collector was calculated with in equation (3.17) (Khanjari et al., 2016) :

$$\dot{E}_{absorbed} = G_t \times \tau_g \times \alpha \times \left(1 - \eta_{ref}\right) \tag{3.17}$$

Heat loss by convection applied to the glass was calculated with equation (3.18) (Shen et al., 2021; Rubbi et al., 2020):

$$-n \times q = h_{g \to a} \times (T_s - T_{amb}) \tag{3.18}$$

Adiabatic boundary condition was applied to the side and bottom surfaces of PVT collector (Shen et al., 2021):

$$-n \times q = 0 \tag{3.19}$$

Equation (3.20) shows the no slip condition at the wall of the solid boundaries for tube and fluid in PVT collector (Shen et al., 2021):

$$u = 0 \tag{3.20}$$

Inlet conditions of fluid domain are shown in equation (3.21) (Shen et al., 2021):

$$u = u_{in} \quad and \quad T = T_{in} \tag{3.21}$$

Outlet pressure of the fluid domain is shown in equation (Shen et al., 2021):

$$P_{out} = 0 \tag{3.22}$$

The solid-fluid interface boundary condition in pipes is shown in equation (3.21) (Shen et al., 2021):

$$(\frac{\partial T_s}{\partial n})_{fluid} = \frac{k_s}{k_f}(\frac{\partial T_s}{\partial n})_{solid} \tag{3.23}$$

The symbols used in Equations 3.17 and 3.23 are:

T_s:	Surface temperature (K)
T_{amb}:	Ambient temperature (K)
k_s:	Solid heat conduction coefficient (W/m.K)
k_f:	Fluid heat conduction coefficient (W/m.K)
G_t:	Total solar radiation (W/m^2)
τ_g:	Transmissivity of glass (0.9)
α:	Absorptivity of solar cell (0.9)
$\dot{E}_{absorbed}$:	Absorbed heat flux (W/m^2)
$h_{g\to a}$:	Heat transfer coefficient from glass to ambient (W/m^{2}K)
η_{ref}:	Reference efficiency for PV panel (0.12)
q:	Heat flux vector
n:	Surface normal

3.3.4. Thermodynamic Analysis

The first law of thermodynamics states that energy can never be destroyed, but can be transformed from one form to another. The electrical and thermal energy amounts are derived from the energy balance equations (Khanjari et al., 2016). If the PVT system is considered as the control volume under steady-state conditions, the energy balance equation includes the radiation from the sun, the radiation on the PVT panel surface, convection between the surface of the PVT panel and the ambient, the thermal energy production, and the electrical output power (Rubbi et al., 2020). The schematic diagram of the energy balance of the PVT system is presented in Figure 3.11.

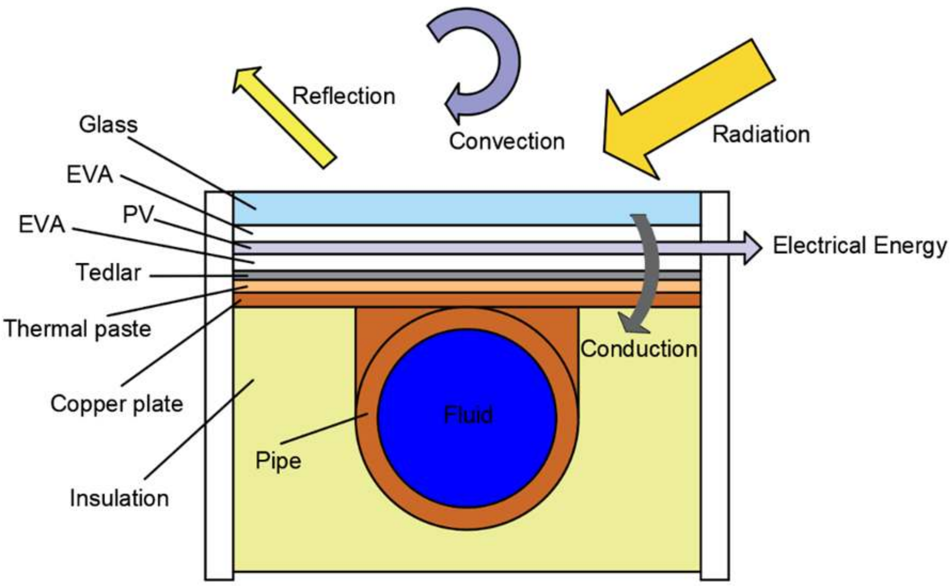

Figure 3.11. Schematic view of the energy balance of the PVT system

In the steady state condition, the energy balance for this control volume is expressed as in equation (3.24):

$$\dot{E}_{absorbed} = \dot{E}_{el} + \dot{E}_{mass,out} + \dot{E}_{loss} - \dot{E}_{mass,in} \tag{3.24}$$

where $\dot{E}_{loss}$ denotes heat losses. $\dot{E}_{mass,out} - \dot{E}_{mass,in}$ expression in equation (3.24) denotes thermal energy production ($\dot{E}_{th}$). This expression is also equal to equation (3.25):

$$\dot{E}_{mass,out} - \dot{E}_{mass,in} = \dot{E}_{th} = \dot{m}_f c_{p,f}(T_o - T_i) \tag{3.25}$$

Here, $\dot{m}_f$ is fluid mass flow rate (kg/s), $c_{p,f}$ is specific heat of fluid (J/kg.K), T_o is outlet temperature from tube (K) and T_i is inlet temperature to tube (K).

The electrical power output ($\dot{E}_{el}$) of the PVT system can be calculated from:

$$\dot{E}_{el} = V_{oc} \times I_{sc} \times FF \tag{3.26}$$

Here, V_{oc} is open circuit voltage (V), I_{sc} is short circuit current (A) and FF is fill factor.

The thermal energy (η_{th}) and electrical energy (η_{el}) efficiencies for the PVT system are presented in equations (3.27) and (3.28), respectively:

$$\eta_{th} = \frac{\dot{E}_{th}}{G_t \times A_{pv}} \tag{3.27}$$

$$\eta_{el} = \frac{\dot{E}_{el}}{G_t \times A_{pv}} \tag{3.28}$$

Here, A_{pv} means PV area (m^2).

Electrical efficiency can also be defined by equation (3.29):

$$\eta_{el} = \eta_{ref}[1 - \beta(T_c - T_{ref})] \tag{3.29}$$

Here, β is a temperature coefficient (0.0045 °C), T_{ref} is reference temperature and T_c is PV cell temperature.

The overall efficiency (η_{overal}) of PVT system can be calculated using equation (3.30):

$$\eta_{overall} = \eta_{el} + \eta_{th} \quad (3.30)$$

3.3.5. Mesh Independency Analysis

The numerical model in the thesis was discretized using COMSOL Multiphysics software. Dimensions of EVA, silicon, and tedlar layers, the copper absorber plate, and the copper tube are presented in 3.3.1. Model Geometry section. Free tetrahedral mesh generation was applied at the boundaries of the copper pipe and fluid subdomains, and free triangular mesh generation was applied at the remaining boundary elements. A boundary layer mesh was applied near the inner walls of the copper tube to improve the accuracy of the simulations.

In this part of the study, the mesh independency test was performed to demonstrate the reliability of the numerical analysis. Water was used as the fluid and the inlet velocity of the water was 0.16 m/s, the ambient air and inlet water temperature was 25 °C, and the solar radiation was 1000 W/m^2 for the mesh independency test. The outlet temperature of the cooling water and the surface temperature of the cell were compared for five different mesh sizes varying between 395431 and 1927871. The views obtained for each mesh structure performed were presented in Figures 3.12, 3.13, 3.14, 3.15, and 3.16. The mesh independency test results are given in Figure 3.18. As can be seen from the figure, the relative error in cell and outlet temperatures between 1469137 and 1927871 element sizes is very small, being 0.029% and 0.010%, respectively. Therefore, the numerical studies were carried out with a mesh size of 1533133 between mesh sizes of 1469137 and 1927871 (Figure 3.17).

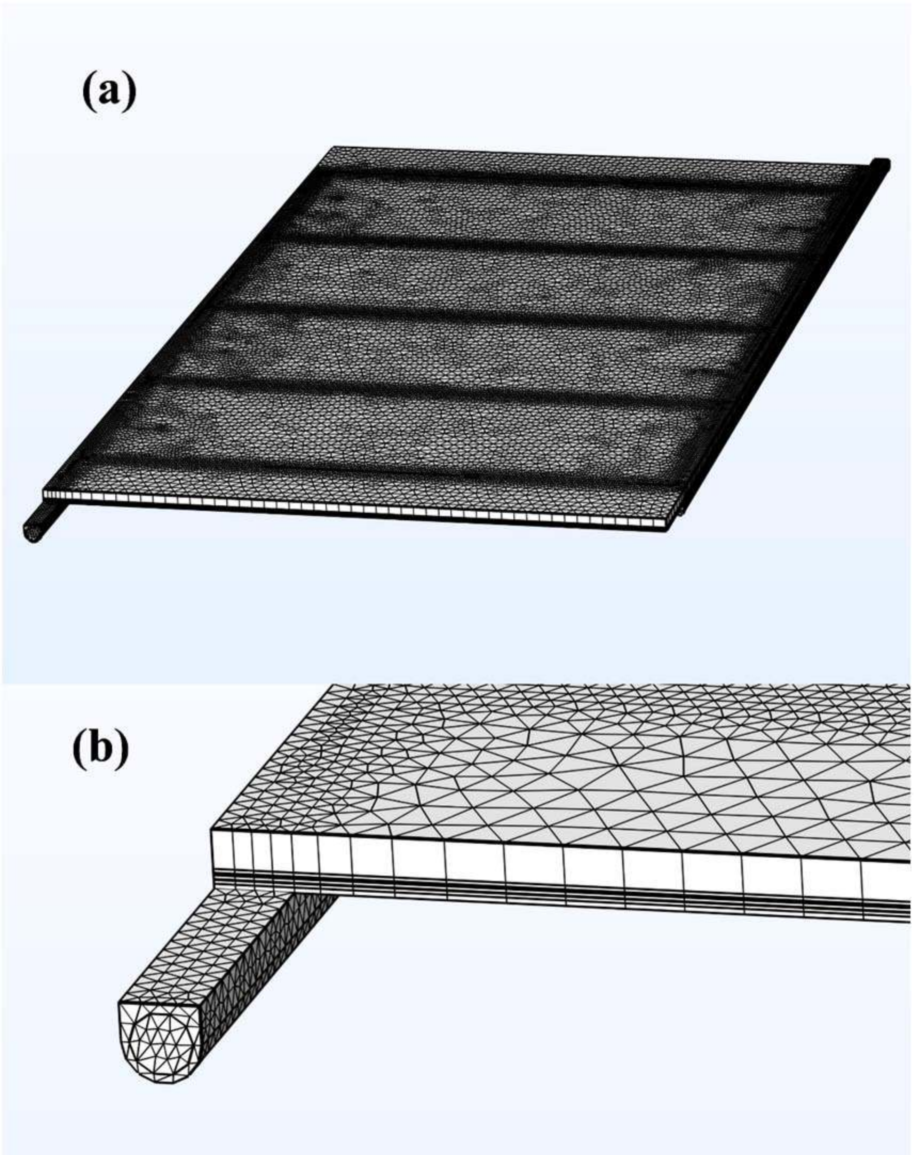

Figure 3.12. The grid distribution of PVT collector with 395431 element number; (a) overall view and (b) zoom view of PVT collector

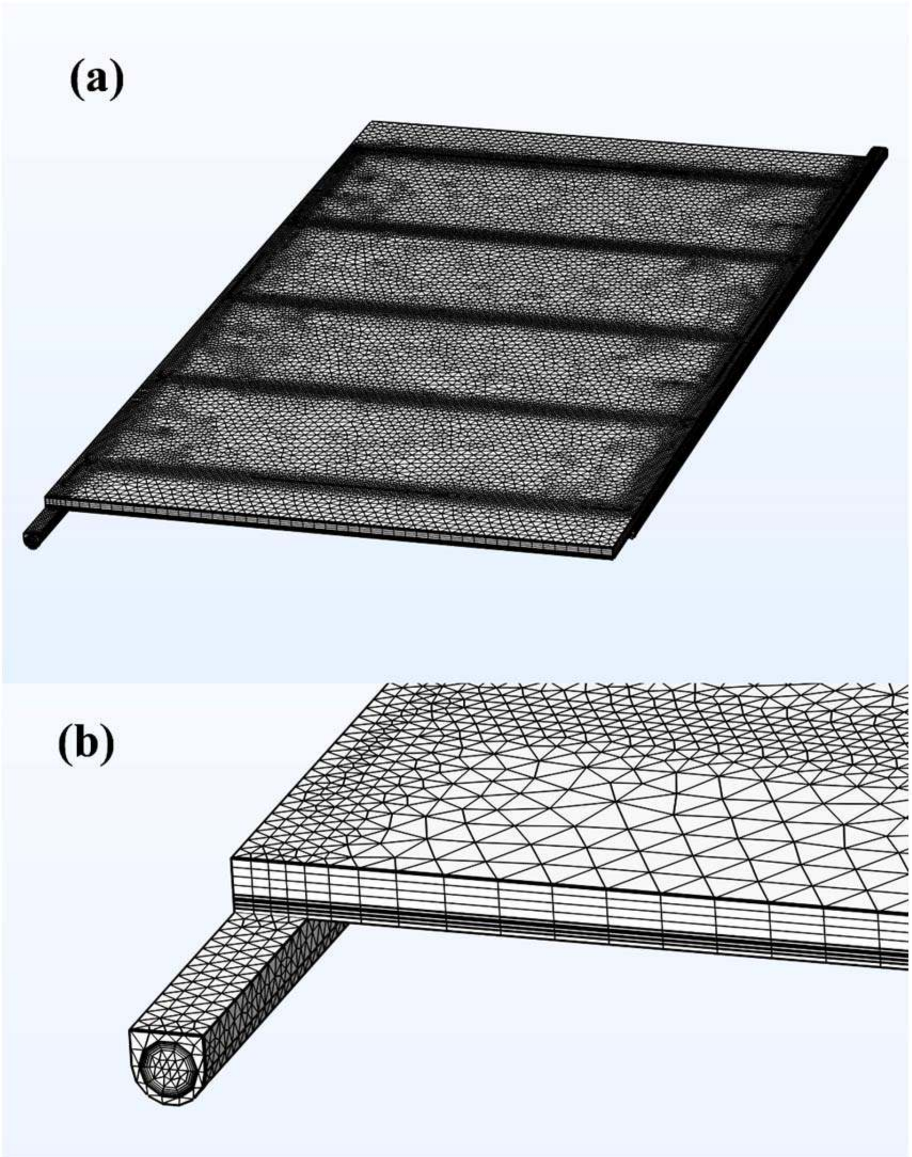

Figure 3.13. The grid distribution of PVT collector with 628985 element number; (a) overall view and (b) zoom view of PVT collector

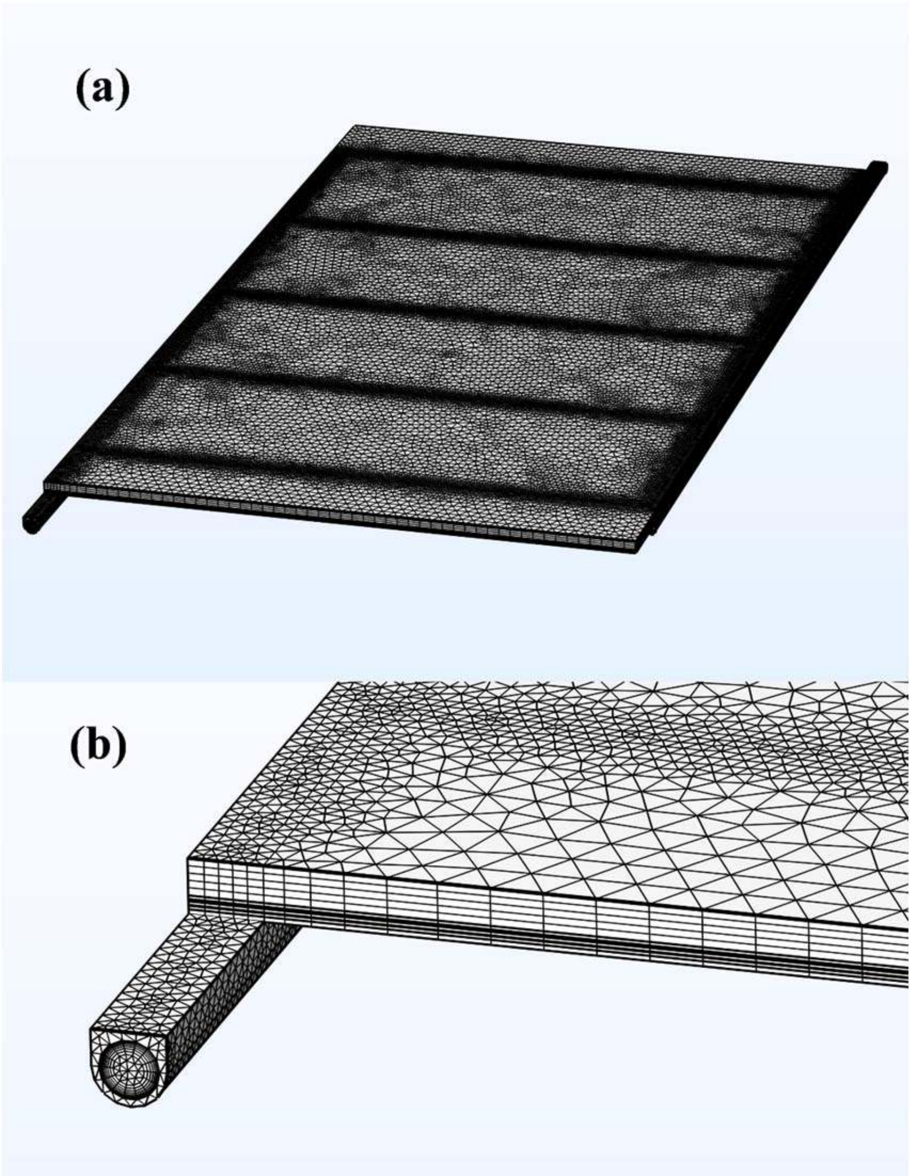

Figure 3.14. The grid distribution of PVT collector with 1093152 element number; (a) overall view and (b) zoom view of PVT collector

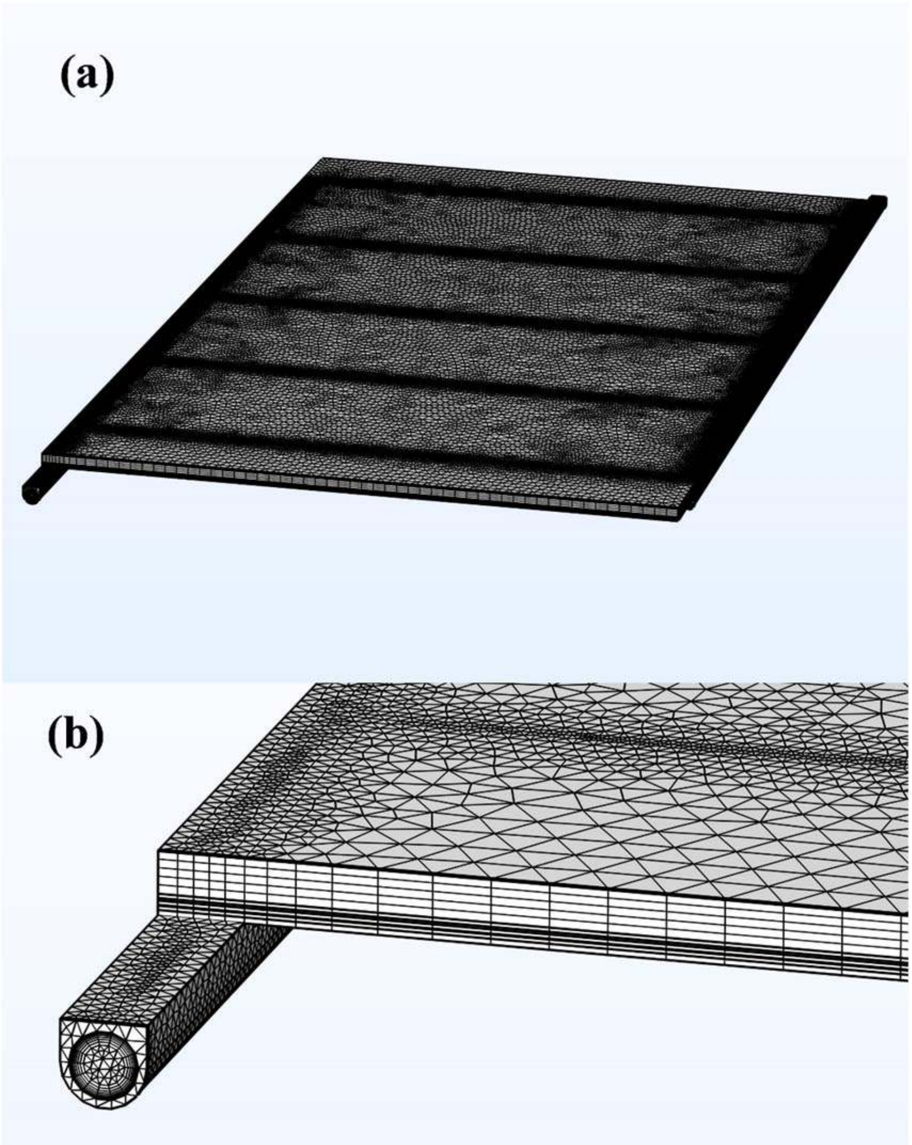

Figure 3.15. The grid distribution of PVT collector with 1469137 element number; (a) overall view and (b) zoom view of PVT collector

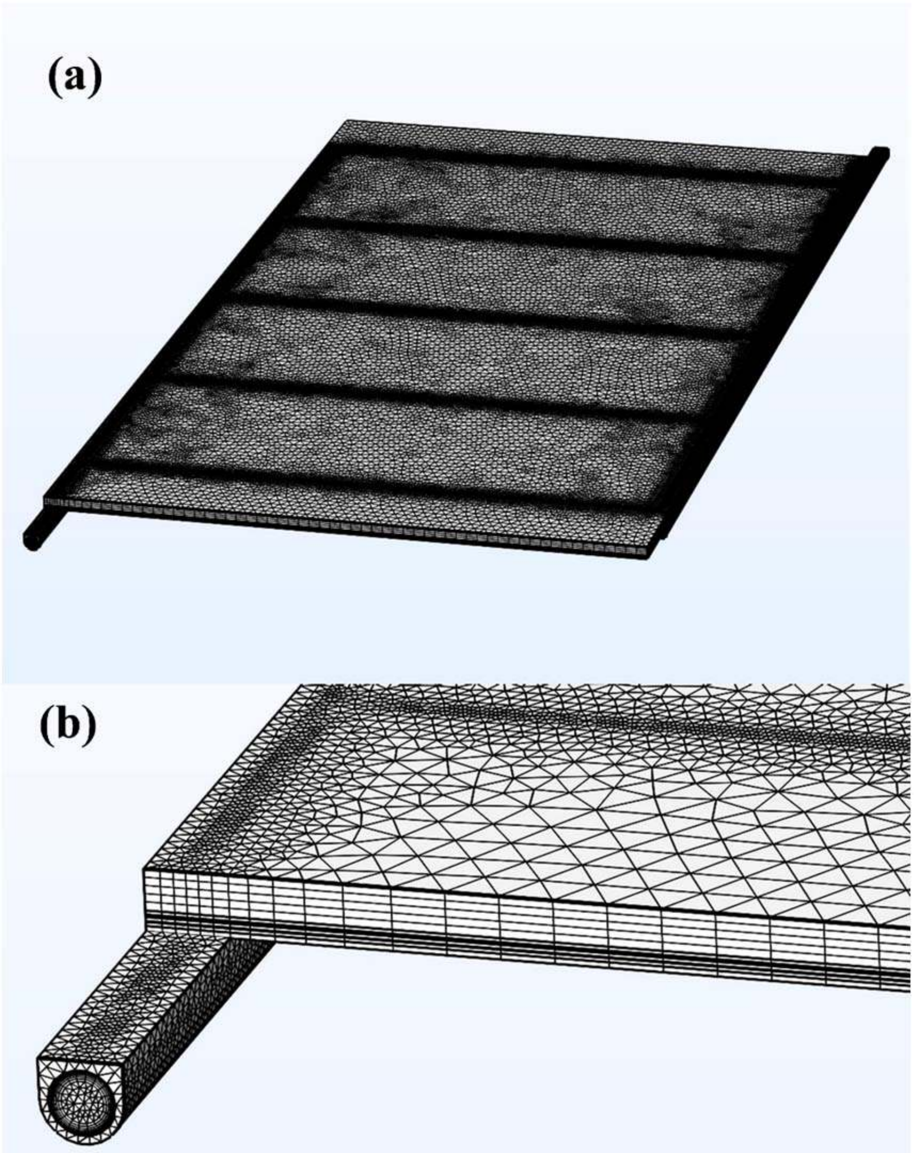

Figure 3.16. The grid distribution of PVT collector with 1927871 element number; (a) overall view and (b) zoom view of PVT collector

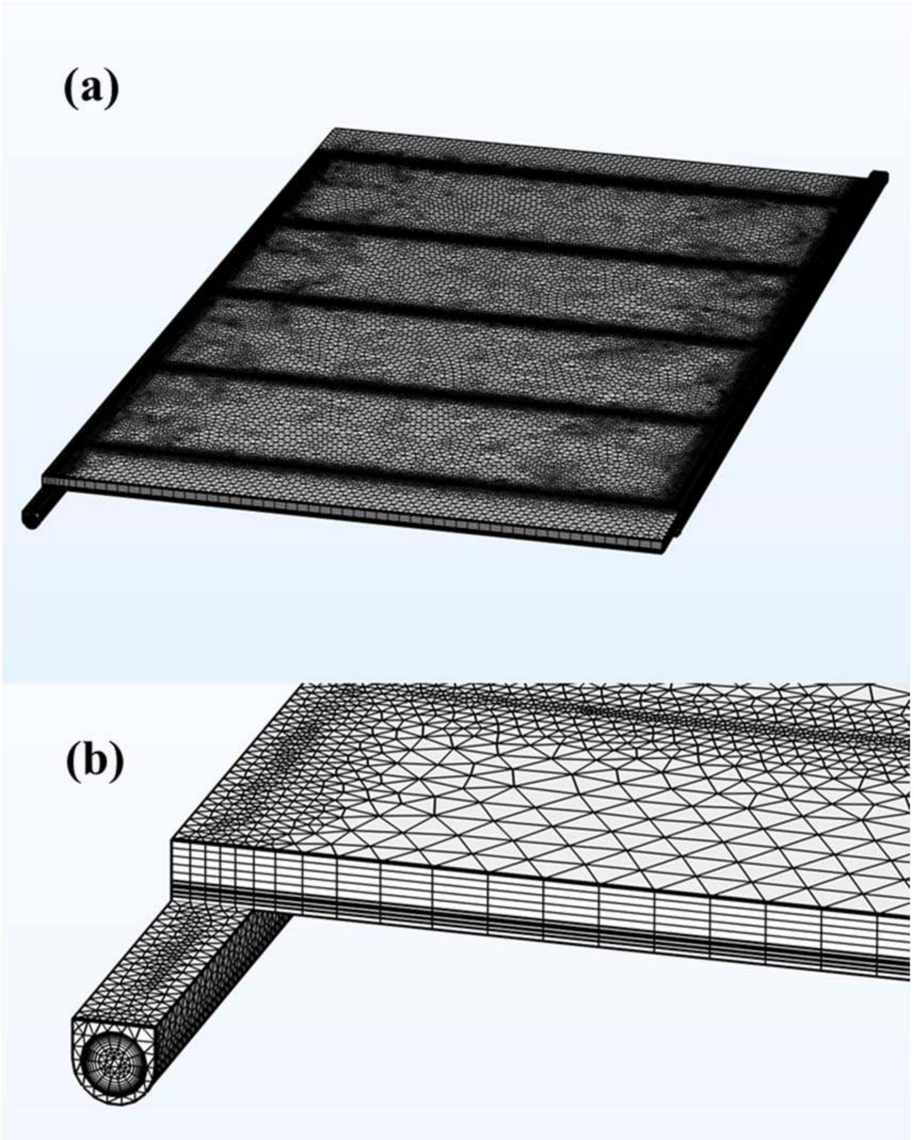

Figure 3.17. Selected grid distribution of PVT collector with 1533133 element number; (a) overall view, and (b) zoom view of PVT collector

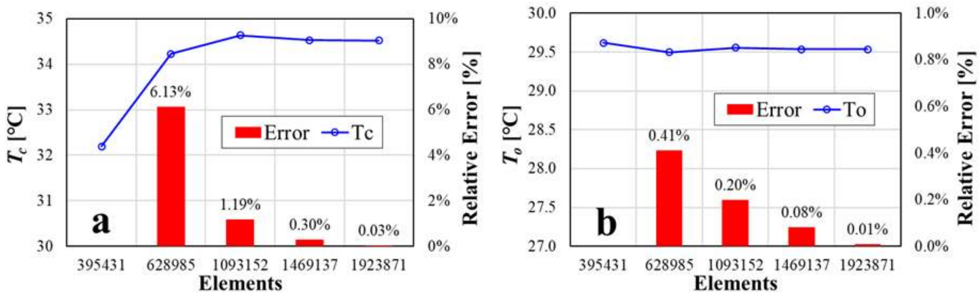

Figure 3.18. Grid test and relative errors for mesh independency; (a) cell temperature (b) outlet temperature of PVT collector

3.3.6. Model Validation

In the current study, numerical results reported by Shen et al. (2021) and experimental results reported by Alous et al. (2019) were used to validate the numerical simulation (Figures 3.19 and 3.20). Two parameters used to determine the efficiency values of PVT systems were considered in the validation process of the numerical simulation. These parameters are the surface temperature of the cell (T_c) and the outlet temperature of the water (T_o) from the PVT.

Shen et al. (2021) performed many dimensional analyzes for two different fins (Design A and Design B). However, the parameters given in Table 3.4 for Design B were employed in the validation process within the scope of the master thesis. The dimensions and experimental working ranges of the PVT systems tested by Alous et al. (2019) are presented in Table 3.5.

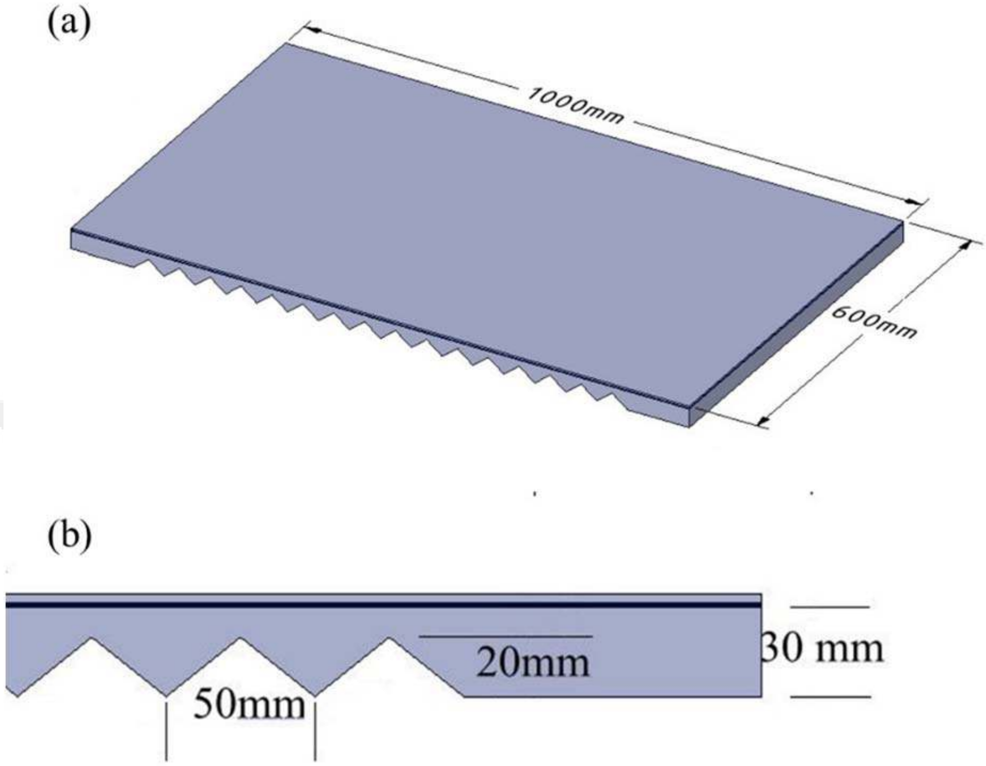

Figure 3.19. Schematic view of the PVT collector designed by Shen et al. (2021)

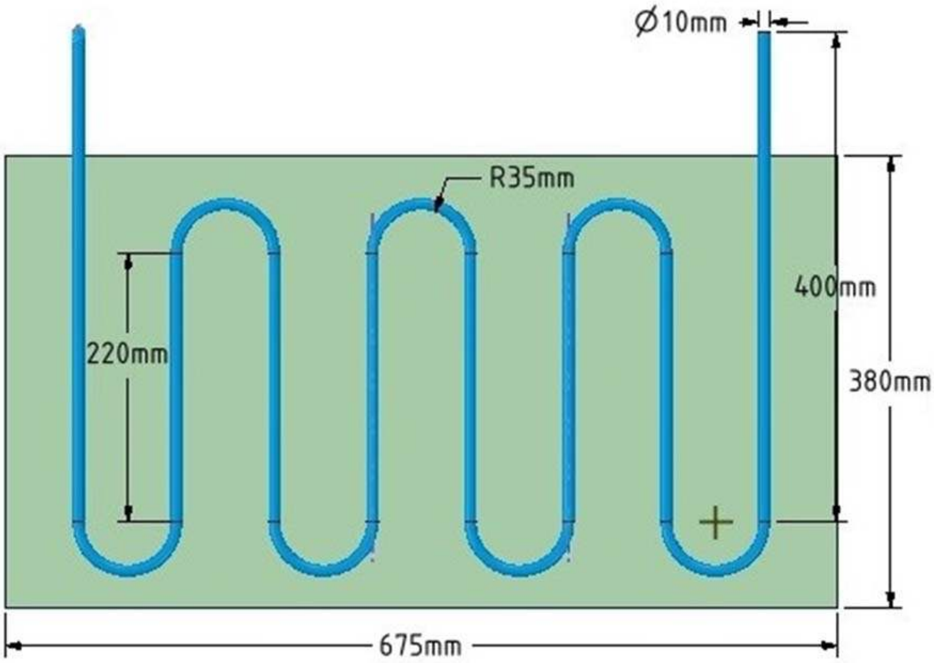

Figure 3.20. Schematic view of the PVT collector studied by Alous et al. (2019)

Table 3.4. Specifications of the PVT system designed by Shen et al. (2021)

Specification	**Value**
Channel length	1 m
Channel width	0.6 m
Channel depth	0.03 m
Width of sawtooth	0.05 m
Peak of sawtooth	0.02 m
Glass transmissivity (τ_g)	0.96
Emissivity of glass (ε_g)	0.04
Solar cell absorptivity (α_c)	0.9
Ambient temperature	20 °C
Inlet temperature	20 °C
Solar radiation	300-1200 W/m^2
Mass flow rate of cooling fluid	0.009 kg/s
Heat transfer coefficient from glass cover to ambient	5.84 W/m^{2}K

Table 3.5. Specifications of the PVT system studied by Alous et al. (2019)

Specification	**Value**
Dimensions of PV panel	380 x 675 x 20 mm
Aperture area	355 x 652 mm
Dimensions of copper plate	355 x 652 x 0.7 mm
Inner diameter of copper tube	8 mm
Outer diameter of copper tube	10 mm
Radiation	452-920 W/m^2
Ambient temperature	22.1-34.9 °C
Fluid inlet temperature	25.4-36.7 °C
Volumetric flow rate of fluid	0.5 L/min

Comparison of T_c and T_o obtained in the current study with the numerical results presented by Shen et al. (2021) is shown in Figure 3.21. The average and maximum relative errors for T_c are 2.6% and 4.2%, respectively. In the case of T_o, the corresponding errors are smaller, being 0.8% and 1.6%, respectively.

Figure 3.22 shows the comparison of the present results with the experimental results of Alous et al. (2019). The average and maximum relative errors for T_c and T_o are 4.96% and 10.56%, and 5.66% and 8.36%, respectively.

It can be concluded that the agreement between the results of the present study and the numerical and experimental study available in the literature is good and the relative errors are at acceptable levels. The reason for the higher relative error in the case of experimental study (Alous et al., 2019) compared to the numerical study is due to the fact that insufficient information was shared about the details of the experimental boundary conditions in the related paper.

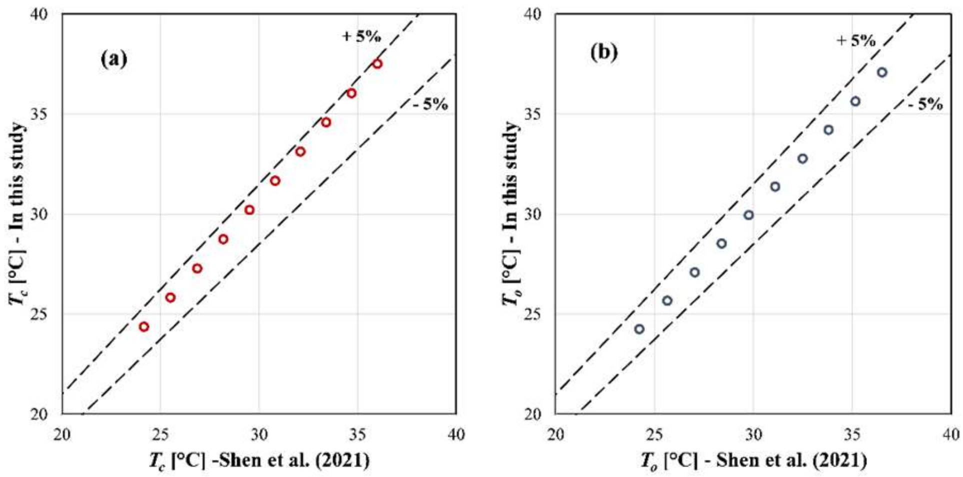

Figure 3.21. Validation of the present T_c and T_o results with Shen et al. (2021)

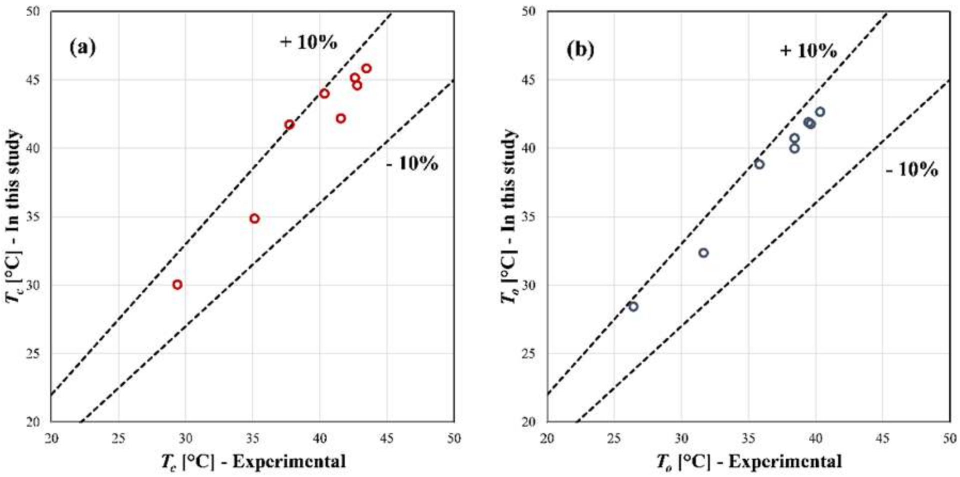

Figure 3.22. Validation of the present T_c and T_o results with Alous et al. (2019)

4. RESULTS AND DISCUSSION

In this thesis, the applicability of hBN nanofluid in PVT systems was investigated by numerical analysis. Finite Element Method (FEM) was used for the numerical analysis. COMSOL Multiphysics software was used for FEM analysis.

First of all, the results obtained by the numerical analyses for hBN/water nanofluid and water were compared. Secondly, analyzes were performed for determining the effect of different hBN concentrations on the performance of the PVT system. Then, the effect of flow rate was studied. Finally, the effect of hBN nanoparticle diameter was investigated. Fluid outlet temperature (T_o), cell temperature (T_c), thermal efficiency (η_{th}), electrical efficiency (η_{el}), and overall efficiency (η_{ov}), which are of great importance in determining the performance of PVT systems, were considered.

4.1. Comparison of results for hBN/water nanofluid and water

In this section, the results for hBN/water and water fluids are compared. In addition to the general assumptions stated in the "3.3.3. Boundary conditions" section, the inlet fluid velocity was chosen as 0.16 m/s and the concentration of nanoparticles was 2 % in the numerical analysis. The incident solar radiation to the top layer of the PV panel was varied between 200 – 1200 W/m^2.

The variations of fluid outlet temperature (T_o) and thermal efficiency (η_{th}) for water and hBN/water nanofluid with solar radiation incident on the PVT collector are shown in Figures 4.1 Figure 4.2, respectively. As expected, T_o and η_{th} for both fluids increase with the increase of solar radiation. T_o for water and hBN/water nanofluid increased by 4.19 °C and 4.25 °C, respectively, with the increase of radiation from 200 W/m^2 to 1200 W/m^2. It is clear from the figure that adding 2% hBN to the water causes a very small increase in the temperature of the water leaving the collector. Average increase is approximately 1.36%.

For the range of solar radiation considered, η_{th} varied between 53.17% and 55.37% for water and between 54.93% and 55.73% for hBN/water nanofluid. The increase in T_o causes a 1.51% increase in the average η_{th} of the hBN/water nanofluid compared to water. Since higher T_o and η_{th} are obtained with hBN/water nanofluid, it is possible to slightly increase the thermal performance of the PVT system by adding hBN.

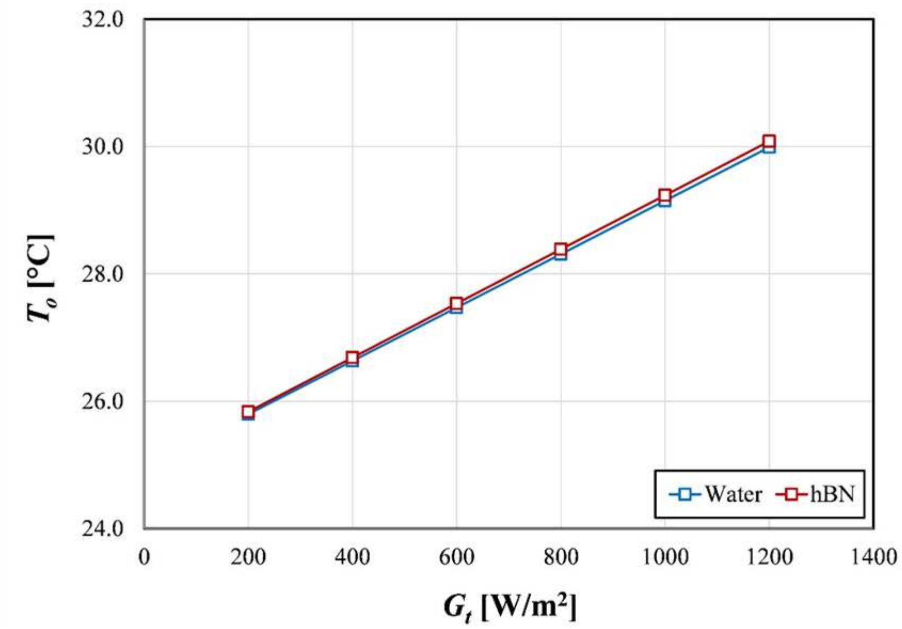

Figure 4.1. Variation of T_o for hBN/water nanofluid with solar radiation

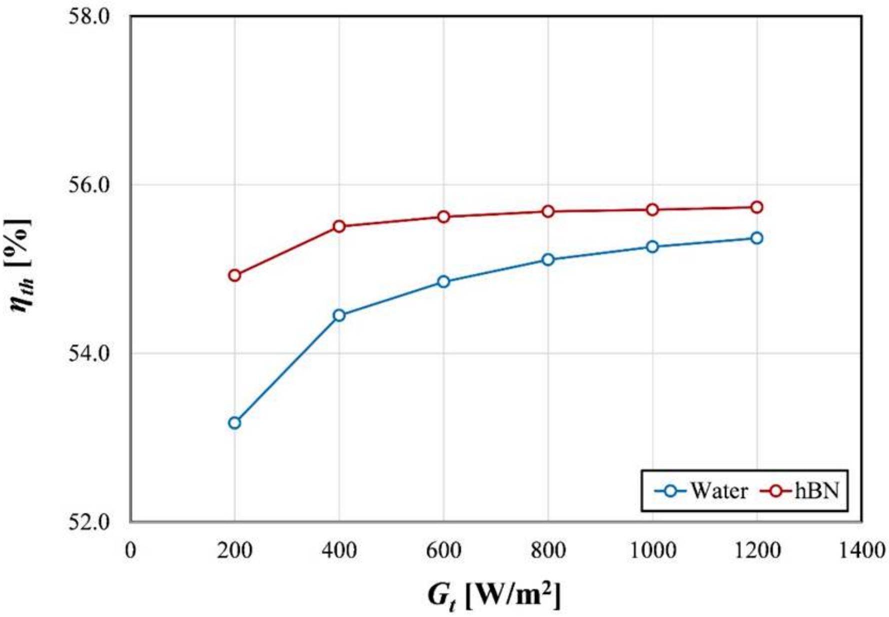

Figure 4.2. Variation of η_{th} for hBN/water nanofluid with solar radiation

In Figures 4.3 and 4.4, variations of cell temperature (T_c) and electrical efficiency (η_{el}) with irradiation are presented when water and hBN/water nanofluid are used. T_c increases with the increase of incident radiation, for both fluids. In general, adding hBN causes a small decrease in T_c. With the increase of incident radiation from 200 W/m^2 to 1200 W/m^2, T_c increases by an average 1.73 °C for water and 1.67 °C for hBN/water nanofluid. T_c for hBN/water nanofluid is on average 3.27% lower than for water.

As can be seen from Figure 4.4, the increase in the cell temperature with increasing solar irradiation results in a decrease in the electrical efficiency (η_{el}). η_{el} varies between 11.90% and 11.44% for PVT using water, and 11.91% to 11.46% for PVT using hBN/water nanofluid. The increase in η_{el} using hBN/water nanofluid is around 0.11% on average compared to water. It can be concluded that adding hBN can slightly contribute to enhance electrical performance of the PVT system.

In addition, use of hBN/water nanofluid instead of water in the PVT system is expected to have a longer lifespan with the decrease in T_c temperature.

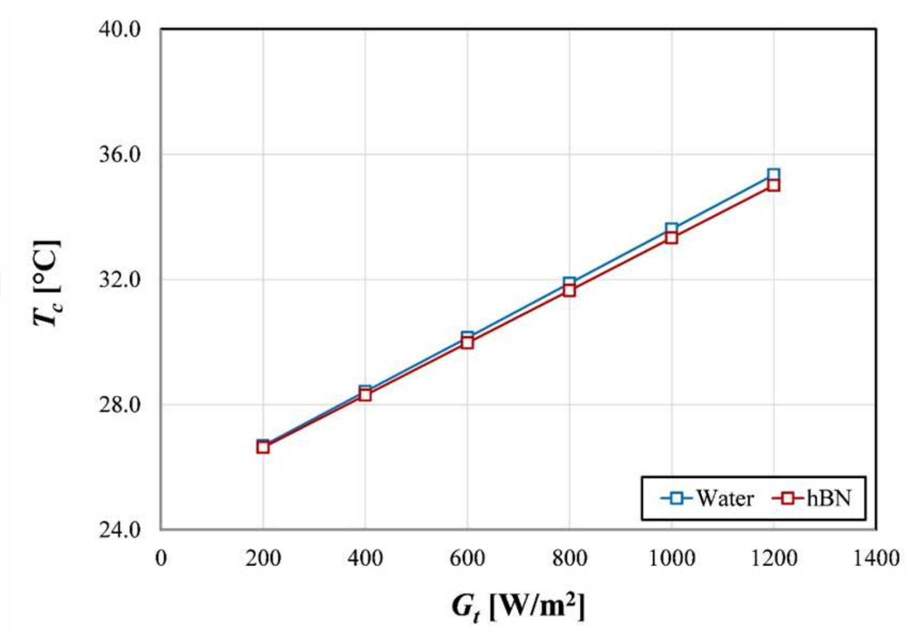

Figure 4.3. Variation of T_c for hBN/water nanofluid with solar radiation

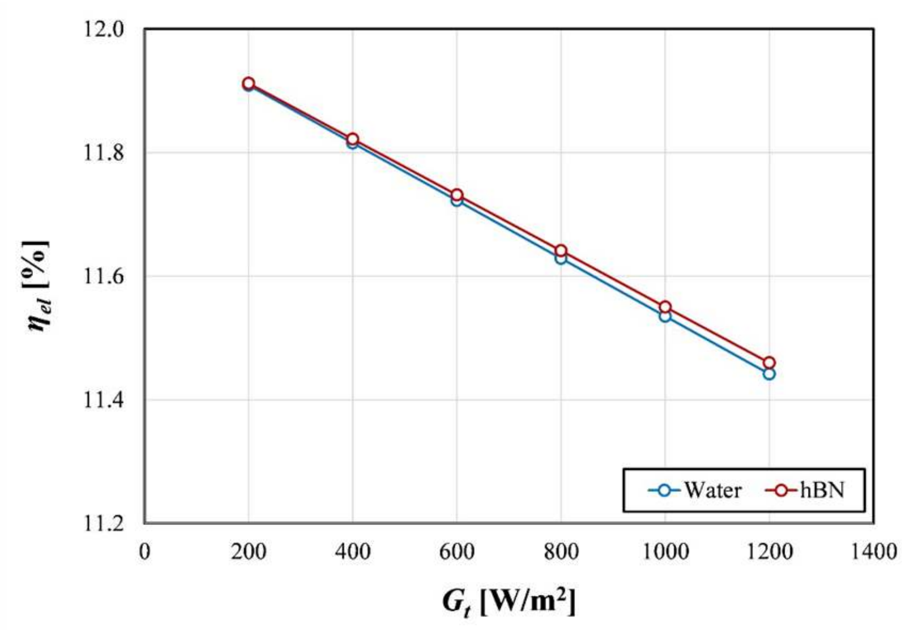

Figure 4.4. Variation of η_{el} for hBN/water nanofluid with solar radiation

The variation of overall efficiency of the PVT system (η_{ov}) with solar irradiation for both fluids is given in Figure 4.5. With the increase in solar radiation, first η_{ov} increases rapidly, at high radiation values the rate of increase decreases, and even in the case of hBN, it decreases slightly after a certain radiation (400 W/m^2). The η_{ov} ranges from 65.08% to 66.81% for the PVT system using water, while it ranges from 66.83% to 67.19% for the PVT system using hBN/water nanofluid. The η_{ov} obtained for the hBN/water nanofluid is 1.26% greater than that of water. While there is a non-linear relationship between solar radiation and η_{th} and η_{ov}, it is linear for η_{el}.

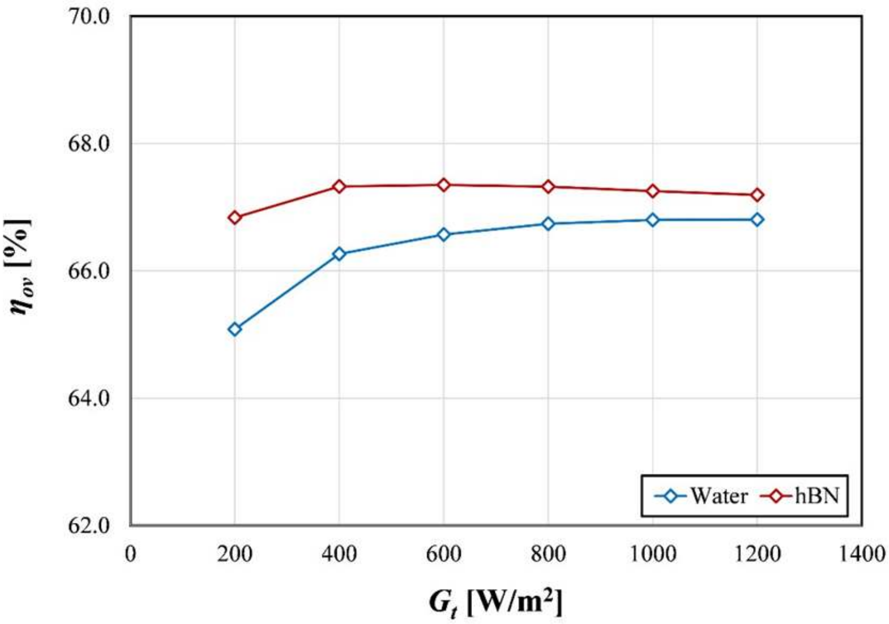

Figure 4.5. Variation of η_{ov} for hBN/water nanofluid with solar radiation

In Figures 4.6 and 4.7, the temperature distribution for water and hBN/water nanofluid, respectively, is presented for different incident solar radiation values. As can be seen from the figures, the highest temperature is reached in the PVT collector with water, and the lowest value is reached with hBN/water nanofluid. As expected, the temperatures increase with increasing irradiance. Considering the temperature distribution of the water channel in PVT collector, there is an increase from inlet to outlet. Looking at the temperature distribution on the upper surface of the PV panel, it is seen that the regions where the PV panel comes into contact with the fluid channels are lower than the regions where the PV panel does not contact the fluid channels.

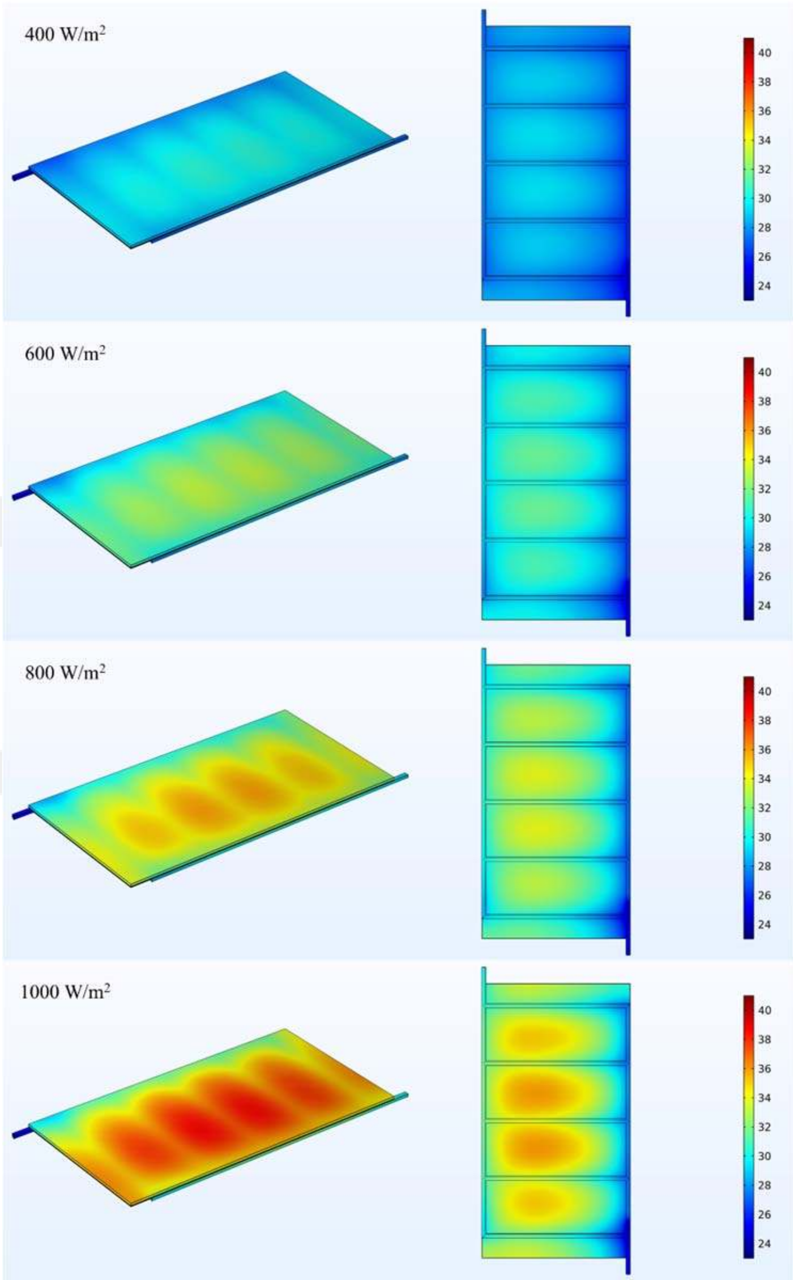

Figure 4.6. Temperature distribution on PVT collector for water at different solar incident radiations

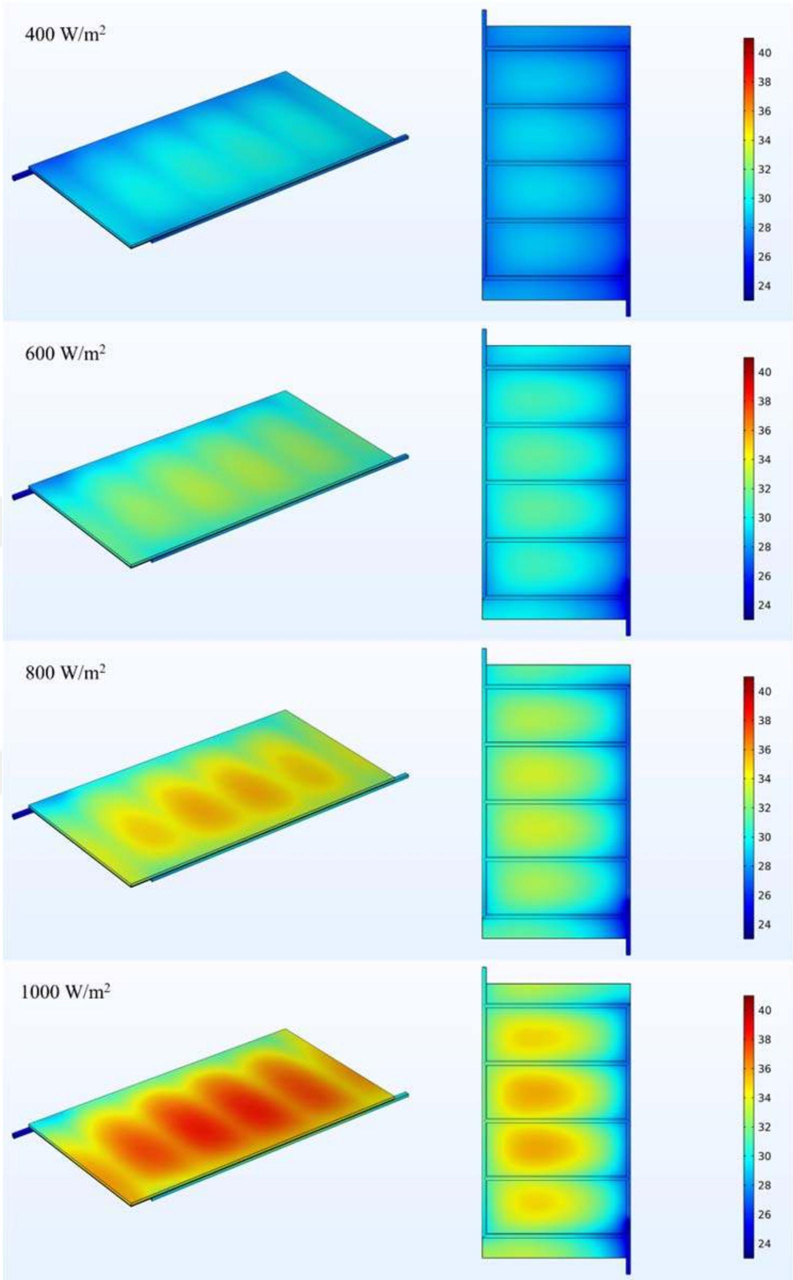

Figure 4.7. Temperature distribution on PVT collector for hBN/water at different solar incident radiations

4.2. Effect of hBN/water nanofluid concentration on the performance of the PVT system

Effects of hBN/water nanofluid concentration on the performance parameters of the PVT system are investigated in this section. In the numerical analysis, the concentration of hBN/water nanofluid was changed from 0% (pure water) to 8% and solar radiation from 600 W/m^2 to 1000 W/m^2. The numerical runs were carried out for a constant fluid inlet temperature of 0.16 m/s.

Increasing the concentration of the nanoparticle causes an increase in both fluid outlet temperature (T_o) and thermal efficiency (η_{th}) (Figures 4.8 and 4.9). As the concentration is increased from 0% to 8%, the T_o and η_{th} increase by 0.64 % and 1.99 % at 600 W/m^2, 0.78 % and 1.63 % at 800 W/m^2, 0.93 % and 1.44 % at 1000 W/m^2, respectively. With the increase in the concentration, the thermophysical properties of the hBN/water nanofluid vary and this variation increases the thermal performance of the PVT system. The increase in the thermal performance with the increase of the concentration leads to the conclusion that the heat transfer in the PVT system is slightly improved.

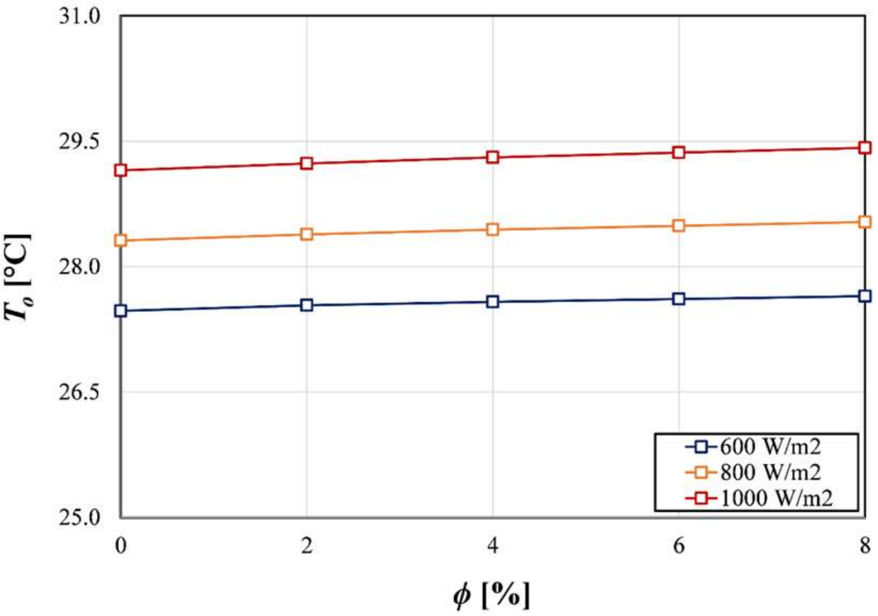

Figure 4.8. Variation of T_o for hBN/water nanofluid with hBN concentration

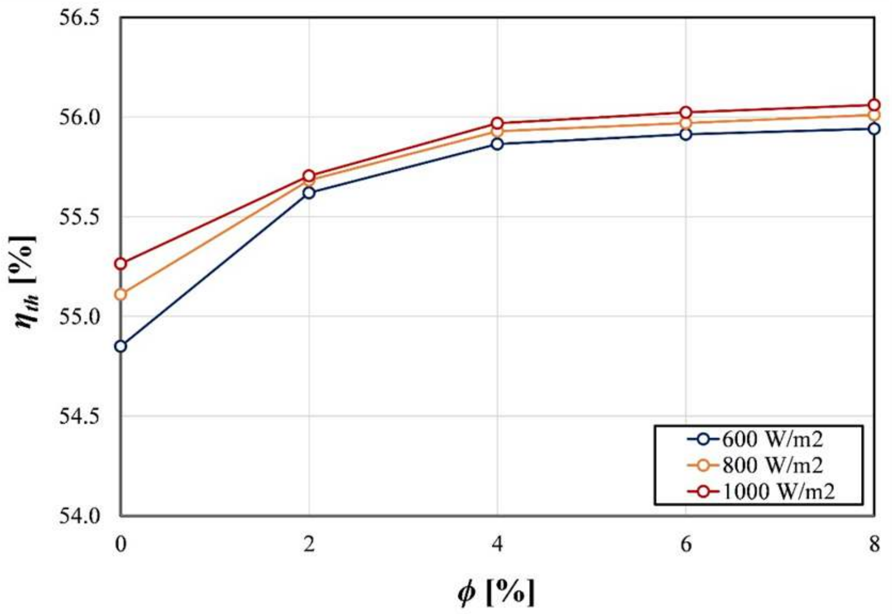

Figure 4.9. Variation of η_{th} for hBN/water nanofluid with hBN concentration

As the concentration is increased, the cell temperature (T_c) decreases, while the electrical efficiency (η_{el}) increases (Figures 4.10 and 4.11). T_c ranges between 29.67 °C and 33.61 °C, and η_{el} ranges between 11.54% and 11.75% for all cases tested. T_c decreases 1.56% at 600 W/m^2, 2.01% at 800 W/m^2, and 2.38% at 1000 W/m^2 with an increase in the concentration from 0% to 8%. For the same concentration range, the electrical efficiency (η_{el}) increases 2.00% at 600 W/m^2, 1.63% at 800 W/m^2, and 1.44% at 1000 W/m^2. Increasing the concentration of hBN/water nanofluid removed more heat from the PV panel and thus improved thermal performance. Removing more heat from the PV panel surface lowered the cell temperature, resulting in an increase in electrical efficiency (Figure 11).

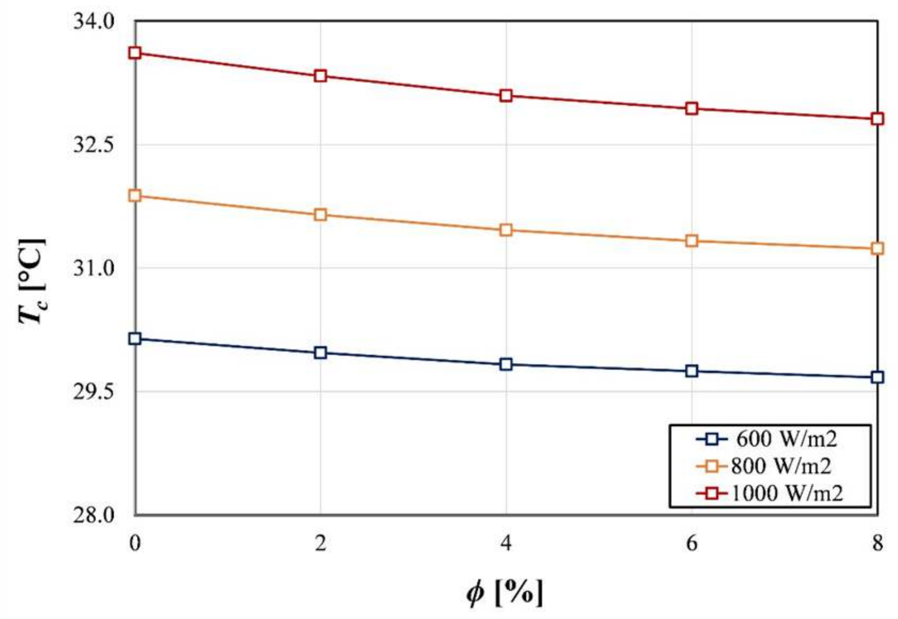

Figure 4.10. Variation of T_c for hBN/water nanofluid with hBN concentration

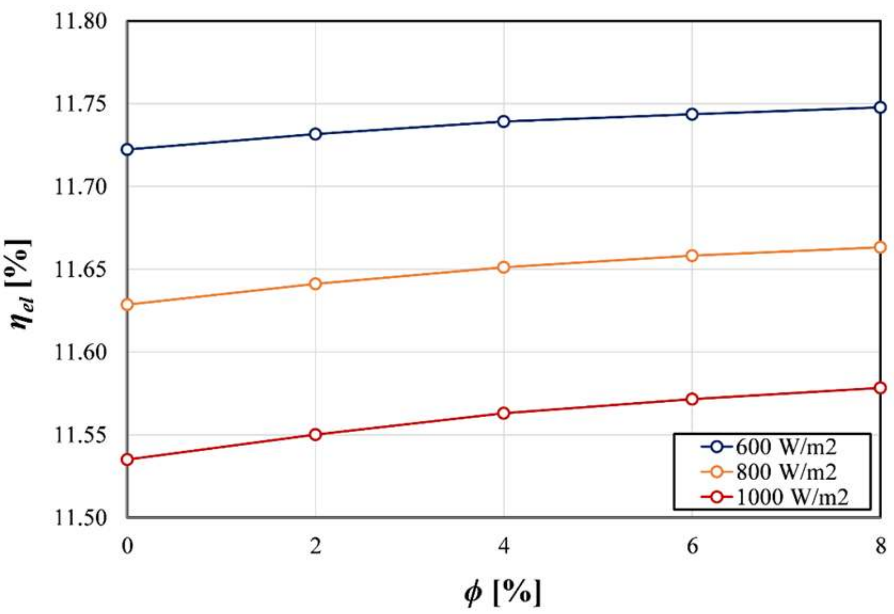

Figure 4.11. Variation of η_{el} for hBN/water nanofluid with hBN concentration

Effect of hBN concentration on overall efficiency of the PVT system (η_{ov}) is depicted in Figure 12. With the increase in concentration, η_{ov} increases 1.68% at 600 W/m^2, 1.40% at 800 W/m^2, and 1.26% at 1000 W/m^2. Increasing the hBN concentration improves the thermal and electrical performance of the PVT system, which is positively reflected in the overall efficiency.

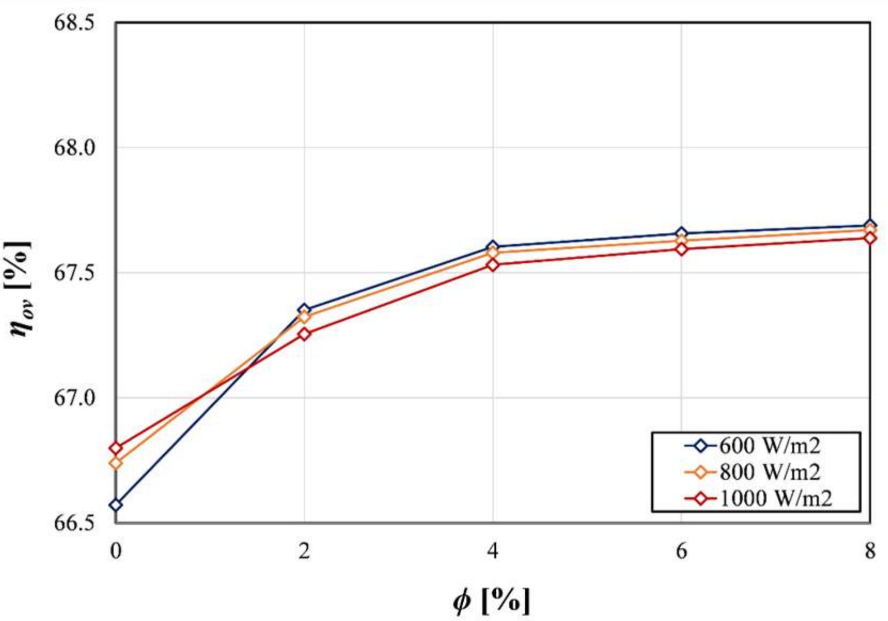

Figure 4.12. Variation of η_{ov} for hBN/water nanofluid with hBN concentration

In Figures 4.13, 4.14, and 4.15, temperature distributions in the PVT system are depicted for hBN concentrations of 2%, 4%, 6% and 8% for solar radiation values of 600 W/m^2, 800 W/m^2, and 1000 W/m^2, respectively. As can be seen from the figures, the maximum cell temperature decreases with increasing nanofluid concentration. This indicates that high concentration of hBN/water nanofluid improves the heat transfer between the absorber plate and the fluid. Similar to the previous section, an increase is observed in the temperature distribution in the flow channel from the inlet to the outlet. In addition, it is understood from the figures that the highest temperature is seen on the PV panel surface that does not come into contact with the fluid channels.

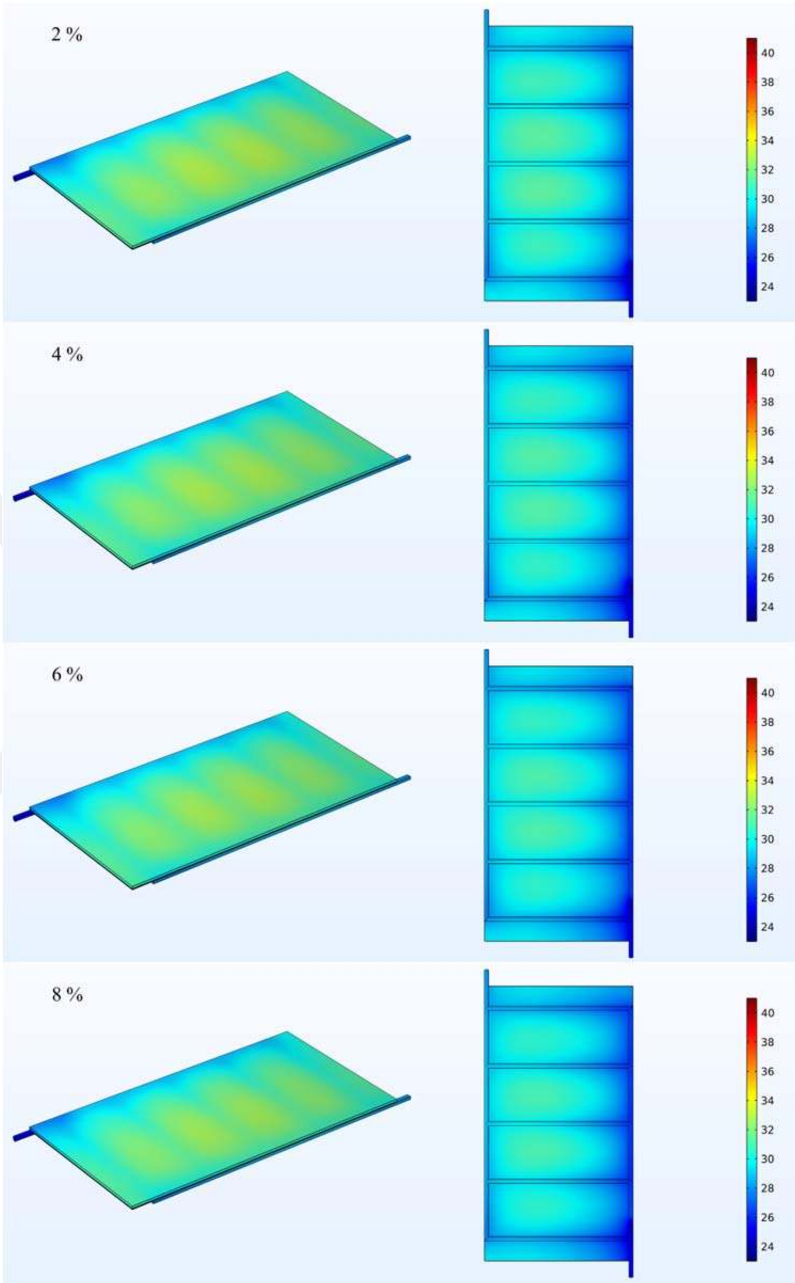

Figure 4.13 Temperature distribution on PVT collector for hBN/water nanofluid with different hBN concentrations at 600 W/m^2

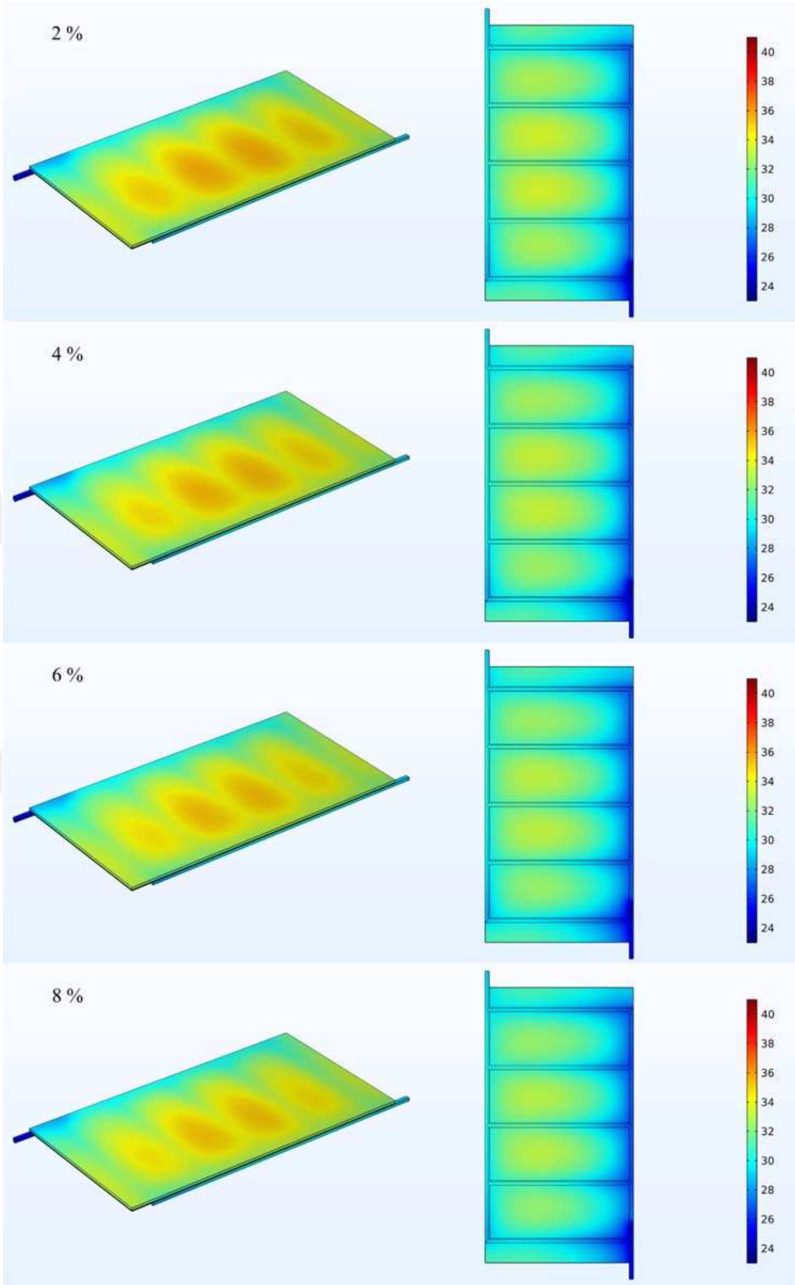

Figure 4.14. Temperature distribution on PVT collector for hBN/water nanofluid with different hBN concentrations at 800 W/m^2

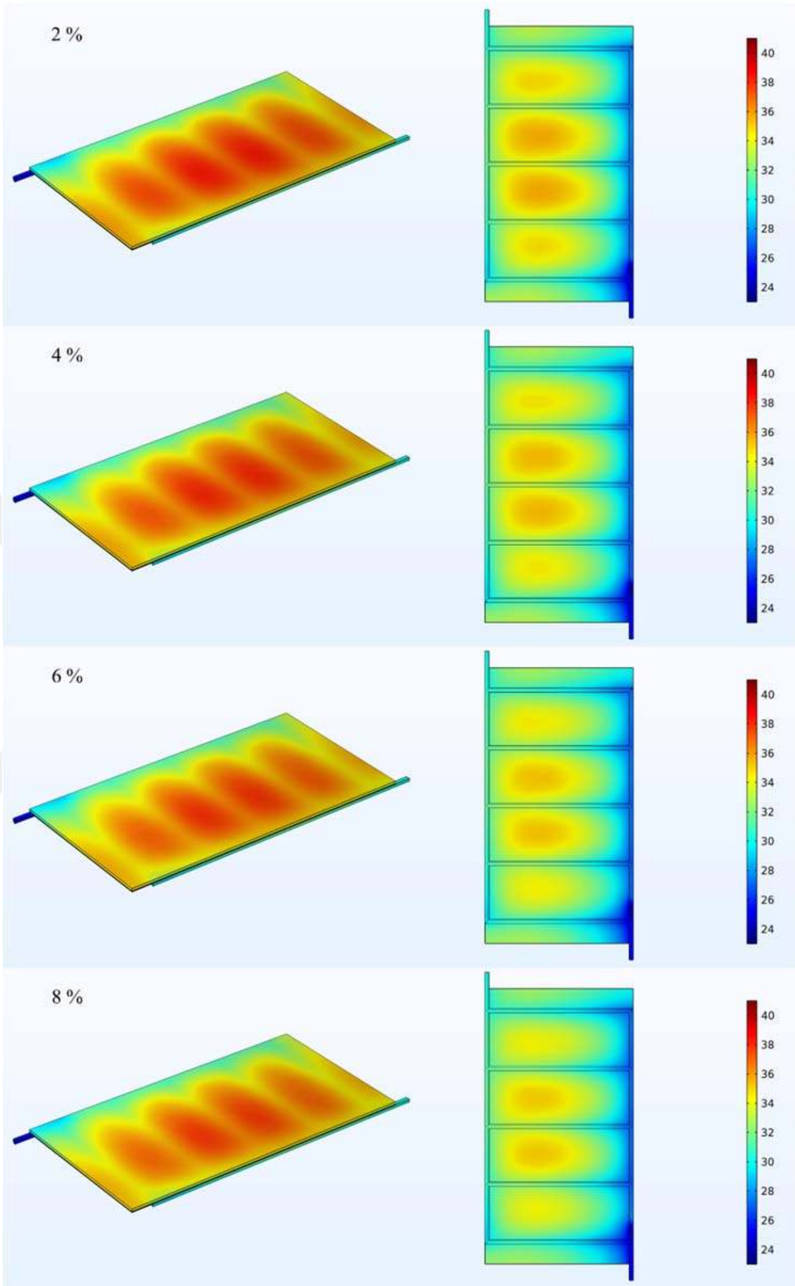

Figure 4.15. Temperature distribution on PVT collector for hBN/water nanofluid with different hBN concentrations at 1000 W/m^2

4.3. Effect of hBN/water nanofluid inlet velocity on the performance of the PVT system

Effect of the hBN/water nanofluid inlet velocity on the performance parameters of the PVT system is investigated in this chapter. In the numerical analysis, the concentration of hBN/water nanofluid, and solar radiation were chosen as 6 % and 1000 W/m^2, respectively. In addition, the diameter of the hBN nanoparticle was selected to be 50 nm like as in the previous two sections. The selected nanofluid inlet velocities are 0.08 m/s, 0.16 m/s and 0.24 m/s.

Increasing the inlet fluid velocity of the hBN/water nanofluid causes a decrease in fluid outlet temperature (T_o), but it causes an increase thermal efficiency (η_{th}) (Figures 4.16 and 4.17). When the velocity is increased from 0.08 m/s to 0.24 m/s, T_o decreases 15.03 %, and η_{th} increases 16.55 %. Since the hBN/water nanofluid at a low inlet velocity is in contact with the PV panel for a longer time, it leaves from the PVT system at higher temperatures.

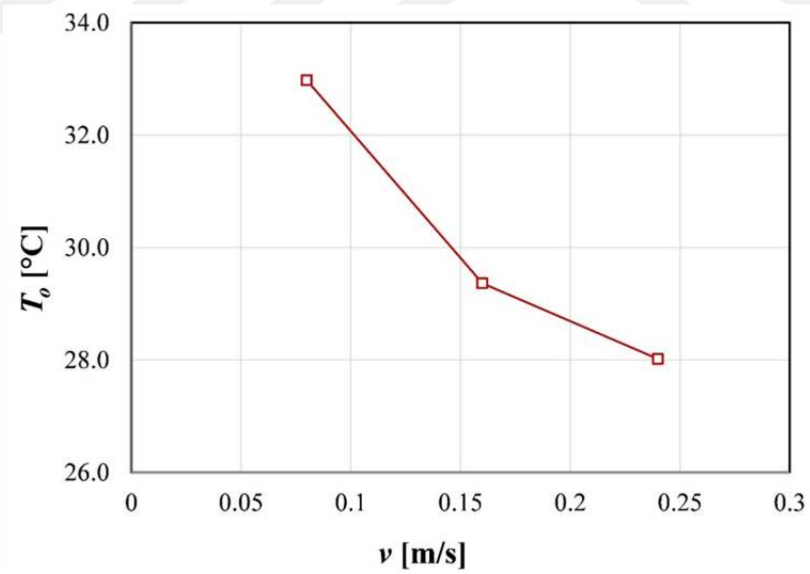

Figure 4.16. Variation of T_o for hBN/water nanofluid with fluid inlet velocity

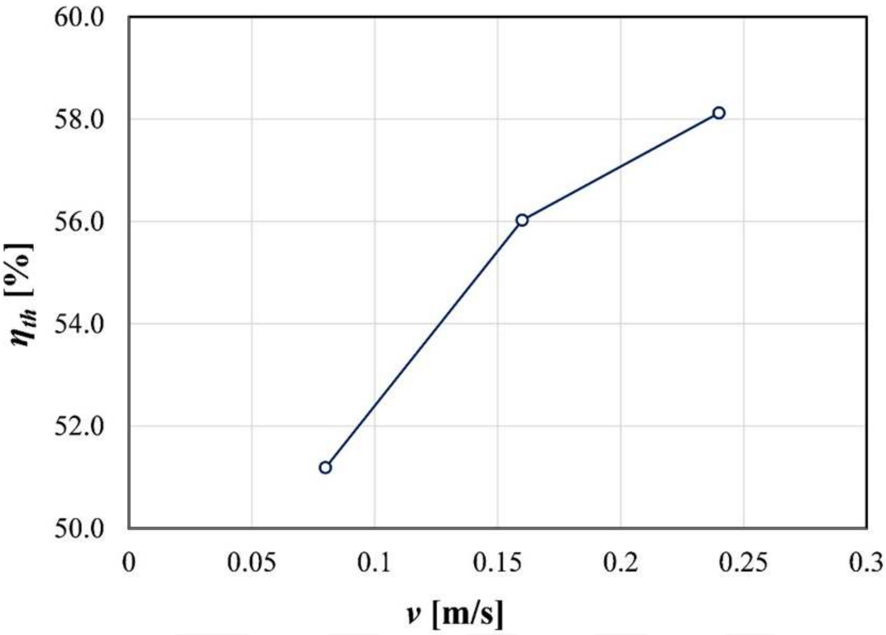

Figure 4.17. Variation of η_{th} for hBN/water nanofluid with fluid inlet velocity

The increase in heat transfer with increasing inlet fluid velocity causes the hBN/water nanofluid to remove more heat from the PV panel. This causes the surface temperature (T_c) of the PV panel to remain low and increases the electrical efficiency (η_{el}). Increasing the inlet fluid velocity from 0.08 m/s to 0.24 m/s induces the fluid outlet temperature (T_c) to decrease by 8.31% and the electrical efficiency to increase by 1.37% (Figures 4.18 and 4.19).

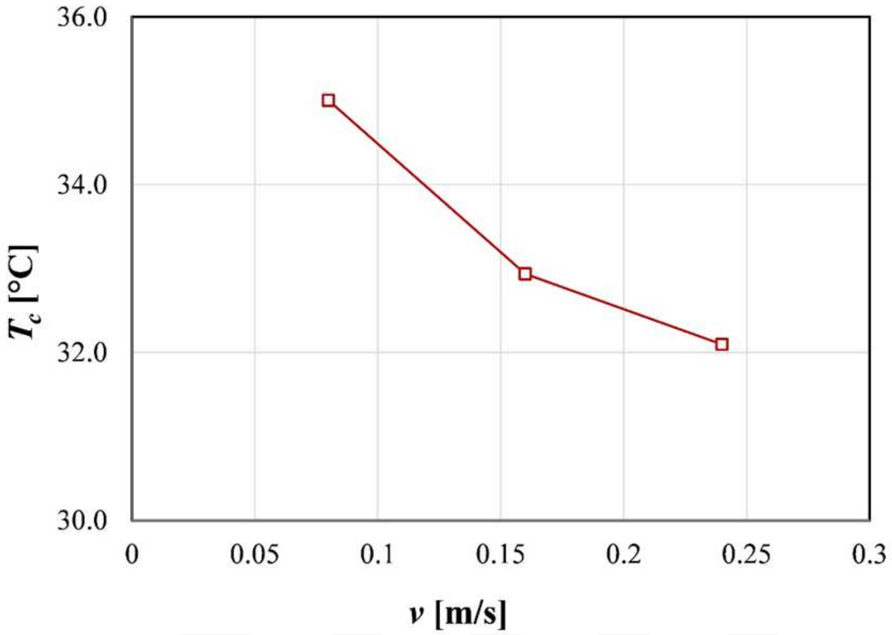

Figure 4.18. Variation of T_c for hBN/water nanofluid with fluid inlet velocity

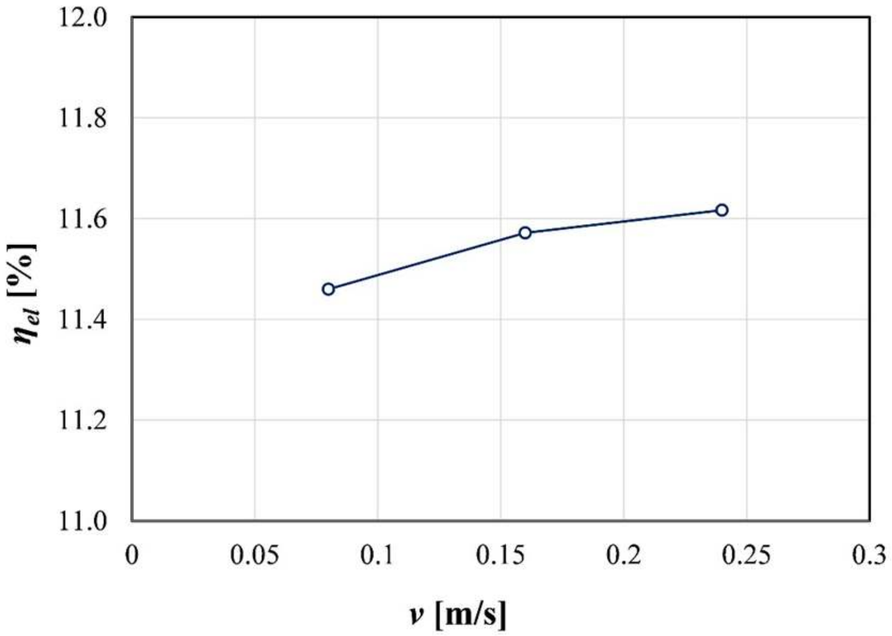

Figure 4.19. Variation of η_{el} for hBN/water nanofluid with fluid inlet velocity

The increase in both thermal (η_{th}) and electrical efficiency (η_{el}) results in an increase in overall efficiency (η_{ov}). Therefore, increasing the inlet fluid velocity increases the thermal efficiency (η_{th}), electrical efficiency (η_{el}) and overall efficiency (η_{ov}), (Figure 4.20). Increasing the inlet velocity from 0.08 m/s to 0.24 m/s results in 11.32% increase in overall efficiency (η_{ov}).

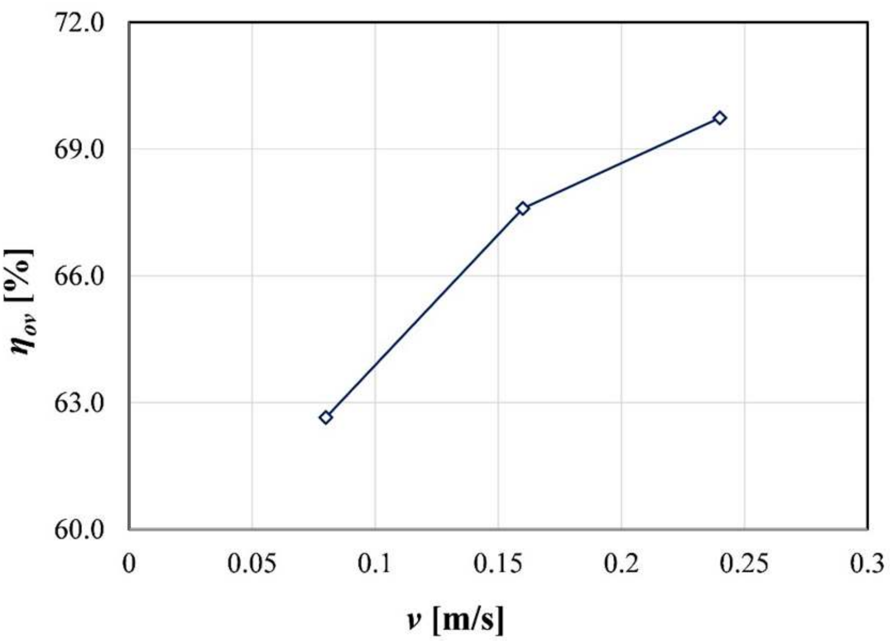

Figure 4.20. Variation of η_{ov} for hBN/water nanofluid with fluid inlet velocity

The temperature distributions of the PVT system using hBN/water nanofluid at different inlet fluid velocities are presented in Figure 4.21. It is seen that the highest temperature (above 40 °C) on PV panel is reached when fluid velocity is the minimum (0.08 m/s). The lowest cell temperature is obtained with maximum velocity (0.24 m/s). In addition, the maximum fluid temperature through the channel at 0.24 m/s is approximately 30 °C, while the maximum fluid temperature through the channel is about 35 °C at 0.08 m/s. These results show that the fluid outlet temperature is higher at 0.08 m/s, but the cell temperature is lower at 0.24 m/s.

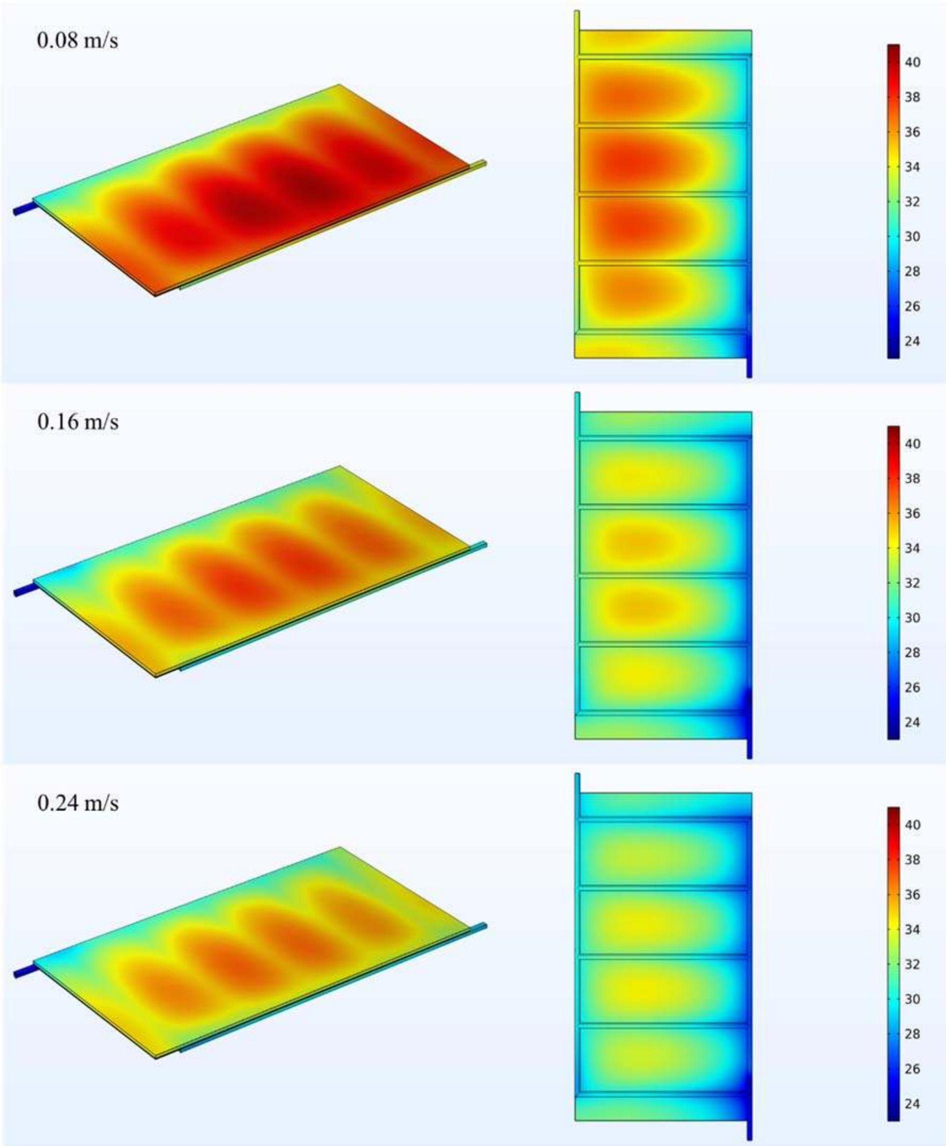

Figure 4.21. Temperature distribution on PVT collector for hBN/water at different fluid inlet velocities

4.4. Effect of hBN nanoparticle diameter on the performance of the PVT system

In the last part of the thesis, the effect of using different nanoparticle diameters of hBN on the performance of the PVT system was investigated. In numerical analysis, the radiation was 1000 W/m^2, the nanoparticle concentration was 6%, and the flow inlet velocity was 0.16 m/s. The diameter of the nanoparticle ranged from 0.25 nm to 0.75 nm.

Variation of nanofluid outlet temperature (T_o) and thermal efficiency (η_{th}) with nanoparticle diameter is presented in Figures 4.22 and 4.23, respectively. As can be seen from the figures, although there is a slight increase in both parameters with the decrease of nanoparticle diameter, the change is insignificant. With the diameter decreasing from 0.75 nm to 0.25 nm, the increase in T_o and η_{th} is only 0.072% and 0.49%, respectively.

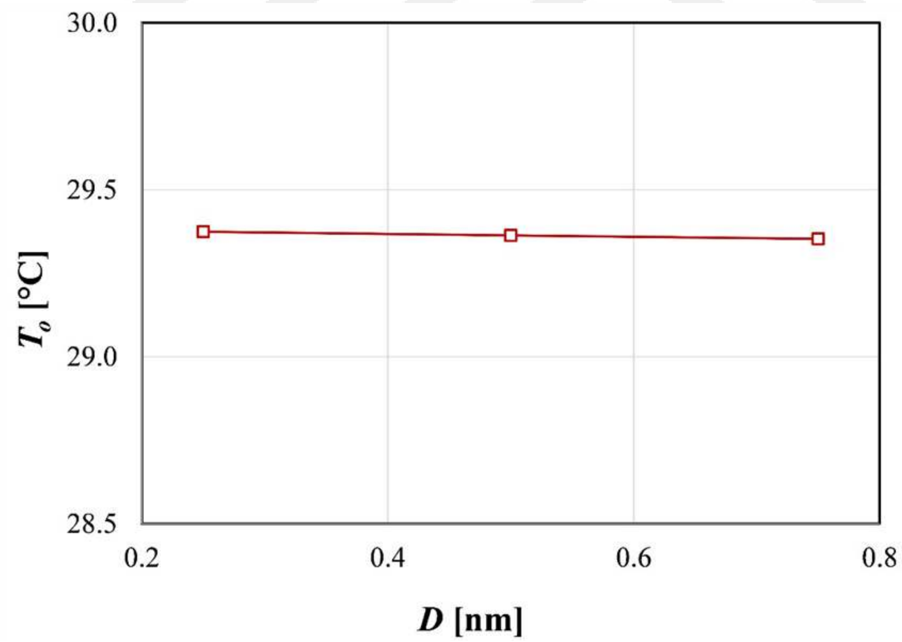

Figure 4.22. Variation of T_o for hBN/water nanofluid with hBN diameter

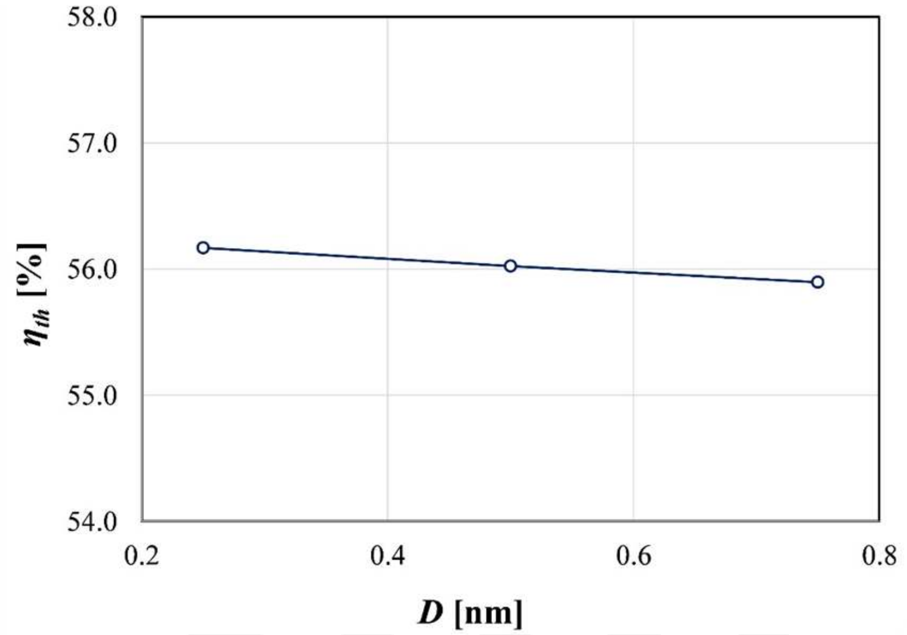

Figure 4.23. Variation of η_{th} for hBN/water nanofluid with hBN diameter

When the effect of nanoparticle diameter on the surface temperature of the PV cell (T_c) and the electrical efficiency (η_{el}) is examined, it is determined that effect of diameter is insignificant (Figures 4.24 and 4.25). Reducing diameter from 0.75 nm to 0.25 nm results only 0.57% decrease in T_c and 0.09% increase in η_{el}.

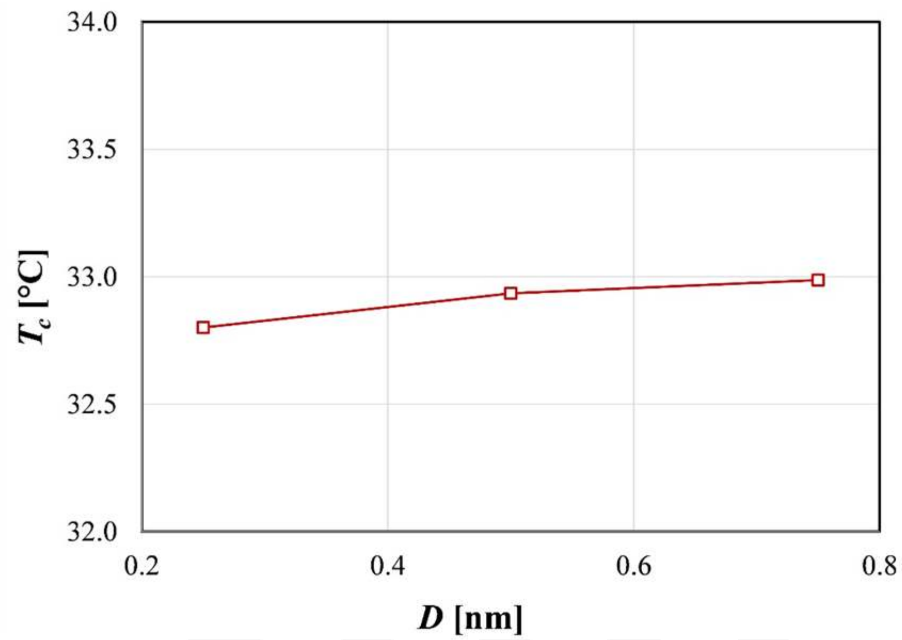

Figure 4.24. Variation of T_c for hBN/water nanofluid with hBN diameter

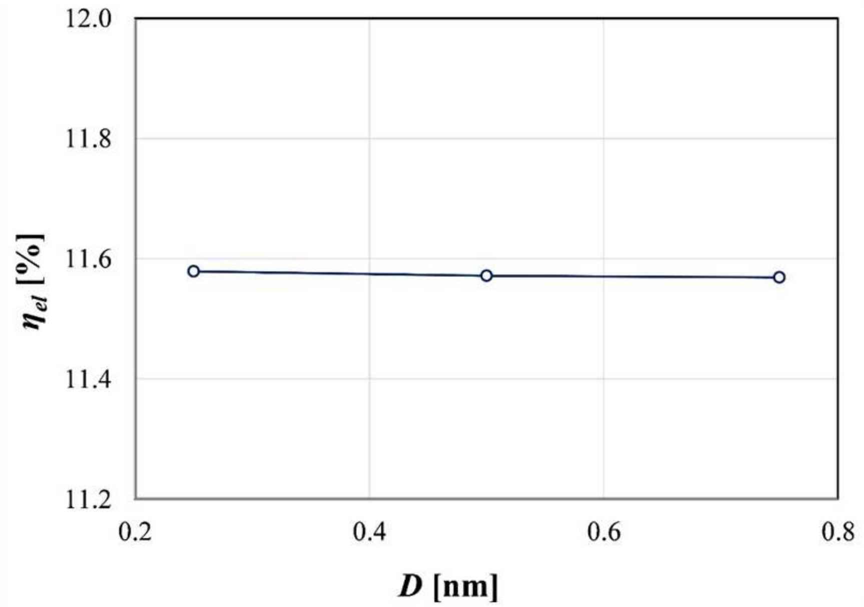

Figure 4.25. Variation of η_{el} for hBN/water nanofluid with hBN diameter

Figure 4.26 shows the effect of nanoparticle diameter on the overall efficiency (η_{ov}) of PVT. The effect of reducing nanoparticle diameter, is to cause a very small increase in thermal (η_{th}), electrical (η_{el}), and overall efficiency (η_{ov}). Reducing the diameter of the nanoparticle from 0.75 nm to 0.25 nm, the overall efficiency (η_{ov}) increases only 0.42%.

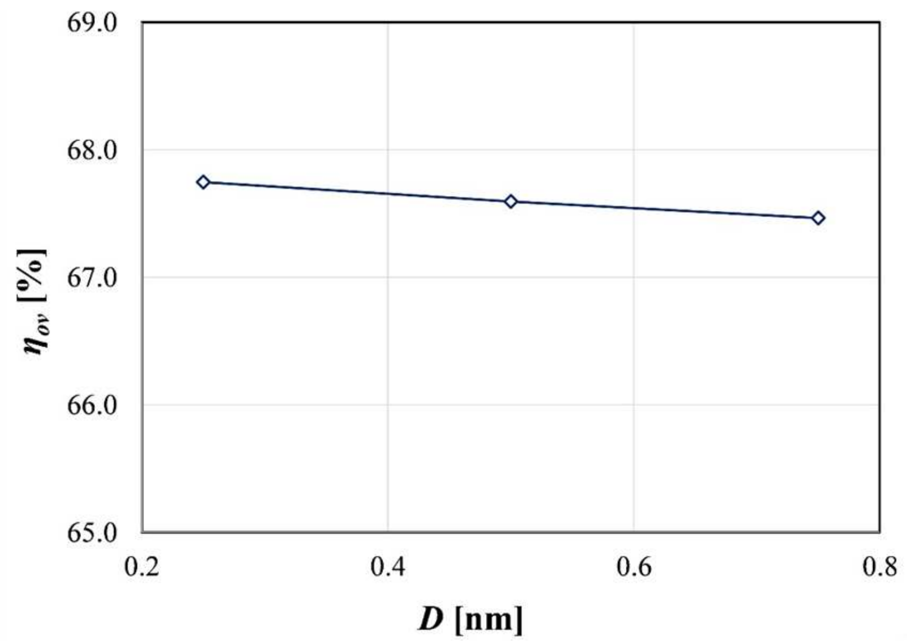

Figure 4.26. Variation of η_{ov} for hBN/water nanofluid with hBN diameter

The temperature distributions of the PVT system using hBN/water nanofluid at different nanoparticle diameters are presented in Figure 4.27. The maximum cell temperature is obtained at 0.75 nm hBN diameter and is around 38 °C. It can be concluded that in the 0.25 nm to 0.75 nm diameter range, the effect of nanoparticle size is not significant for the considered performance parameters of the PVT system.

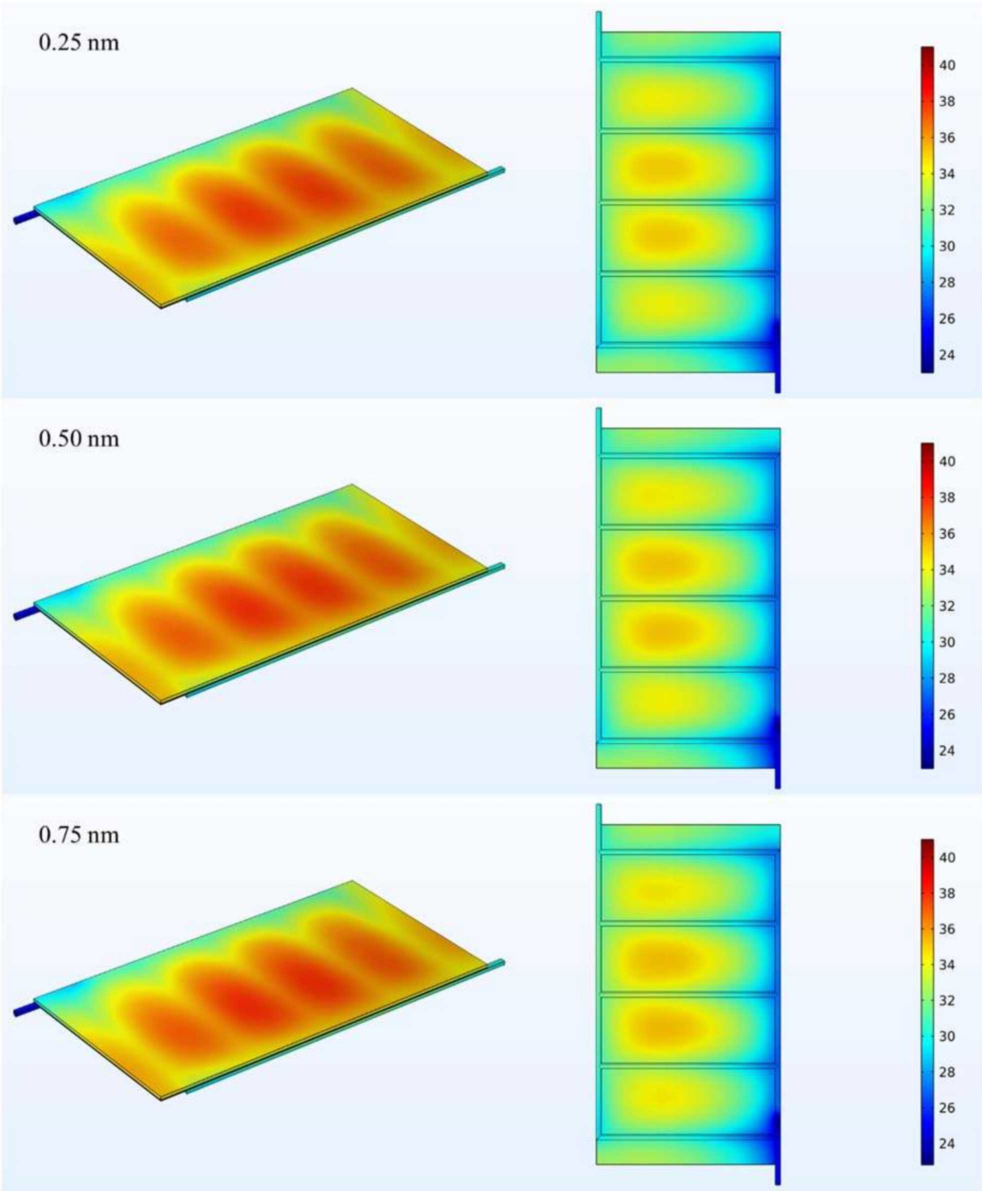

Figure 4.27. Temperature distribution on PVT collector for hBN/water nanofluid at different hBN diameters

5. CONCLUSIONS

In this thesis, a numerical analysis was performed to examine the performance parameters of a PVT system. The primary purpose of the study was to examine the effect of Hexagonal Boron Nitride (hBN)/water nanofluid on the performance of the PVT system. Firstly, water and Hexagonal Boron Nitride (hBN)/water nanofluid were compared as working fluids in the PVT. In addition, the effect of different properties of hBN such as concentration, flow velocity, and nanoparticle diameter has been studied. The outlet temperature of the fluid, cell temperature, thermal, electrical and total efficiency were determined with the numerical analyses of PVT.

Numerical analyzes showed that hBN/water nanofluid with 2% concentration relative to water improves the performance parameters of the PVT system compared to water. It was found that adding 2% hBN to the water causes a very small increase in the temperature of the water leaving the collector, resulting in an increase of approximately 1.51% in the average thermal efficiency. When nanofluid was used, the cell temperature was on average 3.27% lower than water, but the electrical efficiency was 0.11% higher, when nanofluid was used. The overall efficiency of hBN/water nanofluid was obtained greater than water. Also, the outlet temperature of the fluid, thermal efficiency and PV panel surface temperature increased with the increase of radiation from 200 W/m^2 to 1200 W/m^2, while the electrical efficiency decreased for both fluids.

Considering the effect of the concentration of hBN in water the fluid outlet temperature, thermal efficiency, electrical efficiency, and overall efficiency increased with increasing concentration from 0% to 8%. Cell temperature decreased with increasing concentration.

Increasing the inlet fluid velocity of the hBN/water nanofluid from 0.08 m/s to 0.24 m/s caused a decrease in fluid outlet temperature and PV panel temperature, but an increase in thermal, electrical, and overall efficiency. It was seen that the highest cell temperature was reached when fluid velocity was the minimum, but the lowest cell temperature was obtained with maximum velocity. The minimum and maximum values obtained for the outlet temperatures of the fluid are similar to those obtained for PV panel temperature.

Reducing hBN diameter from 0.75 nm to 0.25 nm, there was a slight increase in all performance parameters except for PV panel temperature. There was a slight increase in the PV panel temperature. The maximum cell temperature was obtained at 0.75 nm hBN diameter. It can be concluded that in the 0.25 nm to 0.75 nm diameter range, the effect of nanoparticle size is insignificant for the considered performance parameters of the PVT system.

In numerical analysis, many different parameters were examined to increase the performance of PVT system by using hBN nanoparticles. It was proven that the new nanofluid formed by adding hBN nanoparticles, which were not used in PVT systems before, to the base fluid water, increases slightly the efficiency of the PVT system. However, an experimental investigation was not carried out in the study. Therefore, the effect of the hBN/water nanofluid on the PVT system should be tested in real climatic conditions. In addition, the effect of mixing hBN with other thermal oils on the performance of PVT can be studied both numerically and experimentally. Last, the serial, parallel or serial/parallel connection of PVT collectors to each other should also be investigation.

REFERENCES

Abdallah S.R., Scott H.S., Abdellatif O.E., 2019. Performance analysis for hybrid PVT system using low concentration MWCNT/water nanofluid, Solar Energy, 181:108–115.

Aberoumand S., Ghamari S., Shabani B., 2018. Energy and exergy analysis of a photovoltaic thermal (PV/T) system using nanofluids: An experimental study. Solar Energy, 165:167–177.

Ali H., Babar H., Shah T., Sajid M., Qasim M., Javed S., 2018. Preparation Techniques of TiO_2/water Nanofluids and Challenges: A Review. Applied Sciences, 8(4):587.

Alous S., Kayfeci M., Uysal A., 2019. Experimental Investigations of using MWCNTs and graphene nanoplatelets water-based nanofluids as coolants in PVT systems, Applied Thermal Engineering, 162:114265.

Al-Shamani A. N., Sopian K., Mat S., Hasan H.A., Abed A.M., Ruslan M.H., 2016. Experimental studies of rectangular tube absorber photovoltaic thermal collector with various types of nanofluids under the tropical climate conditions, Energy Conversion and Management, 124:528–542.

Al-Waeli, A.H.A., Chaichan M.T., Kazem H.A., Sopian K., 2017. Comparative study to use nano-(Al_2O_3, CuO, and SiC) with water to enhance photovoltaic thermal PV/T collectors, Energy Conversion and Management, 148:963–973.

Aste, N., Del Pero, C., Leonforte, F., 2017. Water PVT Collector's performance comparison, The 8th International Conference on Applied Energy, 105:961-966.

Batchelor G.K., 1977. The effect of Brownian motion on the bulk stress in a suspension of spherical particles, J Fluid Mech, 83:97–117.

Brinkman H.C., 1952. The viscosity of concentrated suspensions and solutions, J. Chem. Phys, 195:220:571.

Chandrasekar M., Suresh S., Senthilkumar T., Ganesh Karthikeyan M., 2013. Passive cooling of standalone flat PV module with cotton wick structures, Energy Conversion and Management, 71:43-50.

Choi S.U.S., Eastman, J.A., 1995. Enhancing thermal conductivity of fluids with nanoparticles, ASME, 231: 99-106.

Cui Y., Zhu Q., 2012. Study of Photovoltaic/thermal systems with MgO/water nanofluids flowing over silicon solar cells, IEEE, 978: 547-577.

Das P. K., Islam N., Santra A. K., Ganguly R., 2017. Experimental investigation of thermophysical properties of Al_2O_3/water nanofluid: Role of surfactants, Journal of Molecular Liquids, 237:304–312.

Deshmukh G., Naveen J., Shidhav R., Suryawanshi A., Datir R., 2019. Nanofluids: An Introduction to New Generation Heat Transfer Fluids, Acta Scientific Agriculture 3: 41-48.

Ebrahimnia Bajestan E., Charjouei Moghadam M., Niazmand H., Daungthongsuk W., Wongwises S., 2016. Experimental and numerical investigation of nanofluids heat transfer characteristics for application in solar heat exchangers, International Journal of Heat and Mass Transfer, 92:1041–1052.

Einstein A., 1906. Eine neue bestimmung der molekul dimensionen, Ann der Physic, 289-306.

Elmir M., Mehdaouia R., Mojtabi A., 2012. Numerical simulation of cooling a solar cell by forced convection in the presence of a nanofluid, Energy Procedia 18: 594 – 603.

Esfe M.H., Kamyat M.H., Valadkhanib M., 2020. Application of nanofluids and fluids in photovoltaic thermal system: An updated review, Solar Energy, 199: 796-818.

Fayaz H., Nasrin R., Rahim N. A., Hasanuzzaman M., 2018. Energy and exergy analysis of the PVT system: Effect of nanofluid flow rate, Solar Energy, 169:217–230.

Ghadiri M., Sardarabadi M., Passandideh-Fard M., Moghadam A.J., 2015. Experimental investigation of a PVT system performance using nano ferrofluids, Energy Convers Management, 103:468–476.

Gong L., Li Y., Bai Z., Xu M., 2018. Thermal performance of micro channel heat sink with metallic porous/solid compound fin design, Applied Thermal Eng., 137:288-295.

Hassani S., Saidur R., Mekhilef S., Taylor RA., 2016. Environmental and exergy benefit of nanofluid-based hybrid PVT systems. Energy Convers Management, 123:431–444.

Hosseinzadeh M., Salari A., Sardarabadi M., Passandideh-Fard M., 2018. Optimization and parametric analysis of a nanofluid based photovoltaic thermal system: 3D numerical model with experimental validation, Energy Convers Management, 160:93–108.

Hu J., Liu K., Guo M., Zhang G., Chu Z., Wang, M., 2019. Performance improvement of baffle-type solar air collector based on first chamber narrowing, Renewable Energy, 135:701–710.

Jing D., Hu Y., Liu M., Wei J., Guo L., 2015. Preparation of highly dispersed nanofluid and CFD study of its utilization in a concentrating PVT system, Sol Energy, 112:30–40.

Joshi, S. S., Dhoble A. S., 2018. Photovoltaic-Thermal systems (PVT): Technology review and future trends, Renewable and Sustainable Energy Reviews, 92, 848-882.

Karami N., Rahimi M., 2014. Heat transfer enhancement in a PV cell using Boehmite nanofluid, Energy Convers Management, 86:275–285.

Khaled A.R.A., 2010. Investigation of heat transfer enhancement through permeable fins, J. Heat Transfer, 132:3

Khanjari Y., Pourfayaz F., Kasaeian AB., 2016. Numerical investigation on using of nanofluid in a water-cooled photovoltaic thermal system, Energy Convers Management, 122:263–78.

Kostoglou N., Polychronopoulou K., Rebholz C., 2015. Thermal and chemical stability of hexagonal boron nitride (hBN) nanoplatelets, Vacuum, 112:42–45.

Kumar P.G., Kumaresan V., Velraj R., 2017. Stability, viscosity, thermal conductivity, and electrical conductivity enhancement of multi-walled carbon nanotube nanofluid using gum Arabic, Fullerenes, Nanotubes and Carbon Nanostructures, 25:230–240.

Kumar T. A., Pradyumna G., Jahar S., 2012. Investigation of thermal conductivity and viscosity of nanofluids, Journal of Environmental Research and Development, Volume: 7.

Laghari I. A., Samykano M., Pandey A. K., Kadirgama K., Tyagi V. V., 2020. Advancements in PVT Systems with and without Phase Change Materials as Sustainable Energy Solution: Energy, Exergy and Exergoeconomic (3E) Analysis approach, Sustainable Energy & Fuels, 4: 4956-4987.

Maadi S.R., Kolahan A., Passandideh-Fard M., Sardarabadi M., Moloudi M., 2017. Characterization of PVT systems equipped with nanofluids based collector from entropy generation, Energy Convers Management, 150:515–531.

Maxwell J.C., 1881. A treatise on electricity and magnetism. Oxford, UK: Clarendon.

Micheal J.J., Iniyan S., 2015. Performance analysis of a copper sheet laminated photovoltaic thermal collector using copper oxide/water nanofluid, Solar Energy, 119:439-451.

Mishra P. C., Mukherjee S., Nayak S. K., Panda A., 2014. A brief review on viscosity of nanofluids, International Nano Letters, 4:109–120.

Mustapha M., Fudholi A., Chan H. Y., Mohd H. R., 2018. Review on energy and exergy analysis of air and water based photovoltaic thermal (PVT) collector, International Journal of Power Electronics and Drive Systems, 3:1367-1373

Nasrin R., Rahim N. A., Fayaz H., Hasanuzzaman M., 2018. Water/MWCNT nanofluid based cooling system of PVT: Experimental and numerical research. Renewable Energy, 121:286–300.

Noghrehabadi A., Hajidavalloo E., Moravej M., 2016. Experimental investigation of efficiency of square flat-plate solar collector using SiO_2/water nanofluid. Case Studies in Thermal Engineering, 8:378–386.

Pak B.C., Cho Y.I., 1998. Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles, Exp. Heat Transfer Int Journal 11:151–70.

Razali N.F.M., Fudholi A., Ruslan M.H., Sopian K., 2019. Review of water-nanofluid based photovoltaic/thermal (PV/T) systems, Int. J. Electr. Comput. Eng, 9(1):134.

Rejeb O., Sardarabadi M., Ménézo C., Passandideh-Fard M., Dhaou M. H., Jemni A., 2016. Numerical and model validation of uncovered nanofluid sheet and tube type photovoltaic thermal solar system. Energy Conversion and Management, 110:367–377.

Rubbi F., Habib K., Saidur R., Aslfattah N., Yahya S. M., Das L., 2020. Performance optimization of a hybrid PVT solar system using Soybean oil/MXene nanofluids as A new class of heat transfer fluids, Solar Energy, 208:124–138.

Sachit F.A., Rosli M.A.M., Tamaldin N., Misha S., Abdullah A.L., 2018. Nanofluids Used in Photovoltaic Thermal (PVT) Systems: a Review, International Journal of Engineering & Technology, 7:599-611.

Said Z., Sabiha M.A., Saidur R., Hepbasli A., Rahim N.A., Mekhilef S., Ward T.A., 2015. Performance enhancement of a Flat Plate Solar collector using TiO_2 /water nanofluid and Polyethylene Glycol dispersant, Journal of Cleaner Production, 92:343-353.

Said Z. and Saidur, R., 2017. Nanofluid Heat and Mass Transfer in Engineering Problems: Thermophysical Properties of Metal Oxides Nanofluids, Rijeka: Intech, 39-63.

Sangeetha M., Manigandan S., Ashok B., Brindhadevi K., Pugazhendhi A., 2021. Experimental investigation of nanofluid based photovoltaic thermal (PV/T) system for superior electrical efficiency and hydrogen production, Fuel, 286:11942.

Sardarabadi M., Passandideh-Fard M., Zeinali Heris S., 2014. Experimental investigation of the effects of silica/water nanofluid on PTU (photovoltaic thermal units), Solar Energy, 66:264–272.

Sardarabadi M., Passandideh-Fard M., 2016. Experimental and numerical study of metal-oxides/water nanofluids as coolant in photovoltaic thermal systems (PVT). Solar Energy Materials and Solar Cells, 157:533–542.

Sathe T. M., Dhoble A.S., 2017. A review on recent advancements in photovoltaic thermal techniques, Renewable and Sustainable Energy, 76:645-672.

Sathe T. M., Dhoble A.S., 2017. A review on recent advancements in photovoltaic thermal techniques, Renewable and Sustainable Energy, 76:645-672.

Shahrul I. M., Mahbubul I. M., Khaleduzzaman S. S., Saidur R., Sabri M. F. M., 2014. A comparative review on the specific heat of nanofluids for energy perspective, Renewable and Sustainable Energy Reviews, 38:88–98.

Singh, S., Kumar K. S., 2021. Influence of nanomaterials on nanofluid application, AIP Conference Proceedings, 2341.

Soltani S., Kasaeian A., Sarrafha H., Wen D., 2017. An experimental investigation of a hybrid photovoltaic/thermoelectric system with nanofluid application, Solar Energy, 155:1033–1043.

Sudha P. H., Sangeetha K., Vijayalakshmi K., Barhoum A., 2018. Nanomaterial history, classification, unique properties, production and market, Micro and Nano Technologies 341-384.

Tong Y., Lee, Kang W., Cho H., 2019. Energy and exergy comparison of a flat-plate solar collector using water, Al_2O_3/water nanofluid, and CuO nanofluid, Applied Thermal Engineering, 113959.

Vaka M., Walvekar R., Khaliq R., Abdul Khalid M., Panchal H., 2019. A review: emphasizing the nanofluids use in PV/T systems, IEEE Access 1–20.

Xu Z.., Kleinstreuer C., 2014. Concentration photovoltaic–thermal energy co-generation system using nanofluids for cooling and heating, Energy Conversion and Management, 87: 504-512.

Xuan Y., Li Q., Hu W., 2003. Aggregation structure and thermal conductivity of nanofluids, AIChE Journal, 49:1038–1043.

Xuan Y., Roetzel W., 2000. Conceptions for heat transfer correlation of nanofluids, International Journal of Heat and Mass Transfer, 43:3701–3707.

Yuan C., Li J., Lindsay L., Cherns D., Pomeroy J. W., Liu S., Kuball M., 2019. Modulating the thermal conductivity in hexagonal boron nitride via controlled boron isotope concentration, Communications Physics, 2:1.

Zhang Y., Shen C., Zhang C., Pu J., Wei S., Dong Y., 2020. A numerical investigation on optimization of PVT systems with the field synergy theory, Applied Thermal Engineering, 185:116381

CURRICULUM VITAE

Hacı Mehmet Kılıç, graduated from High School, he enrolled in Mechanical Engineering Department of Gaziantep University. He graduated from Gaziantep University as a Mechanical Engineer in January 2017. He started his Master of Science education in Mechanical Engineering Department of Çukurova University in September 2018.