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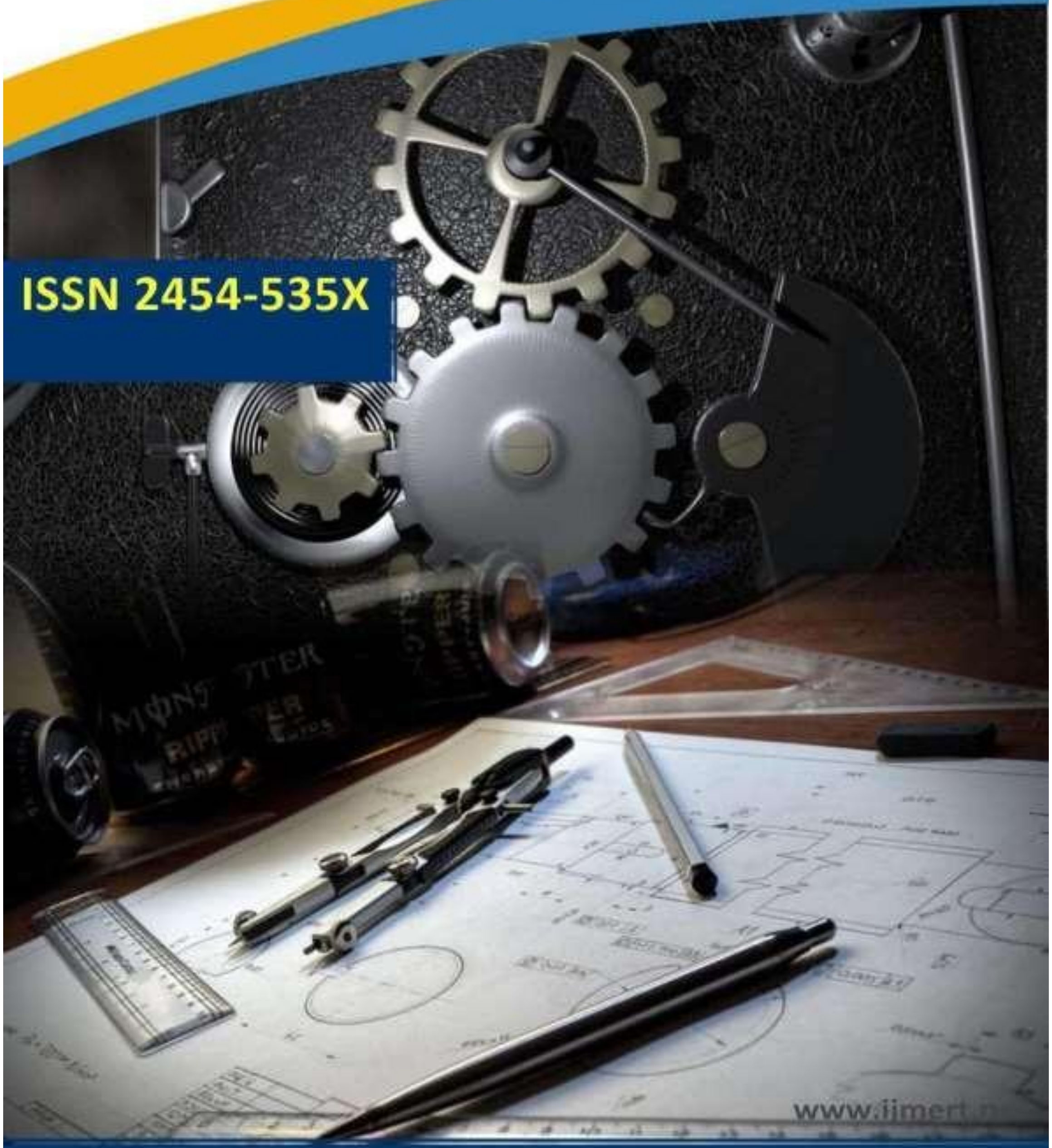

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THERMAL AND FLOW ANALYSIS OF A PARABOLIC TROUGH COLLECTOR USING CFD WITH NANOFLUIDS

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ABSTRACT

Parabolic Trough Collectors (PTCs) represent one of the most mature and commercially deployed technologies in Concentrated Solar Power (CSP) systems. The thermal performance of PTC systems strongly depends on the thermophysical properties of the working fluid circulating inside the absorber tube. Conventional heat transfer fluids such as water exhibit limited thermal conductivity, which restricts system efficiency. To overcome this limitation, nanofluids have emerged as promising advanced heat transfer media.

This study presents a comprehensive Computational Fluid Dynamics (CFD) analysis of a parabolic trough collector using ANSYS Fluent. Water-based nanofluids containing CuO, Al_2O_3, TiO_2, and SiO_2 nanoparticles at 0.2 volumetric concentration were investigated. The finite volume method was used to solve the governing continuity, momentum, and energy equations under steady-state conditions. Solar radiation effects were modeled using the Solar Load Model combined with the Surface-to-Surface (S2S) radiation model.

Keywords: Parabolic Trough Collector, Nanofluids, CFD, ANSYS Fluent, Solar Load Model, Heat Transfer Enhancement

1. INTRODUCTION

Growing global energy demand and environmental concerns associated with fossil fuels have accelerated the development of renewable energy technologies. Among them, solar energy remains the most abundant and sustainable source. Concentrated Solar

Power (CSP) systems use reflective optics to concentrate direct solar radiation onto a receiver, converting solar energy into thermal energy.

Among CSP technologies, the Parabolic Trough Collector (PTC) is the most widely deployed linear concentrating system. PTCs typically operate at temperatures up to 390–550°C depending on the working fluid. However, system performance is constrained by the limited thermal conductivity of conventional fluids such as water and synthetic oils.

Nanofluids—engineered suspensions of nanoparticles in base fluids—have demonstrated improved thermal properties, including:

- Increased thermal conductivity
- Enhanced convective heat transfer
- Improved energy transport capability

This study numerically investigates the influence of CuO, Al_2O_3, TiO_2, and SiO_2 nanofluids on the thermal performance of a PTC system using CFD simulation.

1.1.1 SOLAR ENERGY

Solar energy is harnessed by converting solar energy directly into electrical energy in solar plants. Photosynthesis process carries out this process of conversion of solar energy. In photosynthesis, green plants absorb solar energy and convert it into chemical energy.

Solar energy is an essential energy of all non-conventional sources but its usage amount is very less. It is the most important non-conventional source of energy and it gives non-polluting environment-friendly output and is available in abundant.

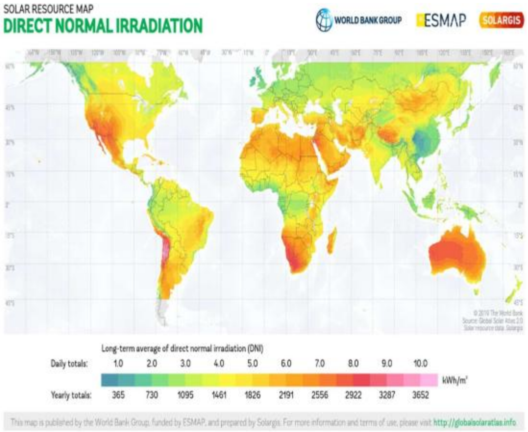


Figure 1.1: Map showing Direct normal irradiation of different countries

1.1 ROLE OF RENEWABLE ENERGY

Renewable energy (RE) utilisation is not new. A little more than 150 years ago, people were capable to create technology to extract energy from biomass. As the use of coal, petroleum and natural gas expanded, people became less reliant on bioenergy. Today, the world again are looking at renewable energy resources to meet growing energy demand. Global energy consumption by fuels over the last 48 years (1965 to 2013) is shown in Figure 1.2 (EC, 2014).

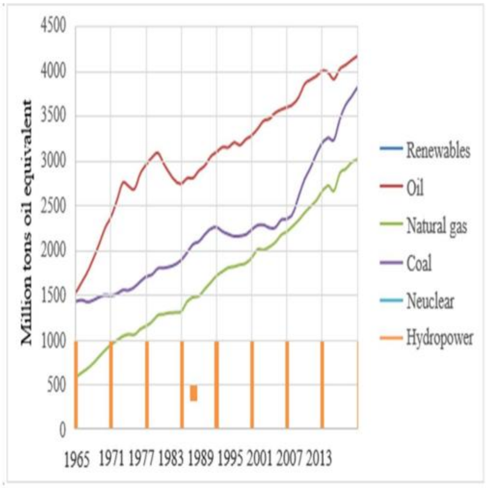
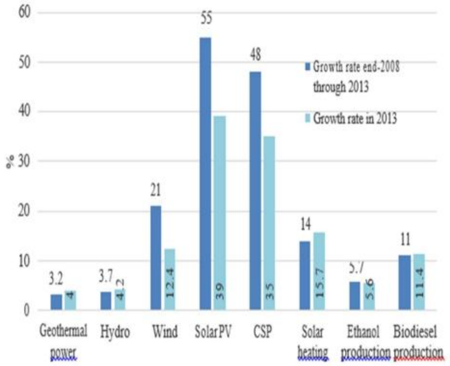


Figure 1.2: Global energy consumption by fuels (EC, 2014)



However according to Figure 1.3 (REGS, 2014), in 2012 RE shared 19% of global energy consumption and sustained to grow significantly in 2013. About 9% RE share (traditional or solid biomass) in 2012 was used for household primary energy consumption. The rest 10% of RE (modern renewables: solar/ geothermal/ wind/ hydro/ biomass /biofuels) share was used in four distinct sectors: electricity generation, cooling and heating, fuel transportation and rural off-grid services. Modern renewables' uses increase dramatically due to slow migration away from traditional biomass and increased energy demand.

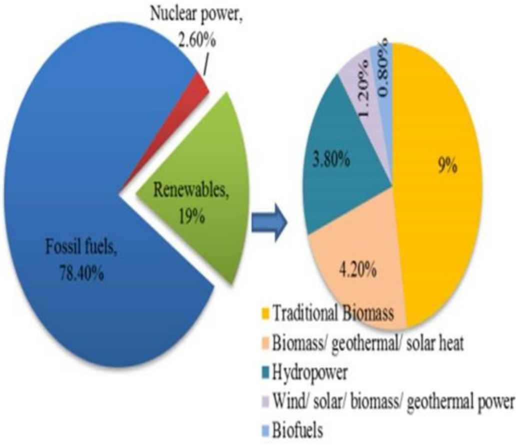


Figure 1.3: Estimated global final renewables share of energy consumption, 2012 (REGS, 2014).

Figure 1.4: Annual Renewable Energy Capacity Growth Rates, End 2008–2013 and in 2013 (REGS,

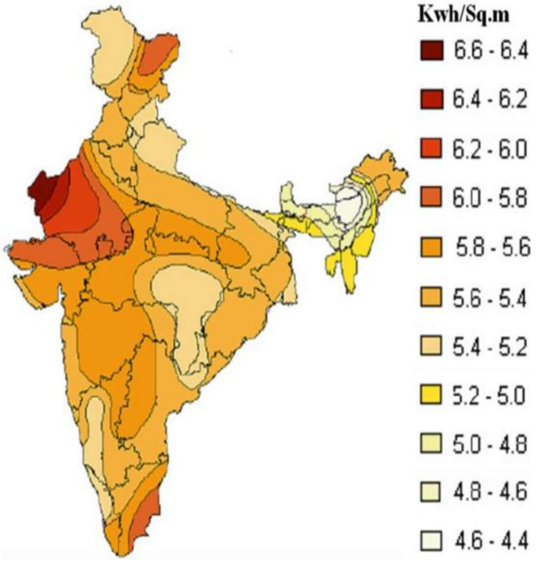
2014)

2. LITERATURE REVIEW

Recent investigations have explored the impact of metal-oxide nanoparticles in solar collectors. Hamzat (2025) reported thermal efficiency improvements exceeding 100% using CuO and TiO_2 nanofluids. Soudani (2025) highlighted seasonal performance variations among Al_2O_3, CuO, TiO_2, and SiO_2 nanofluids.

Munusamy (2025) demonstrated that CuO-water nanofluid yields superior Nusselt number enhancement due to higher intrinsic thermal conductivity. Bamisile (2024) analyzed thermodynamic efficiency improvements using hybrid nanofluids and reported reduced entropy generation.

However, most studies focus on low nanoparticle concentrations. Limited research evaluates high volumetric fractions under solar load modeling conditions using detailed CFD radiation coupling. This work addresses that gap.



1.1 SOLARENERGY POTENTIAL IN INDIA

Now a day’s most of the countries are emphasizing on the development of renewable energy resources. In the renewable energy resources , solar energy plays important role and it is a tremendous sources of energy. The sun is the planet’s most powerful source of energy and also the most unused source of energy by humans. The rate of energy received by the earth from solar energy is approximately 1,20,000 TW.

Figure 1.5: Global horizontal irradiance of India map

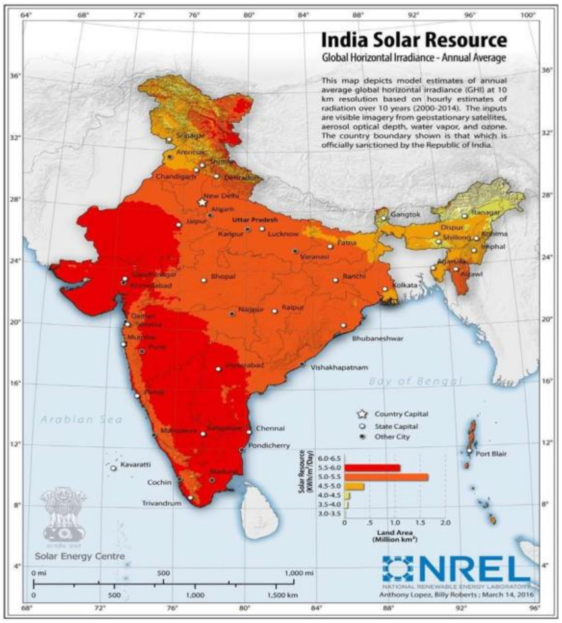


Figure 1.6: solar irradiation values of Indian geographical area

3.PARABOLIC TROUGH COLLECTOR MODEL

The thermal energy is removed by the heat transfer fluid (e.g. synthetic oil, molten salt) flowing in the heat-absorbing pipe and transferred to a steam generator to produce the super-heated steam that drives the turbine [3]. Once the fluid transfers its heat, it is recirculated into the system for reuse. The steam is also cooled, condensed and reused.Furthermore, the heated fluid in Solar Parabolic trough technology can also provide heat to thermal storage systems, which can be used to generate electricity at times when the sun is not shining. Most PT plants currently in operation have capacities between 30-100 MW, efficiencies of around 14-16% (i.e. the ratio of solar irradiance power to net electric output) and maximum operating temperatures of 390°C, which is limited by the degradation of synthetic oil used for heat transfer. The use of molten salt at 550°C and water-steam at 500°C for heat transfer purposes in PT plants is under investigation. High temperature molten salt may increase both plant efficiency (e.g. 15%-17%) and thermal storage capacity.

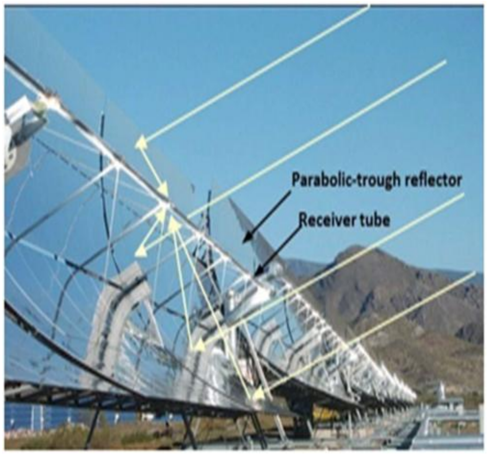


Figure 1.7. Parabolic-trough collector

The PTC consists of:

- Parabolic reflector (Aluminium)
- Copper absorber tube
- Working fluid domain
- Single-axis solar tracking

Geometric Parameters

Parameter	Value
Length	2 m
Aperture Width	1.5 m
Focal Length	0.375 m

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Parameter	**Value**
Rim Angle	90°
Reflectivity	0.9

Absorber Tube:

Parameter	**Value**
Inner Diameter	0.038 m
Outer Diameter	0.042 m
Length	2 m
Absorptivity	0.94

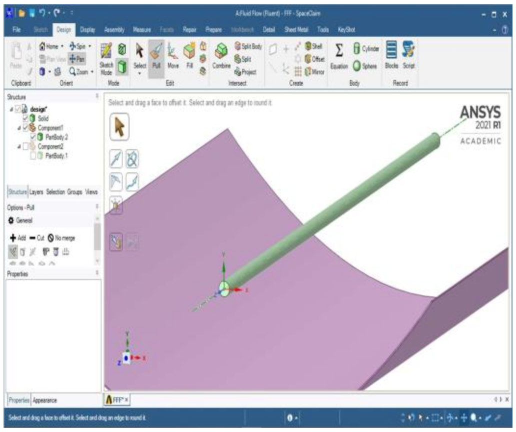
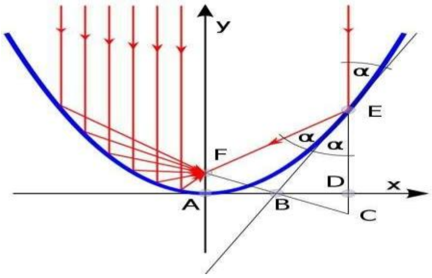


Figure 5.3: Fluid domain model designed in space claim

COLLECTOR GEOMETRY:

The collector, the parabolic trough, is a trough the cross-section of which has the shape of a part of a parabola. More exactly, it is a symmetrical section of a parabola around its vertex.

Parabolic troughs have a focal line, which consists of the focal points of the parabolic cross-sections. Radiation that enters in a plane parallel to the optical plane is reflected in such a way that it passes through the focal line.



4. NANOFLUID PROPERTIES

Nanoparticles used:

- CuO
- Al_2O_3
- TiO_2
- SiO_2

Average particle size: 20–60 nm
Volumetric concentration: 0.2

Thermophysical properties were calculated using standard mixture models:

Density:

$$\rho_{nf} = \phi\rho_{np} + (1-\phi)\rho_{bf}$$

Specific Heat:

$$C_{nf} = \frac{\phi \rho_{np} C_{p,np} + (1-\phi)\rho_{bf} C_{p,bf}}{\rho_{nf}}$$

Thermal Conductivity: Maxwell Model applied.

Viscosity:

$$\mu_{nf} = \mu_{bf}(1-\phi)^{-2.5}$$

3.1 KEY COMPONENTS OF PARABOLIC TROUGH COLLECTOR:

Key components of Parabolic Trough based system can be classified on the basis of their individual functions:Collector Receiver Trough stand Tracking system

3.1.1 COLLECTOR:

The collector of a parabolic trough is an assembly of curved shaped reflectors arranged on a structural steel framework. The reflectors are arranged so as to give a parabolic shape and reflect the incident solar radiation onto to a tubular receiver.

Figure 3.4: (a) Mirror (b) support structure

Specifications:

TYPE	SPECIFICATION

Glass mirror	Material – Tempered and toughened solar grade glass tested for scratches and durability Shape - parabolic Thickness – 3-4 mm Reflective coating – silver back coating Specular reflectivity – more than 93% Protective coating – edge sealing coat on all sides of mirrors cut in different sizes after rubbing and cleaning them properly
Glass mirror	Special weather protection coat to be made for mirrors to be used in coastal and colder regions Strength & durability – applicable standards ISO 6270-2:2005,ISO 9227:2012
Silver reflective film backed by Aluminium	Material – painted (polyesters, acrylics and epoxy/polyester paints) Aluminium substrate Substrate thickness- 0.38- 0.50 mm Shape- parabolic Reflective coating – solar grade silver film of 0.10-0.12 mm thickness Edge sealing – use of edge tape/caulk Specular Reflectivity – more than 94% Strength & durability – EN 485-2:2008; ASTM D882; ISO 9227:2012
Solar grade anodized aluminium reflector	Material – Solar Grade Anodized Aluminium substrate Shape – Parabolic Thickness – 0.3 – 0.8mm Reflective Coating – PVD (Physical Vapour Deposition) coating Specular Reflectivity – at least 88 %

	Protective Coating – Solar lacquer/Teflon coating/Epoxy coating for corrosion protection Strength & Durability – ISO 9227:2012, ISO 4623,EN 485-2: 2008; ASTM D882

Table 3.1: Specifications of collector

3.1.2 RECEIVER:

The receiver of parabolic trough is placed at the line focus of a trough so as to capture the solar radiation and transfer the same to the thermal medium used in the system. In India, the receiver being used is evacuated/non-evacuated type comprising of a linear absorber constructed of a metallic tube surrounded by a glass tube.

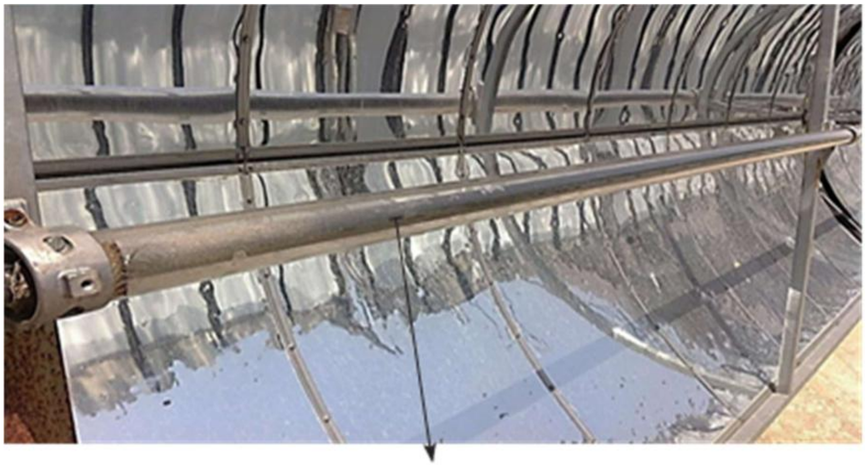


Figure 3.5: Receiver

Specifications:

SUB COMPONENTS	SPECIFICATION
Absorber	Design – Linear round tube Material – Stainless Steel 304 grade Thickness – 1 - 2mm Diameter – 25 - 35 mm Durability – Minimum 10 years

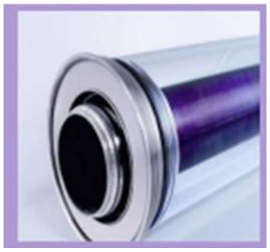
Absorber coating	Material – Black Chrome/ Solar grade absorber paint/Selective Coating (AS (C2-80)) Absorptivity – 0.90 – 0.95 Emissivity – 0.09 - 0.15
Glass cover	Design - Linear round tube Material - Borosilicate glass Transitivity – At least 95% Thickness – 2 - 3mm Diameter – 50 - 80 mm Durability – Minimum 10 years
Absorber glass fixing	Glass to Metal sealing methods – Matched thermal expansion seal and unmatched thermal expansion sea  Figure 3.6: absorber glass fixing
Receiver fixing	A receiver is fixed on to a mirror support structure with the help of standard steel sections/angles, die cast Aluminium clamps and fasteners and should have adequate expansion provision.

Table 3.2: Specifications of receiver

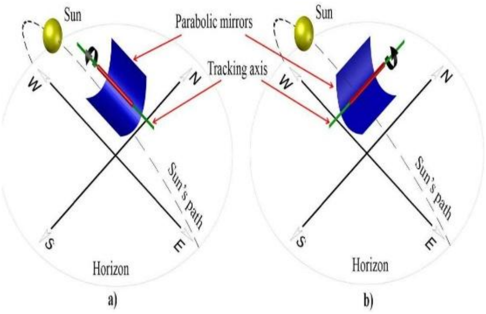
3.1.3 TROUGH STAND:

The basic framework of a trough stand is a steel structure. The structure is designed so as to withstand wind speed in an operating condition as well as in parked stage as per the existing structural design code. Overall system rests on a civil foundation made for the purpose.

Figure 3.7: Trough stand

3.1.4 RACKING SYSTEM:

A PTC uses direct solar radiation as a heat source. As the sun’s relative position changes every second, a solar tracking system is needed to improve its efficiency. Two types of solar tracking are used in PTCs namely, north-south and east-west, as represented in below figure.



(a) north-south (b) east-west.

Figure 3.8: Common tracking methods

5.1 MESH:

Discretization of the given geometry in to smaller number of cells is called meshing. The purpose of meshing is to actually make the problem solvable using finite element.

By meshing we can break down the domain in to number of pieces, each piece representing an element or cell. need these elements to apply finite element since, finite element is about solving the elements to get a local solution and combining all these solutions of elements to build the global solution for the problem. Another aspect of meshing is the accuracy

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of the solution. A refined mesh will generate an accurate global solution.

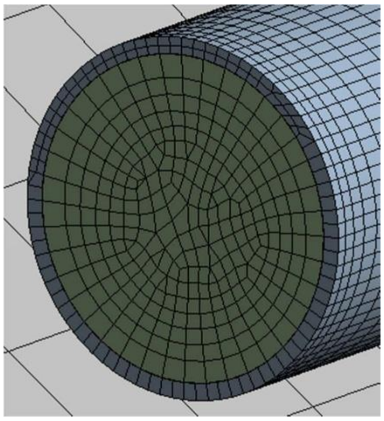


Figure 5.4: Mesh of fluid domain

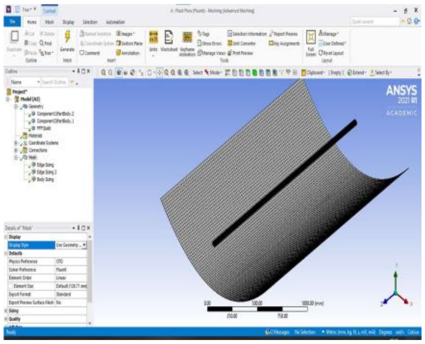
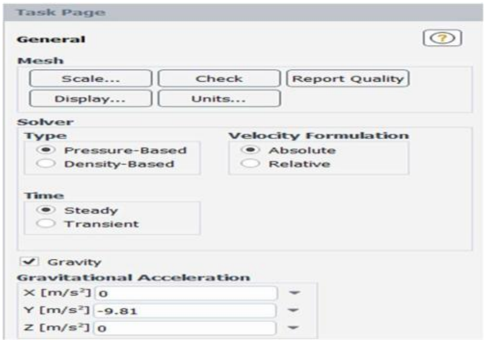


Figure 5.5: Meshed domain

5.2 SET UP:

The analysis has to be done using fluent solver. The set up will launch a fluent solver which is used to apply physics and solver configuration of the analysis. In the schematic double-clicking the set up will launch the ANSYS Fluent. When the ANSYS Fluent is first started fluent launcher is displayed, allowing to view and set certain ANSYS FLUENT start-up options. The mesh is automatically loaded and displayed in the graphics window by default when fluent setup is started. Double precision and parallel processing option has been selected for a faster and more accurate solution.

5.2.1 GENERAL PROPERTIES:



Solver

Type
● Pressure-Based
○ Density-Based

Velocity Formulation
● Absolute
○ Relative

Time
● Steady
○ Transient

☑ Gravity

Gravitational Acceleration
X [m/s²] 0
Y [m/s²] -9.81
Z [m/s²] 0

The steady model has been selected as the analysis being done is not a time dependent analysis, and gravity i.e. acceleration due to gravity of 9.81 m2/s is applied in negative Y direction.

5.2.2 MATERIALS:

This section involves copying the required materials that are to be assigned for the components of the model, from the ANSYS FLUENT material database and defining the materials that are not available in the database. The required materials are aluminium, copper, water, water based Al2O3, CuO, SiO2, Ti2 Nano fluid.

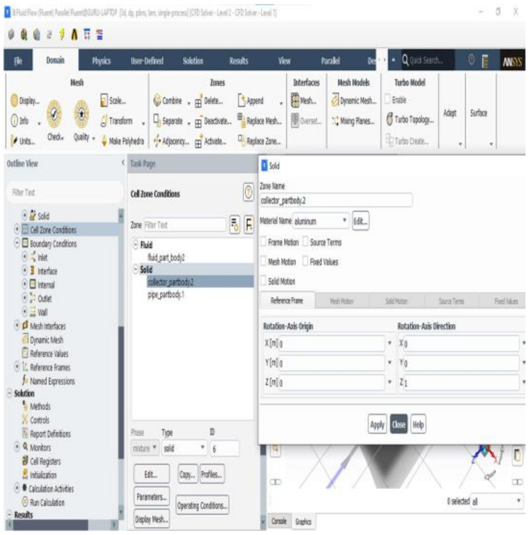
Material	Density(kg/m3)	Specific heat(J/kg-K)	Thermal conductivity (W/m-K)	Viscosity (kg/m-s)
Aluminium	2719	871	202.4	-
Copper	8978	381	387.6	-
Silicon	2220	703	1.38	-
Titanium	4250	686.2	8.9	-
Water	997.1	4178	0.61	0.000853

Table 5.4: Physical properties of materials

5.1.1 CELL ZONE CONDITIONS:

This section involves assigning the material to the respective components of the model as per the specification. So the material assignment is as follows

Parabolic trough [collector]:
Aluminium Absorber tube: Copper
Fluid domain: water, Nano fluids.



Solid

Zone Name: collector_partbody.2

Material Name: aluminum

☐ Frame Motion ☐ Source Terms

☐ Mesh Motion ☐ Fixed Values

☐ Solid Motion

Reference Frame

Rotation-Axis Origin	Rotation-Axis Direction
X [m] 0	X 0
Y [m] 0	Y 0
Z [m] 0	Z 1

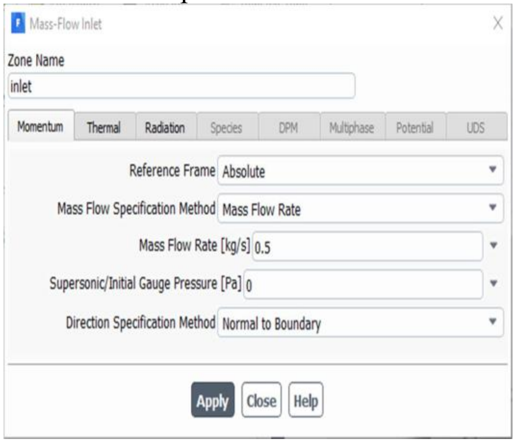
Phase: mixture Type: solid ID: 6

Figure 5.9: cell zone condition for PTC

5.1.2 BOUNDARY CONDITIONS:

Various boundary conditions are applied for the wall boundaries created for solving the governing equations. They are

Inlet: mass flow rate inlet with 0.5 kg/s and fluid inlet temperature of 300K.



Zone Name: inlet

Reference Frame: Absolute

Mass Flow Specification Method: Mass Flow Rate

Mass Flow Rate [kg/s]: 0.5

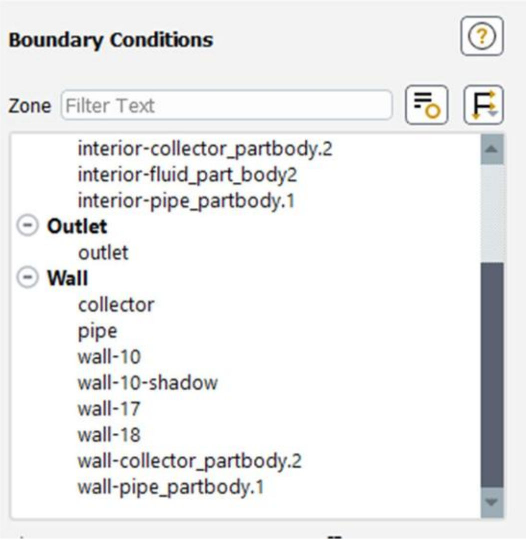
Supersonic/Initial Gauge Pressure [Pa]: 0

Direction Specification Method: Normal to Boundary

Figure 5.10: inlet boundary condition

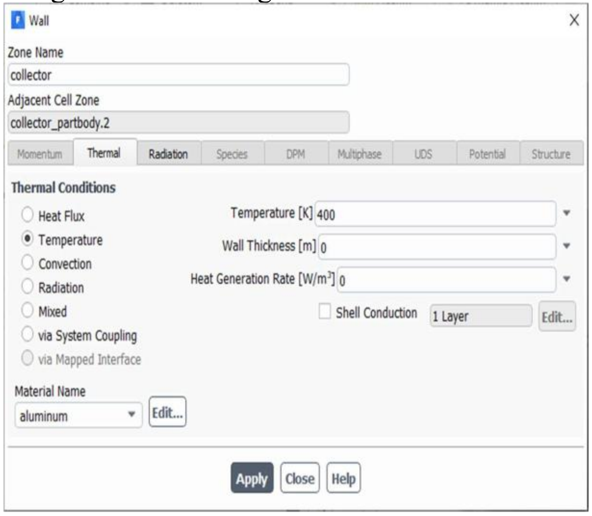
Outlet: it is assigned as outflow condition

The walls that are generated by the mesh are shown in the given below.



interior-collector_partbody.2
interior-fluid_part_body2
interior-pipe_partbody.1
Outlet
outlet
Wall
collector
pipe
wall-10
wall-10-shadow
wall-17
wall-18
wall-collector_partbody.2
wall-pipe_partbody.1

Figure 5.11: Walls generated



Zone Name: collector

Adjacent Cell Zone: collector_partbody.2

Thermal Conditions

○ Heat Flux
● Temperature
○ Convection
○ Radiation
○ Mixed
○ via System Coupling
○ via Mapped Interface

Temperature [K]: 400

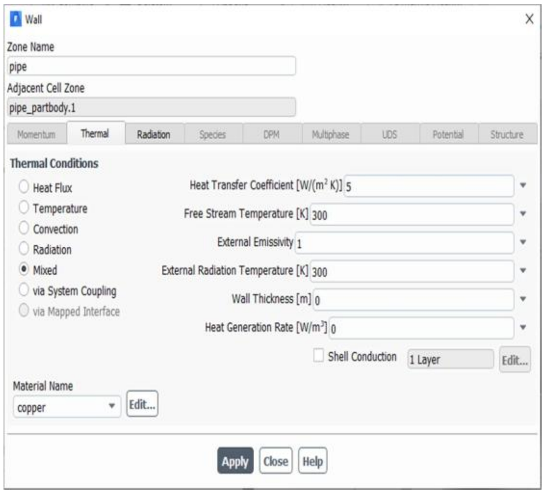
Wall Thickness [m]: 0

Heat Generation Rate [W/m³]: 0

☐ Shell Conduction 1 Layer

Material Name: aluminum

Figure 5.12: Boundary condition for collector



Zone Name: pipe
Adjacent Cell Zone: pipe_partbody.1

Thermal Conditions
○ Heat Flux
○ Temperature
○ Convection
○ Radiation
● Mixed
○ via System Coupling
○ via Mapped Interface

Heat Transfer Coefficient [W/(m² K)] 5
Free Stream Temperature [K] 300
External Emissivity 1
External Radiation Temperature [K] 300
Wall Thickness [m] 0
Heat Generation Rate [W/m³] 0
☐ Shell Conduction 1 Layer Edit...

Material Name: copper Edit...

Figure 5.13: Boundary condition for absorbing surface wall

For all other walls that are generated coupled thermal condition is applied with the respective radiation parameters and participation in solar ray tracing is enabled.

After that view factor file is computed in the radiation model for the calculation of view factors between the components involving in the radiation.

5. NUMERICAL METHODOLOGY

5.1 Governing Equations

Continuity:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0$$

Momentum:

$$\rho(\vec{u} \cdot \nabla)\vec{u} = -\nabla p + \mu \nabla^2 \vec{u} + \rho g$$

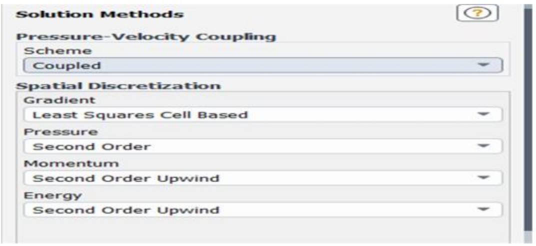
Energy:

$$\rho C_p(\vec{u} \cdot \nabla T) = k \nabla^2 T + S_T$$

Different governing equations of mass, momentum and energy are solved through the finite volume method using pressure based segregated spatially implicit solver. Analysis is carried out for stead state condition to observe the temperature raise in working fluid due to absorption of energy.

5.1.3 SOLUTION METHODS:

In this section methods to solve the governing equations of mass, momentum and energy is selected. Coupled scheme is selected in the pressure- velocity coupling.


Solution Methods

Pressure-Velocity Coupling
Scheme: Coupled

Spatial Discretization
Gradient: Least Squares Cell Based
Pressure: Second Order
Momentum: Second Order Upwind
Energy: Second Order Upwind

Figure 5.14: Solution methods

5.2 CFD Setup

Software: ANSYS Fluent R18
Solver: Pressure-based, steady state

Viscous model: Laminar
Radiation:

- Surface-to-Surface (S2S)
- Solar Load Model

Solar radiation at Tirupati (13°N, 79°E):

Parameter	**Value**
Direct Normal Irradiation	878 W/m²
Diffuse Irradiation	117 W/m²

Boundary Conditions:

- Inlet: Mass flow rate = 0.5 kg/s
- Inlet Temperature = 300 K
- Outlet: Outflow

6. RESULTS AND DISCUSSION

6.1 Water as Base Fluid

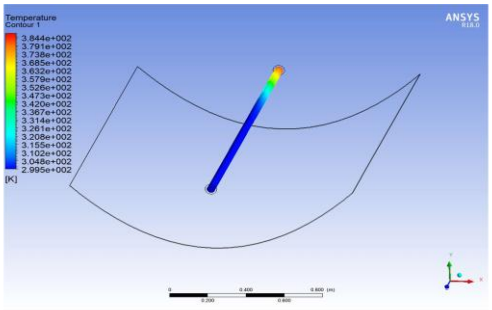


Figure 6.1: Temperature contour with water as working fluid

Outlet Temperature: 380 K
Outlet Velocity: 0.37 m/s

Temperature gradient shows maximum heat absorption near absorber wall.

6.2 Nanofluid Performance Comparison

Nanofluid	**Outlet Temp (K)**	**Velocity (m/s)**
CuO	395.3	0.40
SiO_2	392.1	0.397
Al_2O_3	385.7	0.39
TiO_2	386.6	0.386

CuO exhibits highest enhancement due to:

- Higher thermal conductivity (20 W/mK)
- Improved convective heat transfer
- Stronger absorption capability

Nanofluids Volumetric Concentration (%)	**Water Concentration [%]**	**Maximum Temperature [k]**	**Maximum Velocity [V](m/s)**
CUO – 0.2	0.8	395.3	0.40
SiO2 – 0.2	0.8	392.1	0.397
Al2O3 – 0.2	0.8	385.7	0.39
Ti2 – 0.2	0.8	386.6	0.386

Table: Maximum outlet temperature and velocity of CUO, SiO2, Al2O3 and Ti2 – water nanofluids

6.3 Thermal Enhancement Mechanism

Enhancement is attributed to:

- Increased thermal conductivity
- Brownian motion effects
- Improved energy transport
- Higher Nusselt number

However, higher concentration increases viscosity, leading to increased pumping power.

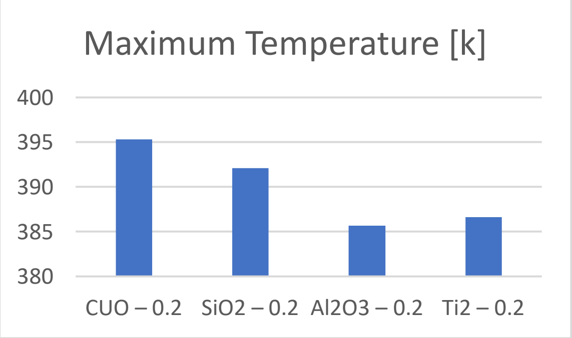
7. CONCLUSION

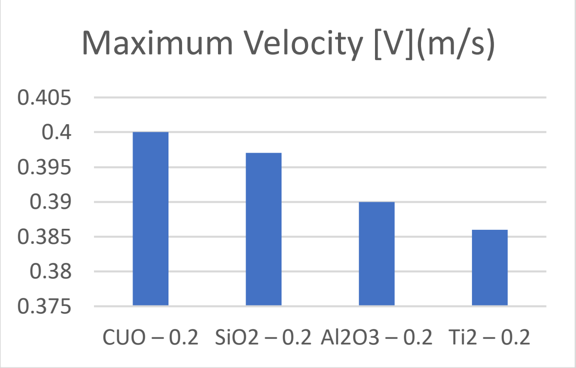
This study performed a detailed CFD-based thermal and flow analysis of a Parabolic Trough Collector using water-based nanofluids.

Key findings:

1. Nanofluids significantly improve outlet temperature compared to pure water.
2. CuO-water nanofluid delivers maximum thermal enhancement (395.3 K).
3. Velocity profiles improve due to enhanced energy absorption.
4. Solar load modeling accurately predicts realistic radiation effects.
5. High concentration improves heat transfer but may increase hydraulic losses.

Nanofluids present a promising solution for improving CSP performance.





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