ISLAMIC UNIVERSITY OF TECHNOLOGY

ORGANISATION OF ISLAMIC CORPORATION

Study of Nanofluid Based Direct Absorption Solar Collector

A thesis presented to the Department of Mechanical and Production Engineering, Islamic University of Technology in partial fulfilment of the requirement for the award of the degree of Bachelor of science in Mechanical Engineering

Authors

Touhid Islam (16000110047)

Asif Rahman Antik (160011057)

Mir Karim Ebne Alam(160011068)

Supervised By

Dr. Md. Rezwanul Karim

Assistant Professor

Department of Mechanical and Production Engineering (MPE)

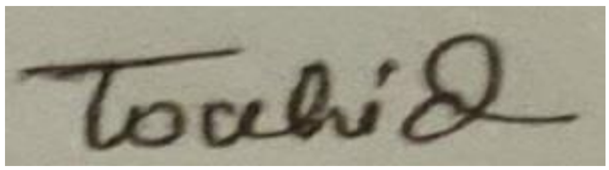
Islamic University of Technology (IUT)

March 2021

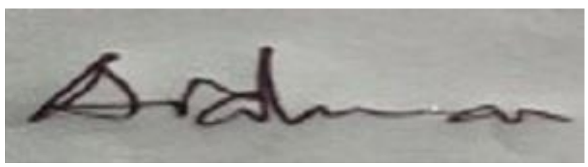
CANDIDATE'S DECLARATION

It is hereby declared that, this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

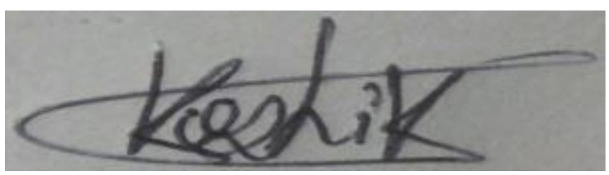
Signature of Candidates



TOUHID ISLAM (160011047)



ASIF RAHMAN ANTIK (160011057)



MIR KARIM EBNE ALAM (160011068)

Department of Mechanical and Production Engineering (MPE)
Islamic University of Technology (IUT)
Board Bazar, Gazipur
Dhaka, Bangladesh

CERTIFICATE OF RESEARCH

The thesis title **"STUDY OF NANOFLUID BASED DIRECT ABSORPTION SOLAR COLLECTOR"** submitted by **TOUHID ISLAM (160011047)**, **ASIF RAHMAN ANTIK (160011057)** and **MIR KARIM EBNE ALAM (160011068)** has been accepted as satisfactory in partial fulfilment of the requirement for the degree of Bachelor of Science in Mechanical Engineering on March 2021.

Supervisor

DR. MD. REZWANUL KARIM

Assistant Professor

Department of Mechanical and Production Engineering (MPE)

Islamic University of Technology (IUT)

ACKNOWLEDGEMENT

First of all, the authors would like to express gratitude to the Almighty Allah (SWT) for his blessings, which enabled us to complete this thesis successfully.

The authors express gratitude to their supervisor Dr. Md. Rezwanul Karim, Assistant Professor, Department of Mechanical and Production Engineering (MPE), Islamic University of Technology (IUT), for his continuous guidance, helpful suggestions and supervision at all stages of this thesis work.

And the authors are indebted to their family members for providing financial and mental support in pursuing a Bachelor od Science degree in Mechanical Engineering at Islamic University of Technology (IUT).

Abstract

As technology advances finding new sources of energy is getting more and more importance. Solar energy is the most significant source of renewable energy hence researches focus on using the most of it. Solar collectors are now-a-days vastly used to utilize solar energy. Nanofluid based Direct Absorption Solar Collectors (DASC) are introduced for efficient conversion of solar energy. Direct Absorption Solar Collectors are more efficient than conventional solar thermal collectors in terms of thermal performance. However, as a new technology, the nanofluid based DASC's need more optimization in order to be used on a larger scale. Similarly, nanofluid based solar thermal collectors are studied by many researchers for performance improvement. The stability of nanofluids is a challenge and the performance degradation happens with time.

In this thesis, an experimental setup was designed for a Direct Absorption Solar Collector with aluminium oxide nanofluid. Due to COVID 19 pandemic, the experimental setup based study was not possible. So, a numerical study of a simple flat plate solar collector using graphite nanoparticle was carried out. The thermal performance and efficiency of the solar collector was analyzed. Results obtained have been compared with the available literature. It was found that, the efficiency of the collector increases until there is a critical value of the nanoparticle concentration reached. After that, the performance was decreased due to the agglomeration of particles which leads to clogging.

Contents

List of Figures

List of Tables

Nomenclature

A_c	Surface Area of Solar Collector (m^2)
C_p	Heat Capacity (J/Kg-K)
$C_{p,bf}$	Heat Capacity of base fluid (J/Kg-K)
$C_{p,np}$	Heat Capacity of nanoparticle (J/Kg-K)
$C_{p,nf}$	Heat Capacity of nanofluid (J/Kg-K)
G_T	Global Solar Radiation (W/m^2)
$\dot{m}$	Mass flow rate of fluid flow (Kg/s)
T_a	Ambient Temperature (K)
T_i	Inlet Fluid Temperature of Solar Collector (K)
T_o	Outlet Fluid Temperature of Solar Collector (K)
η	Collector Efficiency
Φ	Volume Fraction of Nanoparticle in Nanofluid
ρ_{nf}	Density of Nanofluids
ρ_{bf}	Density of Basefluid
ρ_{np}	Density of Nanoparticle

Chapter 1: Introduction

The world is advancing day by day and the usage of fossil fuel is increasing rapidly. As fossil fuels are limited, scientists are becoming eager to find alternate sources of energy. Various renewable energy sources are now vastly used to meet the demands of industry, households etc. Solar energy is the most accessible form of renewable energy, so research is conducted to optimize solar energy use significantly.

Recently, as energy consumption is rising while conventional energy supplies are nearly finished, there is rising demand for new technologies in renewable sector. Solar thermal energy consists of the sun's power to produce thermal energy which can be applied for different uses, such as generating electricity.

Solar thermal energy takes advantage of the Sun's radiation to produce thermal energy. The energy conversion in solar thermal collector is from solar to heat energy. Different types of solar collectors are used to trap solar radiation in both household and factories. A section of solar-thermal collector design is DASC. DASC stands for Direct Absorption Solar Collector. The difficulty in this research sector is to develop a cost-efficient technology that can compete with fossil fuel power generation technologies.

Conventional solar thermal collectors are now vastly used. But they have low thermal efficiency. Researches are conducted on a regular basis to optimize the solar thermal collectors. Direct absorption solar collectors are the result of these researches. DASC is more efficient than conventional solar collectors. [1]

DASC is a solar collector where the working fluid is enclosed inside the collector by transparent glazing and frame of the collector. Solar radiation is absorbed in the working fluid. Nanofluid based DASC is seemingly more efficient than conventional DASC.

At present, solar thermal energy systems face great losses due to the heat transfer processes. For this, nanofluids have been implemented in DASC to boost solar collectors efficiency. By doing this the overall efficiency of the process is increased considerably at a cheaper rate and creating a replacement of fossil fuels by renewable energy sources. Generally, the fluid used in DASC is a nanofluid. Nanofluids are better than conventional fluids in the sense that they enhance the heat transfer capability of the fluid. They have a huge prospect due to their unique optical features.

Nanofluid is made by suspending tiny particles (less than 100 nm) in a base fluid (water,oil etc.) to form a solution. The nanoparticles used in nanofluids are typically made of metals, oxides or carbon nanotubes. However, the drawback of using nanofluids is its instability. Before choosing a nanofluid the improvement in physical quality as well as the stability should be taken into account. Nanofluid based DASCs are not yet used on an industrial scale. Some small-scale home applications are available. Researches are being conducted to further optimize nanofluid based DASCs.

In this thesis, two different nanofluids as well as two different transparent covers were to be used. In each case the values were to be compared with one another to find out which combination was more feasible in terms of efficiency, cost, heat absorption etc. To calculate the efficiency using plastic material as cover and to compare the values with that of glass cover, to investigate different coatings and compare results with conventional setup, to determine if plastic materials can be used with complex geometries and if they are feasible to be used in solar water heating systems were the main objectives of this experimental thesis. The sun radiation to thermal energy conversion was be evaluated to ensure the maximum efficiency of the nanofluids under this study.

But due to COVID19 lockdown the initial plan for the experimental setup was hampered and the experimental set-up never came to being. Thus the thesis had to take a different turn from experimental type to a numerical type.

In this research the purpose was to explore opportunities to optimize nanofluid based DASCs using different types of cover materials. But due to unfortunate event of COVID19 pandemics the desired research work was not finished. The study was shifted to a numerical analysis of a simple flat plate collector using graphite nanoparticles. Using nanofluids it is observed that efficiency increases by a significant amount but it also depends on the concentration of nanofluid.

Chapter 2: Literature Review

2.1: Evolution of Industry and Energy

Energy has always been a vital element in any system. With the recent growing of industrial system energy has become more vital element. Economic development has become an inseparable quantity with the advance of energy demand [2]. The increasing demand of energy which is mostly conventional energy brings severe effects on environment by emission of greenhouse gasses. Society cannot ignore the global warming and greenhouse-gas emission reductions while seeking solution of energy, environmental and food challenges with conventional energy [3].

A nations prosperity is known by the amount of energy they consume. This prosperity has come to this far because of the industrial revolution through different ages. At the very beginning of time that is pre industrial revolution human was dependent on animals and labor. People used stoned to make weapon to survive. Then fire was invented and people started to craft iro n and other metals. It was before 13th century to 17th. In 1785, James Watt invented the steam engine and then industry got a new revolutionary advancement. This led us to the 1st industrial revolution which is mechanical age. In 19th century factory system and internal combustion engine developed. Thus, industry got higher priority and mankind lifestyle started to change with time. This surge spread all over the world within a short period of time. On the end of 19th century Taylor system was developed and soon after Nikola tesla invented commercial induction motor. This introduces mankind to a new era that is electrical era, Industry 2.0. Mass production of electricity started and later dc motor was introduced. With the flow of revolution people started to utilize cost effectiveness, less manpower and low efficiency systems. Then Industry 3.0 solves the problems by bringing autonomous concept to the industry. The invention of transistor in 1948, by Bardeen, Brattain, and Shockley of Bell Laboratories, led us to electronics and IT age. Later in 1956, invention of thyristor, led the path to General Electric (GE). Among the 1st and 2nd electronics revolution transistor and thyristor are considered respectively. During 1st to 3rd industrial revolution the energy generation rate increase at its peak as well energy consumption too. Currently the world is in Industry 4.0 where everything is computerized and the system is run by cloud system. This cloud system consumes energy from data centers. Currently 2% of the world electricity energy consumed by data centers and in 2030 the rate is expected to 8%. All the energy is mainly conventional energy having a little amount of renewable energy. The main drawback of this conventional energy is its carbon emission which essentially troughing us towards global warming. In order to cure environmental pollution one must use renewable source of energy.

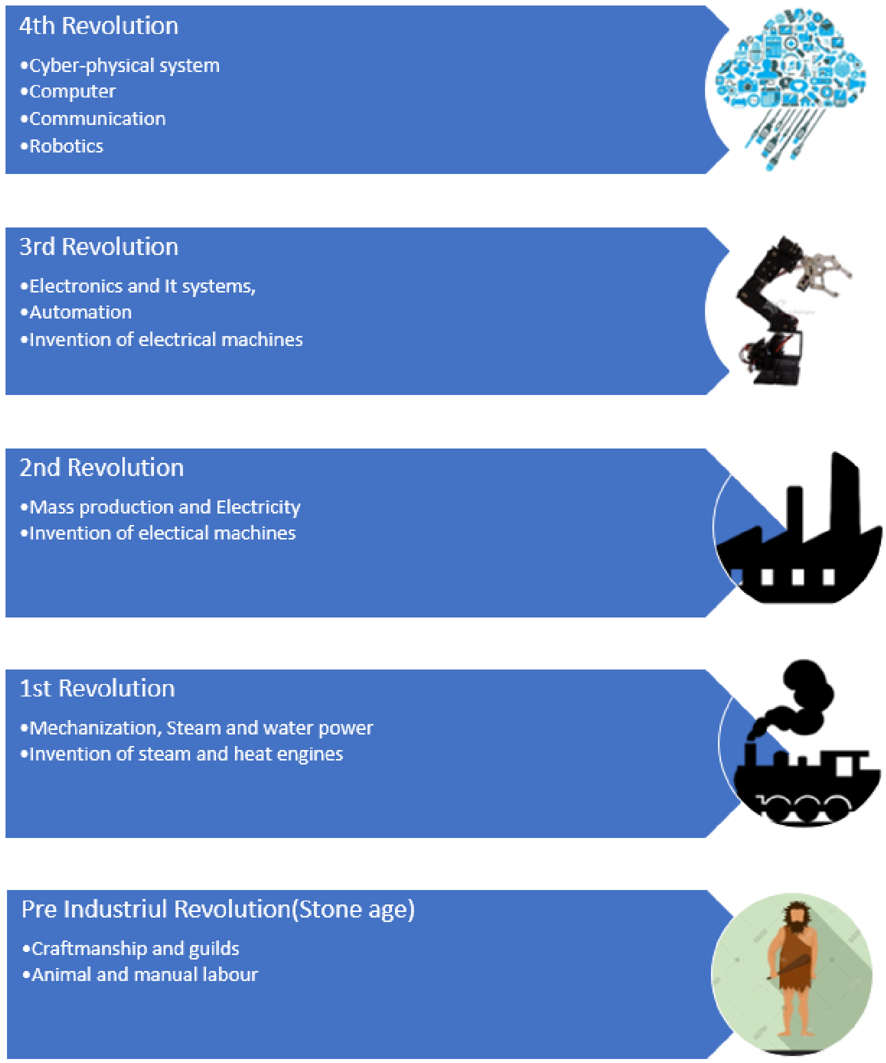


Figure 1: Industrial revolutions

2.2: Environmental Prospects with Energy

At recent time talking about energy is mainly talking about conventional energy. The main resources for the energy are Fossil fuel, Coal, Oil. Petroleum etc. All of them are rich with carbon (C). Burning this fuel will eventually deal with C emission which is the main cause of greenhouse effect. This plays a vital role in global warming. Also, the toxic wastes and residuals from the energy production Industry are polluting environment. Other gases emission like SO_2, CO, NO_X, HC are also reason for this pollution. Again, a vast amount of CO_2 mixed with rain water and creates carbonic acid which pollutes water. In photosynthesis some amount is consumed by trees. But the generation rate is far higher and more dangerous. These problems cause ecological imbalance and reason of environmental calamity.

Environment pollution has become a sensitive issue for this current world. Different countries taking measures on how to reduce this pollution. The most probable solution comes through is switching to renewable source of energy. In Figure 2 it can be seen the current scenario of energy generation throughout the world [4].

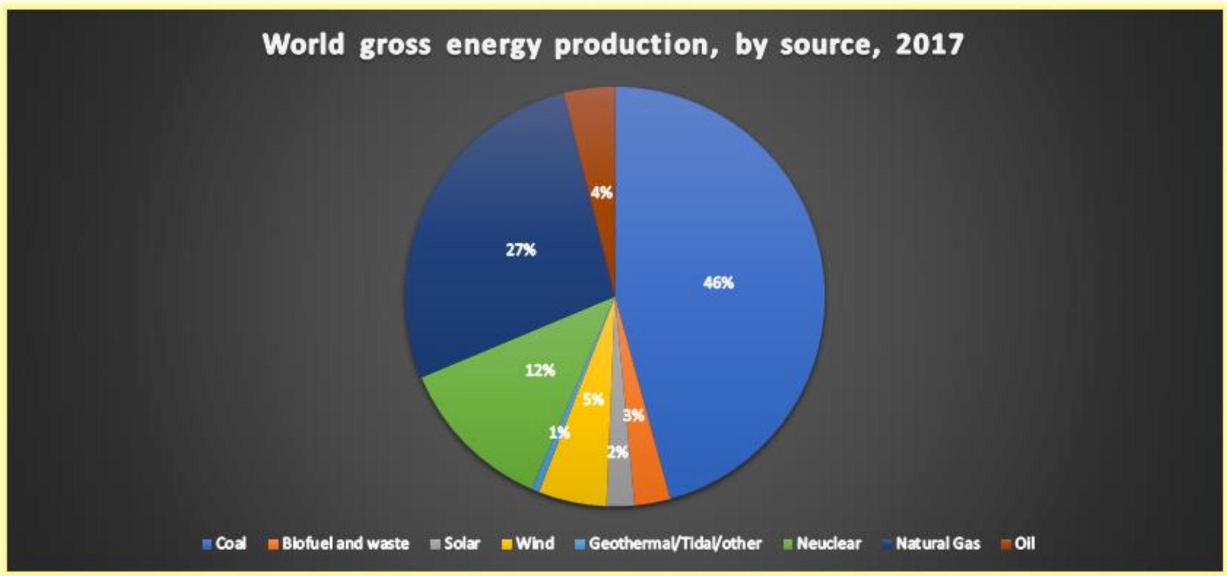


Figure 2: Global Gross Energy scenario

If a Global Gross Energy scenario is observed, a more vivid understanding of the necessity of the Solar Energy is noticed. This graph shows around 25% of global energy now dependent on renewable sourced (Solar, wind, Geothermal, Tidal, Nuclear). Few years ago, this ratio was around 10-12%. With the growing concern of people about environmental dis-integrity, it increased a lot.

2.3: Solar System and Energy

The solar system is a gravitationally bound system of the sun and the object that orbit it. In solar system sun is the only star that can deliver energy to the whole system. This energy flows in a form of electromagnetic radiation known as the solar radiation. This is the only and primary energy source for the earth also. The sun is a blackbody having temperature around 5800K. This huge amount of temperature is created by mostly hydrogen and helium. Measured average diameter of the sun is 1.39x109 m. It has distance of 1.5x 1011 m from the earth. The energy flux which the sun emits from its surface is measured around 63 × 106 W·m–2. This value is calculated through Stefan-Boltzmann equation[5] .

The use of solar energy is nothing a new. From the very beginning of the earth an ecosystem has been formed based on the energy of the sun. Solar energy is considered as the cleanest form of energy. In the sun nuclear fusion occurs between hydrogen and helium for generating energy.

By history we learn that in early 7th century B.C. humans used to light fires by sunlight using materials which are very similar to glass or which has properties like glass. Greeks used solar power to light torches for religious ceremonies back in 3rd century B.C. At 20 AD. Chinese document shows the usage of burning mirrors to light torches for religious purposes. In 1st to 4th century A.D. large south facing windows were used to let in sun's warmth on Roman bath houses[6].

2.4: Solar Thermal Collectors

Solar thermal collectors are responsible for collecting heat from Sunlight by absorbing the incoming Solar radiation.The heat can then be used for various applications such as water heating systems in houses or in small scale factories.

Solar thermal collectors can be broadly classified into two types-

1.Concentrating

2.Non-concentrating

Concentrating collectors work by directing the solar radiation to a particular area which carries the working fluid. So, in these types of collectors, the absorber area is much smaller but the intensity of solar radiation directed to it is much higher.

These types of systems usually have a solar tracking system so that they can adjust their position and direct the radiation to proper direction due to the movement of the Sun. Typically,they are used for electricity generation.

In non-concentrating collectors, there is an absorber plate whose function us to absorb the solar radiation. The absorber is made up of a metal plate and painted with dark colour to allow maximum radiation to be absorbed. Heat is transferred to working fluid in pipes attached to the plate. In these types of collectors, the absorber area is close to the total area of the collector. These systems are used in homes or commercial buildings.

The most common setups in the solar concentrating systems are: parabolic trough systems, dish systems and central receiver systems, as can be observed in the Figure 3 given below:

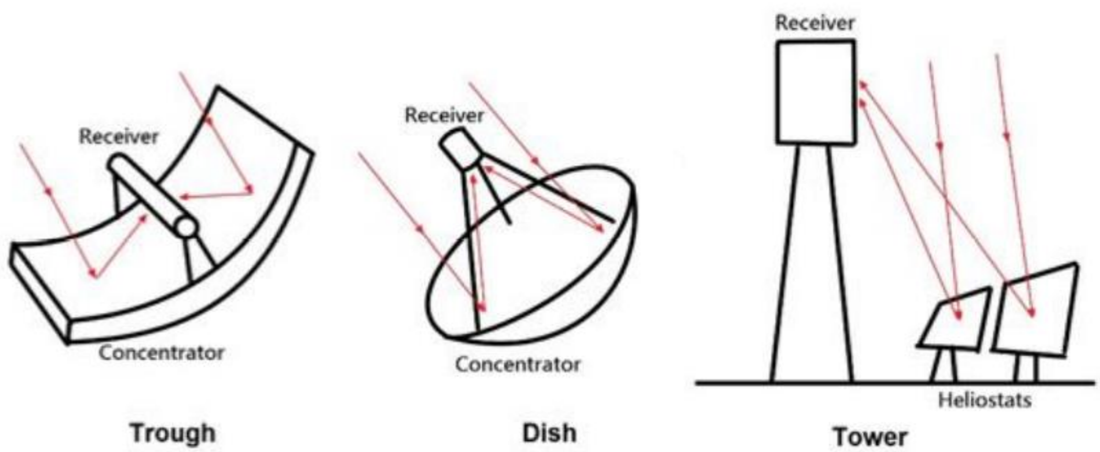


Figure 3: The trough, dish and central receiver (tower) concentrating solar panel systems

2.4.1: Working principle

Solar collector is the main element of a solar energy generation unit. Solar energy is captured by solar collector. Then the collector converts the solar energy to heat energy. Heat can be absorbed by heat transfer fluids such as water, paraffin etc. This solar heat is stored and later can be used for various purposes especially in cloudy days or nights. The Figure 4 given below shows us an overview of the working principle of a conventional solar thermal collector [7].

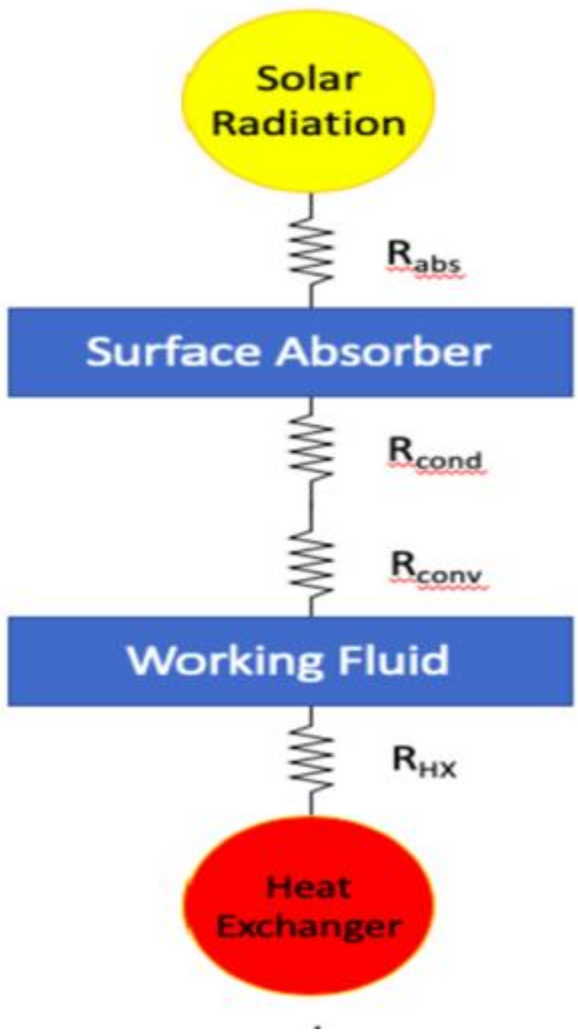


Figure 4: Schematic showing working principle of a conventional solar thermal collector [7]

2.5: Different types of Solar Collector

Solar collectors are of different types. A brief discussion on different types of Solar collectors is given below:

2.5.1: Flat Plate Collector

Flat plate collector is a type of heat exchanger. It collects solar energy and usage the energy to heat water. It is a cost-effective collector compared to other water heating collector types, due to its simple design and easier installation process. Also, it is capable of working on moderate temperature requirement in heating processes up to 100℃ [8] . A typical Flat plate collector is shown in Figure 5, from which the main components of FPC can be identified which are:

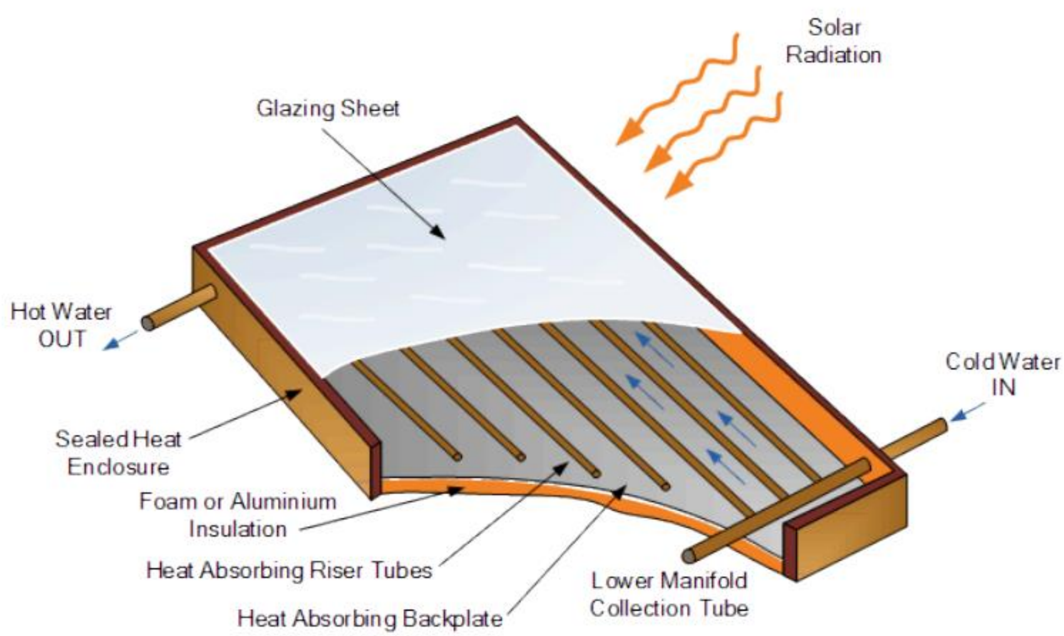


Figure 5: Flat Plate Collector[8]

Cover:

Single or multiple glass sheets over the absorber plate. The cover is glazed mostly. Heat absorbing plate: A large sheet of good conductors of heat like copper or aluminum which is painted black. The black absorbs as much solar radiation as possible for maximum efficiency.

Riser Tubes:

With the heat absorber plate there are several parallel copper pipes called risers. This pipe contains heat transfer fluid, typically water. To ensure maximum surface contact for efficient heat transfer the copper tubes are soldered directly to the absorber plate.

Manifold:

For incoming and outgoing flow of fluid or water there is an admit and a discharge duct called manifold.

Insulation:

The surface is insulated to minimize heat loss from the collector plates.

Containers:

Protective container surrounds all the components and protects them from dust and moisture.

There are many advantages of Solar Flat plate collector. Some are:

- Easy to manufacture
- Less costly
- Collect beam and diffuse radiation
- Permanently fixed
- Very little maintenance needed

Now the flat plate collectors are also of many types. An overview is shown below on the chart (Figure 6).

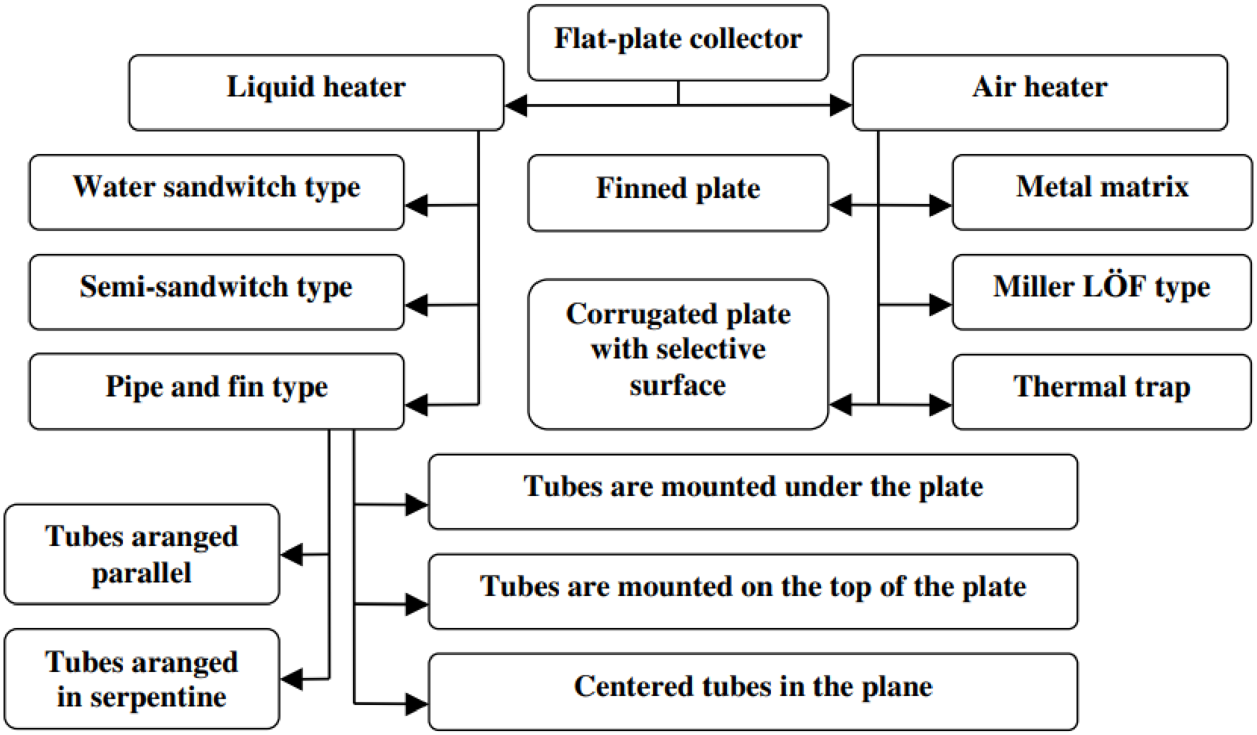


Figure 6: Classification of flat-plate solar collectors[9]

2.5.2: Evacuated Flat Plate Collector (EFPC)

Evacuated Flat plate collector (EFPC) is a flat plate collector but is designed to operate above 100°C in large-scale industries and has lesser heat losses. It consists of highly active flat surface and high-vacuum for best performance [10]. It is fully recyclable. A prototype collector based on the commercially available flat plate collector was constructed by Benz and Beikircher [11]. A sun powered pump maintained ultrahigh vacuum made it possible to reach 300°C. Later study shows that, while operating on 140°C, EFPC got an around 60-65% improvement while generic FPC got 25% of improvement[12] . Most recent studies improvised the operating temperature 200°C and the efficiency improvement raised up to 50%.[13].

A EFPC is shown in the Figure 7 provided below Though it has higher thermal output, these collectors have the advantage of longer lifetime compared to non-evacuated collectors. The gas heat conduction remains fully developed although convection losses are suppressed.

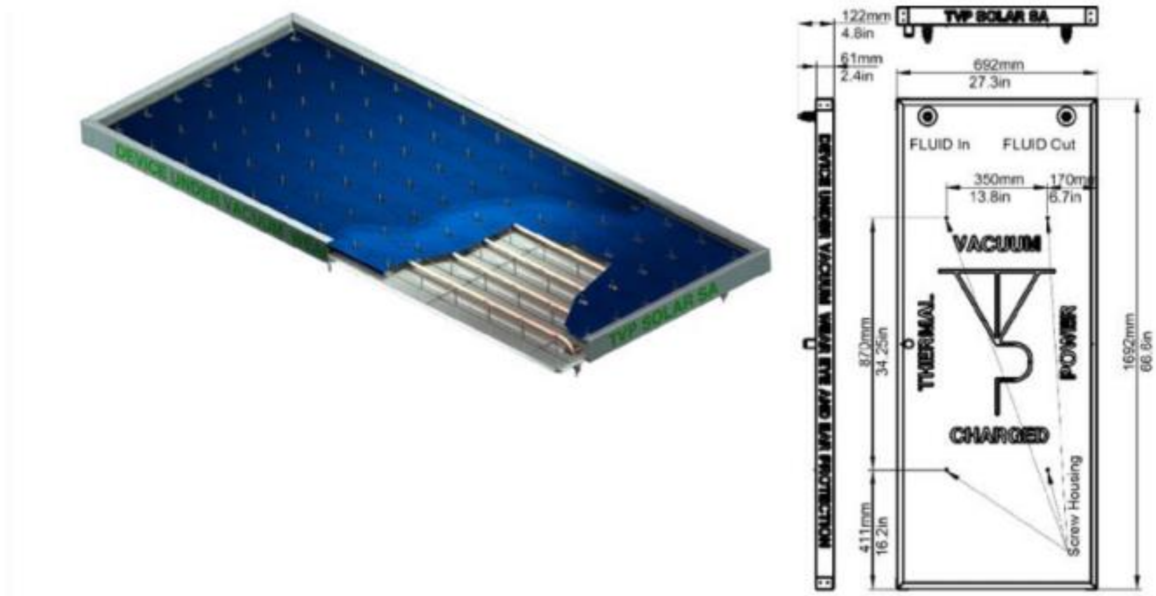


Figure 7: Evacuated Flat Plate Collector[14]

2.5.3: Evacuated Tube Collector

The construction of evacuated tube collectors is for different operations. This type of collectors is made with a number of glass tubes. The glass use in this collector is unique because the glass is annealed. Each glass tube contains an absorber plate. During production a vacuum is created in each of the tubes to minimize heat loss by conduction and convection.So,higher temperatures can be obtained in this collector.

To further increase the effectiveness of absorption of radiation different types of concentrators can be used with it. A schematic diagram of an evacuated tube collector is given below in Figure 8.

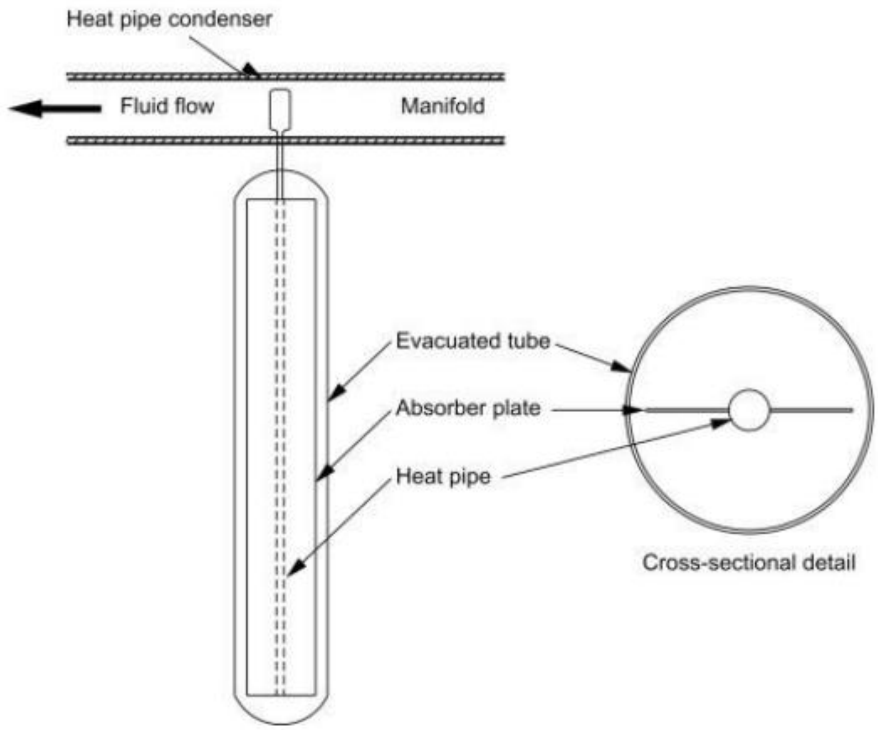


Figure 8: Schematic diagram of an evacuated tube collector[15]

The Evacuated Tube Collectors are also of several types. Classification of evacuated solar collectors is shown in Figure 9. There are plenty of designs of evacuated collectors, but in all of them selective coating as an absorber is used as it would be more effective.[16].

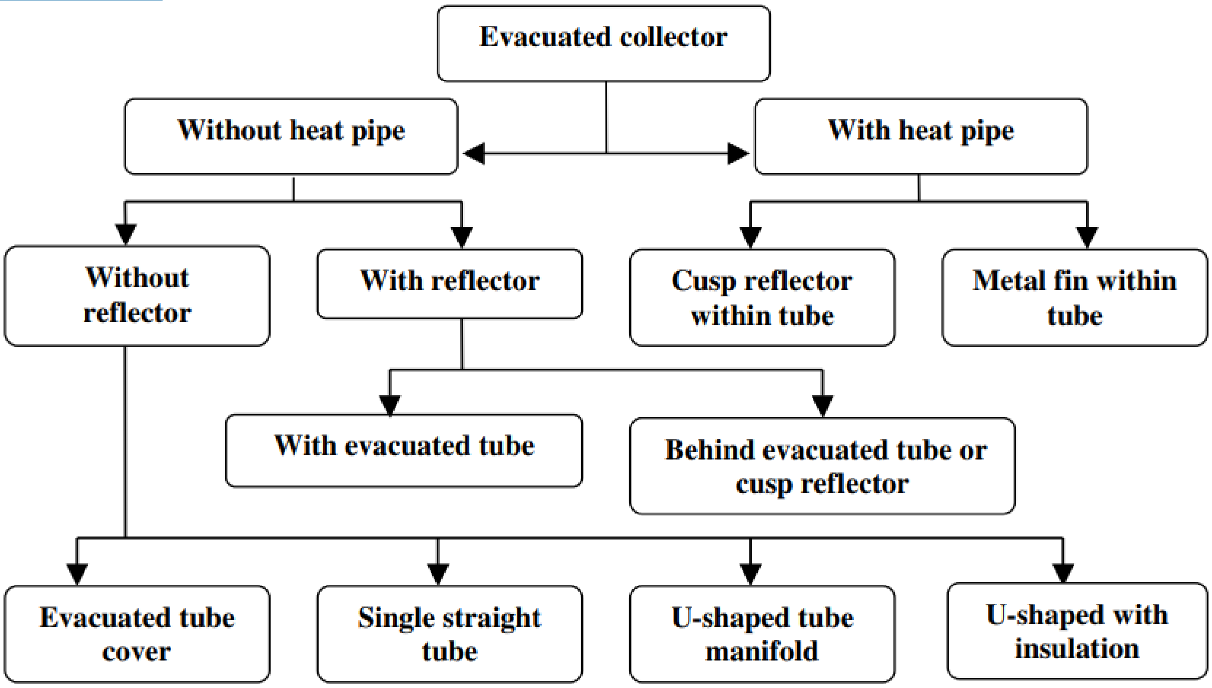


Figure 9: Classification of evacuated solar collector[9]

2.5.4: Compound Parabolic Collector (CPC)

This collectors first concept was originated back in the late 1950s. Static concentrator was proposed by Tabor[17] . In the late 1960s Winston et al [18] started the research on non-imaging concentrators. These concentrators were started to known as compound parabolic concentrators (CPCs) when the U.S. Argonne National Laboratory established research on non-imaging concentrators.[19].

Compound Parabolic Concentrators (CPCs) are designed in such a way that it efficiently collects and concentrates distant light sources. It's fabricated in the shape of two meeting parabolas (Figure 10). This is a non-imaging concentrator but does have highest possible concentrating ratio.

The concentration ratio can be achieved by non-tracking mode which is up to 10. Hence, it is cost saving. This collector has the most concentration permissible by thermodynamic limit for a given acceptance angle. Its large acceptance angle results in intermittent tracking towards the sun.

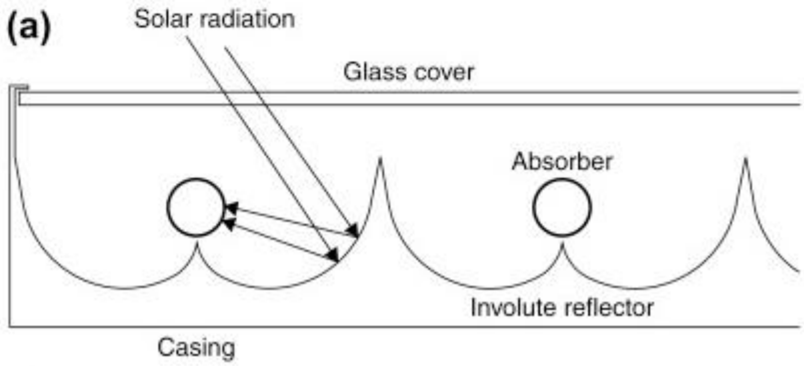


Figure 10: Panel CPC collector with cylindrical absorbers schematic diagram [20]

A research on improvement of the optical and thermal performance of external concentrating tubular absorber CPCs was done by Eames[21] They showed that by setting a baffle inside the CPC, internal convection can be reduced, thereby reducing heat loss. The figure below shows their experimental set-up-

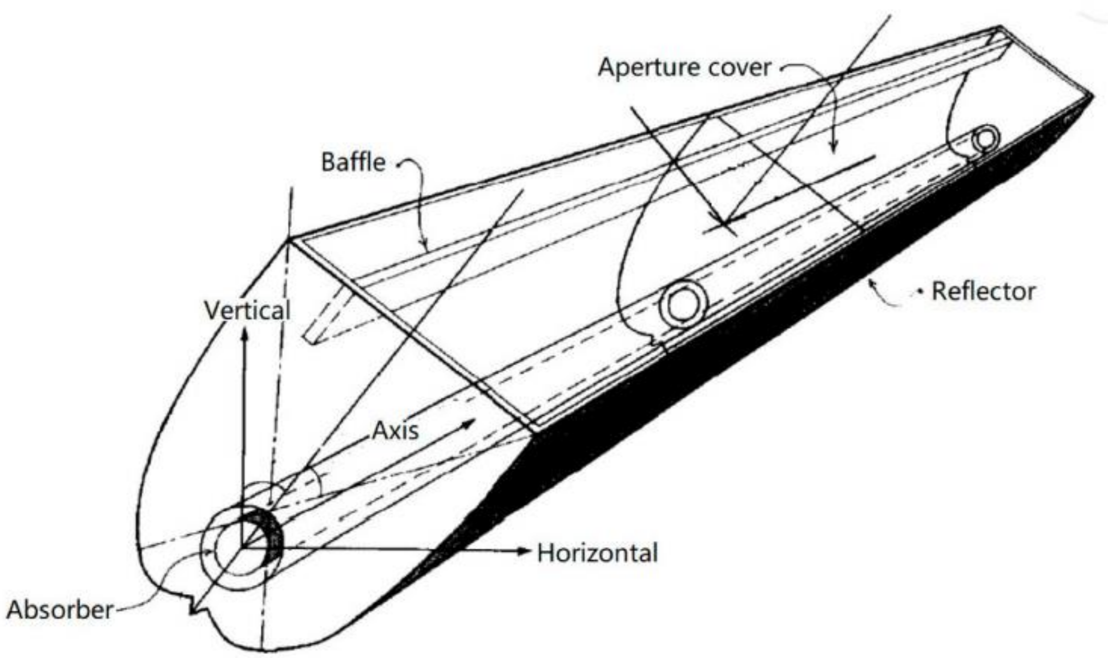


Figure 11: External concentrating tubular absorber CPC with baffle[21]

2.5.5: Parabolic Trough Collector (PTC)

Parabolic trough is a device in a parabolic shape, having small focal length. It's a concentrating, high performance, sun tracking collector. It can deliver high performance output in high temperature maintaining good efficiency. Figure 12 provided below shows the geometry of a parabolic through collector.

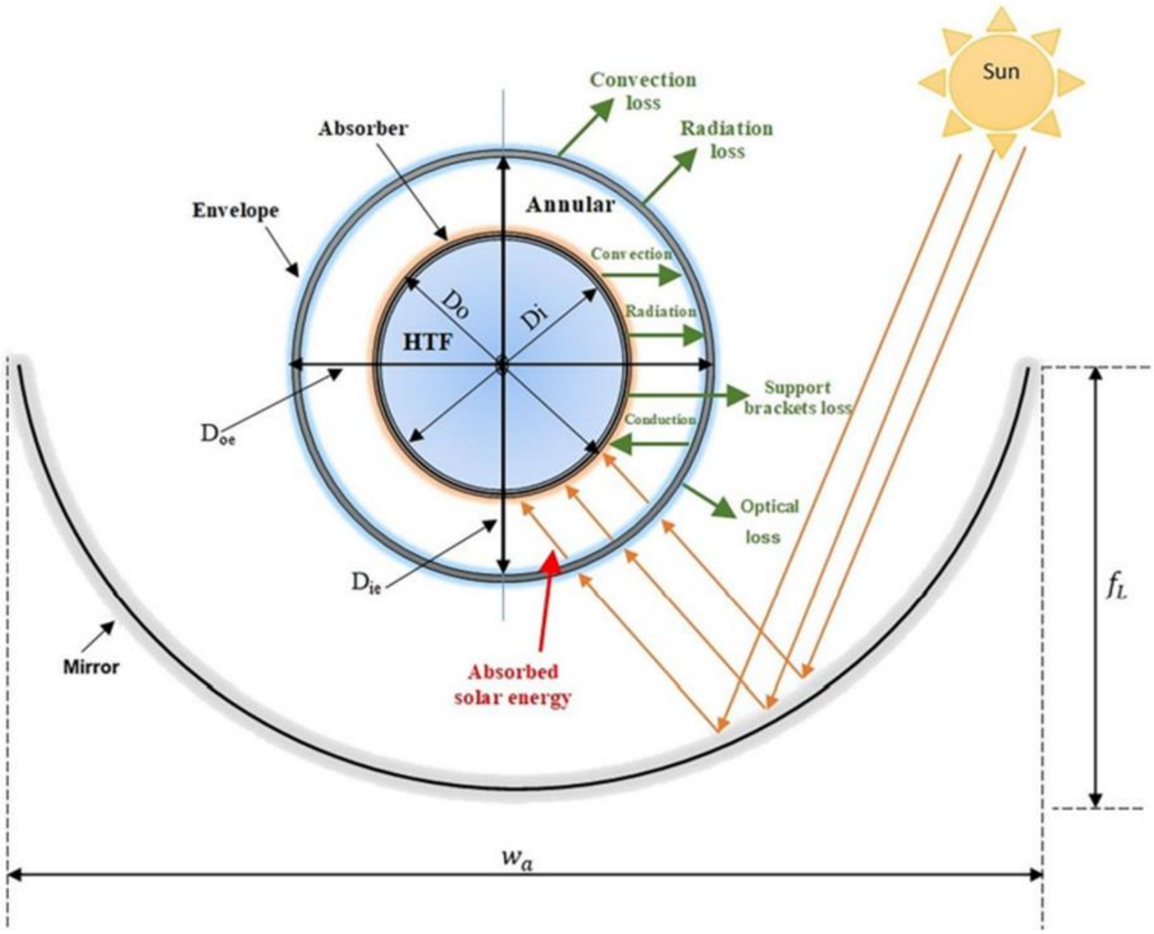


Figure 12: Geometry of Parabolic trough collector[22]

The main components are the solar absorber, the glass envelope, the positioning system, the support structure, and the reflector surface. There is a copper tube placed at a focal point of 48 parabolic trough collector. Parabolic trough collector concentrates solar radiation on that tube. The schematic of Parabolic trough collector can be seen from Figure 13 given below.

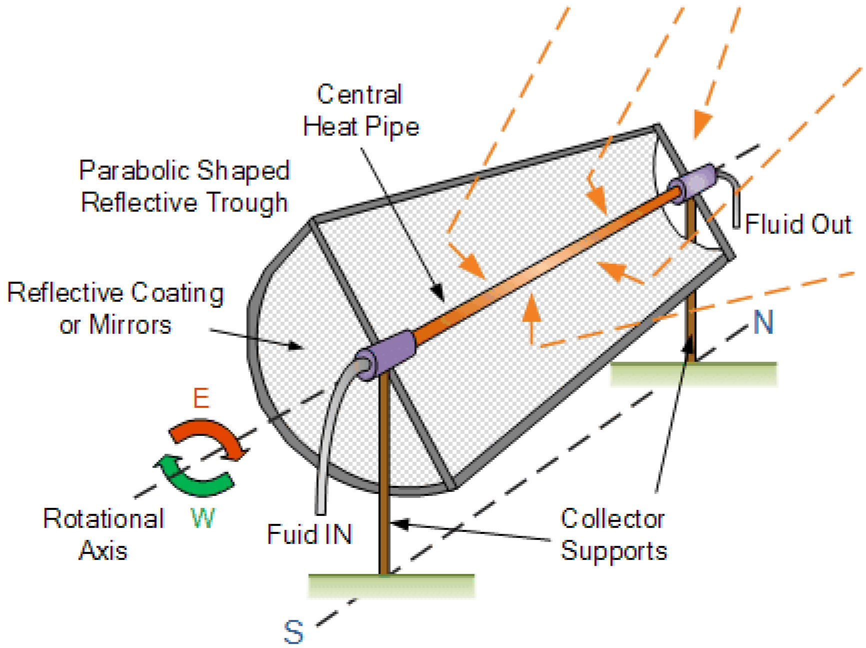


Figure 13: Schematic of parabolic through collector [23]

2.5.6: Parabolic Dish Reflector (PDR)

A parabolic dish collector is a concentrating solar collector that resembles a large satellite dish. It works by focusing the incoming solar radiation to a small area using reflectors at the focalpoint of the dish. The advantage of this is that it magnifies the intensity of the incoming radiation by many times. The collector is able to track the Sun in two axes. The dish is designed and placed in such a way so that it can track solar radiation and reflect the radiation to the focal point.

These highly polished mirrors can reflect more than 90% of the sunlight that hits them increasing the efficiency of the dish by more than 20% compared to the parabolic trough collector [24].

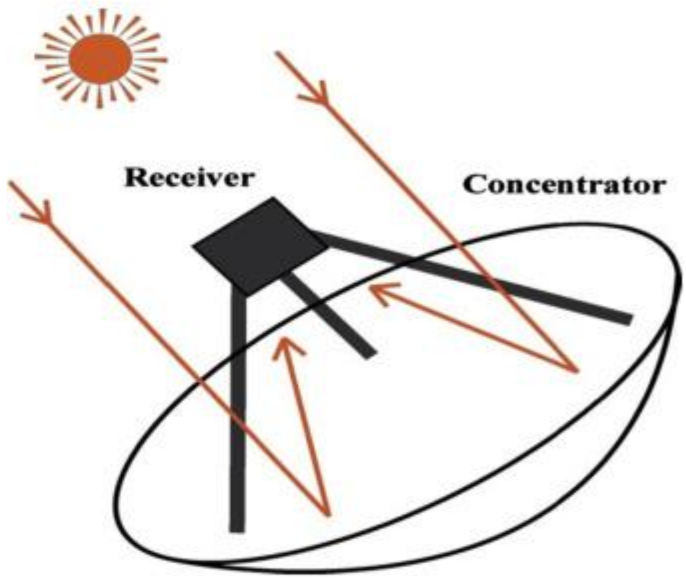


Figure 14: Parabolic dish reflector [24]

The Figure 14 shows a parabolic dish reflector design. The working fluid inside the receiver is oil type fluid due to its high heat absorbing property. Water is not used as the working fluid because thermal oil fluid can utilize the high solar radiation incoming to the collector.

2.5.7: Linear Fresnel reflector (LFR)

This type of solar collector uses mirrors. The difference of this type of collector compared to solar parabolic collectors is that it uses flat mirrors instead of parabolic mirrors. However, the basic principle remains identical. The energy from solar radiation is used to heat water which produces steam. The steam is used to rotate a turbine to produce electrical power. Here, the heat is directly used to generate power. There is no working fluid or heat exchanging mechanism taking place to transfer the heat to the desired place.

The collector works on Fresnel lens effect which was first developed by French physicist Augustin Jean Fresnel[25]. Fresnel collectors have two variations: the Fresnel lens collector (FLC) and the linear Fresnel reflector (LFR).

The following Figure 15 shows the working principle of a LFR.

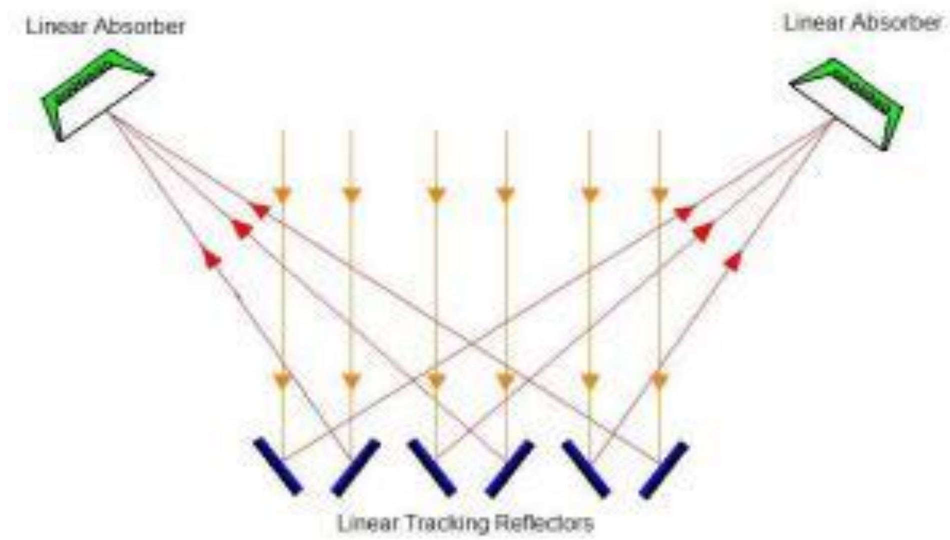


Figure 15: Linear Fresnel Reflector solar system [26]

There are several advantages as well as disadvantages of this kind of system. Cheaper flat mirrors are used in this type of collector. The benefit is that a greater number of reflectors can be placed in a particular area. So, the incoming solar radiation can be absorbed and utilized more efficiently. The structure required for this type of collector can be made very easily with widely available materials and the cost of maintenance is also lower compared to other collectors.

Linear Fresnel Reflectors generally produce steam directly and do away with the requirement of expensive heat exchangers. Land use is less because of efficient use of space. Leveling of land is not necessary and thus less expensive. No use of toxic materials [26]. There are several setbacks in this type of collector. The significant setback is that more area is required to place the mirrors because to use this collector efficiently the mirrors need to be completely exposed to the Sunlight. This will also increase the initial cost of setting up the collector.

2.5.8: Heliostat Field Collector (HFC)

A heliostat is a device that includes a plane mirror which turns so as to keep reflecting sunlight towards a predetermined target or object usually having exterior heat transfer surface.

Heliostats are the potentially the low-cost collectors. These collector systems can provide for domestic heating, electricity, and lighting. Altazimuth mounts are used to focus the incoming solar radiation onto a central receiver which absorbs the high intensity of solar radiation. Concave mirrors are also used in heliostats. They help in large amounts of incoming solar energy to be focused into the cavity of a steam generator to produce steam. This steam is produced at high temperature and pressure.

The redirected heat energy captured by the receiver is then transferred to a circulating working fluid that can be stored and further used to produce power [27].

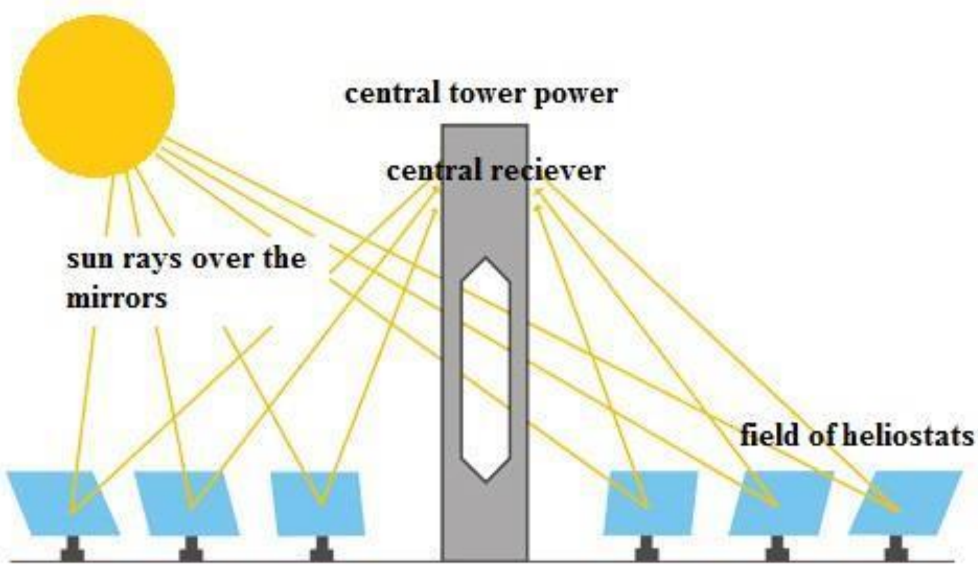


Figure 16: Heliostat field collector [28]

Table 1 provided below shows different solar collectors and their properties.

Collector Name	**Absorber Type**	**Concentration Ratio**	**Temperature Range (°C)**
Flat plate collector (FPC)	Flat	1	30-80 [29]
Evacuated tube collector (ETC)	Flat	1	50-200 [29]
Evacuated Flat Plate Collector (EFPC)	Flat	1	40-60 [29]
Compound parabolic collector (CPC)	Tubular	1-5	60-240 [29]
Parabolic trough collector (PTC)	Tubular	15-45	60-300 [29]
Parabolic dish reflector (PDR)	Point	100-100	100-500 [29]
Linear Fresnel reflector (LFR)	Tubular	10-40	60-250 [29]
Heliostat field collector (HFC)	Point	100-1500	120-2000 [29]

Table 1: Different solar collectors and their properties

2.6: Direct Absorption Solar Collector

2.6.1: DASC

DASC stands for Direct Absorption Solar Collector. It is a solar collector where nanofluid is enclosed inside the collector by a transparent glazing and frame of the collector. Solar radiation is absorbed directly in the working fluid which is usually a nanofluid. The following Figure 17 represents the components and set-up of a simple DASC water heating system for domestic usage.

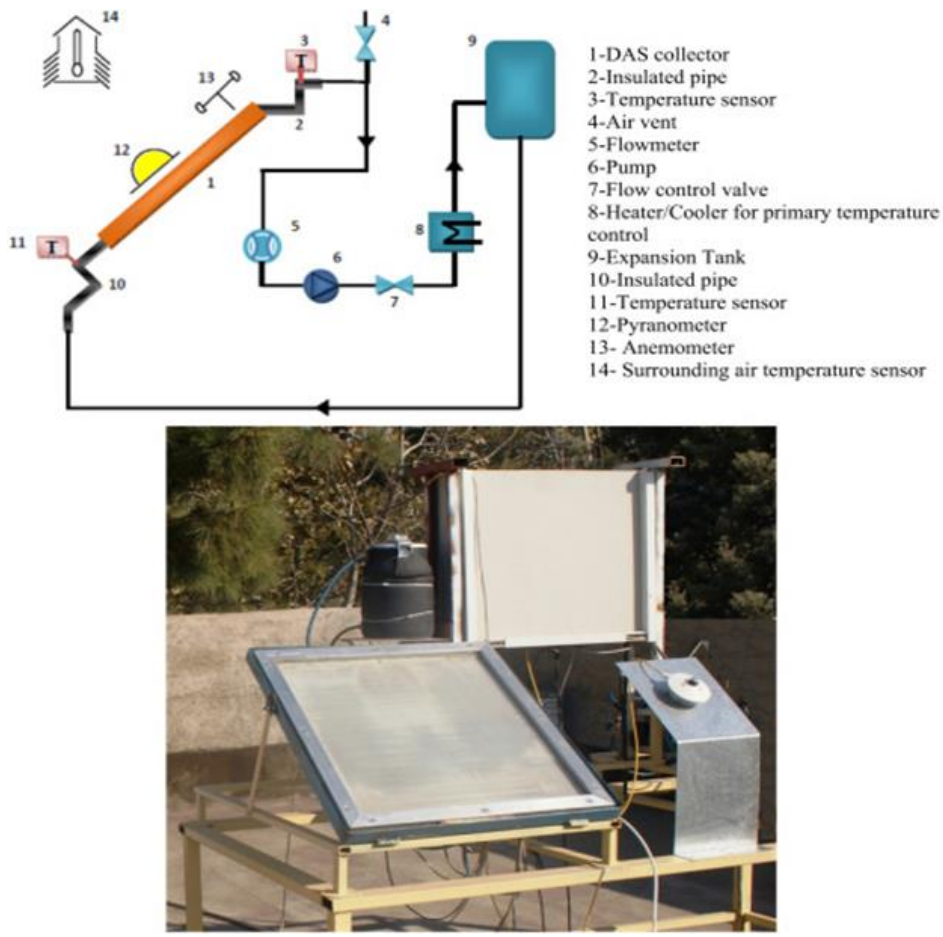


Figure 17: Simple DASC Set-up[30]

2.6.2: Working principle

If the working principle of a DASC is observed, it shows that the incoming solar energy is absorbed in the nanofluid. So, heat energy is transferred directly to working fluid and temperature distribution in the working fluid is more uniform.[7]

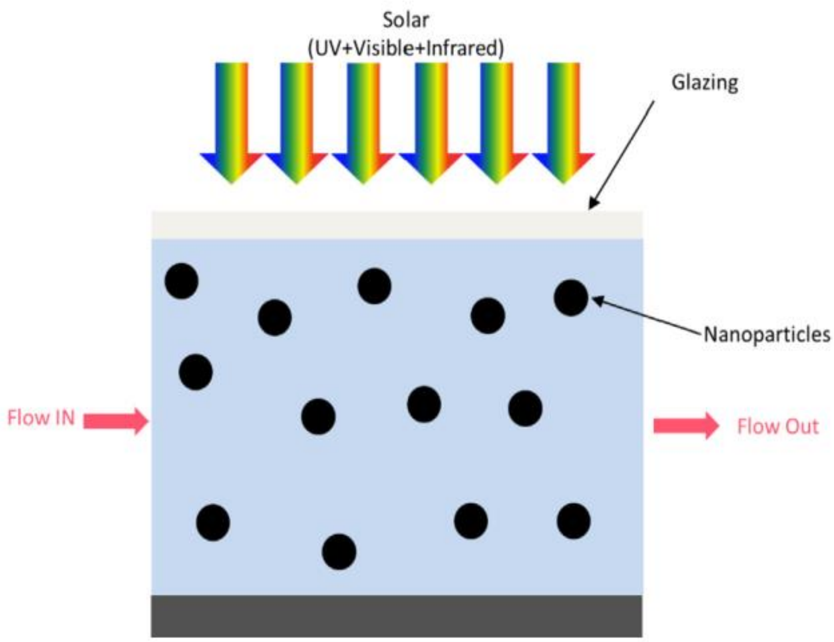


Figure 18: Working principle of DASC[7]

2.6.3: Types of Direct-Absorption Solar Collectors

DASC can be classified into three types according to the temperature reached inside the collector. The first one is Low temperature DASC where the temperature is less than 250°C, the second one is medium temperature DASC where temperature is in the range of 250-500°C, and the last one is high temperature DASC where the temperature is greater than 500°C.So, according to usage requirement the type of nanoparticles and base fluid is selected.

2.6.3.1: Low-Temperature Systems:

This type of systems is usually simple and cheap. Besides, a greater number of working fluids can operate in this system. The most common option is water.

Water is used as a base fluid in the majority of direct-absorption research[31] albeit generally at temperatures below 100°C.

Researchers are mainly focusing on to determine optimal performance with respect to size of nanoparticles or particle diameter, shape, concentration of nanofluid and operating conditions.

2.6.3.2: Medium-Temperature Systems:

The fluid options which can be used in this system are limited. A few organic fluids can operate above 250°C but generally organic fluids are used in low-temperature systems. Liquid metals and molten salts are the feasible options which can be used in medium temperature systems. There are different types of liquid metal but only mercury and sodium have been used in solar systems.Tammen patented a concept where reflective liquid metal serves as a reflective concentrator and as the working fluid inside the receiver [32].

2.6.3.3: High-Temperature Systems:

In this type of system, temperatures get high as it absorbs energy from incoming solar radiation of prime quality. This system also requires less pumping power. The main disadvantage of reaching high temperatures is that the radiative heat losses can be significant. Besides, expensive materials have to be used to withstand high temperature generated in the collector. So, the overall initial set up cost increases.

The stability of nanoparticles is always important but at high temperatures most nanoparticles are stable so nanoparticles can be chosen from a wide range of available options. The biggest concern in this case is to find a suitable base fluid which can operate at high temperatures. Nitrate molten salts are the most commonly used base fluid for higher temperature receivers [33].

2.6.4: Difference between DASC and conventional solar thermal collectors

DASC	Conventional Solar Thermal Collector
1.Incoming solar energy is absorbed in the nanofluid.	1.Requires a solid surface to absorb and convert incoming solar energy to useful thermal energy.
2.Heat energy is transferred directly to working fluid and temperature distribution in the working fluid is more uniform.	2.Heat energy is transferred to working fluid flowing via conduction and convection, which results in a temperature drop

Table 2: Difference between DASC and conventional solar thermal collectors

The Figure 19 provided below is shown to understand the difference in the working principle between a DASC and a conventional solar thermal collector in a more adequate way.

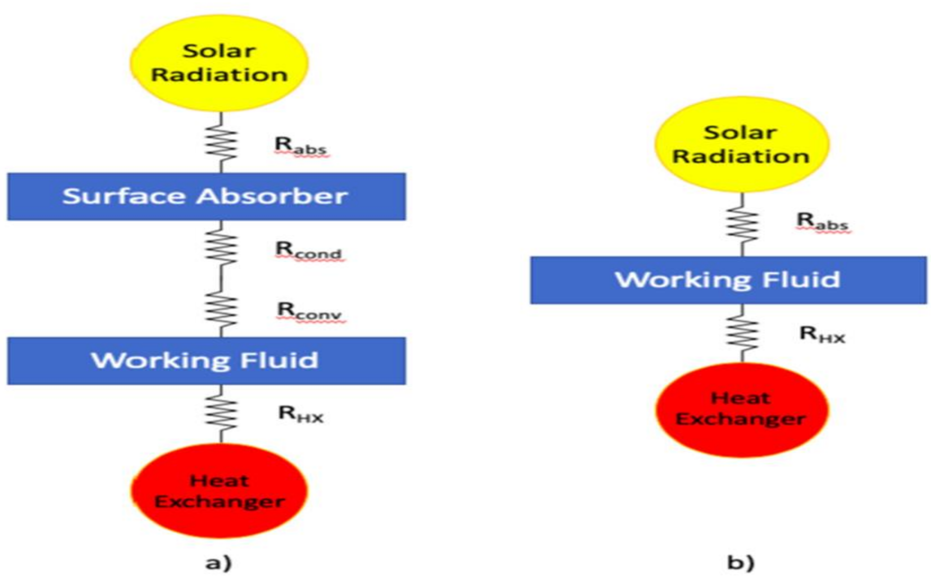


Figure 19: Difference between DASC and conventional solar thermal collectors.

a)Surface absorption b)Volumetric absorption [7]

2.7: Nanofluids

A nanofluid is a fluid in which nanometer-sized particles, suspended in the base fluid, form a colloidal solution of nanoparticles in a base fluid. The nanoparticles used in nanofluids are typically made of different metals, oxides or carbon nanotubes. Common base fluids include water, ethylene glycol and oil. However the drawback of using nanofluids is its instability. Selection of nanofluid for any application should consider the improvement in its physical properties and also its stability.

2.7.1: Applications of Nanofluid in Solar Energy

Nanofluids can be used to boost the efficiency of different solar energy systems. The thermal conductivity of the nanofluids is the most crucial factor that affects the performance of solar energy systems as increasing the nanoparticles volume percentage seldom result in better performance. The effect of nanoparticles size on the performance of solar collectors is still not sure, so more experimental and theoretical researches are needed to figure out the particles size effect. The superior thermo-physical properties of nanofluids result in a significant boost in the heat transfer process, which in turn results in reducing the size of the solar devices. The high cost of nanofluids and its stability are main factors that barriers its use in commercial and industrial applications. Many economic and environmental advantages could be achieved using nanofluids in different solar systems. [34]

2.7.2: Classification of Nanofluid

Depending on the different types of nanoparticle used for making of nanofluid, nanofluid can be classified into four categories: (a) metal based, (b) metal oxide based, (c) carbon based and, (d) hybrid/mixed metal based. Nanofluid selection for any application should consider not only the improvement in its physical properties but also its stability.[35]

.

2.7.3: Preparation of Nanofluid

Method: Ultrasonic mixing of nanopowder in base fluid.
Procedure:

- Measure amount of nanoparticles required
- Ultrasonication was applied for 6–7 h to mix calculated amount of Al_2O_3 nanoparticles in distilled water using ultrasonic vibration mixer
- Observe nanofluid for 24 hours to see if agglomeration occurs.

2.7.4: Applications of Nanofluid in Solar Energy Systems

Nanofluids are being used in solar thermal collectors to improve their efficiency. The main benefits of using nanofluids in solar technologies are

- Large surface area in a small particle increases heat capacity by a great margin.
- The optical Properties of nanofluid are better than conventional fluid.
- Thermal conductivity of nanofluid is significantly higher than conventional fluids.
- It reduces heat transfer area so in theory reduces the cost of Solar collectors.

2.8: State-of-the-art and future reseach scopes

Simonetti (2020) suggested that in future studies the use of a plastic material as transparent envelope of the DASC can be studied, providing, at a low cost, much more freedom to use different and more complex geometries, that could be more easy to integrate in buildings.[36]

Goel (2020) suggested to investigate coatings that can results in high solar weighted transmittance while vastly lowering the overall thermal emittance experimentally.[7]

Natarajan and Sathish researched about the improvement of thermal conductivity of DASC using CNT nanofluids and showed the nanoparticles are potential for improving the radiative properties of fluids. They also mentioned that the efficiency of DASC enhanced. [37]

Vakili, Hosseinalipour found experimentally that the optical property and the thermal conductivity of graphene for low-temperature DASC, applied 0.00025, 0.0005 and 0.005 wt% of nanoparticles. They showed that absorption and conductivity increased with increasing of weight percentage. The overall performance of the collector increased.[38]

Karami et al studied nanofluid based dasc with different volume fractions of copper oxide nanoparticles in water and ethylene glycol mixture (70%:30% in volume) as the base fluid were prepared and their thermo-physical and optical properties were presented. [39]

Nick Brecke suggested the study to find ways to limit the temperature rise of the transparent walls needed to convey the working fluid. [40]

Investigation of different types of coating in high solar weighted transmittance was suggested by Yasitha L. [41]

Otanicar et al studied nanofluid based DASC experimentally using various types of nanofluid(CNT,Graphite, Cu etc.). [41]

Thomas A cooper showed that water heating can be done even contactlessly with solar driven evaporations. [42]

E Nataranjan studied the improvement of thermal conductivity of DASC using CNT and found the particles are able to improve the radiative properties of the fluid.[37]

From above review it is understandable that solar energy technologies are advancing and nanofluid is being vastly used as a medium to increase the effieciency of collectors.

The thesis study was mainly motivated from the suggestions of Yasitha L. as he showed high potential of efficiency difference by experimenting with different coatings of covers.

Chapter 3: Methodology

3.1: Experimental part

The objective of the experimental study was

- To calculate the efficiency using plastic material as cover and to compare the values with that of glass cover.
- To investigate different coatings and compare results with conventional setup.
- To determine if plastic materials can be used with complex geometries and if they are feasible to be used in solar water heating systems.

A prototype of a DASC was proposed with the following dimensions:

Length:	60 cm
Width:	60 cm
Height:	1 cm

A glass cover will be used as a transparent cover. Different plastic materials such as Polycarbonate sheets (16mm/10mm) and acrylic glass (PMMA-Poly (methyl methacrylate) were selected to be used.

Aluminium dioxide nanoparticles properties were calculated using the following equations:

Thermal Mass of nanoparticle, $m_{np} = V_t.\Phi_{np}.\rho_{np}$

Conductivity of nanofluid, $k_{nf} = k_{bf} + \frac{3\Phi(k_{np}-k_{bf})}{k_{np}+2k_{bf}-\Phi(k_{np}-k_{bf})}$

Density of the nanofluid, $\rho_{nf} = (1-\Phi)\rho_{bf} + \Phi\rho_{np}$

Specific Heat of the nanofluid, $C_{p_{nf}} = \frac{(1-\Phi)\rho_{bf}c_{p_{bf}}+\Phi\rho_{np}c_{p_{np}}}{\rho_{nf}}$

Viscosity of the nanofluid, $\nu_{nf} = \frac{\mu_{bf}}{\rho_{nf}}(1+39.11\Phi+533.9\Phi^2)$

The calculated values were then tabulated:

Volume Fraction, Φ(%)	Density (kg/m^3)	Viscosity (kg/ms)	Heat Conductivity (W/mK)	Specific heat (J/kgK)
0	998.2	9.98e-4	0.5970	4182.0
1	1027.018	1.023e-3	0.6200	4053.21
2	1055.836	1.048e-3	0.6436	3931.451
3	1084.654	1.079e-3	0.6678	3816.162
4	1113.472	1.098e-3	0.6926	3706.840

Table 3: Aluminium Oxide Properties

3.1.1: Setup Design

A schematic of the experimental setup is shown below in Figure 20.

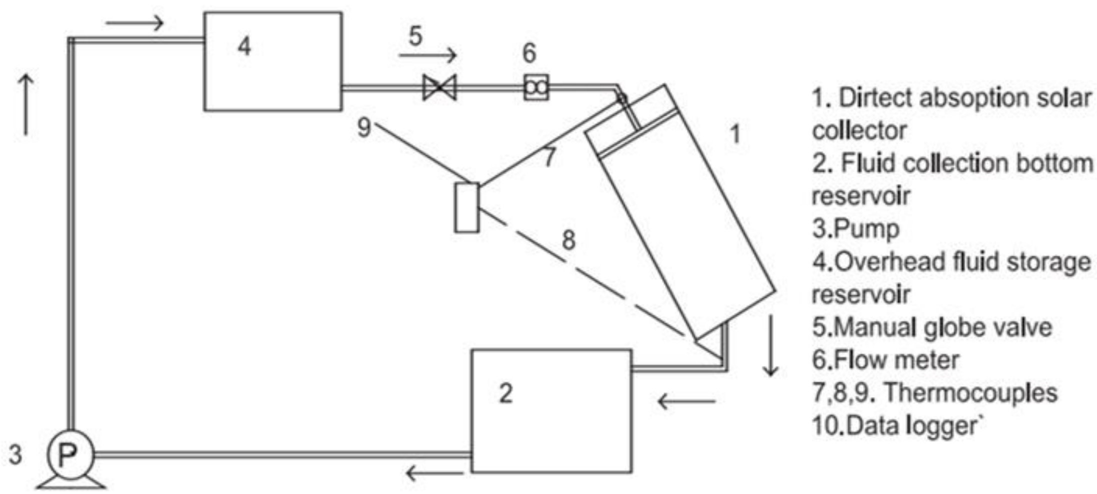


Figure 20: Schematic of the experimental setup

The design is a very simple one. The function of pump is to vary the flowrate. Manual globe valve will allow the flow in one direction only. Overhead fluid reservoir and fluid collection bottom reservoir store the fluid. Flowmeter measures the flowrate of nanofluid. Thermocouples measure temperature and data logger keeps record of the values.

3.1.2: Nanofluid Preparation

Method: Ultrasonic mixing of nanopowder in base fluid.

Procedure:

1) Measure amount of nanoparticles required

2) Ultrasonication was applied for 6–7 h to mix calculated amount of Al_2O_3 nanoparticles in distilled water using ultrasonic vibration mixer

3) Observe nanofluid for 24 hours to see if agglomeration occurs.

3.2: Numerical part

A flat plate collector was simulated in ANSYS Fluent by using five different volume fractions of graphite nanoparticles. The materials used in flat plate collector are-
a) Absorber-Copper b) Walls-Aluminium c) Glazing-Glass
The reason for choosing copper as the material for absorber plate is due to its high thermal conductivity and resistance to corrosion. The walls are made up of aluminium because it is lightweight and also provides enough structural strength to support the collector. The top glazing is made up of glass to allow most of the radiation to pass through to be absorbed by the copper absorber. The volume fraction of graphite nanofluid was varied and the efficiency was calculated.

3.2.1: Governing equations

For the numerical simulation of flat plate collector in ANSYS Fluent Rosseland radiation model was selected. The medium is optically thick enough for this model to be used. The Rosseland radiation model can be derived from the P-1 model.

The radiative heat flux vector can be expressed as $q_r = -\Gamma \nabla G$
It is assumed in the Rosseland model that the intensity is the black-body intensity at the gas temperature.

$$G = 4\sigma n^2 T^4$$

Substituting value of G in radiative heat flux vector the following expression can be achieved:

$$q_r = -16\sigma \Gamma n^2 T^3 \boldsymbol{\nabla} T$$

The radiative heat flux has the same form as the Fourier conduction law, so it can be expressed as-

$$q = q_e + q_r$$

$$= -(k + k_T)\nabla T$$

$$k_r = 16\sigma \Gamma n^2 T^3$$

3.2.2: Geometry

The absorber plate of the solar collector has dimensions of 60 cm * 50 cm. The absorber plate is responsible for absorbing the incoming solar radiation. While calculating the efficiency the surface area of absorber plate has been taken as the surface area of the collector. The schematic of the geometry is shown below:

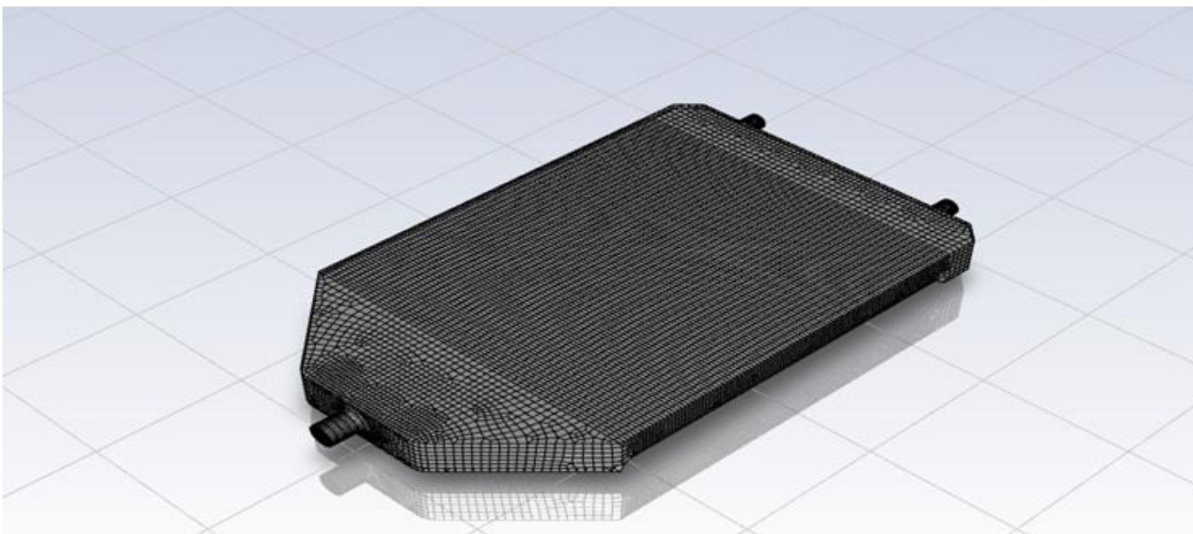
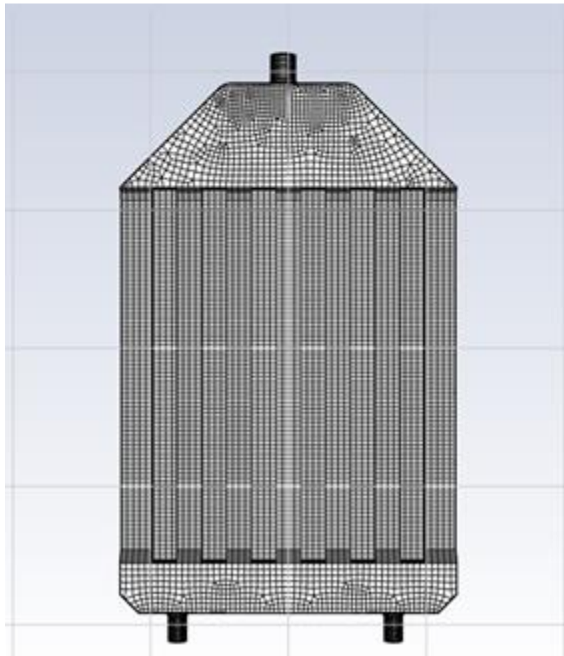


Figure 21: Schematic of the geometry

3.2.3: Mesh generation

Different types of mesh were created in the collector to form an unstructured grid. The types of mesh according to types used in the geometry are tetrahedral, hexagonal, pentagonal, quadrilateral and pyramidal. The number of elements according to mesh types are- tetrahedral:6562, hexagonal:49871, pentagonal:2377, quadrilateral:24043 and pyramidal:13016. The number of elements according to element parts are –absorber plate:1174, collector:71826, glazing:5000, inlet:127, outlet:254, walls:6920.

The total number of elements in the geometry is 95869 and total number of nodes in the geometry is 68234.



(a)

(b)

Figure 22: Different views of the generated mesh

3.2.4: Nanofluid properties

Table 4 shows the properties of graphite nanoparticles with different volume fraction.

Case No	**Graphite nanoparticles (volume fraction)**	**Density (kg/m^3)**	**Viscosity (kg/m-s)**	**Heat Conductivity (W/m-k)**	**Specific Heat (J/kg-K)**
1	0	998	0.001003	0.6	4182
2	0.01	1006.02	1.72e-3	0.6227	4119.699
3	0.025	1018.05	4.75e-3	0.657	4028.088
4	0.05	1038.1	1.43e-2	0.726	3880.121
5	0.075	1058.15	2.95e-2	0.779	3737.762
6	0.1	1078.2	4.5e-2	0.8432	3600.7

Table 4: properties of graphite nanoparticles

Different cases of volume fraction affect the thermal conductivity, density and specific heat of the nanofluid. The effects are shown with figures below:

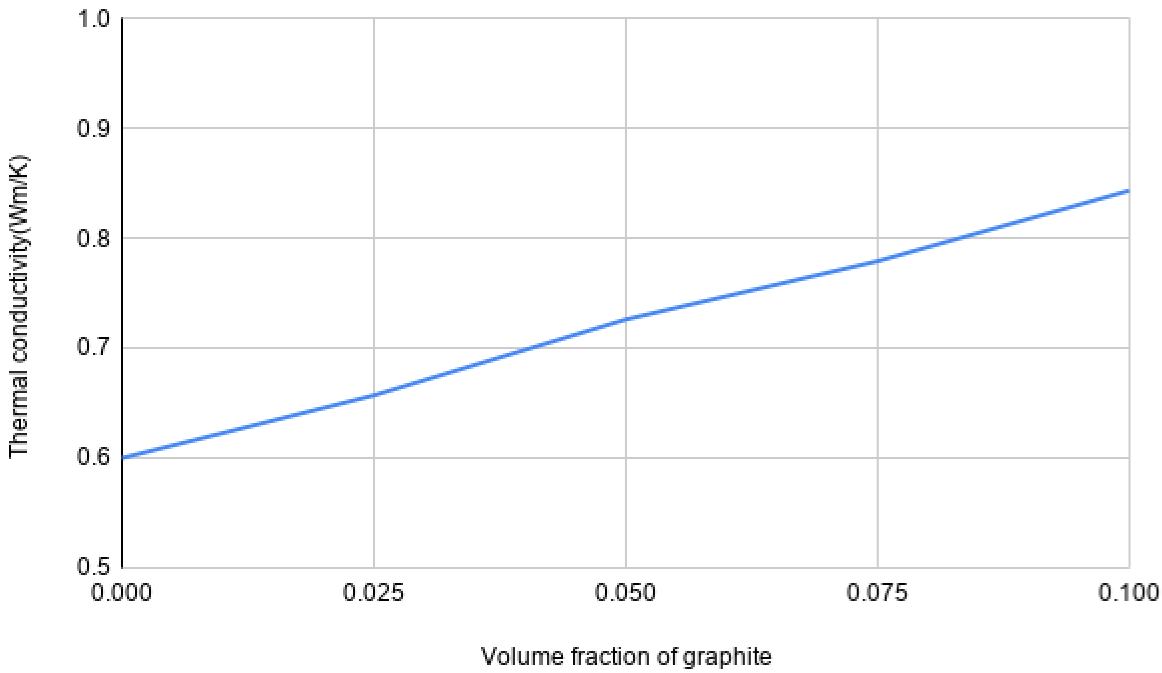


Figure 23: Effect on Thermal Conductivity

From Figure 23 it can be observed that, the thermal conductivity increases with an increase in the volume fraction of graphite. This is because increasing the volume fraction increases the surface area and number of particles which in turn enhances thermal conductivity.

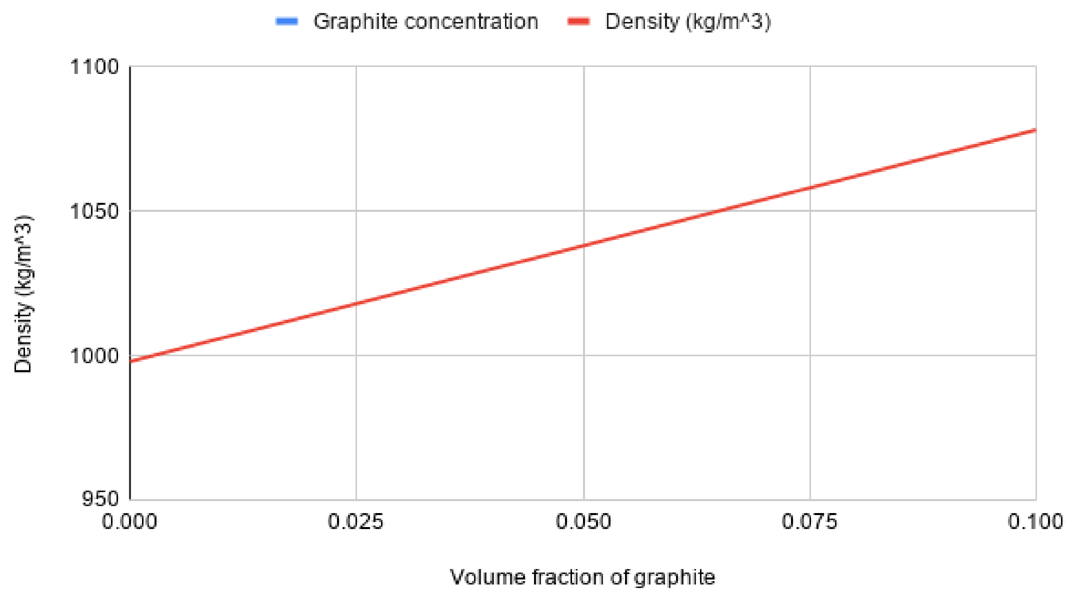


Figure 24: Effect on Density

The relationship of density with concentration of graphite is directly proportional as can be seen from Figure 24. This is because density of solid is usually greater than the base fluid and as volume fraction increases the potion of solid partcles increases.

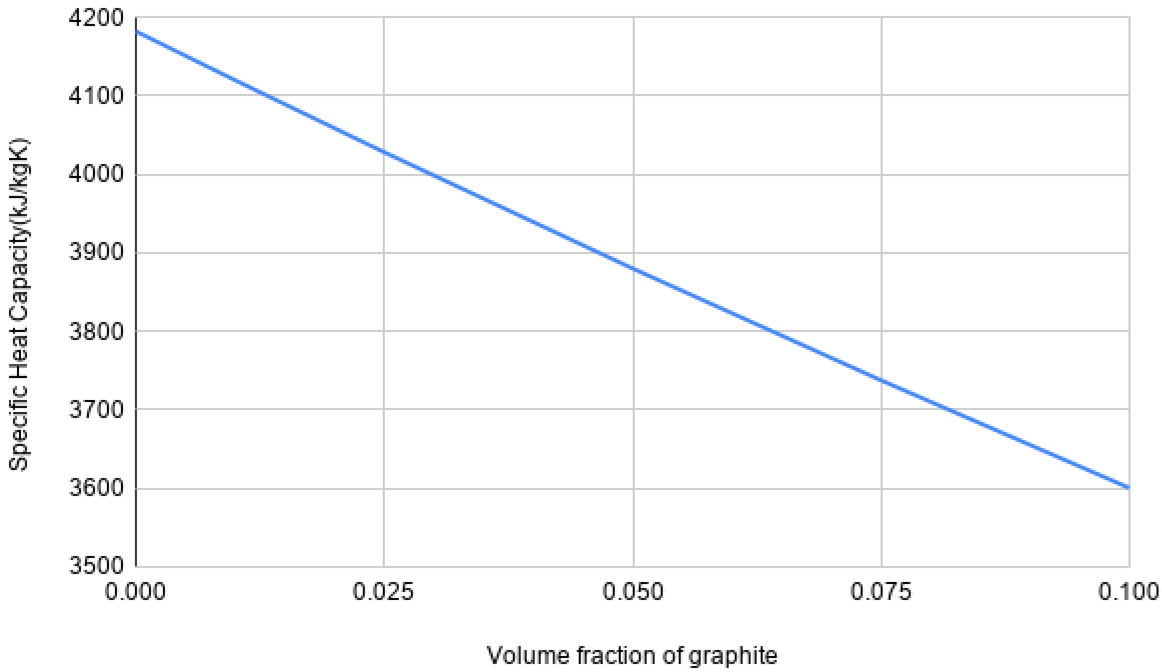


Figure 25: Effect on Specific Heat

From the Figure 25 it is observed that, the specific heat capacity decreases as more nanoparticles are added. This is because it takes less energy to active nanoparticles.

3.2.5: Boundary conditions

Mass flow rate is taken as 0.0005 kg/s and temperature was set as 298 K. Walls take part in convection so heat transfer coefficient was taken as 5W/m^{2}K.Absorptivity of direct visible and Direct IR radiation has been taken as 0.9.

3.2.6: Solution methods

The energy model and viscous realizable k-epsilon 2-equation model was used. In the viscous realizable k-epsilon model enhanced wall treatment as well as thermal effects were considered.

To account for the incoming solar radiation, the Rosseland radiation model was used. Solar ray tracing and solar load calculation were used to calculate direct solar irradiation in the solar collector. The latitude and longitude were set to Dhaka's coordinate.

The SIMPLE scheme was selected in pressure velocity coupling. The second order upwind scheme was used for pressure, momentum, turbulent kinetic energy, turbulent dissipation rate, and energy. The second order upwind scheme was used because it goes more accurate results. Standard initialization was used to initialize the calculation. This was done so that reference values can be set. The calculation was run for 30s for each time step.

The total flow time simulated is 3600s. Maximum number of iterations used in each time step was 35.

Chapter 4: Results and Discussions

4.1: Effect of nanofluid concentration on thermal performance of DASC

The simulation has been run in ANSYS Fluent for all the cases and the following temperature contours have been generated from the results obtained.

Case-1 (for water only)

The increase in temperature is observed 53.6K.

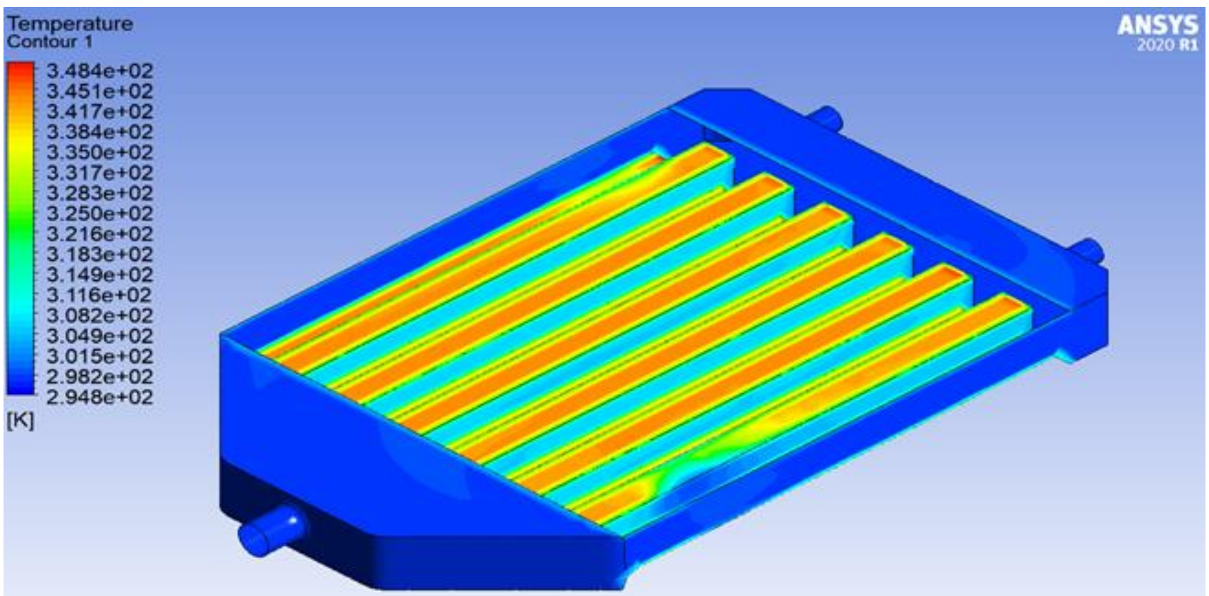


Figure 26: Temperature contour for water

For Case 1, no nanofluids were added so only water has been used as the working fluid in the collector. In the collector absorber plate the temperature increases from 294.8K to 348.4K. In any nanofluid based study of solar collector it is important to study the effect with only base fluid so that the effect of adding nanofluid can be demonstrated.

Case-2 (for Graphite 0.01)

The increase in temperature is 54.3K. As nanofluid is added the temperature increases. This happens because adding nanofluid enhances heat transfer and increases the absorbtion of solar radiation.

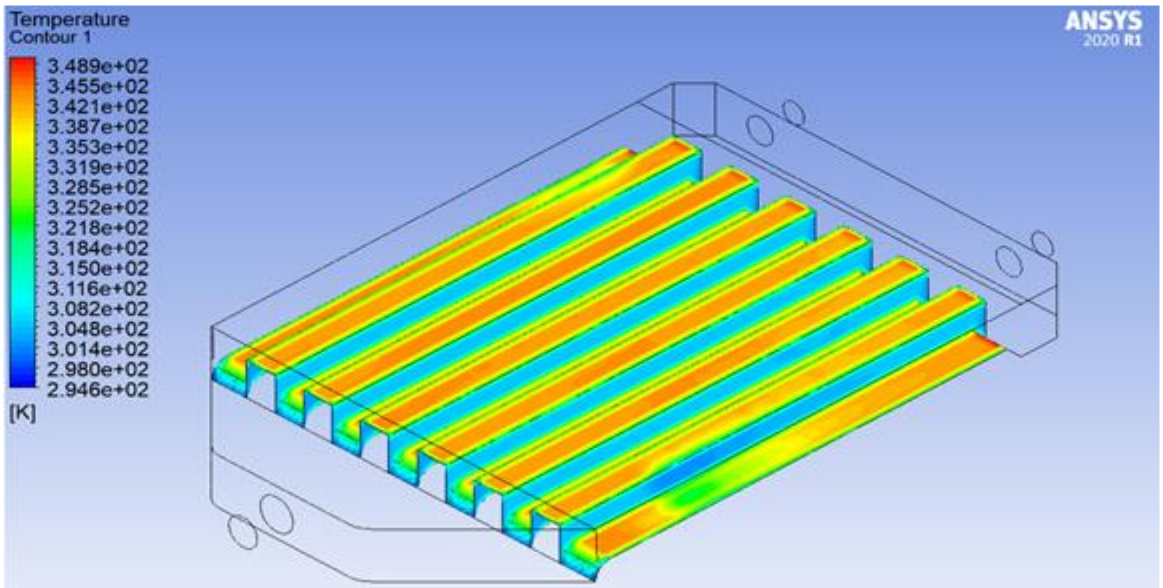


Figure 27: Temperature contour for graphite 0.01

For Case 2 graphite nanoparticles with a concentration of 0.01 has been added to the base fluid water to make nanofluid. In the copper absorber plate temperature increases from 294.6K to 348.9K.

Case-3 (for Graphite 0.025)

The increase in temperature is 62.1K.Further increasing the concentration increases the temperature by a significant amount.

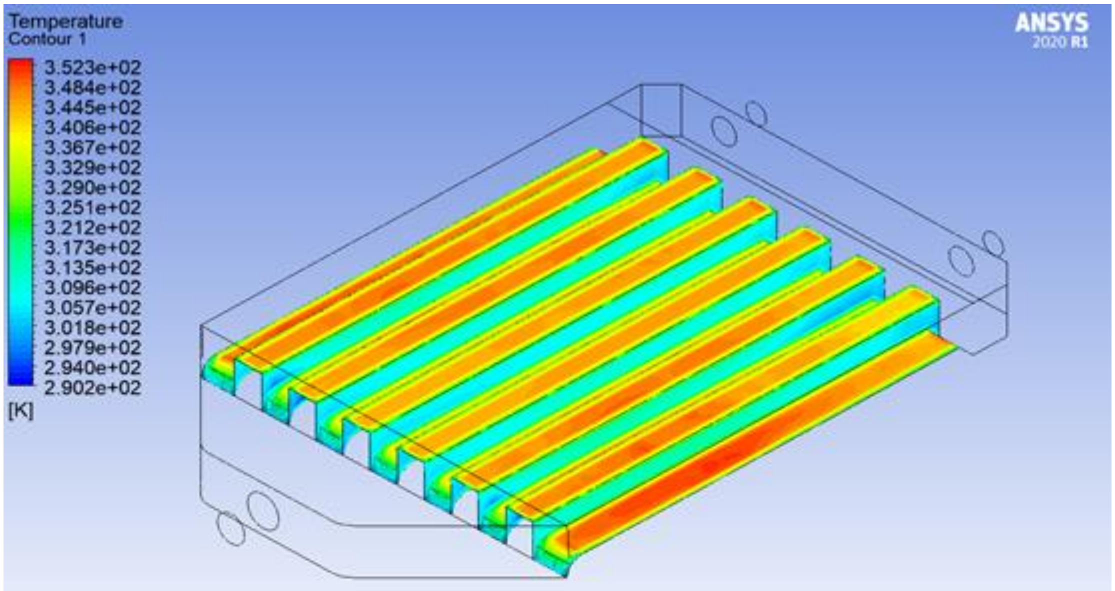


Figure 28: Temperature contour for graphite 0.025

For Case 3 graphite nanoparticles with a concentration of 0.025 has been added to the base fluid water to make nanofluid. In the copper absorber plate temperature increases from 290.2K to 352.3K

Case-4 (for Graphite 0.05)

The increase in temperature is 59K.In this case increasing the concentration does not improve the change in temperature.

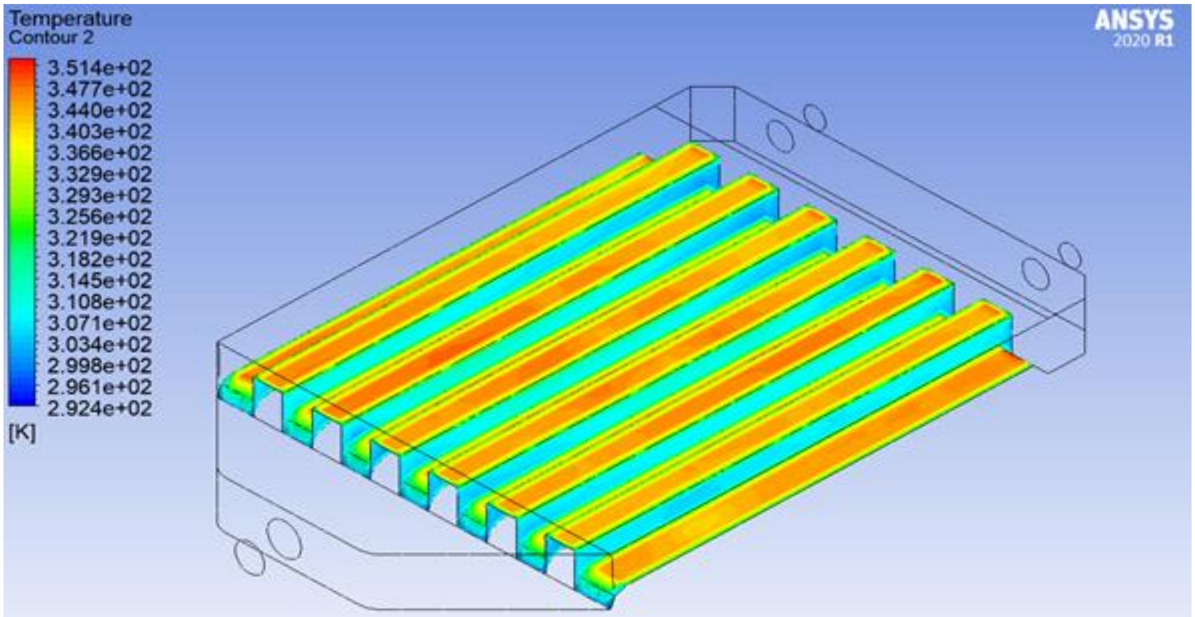


Figure 29: Temperature contour for graphite 0.05

For Case 4 graphite nanoparticles with a concentration of 0.05 has been added to the base fluid water to make nanofluid. In the copper absorber plate temperature increases from 292.4K to 351.4K.

Case-5 (for Graphite 0.075)

The increase in temperature is 43K.Increasing the concemtration decreases the increase in temperature because the nanoparticles loses its stability and causes clustering.

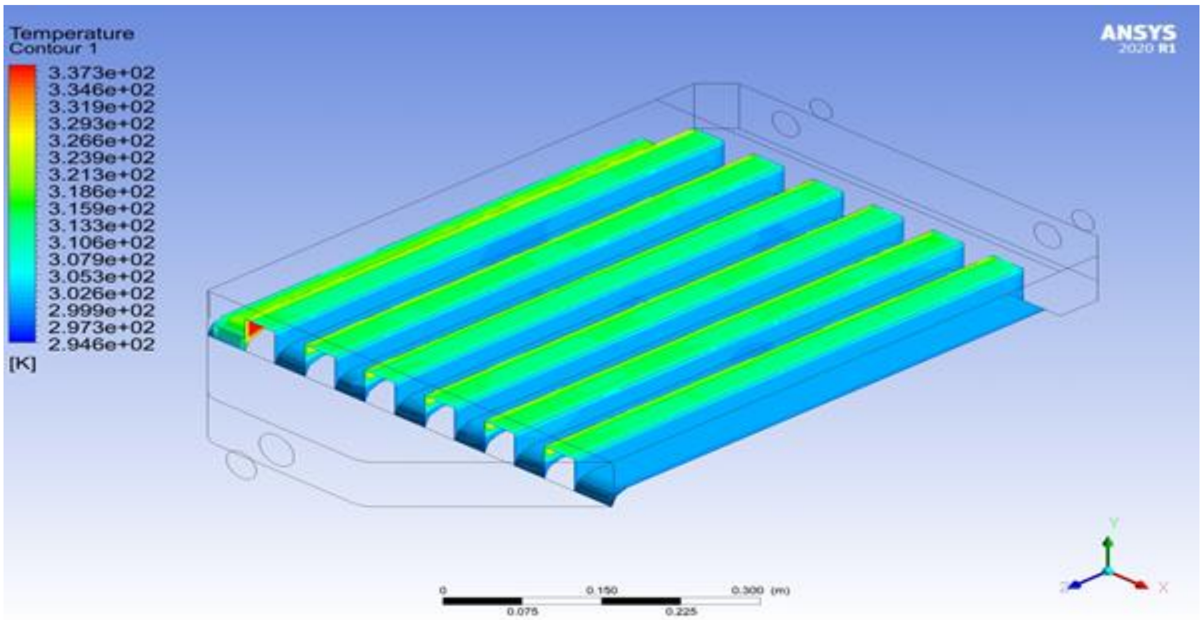


Figure 30: Temperature contour for graphite 0.075

For Case 5 graphite nanoparticles with a concentration of 0.075 has been added to the base fluid water to make nanofluid. In the copper absorber plate temperature increases from 294.6K to 337.3K.

Case-6(for Graphite 0.1)

The increase in temperature is 42.8K.This is the same effect as case 5.

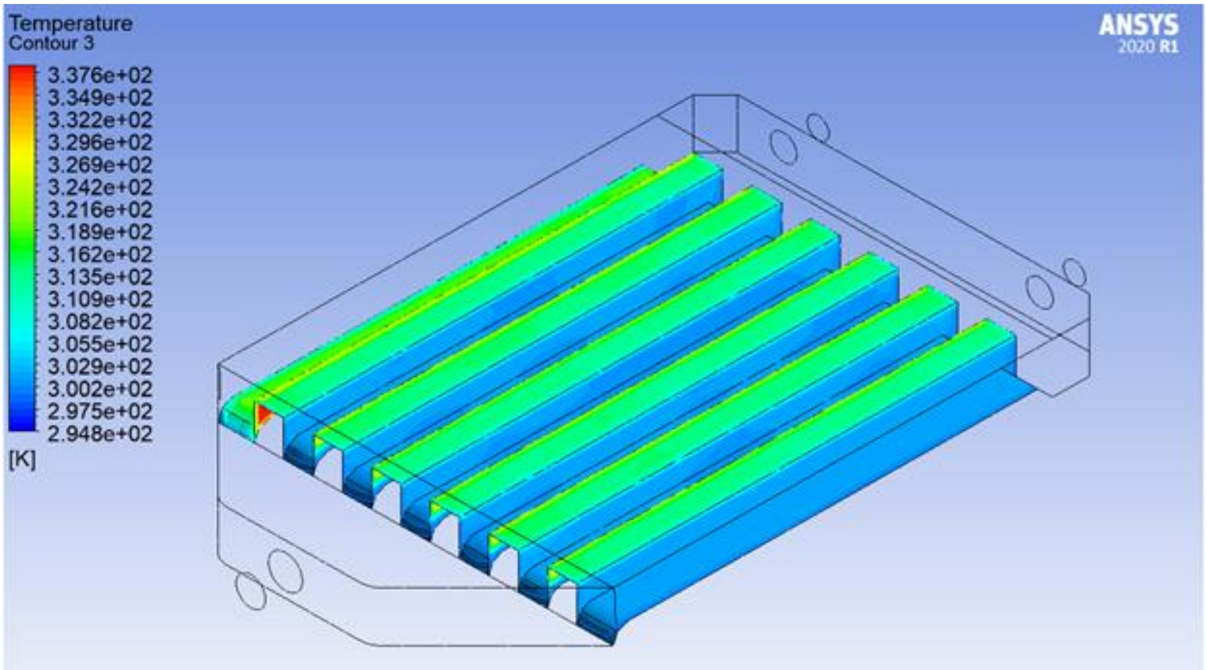


Figure 31: Temperature contour for graphite 0.1

For Case 6 graphite nanoparticles with a concentration of 0.1 has been added to the base fluid water to make nanofluid. In the copper absorber plate temperature increases from 294.8K to 337.6K.

4.2: Effect of nanofluid concentration on collector efficiency

The efiiciency has been calculated using the Duffie and Beckman equation.[43]

Efficiency equation, $\eta_i = \frac{m\dot{q}}{AG} = \frac{\dot{M}c_p(T_{out}-T_{in})}{AG_T}$

Graphite nanoparticles (volume fraction)	Collector efficiency (percentage)
0	41.20
0.01	42.44
0.025	46.85
0.05	43.29
0.075	30.18
0.1	29.14

Table 5: Calculated efficiencies

A graph of collector efficiency vs graphite nanoparticles has been plotted. It is seen that as the volume of graphite nanoparticles increase the collector efficiency increases up to 0.025 then it starts to decrease gradually till 0.075 concentration of graphite nanoparticles. It has been seen in the works of Gorji(2015) and Otanicar(2010) that after a certain value ,increasing the nanoparticle concentration has no effect on the performance of collector efficiency.The same is observed in this numerical work.This is because increasing the concentration too much will clog the pipes in the collector which will afftect the movement of water and decrease the efficiency. The graph is shown below in Figure 32.

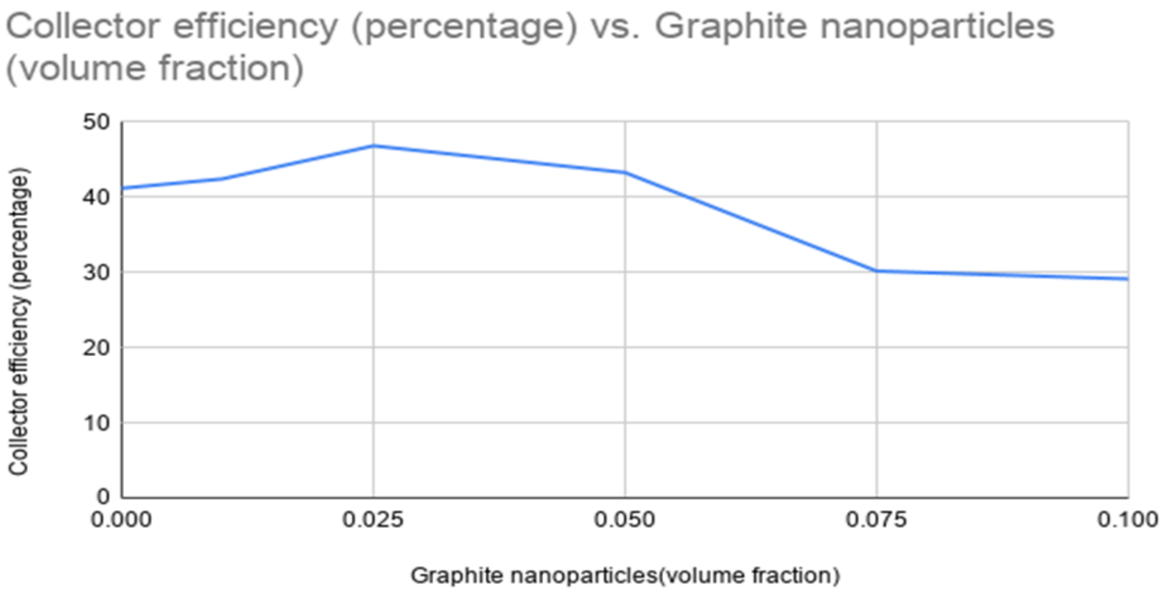


Figure 32: Collector Efficiency vs Graphite Nanoparticle Graph

4.3: Comparison of results

Reference papers	Maximum Collector efficiency(%)
Otanicar(experimental DASC) [1]	54
Otanicar(numerical DASC) [1]	59
Gorji(DASC)[44]	58
Present simulation(Flat plate)	46.85

Table 6: Comparison of Results

All of the above studies have been done with graphite nanoparticles. The maximum efficiency obtained using DASC is close to 60% in both numerical studies of Otanicar and Gorji. For the present simulation an efficiency of 46.85% was achieved. However, the present simulation has been done with flat plate collector and as the heat is transferred indirectly in this type of collector, so the maximum efficiency obtained is expected to be less and this has been observed after the numerical study.

Chapter 5: Conclusion

The use of nanofluids in DASC has been studied thoroughly over the years both numerically and experimentally over the years. The potential of using DASC as domestic hot water system is huge because of it requiring less materials and reaching higher temperature than other collectors. However, this type of collector has not been popular or widely used. Part of this is because there is difficulty in manufacturing nanofluids. The stability of nanofluids is also a challenge because some nanofluids lose their stability after few weeks and then they have to be replaced.

After running the numerical simulation it is seen that using nanofluids, solar collector efficiency of DASC and flat plate increases. The increase in efficiency is lower in flat plate collectors. For flat plate collectors, little change is seen in efficiency for 1% volume fraction of nanoparticles. However, for 2.5% volume fraction the efficiency increases by about 5%. For, 7.5% and 10% volume fraction it is seen that efficiency drops even lower than when only water is used. This might be due to the agglomeration of particles which leads to clogging of pipes. So,it is important that the right quantity of nanoparticle is chosen to make nanofluid.

Future work can be done to navigate ways to increase the stability of nanofluids. Different materials can also be investigated as covers to find out if they increase efficiency of DASC.

References

[1] T. P. Otanicar, P. E. Phelan, R. S. Prasher, G. Rosengarten, and R. A. Taylor, "Nanofluid-based direct absorption solar collector," *J. Renew. Sustain. Energy*, vol. 2, no. 3, p. 033102, May 2010, doi: 10.1063/1.3429737.

[2] H. Esen, M. Inalli, and M. Esen, "Technoeconomic appraisal of a ground source heat pump system for a heating season in eastern Turkey," *Energy Convers. Manag.*, vol. 47, no. 9–10, pp. 1281–1297, Jun. 2006, doi: 10.1016/j.enconman.2005.06.024.

[3] D. Tilman, R. Socolow, J. Foley, J. Hill, … E. L.-, and undefined 2009, "Beneficial biofuels—the food, energy, and environment trilemma," *science.sciencemag.org*.

[4] International Energy Agency, "Electricity Information: Overview," *Stat. iea*, pp. 1–10, 2019.

[5] M. B. Kirkham, "Solar Radiation, Black Bodies, Heat Budget, and Radiation Balance," in *Principles of Soil and Plant Water Relations*, Elsevier, 2014, pp. 453–472.

[6] "The Roman Baths and Solar Heating — Solar House History." .

[7] N. Goel, R. Taylor, T. O.-R. Energy, and undefined 2020, "A review of nanofluid-based direct absorption solar collectors: Design considerations and experiments with hybrid PV/Thermal and direct steam generation collectors," *Elsevier*.

[8] R. U. Senthil Kumar, *Electrical energy generation , utilisation and conversion*. 2018.

[9] G. Tiwari, "Solar energy: Fundamentals, design, modelling and apllications," 2002.

[10] C. Eaton, H. B.-S. Energy, and undefined 1975, "The use of moderate vacuum environments as a means of increasing the collection efficiencies and operating temperatures of flat-plate solar collectors," *Elsevier*.

[11] N. Benz, T. Beikircher, N. Benz, and T. Beikircher, "HIGH EFFICIENCY EVACUATED FLAT-PLATE SOLAR COLLECTOR FOR † PROCESS STEAM PRODUCTION ‡," *Elsevier*, vol. 65, no. 2, pp. 111–118, Feb. 1999, doi: 10.1016/S0038-092X(98)00122-4.

[12] R. Moss, S. S.-C. P. EuroSun, and undefined 2014, "Design and performance of evacuated solar collector microchannel plates," *proceedings.ises.org*.

[13] G. S. F. Shire, R. W. Moss, P. Henshall, F. Arya, P. C. Eames, and T. Hyde, "Development of an Efficient Low- and Medium-Temperature Vacuum Flat-Plate Solar Thermal Collector," in *Renewable Energy in the Service of Mankind Vol II*, Springer International Publishing, 2016, pp. 859–866.

[14] R. Moss, S. Shire, P. Henshall, F. Arya, P. Eames, and T. Hyde, "Performance of evacuated flat plate solar thermal collectors," *Therm. Sci. Eng. Prog.*, vol. 8, pp. 296–306, Dec. 2018, doi: 10.1016/j.tsep.2018.09.003.

[15] F. Asdrubali and U. Desideri, *Handbook of energy efficiency in buildings: A life cycle approach*. Elsevier, 2018.

[16] Ž. J.- rN and undefined 2008, "Classification of solar collectors," *tf.llu.lv*.

[17] H. T.-S. Energy and undefined 1958, "Stationary mirror systems for solar collectors," *Elsevier*.

[18] H. Hinterberger and R. Winston, "Efficient Light Coupler for Threshold Čerenkov Counters ARTICLES YOU MAY BE INTERESTED IN," *Cite as Rev. Sci. Instruments*, vol. 37, no. 8, p. 1094, 1966, doi: 10.1063/1.1720428.

[19] D. Zlesák, "Obnovitelné zdroje energie ve Spojených státech od roku 1850 do roku 1973 Bakalářská práce," 2018.

[20] "Solar Energy Engineering - 2nd Edition." .

[21] P. Eames, B. N.-S. Energy, and undefined 1995, "Thermal and optical consequences of the introduction of baffles into compound parabolic concentrating solar energy collector cavities," *Elsevier*.

[22] N. Abed and I. Afgan, "An extensive review of various technologies for enhancing the thermal and optical performances of parabolic trough collectors," *Int. J. Energy Res.*, vol. 44, no. 7, pp. 5117–5164, Jun. 2020, doi: 10.1002/er.5271.

[23] H. Olia, M. Torabi, M. Bahiraei, M. H. Ahmadi, M. Goodarzi, and M. R. Safaei, "Application of nanofluids in thermal performance enhancement of parabolic trough solar collector: State-of-the-art," *Applied Sciences (Switzerland)*, vol. 9, no. 3. MDPI AG, Jan.

2019, doi: 10.3390/app9030463.

[24] "Clean Energy for Sustainable Development - 1st Edition." .

[25] Y. Tripanagnostopoulos, C. Siabekou, and J. K. Tonui, "The Fresnel lens concept for solar control of buildings," *Sol. Energy*, vol. 81, no. 5, pp. 661–675, May 2007, doi: 10.1016/j.solener.2006.08.013.

[26] "Linear Fresnel Reflector - Green Clean Guide." .

[27] W. van Sark, B. C.-T. L. in the T. to a Low, and undefined 2020, "Concentrating solar power," *Elsevier*.

[28] "(PDF) Introduction of solar collectors and energy and exergy analysis of a heliostat plant."

[29] S. K.-P. in energy and combustion science and undefined 2004, "Solar thermal collectors and applications," *Elsevier*.

[30] M. Karami, M. Akhavan-Bahabadi, … S. D.-… and S. E., and undefined 2015, "Experimental investigation of CuO nanofluid-based direct absorption solar collector for residential applications," *Elsevier*.

[31] P. Phelan, T. Otanicar, R. Taylor, and H. Tyagi, "Trends and opportunities in direct-absorption solar thermal collectors," *J. Therm. Sci. Eng. Appl.*, vol. 5, no. 2, May 2013, doi: 10.1115/1.4023930.

[32] 454,865 BJ Tammen - US Patent 4 and undefined 1984, "Liquid metal solar power system."

[33] C. S. Power, "Technology Roadmap Concentrating Solar Power," *Current*, vol. 5, pp. 1–52, 2010.

[34] A. H. Elsheikh, S. W. Sharshir, M. E. Mostafa, F. A. Essa, and M. K. Ahmed Ali, "Applications of nanofluids in solar energy: A review of recent advances," *Renew. Sustain. Energy Rev.*, vol. 82, no. November, pp. 3483–3502, 2018, doi: 10.1016/j.rser.2017.10.108.

[35] S. Chakraborty and P. K. Panigrahi, "Stability of nanofluid: A review," *Appl. Therm. Eng.*, vol. 174, no. March, 2020, doi: 10.1016/j.applthermaleng.2020.115259.

[36] M. Simonetti, F. Restagno, E. Sani, and M. Noussan, "Numerical investigation of direct

absorption solar collectors (DASC), based on carbon-nanohorn nanofluids, for low temperature applications," *Sol. Energy*, vol. 195, pp. 166–175, Jan. 2020, doi: 10.1016/j.solener.2019.11.044.

[37] E. Natarajan and R. Sathish, "Role of nanofluids in solar water heater," *Int. J. Adv. Manuf. Technol.*, pp. 3–7, 2009, doi: 10.1007/s00170-008-1876-8.

[38] M. Vakili, S. M. Hosseinalipour, S. Delfani, and S. Khosrojerdi, "Photothermal properties of graphene nanoplatelets nanofluid for low-temperature direct absorption solar collectors," *Sol. Energy Mater. Sol. Cells*, vol. 152, pp. 187–191, Aug. 2016, doi: 10.1016/j.solmat.2016.01.038.

[39] M. Karami, M. A. Akhavan-Bahabadi, S. Delfani, and M. Raisee, "Experimental investigation of CuO nanofluid-based Direct Absorption Solar Collector for residential applications," *Renewable and Sustainable Energy Reviews*, vol. 52. Elsevier Ltd, pp. 793–801, Aug. 22, 2015, doi: 10.1016/j.rser.2015.07.131.

[40] N. Brekke, T. Otanicar, D. DeJarnette, and P. Hari, "A Parametric Investigation of a Concentrating Photovoltaic/Thermal System with Spectral Filtering Utilizing a Two-Dimensional Heat Transfer Model," *J. Sol. Energy Eng. Trans. ASME*, vol. 138, no. 2, Apr. 2016, doi: 10.1115/1.4032452.

[41] Y. L. Hewakuruppu *et al.*, "Limits of selectivity of direct volumetric solar absorption," *Sol. Energy*, vol. 114, pp. 206–216, Apr. 2015, doi: 10.1016/j.solener.2015.01.043.

[42] T. A. Cooper *et al.*, "Contactless steam generation and superheating under one sun illumination," *Nat. Commun.*, vol. 9, no. 1, pp. 1–10, Dec. 2018, doi: 10.1038/s41467-018-07494-2.

[43] J. Duffie and W. Beckman, *Solar engineering of thermal processes*. 2013.

[44] T. B. Gorji and A. A. Ranjbar, "Geometry optimization of a nanofluid-based direct absorption solar collector using response surface methodology," *Sol. Energy*, vol. 122, pp. 314–325, Dec. 2015, doi: 10.1016/j.solener.2015.09.007.

~*~