CFD SIMULATION OF HEAT TRANSFER IN AN EVACUATED TUBE COLLECTOR

By

Ankit G. Fanasiya

14MMET07

NIRMA UNIVERSITY
INSTITUTE OF TECHNOLOGY
NAAC ACCREDITED 'A' GRADE

DEPARTMENT OF MECHANICAL ENGINEERING

INSTITUTE OF TECHNOLOGY
NIRMA UNIVERSITY

AHMEDABAD-382481

MAY 2016

CFD SIMULATION OF HEAT TRANSFER IN AN EVACUATED TUBE COLLECTOR

Major Project

Submitted in partial fulfillment of the requirements

For the Degree of

Master of Technology in Mechanical Engineering (Thermal Engineering)

By

Ankit G. Fanasiya

(14MMET07)

Guided By

Dr. V. J. Lakhera

DEPARTMENT OF MECHANICAL ENGINEERING

INSTITUTE OF TECHNOLOGY
NIRMA UNIVERSITY

AHMEDABAD-382481

MAY 2016

Declaration

This is to certify that

1. The thesis comprises my original work towards the degree of Master of Technology in Thermal Engineering at Nirma University and has not been submitted elsewhere for a degree or diploma.

2. Due acknowledgement has been made in the text to all other material used.

Ankit G. Fanasiya

14MMET07

Undertaking for Originality of the Work

I, **Ankit G. Fanasiya**, Roll. No. **14MMET07**, give undertaking that the Major Project entitled "**CFD Simulation of Heat Transfer in an Evacuated Tube Collector**" submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in **Mechanical Engineering (Thermal Engineering)** of Nirma University, Ahmedabad, is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

Signature of Student

Date:

Place: Nirma University, Ahmedabad.

Endorsed by

(Signature of Guide)

Certificate

This is to certify that the Major Project Report entitled "**CFD Simulation of Heat Transfer in an Evacuated Tube Collector**" submitted by **Mr. Ankit G. Fanasiya (14MMET07)**, towards the partial fulfillment of the requirements for the award of Degree of **Master of Technology in Mechanical Engineering (Thermal Engineering)** of Institute of Technology, Nirma University, Ahmadabad is the record of work carried out by him under our supervision and guidance. In our opinion, the submitted work has reached a level required for being accepted for examination.The result embodied in this major project, to the best of our knowledge, has not been submitted to any other University or Institution for award of any degree.

Dr. V. J. Lakhera
Professor,
Department of Mechanical Engineering,
Institute of Technology,
Nirma University,
Ahmedabad.

Dr. R. N. Patel
Professor and Head,
Department of Mechanical Engineering,
Institute of Technology,
Nirma University,
Ahmedabad.

Dr. P. N. Tekwani
Director,
Institute of Technology,
Nirma University,
Ahmedabad.

Acknowledgments

I take this opportunity to express deep sense of gratitude and sincere thanks for the invaluable assistance that I have received from my honorable and learned guide Prof V J Lakhera (Professor, Mechanical Engineering Department, IT, NU). He is the constant source of encouragement and momentum that any intricacy becomes simple. I gained a lot of invaluable guidance and prompt suggestions from him during my thesis work. I remain indebted of him forever and I take pride to work under him. I would also like to thanks Dr R N Patel (HOD, Department of Mech. Engg., IT, NU). I am very thankful to Dr P N Tekwani (Director, IT, NU) and all the faculty members of Mechanical Engineering Department who have directly or indirectly helped me during this dissertation work specially Dr S V Jain and Dr A M Lakdawala. I also thank my juniors Nihar Thakkar, Taha Poonawala and Aniket Patel for their cooperation and support. My special thanks to my friends of M.Tech Thermal Engineering specially Mehul Rana and Akash Pandya. At the end I am thankful to god, my family, and colleagues who have directly or indirectly helped me during this dissertation work and for their encouragement.

ANKIT G. FANASIYA

Abstract

Evacuated tube collectors (ETC) are more attractive alternative to flat plate collectors. ETC evacuated tube solar collectors convert energy from the sun into usable heat in a solar water heating system. This energy can be used for domestic and commercial hot water heating, pool heating, space heating or even air conditioning. The present study attempts to investigate the characteristic of water-in-glass evacuated tube collectors. A geometric model of the ETC and tank is prepared in ANSYS and the same is subjected to CFD analysis in Fluent. The CFD study of ETC revealed that for a 30^o tilt angle, the temperature profile in the storage tank provided the maximum temperature gain due to a reduced gravitational head. For the enhancement of heat transfer within an ETC, devices such as twisted tape inserts can be employed. In the present study, the ETC was modelled and analysed with and without twisted tape inserts. The numerical study done using twisted tape inserts in an ETC collector revealed that there is an appreciable increase in storage tank temperature as compared to a simple ETC collector. Considering a width/pitch ratio of 1:1 for the twisted tape insert indicated the fastest temperature rise in the storage tank.
Keywords: Twisted tape inserts, Evacuated tube

Contents

List of Figures

List of Tables

Nomenclature

A_s	The area of the heat transfer section, m^2
A_c	Cross section area of tube, m^2
dF	Difference between the weight of luid,N
$d\rho$	density diference between the hot and cold fluid columns,kg/m^3
g	Gravitional acceleration, m/s^2
dV	volume of fluid, m^3
β	Thermal expansion coeficient, $1/K$
dT	Tempearture diference between the hot and cold fluid columns, K
h	Vertical distance, m
C_p	the specific heat of water,4180 $J/kg.K$
u	average flow velocity in the tube,m/s
$\dot{m}$	the natural circulation flow rate throgh the evacuated tube,kg/s
q	heat transfer rate ,W/m^2
dp	pressure difference, Pa
$\triangle P_f$	pressure drop due to friction, Pa
f	friction factor,
Re	Reynolds Number
$\overline{h}$	heat transfer cofficient, $W/m^2.K$
T_w	wall temperature, K
Nu	Nusselt Number
Gr	Grashof Number
Pr	Prandtl Number

Abbriviations

ETC	Evacuated Tube Collector
CFD	Computational Fluid Dynamics
CPC	Compound Parabolic Concentrator

Chapter 1

Introduction

Heat collection is the main objective in a solar water heating system, together with moving the heat from collecting surface, and transferring to storage than finally using it to heat the domestic hot water. Solar water heating system have two main parts: a solar collector and a storage tank. Solar water heating system can be either active or passive. In active system move the liquid between storage tank and collector by pump. In passive system it depend on gravity and water naturally circulate as it is heated. Solar collectors are key component of solar water heating system. Solar thermal collectors collects the energy from the sun and transfer in to heat by solar radiation. There are serval type of solar collectors. For residential and commercial application that require the temperature below the 366 K normally uses flat plate collectors, whereas requiring temperature more than the 366 K uses evacuated tube collectors.

1.1 Solar thermal collectors

A solar thermal collectors collects heat from sunlight by absorption. A device of collector is capturing solar radiation. Solar radiation is energy in the form of electromagnetic radiation from the long wavelength of infrared to short wavelength of ultraviolet. The quantity of solar energy striking on the earth surface averages of 1000 watt per square meter in the clear sky. It is depend upon the weather condition, location and orientation.
Complex collectors uses in concentrated solar power plants to generate the electricity by heating fluid to drive a turbine which connected to the electrical generator. Simple collectors are used in commercial and residential building for space heating. The efficiency of a solar thermal collector is related to the heat losses from the collector surface. The sources of heat loss are convection and radiation in the context of a solar collector. Thermal insulation is used for reduces heat losses from a hot object to its environment. Temperature difference between the hot object and its

environment is larger in that case the heat lost is more. The heat loss is governed by the thermal gradient that is between the temperature of the collector surface and ambient temperature. Solar collectors are either concentrating or non-concentrating. In the non-concentrating type, the absorber area and the collector area is same. Ex. the whole solar panel absorbs light. In the concentrating collectors have bigger interceptor than absorber.

1.1.1 Flat plate collectors

Flat plate collectors, developed by Hottel and whillier [1] in the 1950.
Flat plate consists of:
a) Dark flat plate absorber.
b) Transparent cover that reduces the heat loss.
c) Heat transport fluid to remove heat from the absorber.
d) Heat insulating backing

Figure 1.1: Flat plate thermal system for water heating [1]

The absorber consists of thin absorber sheet. It is thermally stable polymers, copper or steel, aluminium. Absorber sheet backed by coil of fluid tubing placed in the insulated casing with glass. In water heat panels, fluid is circulated through tube to transfer heat from the absorber to an insulated tank. Most of air heaters and water heaters manufacturers have flooded absorber consisting of two sheet of metal. The fluid passes between this two sheet. The grater heat exchange area is more efficient than traditional absorber. Sunlight strikes on the absorber plate, which heats up and changing the solar energy in to the heat energy. Heat is transferred to liquid and passing through the pipes which connected to the absorber plate. Absorber plates are painted with ‘selective coating’ which absorb and retain heat better than the black paint. Absorber plates are made of metal because the metal is a good heat conductor as a copper or aluminium. Copper is more expensive but it is better conductor and less corrosive. Polymer flat plate are now being produced in Europe and are alternative to the metal collectors. Polymers are flexible and freeze-tolerant so that they may be plumbed directly in to the water tanks instead of heat exchanger. By dispensing of heat exchanger polymer can be more efficient. But some selective coated polymer collectors suffered from overheating when insulated because the stagnation temperature can exceed the polymer’s melting point [1].

1.1.2 Evacuated tube collectors

Evacuated heat pipe tubes are made of multiple evacuated glass tube and each containing an absorber plate combine to a heat pipe. The heat is transferred by the fluid of space heating system in a heat exchanger called ‘manifold’. The manifold is enveloped in insulation and enclose by protective sheet metal. The vacuum inside the evacuated tube collector. The vacuum outside of the tube reduces the convection and conduction heat loss. So that achieving more efficiency than flat plate collectors in colder condition. But in warmer climates, the high temperature can occur may require special design to prevent overheating.

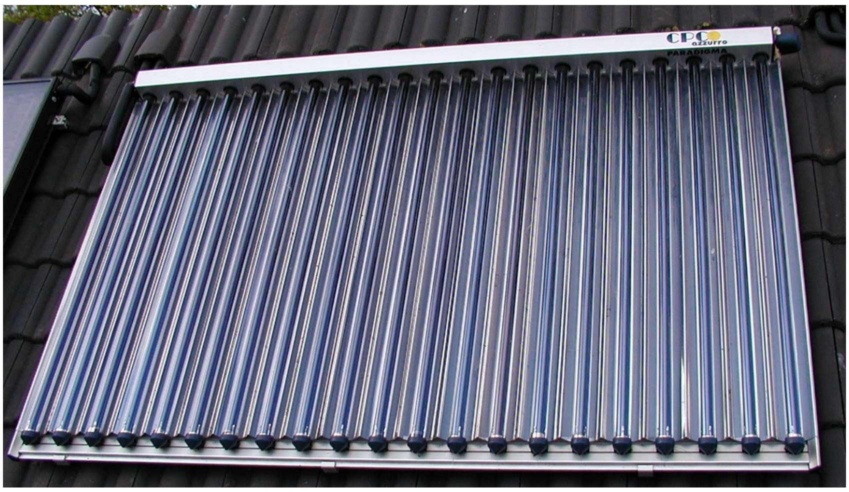

Figure 1.2: Evacuated tube collector [1]

Some evacuated tubes are made with one layer glass that combine to the heat pipe and absorber in the vacuum. Glass-glass evacuated tubes are made with a double layer of glass combined at one end or both end with a vacuum between the layers. Glass-glass evacuated tubes have a highly reliable but the one disadvantage that reduce the light that reaches the absorber. Corrosion may be occur when the moisture enter in the non-evacuated area of tube. Glass-metal tubes allow more light to reach the absorber and also prevent from corrosion if they are made of different materials [1].

1.1.3 Comparison of flat plate and evacuated tube collectors

Table 1.1: Comparison of flat plate and evacuated tube collectors [1]

Evacuated tube collectors	**Flat plate collectors**
The collector hermetically sealed inside an evacuated tube collector. Convection and conduction heat loss eliminated and no effect on collectors from ambient condition. So that no heat losses due to the conduction and convection. And no effect on performance of the collector due to the corrosion.	The collector is placed in casing with the glass shield to reduce the heat loss. During cold and windy days the heat losses occur in the air gap between the absorber and cover plane. Corrosion will be occur due to condensation so that reducing the performance ad durability.
Evacuated has maximum working temperature through the physical property of fluid and safeguarding system.	Flat plate collector not working on high temperature due to no internal method of limiting heat build up.
Thermal flows one way only from collector to water and never in the reverse.	If the collector becomes colder than the water temperature that can be possible the rob water of built up heat.
Easy installation and no maintenance cost.	Installation difficult.
No require any special placement angle.	In flat plate collector require more accurate southern exposure and elevation placement.

1.1.4 Bowl type of collector

This type of solar collector operates same to a parabolic dish. But in this type of collector the uses the fixed spherical mirror with tracking receiver instead of tracking parabolic mirror with fixed receiver. It is also called fixed mirror distributed focus solar power system shown in Fig. 1.3.

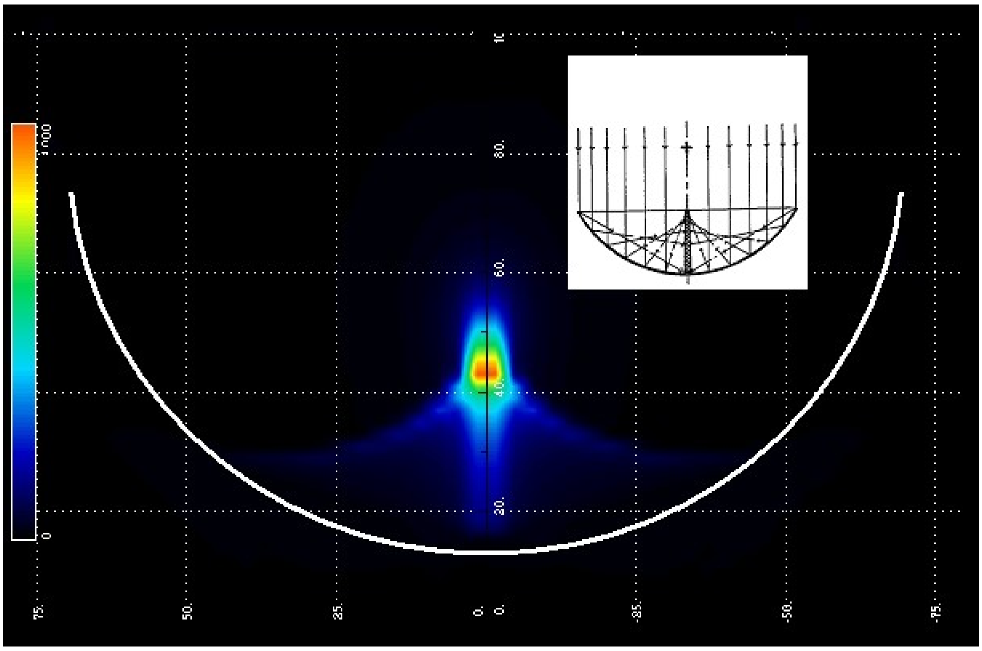

Figure 1.3: Spherical reflector [1]

In fixed parabolic mirror the various shape of the image of sun creates when it moves across the sky. The mirror is pointed directly at the sun does the light focus on one point. A fixed spherical mirror focuses light in same place not dependent on the sun's positions. The light is not directed to the one point but is distributed on line from the surface of the mirror to one half radius [1].

1.1.5 ICS or Batch collectors

This type of collectors reduces heat loss by the water tank placed in thermal insulated box. The heat is allowed from glass-topped box and other walls of the box are thermally insulated that reducing convection and radiation to the environment. The reflective surface on the inside of the box so that the reflects heat loss from the tank back towards the tank. Using a box largely reduces heat loss from the tank to the environment.

There are limits the efficiency of ICS collectors that a small surface-to-volume ratio. Where the amount of heat that a tank can absorb from the sun is largely depended on the surface of tank that is exposed to the sun. But now most modern collectors attempt to increase this ratio for efficient heating of the water in the tank. Some ICS collectors comprising water contains and including evacuated glass tube technology. This type of ICS system known as an evacuated tube Batch collector (ETB collector) [1].

1.1.6 Application

- Commercial application as Laundromats, car washing, military laundry facilities and eating establishments.
- This technology also used in space heating.
- Swimming pools

1.2 Solar water heating system types

1.2.1 Direct and Indirect system

In direct system uses a pump to circulate the water through the collectors. These systems are suitable in areas that do not freeze for long periods and do not have hard water. These systems are not approved by the Solar Rating & Certification Corporation (SRCC) if they use recirculation freeze protection. Because that requires electrical power for the protection to be effective. They are relatively cheaper but they have disadvantages. They have no overheat until they have heat export pump. They have no freeze protection until the collectors are freeze-tolerant. Collectors accumulate scale in hard water areas until an ion-exchange softener is used. If it not become of freeze-tolerant solar collectors, till they were not considered suitable for cold climates. There are possible the collector being damaged by a freeze.
Indirect system as a heat exchanger that separates the portable water from the fluid is known as the heat transfer fluid. The most common heat transfer fluid are water and antifreeze. After being heated in the panels, the heat transfer fluid travels to the heat exchanger, where the heat transferred to the portable water. So that indirect systems have freeze protection and overheat protection as well.

Passive and active system : Passive system depend on heat pipes to circulate water. The system cost is less and they have no maintenance cost in the passive solar water heating system. But the efficiency of a passive system is lower than of an active system. In passive system the overheating and freezing is a major problem.

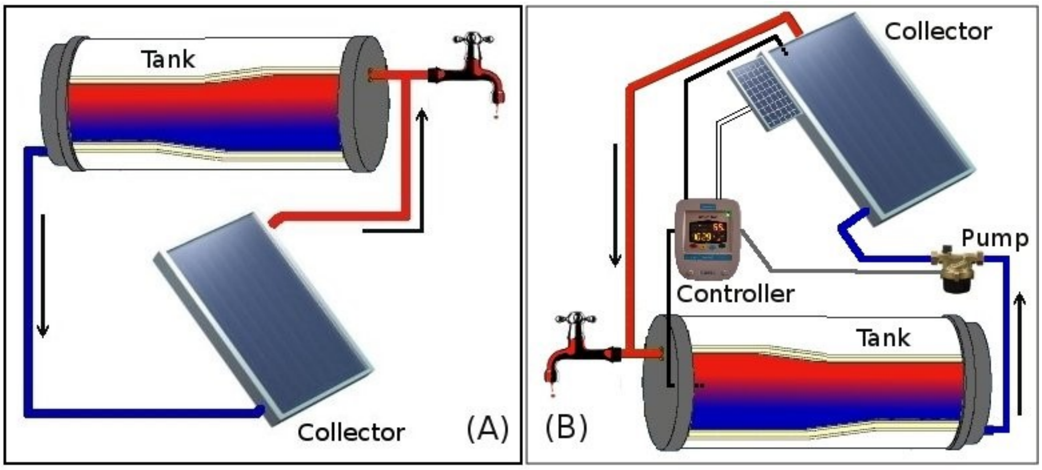

Figure 1.4: Direct system:A) Passive CHS system with tank above collector.B) Active system with a pump and controller driven by a photovoltaic panel [1]

As shown in Fig. 1.4 active system use one or more pump to circulate water in the system. The storage tank can be suited lower than the collectors. So that more freedom in system design and also allow the pre-existing storage tank to be used. It have superior efficiency and increased control over the system. The Storage tank can be place in the conditioned space to reducing heat loss and drain back tank can also be used. Modern active solar water system have electronic controllers that provide a wide range of functionality like the modification of setting that control the system, interaction with electric or gas-driven water heater, calculation of the energy saved by a solar water heater system, safety function, remote access, temperature readings. The most popular pump controller is a differential controller that is difference between water leaving the solar collector and the water in the storage tank near the heat exchanger. In active system , the controller turns the pump ON when the water in the collector is about 8-10^{o}C hotter than the water in the tank and it turns the pump OFF when the temperature difference 3-5^o C.
An active solar water heating system can be provide with a bubble pump instead of an electric pump. A bubble pump circulates the heat transfer fluid between the collector and storage tank using solar power and without the use of any external sources. It is suitable for flat panel as well as vacuum tube system. The closed HTF circuit is under reduced pressure in the bubble pump system, start the liquid to boil at low temperature as it is heated by the sun. The system is designed that the bubbles are separated from the hot fluid and condensed at the highest point in the circuit. The heat transfer fluid enter at the heat exchanger at the 70^o C and returns to the circulating pump at 50^o C. Pump start at about 50^o C and increases as the sun rises unless equilibrium is reached that is depend upon the efficiency of the heat exchanger, the temperature of hot water, and the total solar energy availability [1].

Passive direct system : An integrated collector storage(ICS or Batch Heater) system uses a tank. It acts as both storage and solar collector. The Batch heaters are thin rectangular tanks. A glass side of tank facing the sun position at noon. They are simple and low costly compare to plate and tube collectors. But it suffer from heat loss at night because the side facing the sun is largely uninsulated.

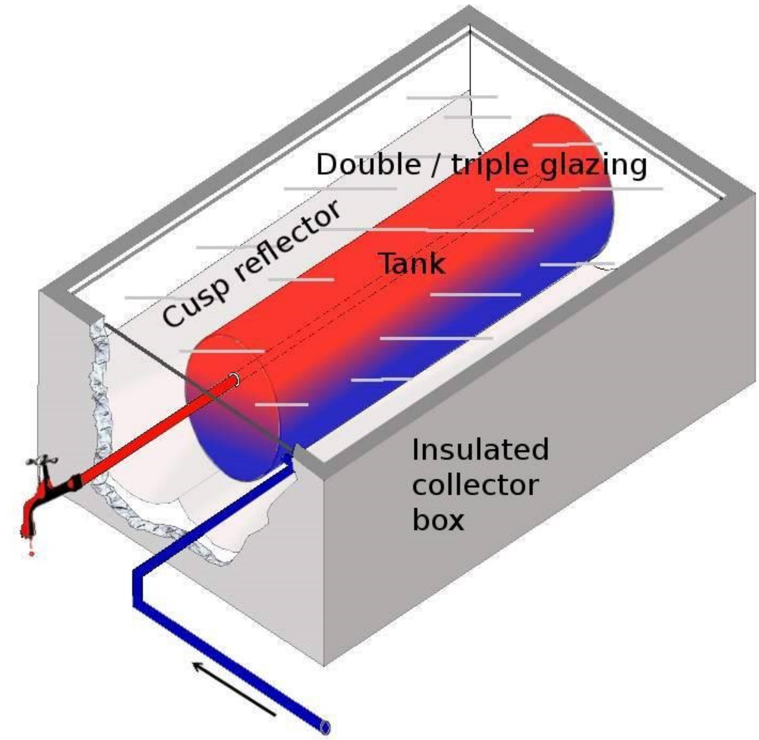

Figure 1.5: Integrated collector storage system [1]

A convection heat store unit (CHS) system is similar to an ICS system, but not including the storage tank and collector are physically separated and transfer between the two is driven by convection. CHS system use flat-plate type or evacuated tube collectors and in this type of collectors the storage tank must be located above the collector for convection properly. There are main advantages of CHS system over an ICS system to avoid the large heat loss where the storage tank can be better insulated and the panels are located below the storage tank so that heat loss in the panel is not affect on convection, as the cold water stay at lowest part of the system [1].

Active indirect system : drain back and antifreeze Antifreeze system have many drawbacks.

- If the HTF gets to hot than the glycol degrades in to acid. After degradation, the glycol is fails to provide freeze protection and also the affect on solar components like the collectors, the pipes, the pump etc due to acid and excessive heat and also reduced the longevity of the parts.

- The glycol/water HTF must be replaced every 3-8 years depending on temperature.
- HTF contains glycol to prevent freezing. So that circulate hot water from the storage tank into the collector at low temperature because of heat loss.
- A drain back system is an indirect active system where the HTF circulates through the collector and it is driven by a pump. The collector piping is not in a pressurized condition. If the pump is OFF , the HTF drains into the drain back reservoir and not remains in the collector. All pipe placed above the drain back tank with the collectors and the slope in the downward in the direction of drain back tank that is able to drain properly. The drain back system require no maintenance [1].

1.3 System Design Requirements

The complexity, type and size of solar water heating system is mostly investigated by,

- Ambient temperature changes and solar radiation between the winter and summer.
- The changes in ambient temperature during the day-light cycle.
- The possibility of portable water or collector fluid overheating.
- The possibility of the portable water or collector fluid freezing.
- The minimum requirements of the system are investigated by the temperature of hot water required during winter, when a system's output and incoming water temperature are typically at their lowest.
- In summer the maximum output of the system is determined by the need to prevent the water in the system from becoming too hot.

Freeze protection
Freeze protection means prevent damage the system due to the expansion of freezing transfer fluid. In drain back system, drain the transfer fluid from the system when the pump stop. Many direct system are antifreeze in the transfer fluid. In some direct system, the collectors can be manually drained when freezing is expected. This approach is common in climates where freezing temperature do not occur often, but is somewhat unreliable. Since the operator can forget to drain the system.

Other direct system use freeze-tolerant collectors made with polymer such as silicon rubber. This is a third type of freeze protection is freeze-tolerance, where low pressure polymer water channels made of silicone rubber that simply expand on freezing.

Overheat protection : When no hot water has been used for a day, so that the fluid in the collectors and storage can reach very high temperature in all system except for those of the drain back variety. When the storage tank in a drain back system reaches its desired temperature and the pumps are shutoff at that condition preventing storage tank from overheating. One method of providing over heat protection is to dump the heat into a hot tub. Some active system intentionally cool the water in the storage tank by circulating hot water through the collector at that times when there is little or at night, promote increased heat loss. This is most effective in direct is virtually ineffective in system that use evacuated tube collectors due to their good insulation. High pressured sealed solar thermal system versions finally depend on the operation of temperature and pressure relief valves [1].

1.4 Motivation

The prediction of solar collector via computational simulation is complex. The number of research in this subject is quite low. Study on evacuated tube collector is more useful in several application, such as dormitories, swimming pool, hotel and manufacturing plants.

CFD simulation is useful in identifying method to improve the efficiency of solar collector and it can also be used for optimizing the geometrical configuration.

1.5 Objective

The following are the objectives of the present study:

1. The CFD analysis of the ETC to find the optimum tilt angle for fastest temperature gain in a transient analysis.

2. The effect on the temperature profile in the storage tank due to insertion of a twisted tape in the ETC.

1.6 Outline of report

The report consists of five chapter. The first chapter deals with introduction of remarks and objective of project. The second chapter relevant to the literature review. The third chapter presents simulation of heat transfer in an evacuated tube collector in ANSYS 14.5. Results and Discussion are presented in fourth chapter. The fifth chapter presents conclusions and future work.

Chapter 2

Literature Review

2.1 Introduction

Heat transfer in an evacuated tube collector is mainly depend on tube diameter, tube spacing, position of tube and which reflector used. This chapter deals with natural circulation flow rate correlation, numerical modelling and computational domain, consider boundary condition .

2.2 Numerical modelling

Heat transfer and fluid flow processes in water-in-glass solar water heater are shown in Fig. 2.1.

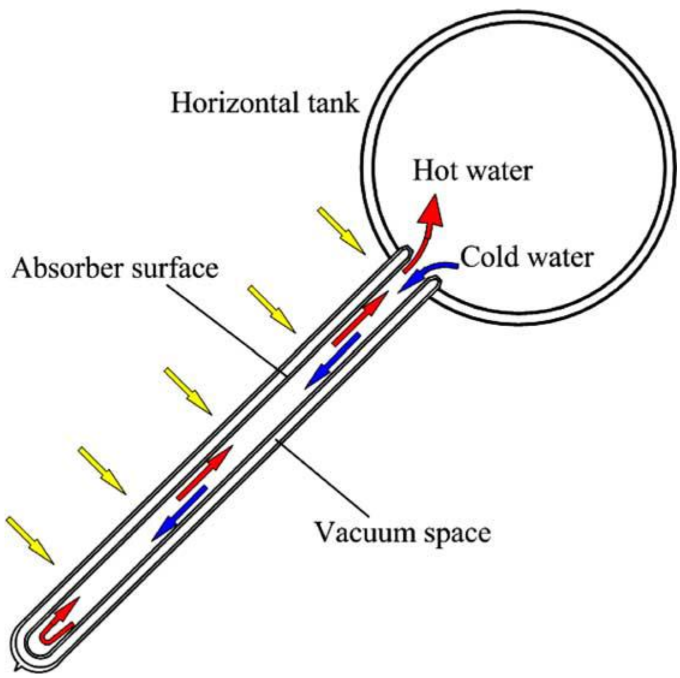

Figure 2.1: Natural circulation in water-in-glass collector [2].

Water in glass solar water heater consists of all glass vacuum tubes inserted directly in to a storage tank. And the water in direct contact with the absorber surface. In the system water in the tubes is heated by solar radiation which received by the absorber surface. Creating the stream of a hot fluid rising along the top section of the tube, and replaced by the colder fluid from the tank entering the bottom section of the tube. The rate of natural circulation through the tubes depends on the solar flux, heat distribution around the tube and storage tank temperature.

2.2.1 Computational domain

In the previous studies, researchers observed that the simulation of collector with 21 tubes is not possible because of a computational limits, these simulated a single ended tube [2] with constant pressure boundary condition at the open end [5, 6, 7] as shown in Fig. 2.2 .

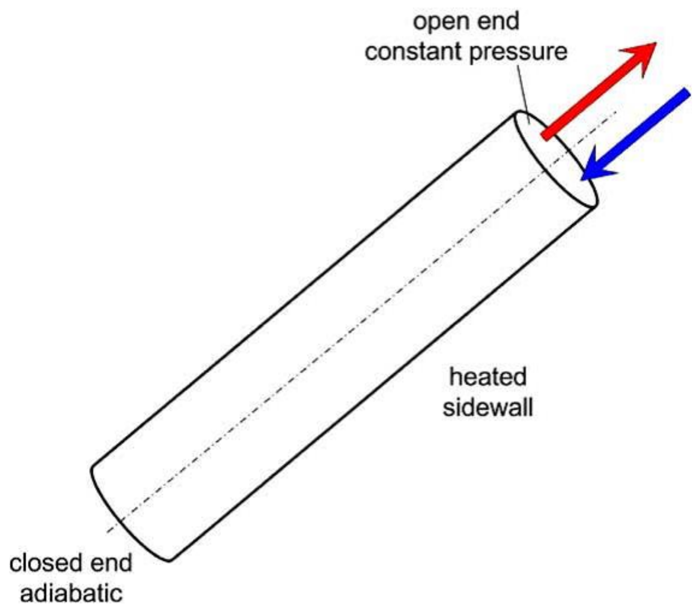

Figure 2.2: Open thermosyphon with boundary conditions[2].

The tube was inclined at 45^o to the vertical with the closed end was assumed as adiabatic [2].

Simulation was limited to a single tube so that assuming the circulation rate through the individual tube was not affected by the flow from the adjacent tubes. In flow and out flow from the tube domain were assumed to be normal to the surface in simulation. In simulation the discretisation scheme was used to compute momentum in second order upwind. SIMPLEC method was used in pressure-velocity coupling [2].

2.2.2 Circumferential heat flux distribution

In the previous studies, researchers observed that the distribution of solar radiation falling onto the absorber surface of an evacuated tube collector depends on a number of factors like tube diameter, tube spacing and backing reflector.

The heat flux distribution measured inside an evacuated tube by the photodiode measuring device .The diameter of 30mm and mounted 70mm above a reflective surface of defuse reflector [4]. The same result was obtained by ray-tracing simulation uses of parabolic reflector [5].

The measurement result shows that the 57% of solar radiation fall on the top half the tube. The average absorbed heat flux around the tube circumference is approximation 500 W/m^2 [4]. Presented plot of heat distribution as shown in Fig. 2.3 .

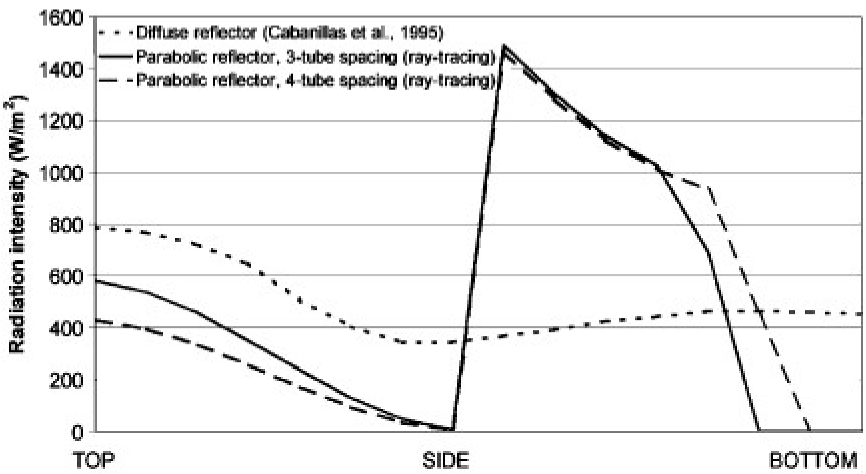

Figure 2.3: Circumferential heat distribution on evacuated tube mounted over a diffuse reflector and parabolic reflector for a fixed total heat input of 82 W [2].

Simulated of ray-tracing method for a constant total heat input of 82W with heat distribution between the top half and bottom half of the tube circumference of 100:0, 75:25, 50:50, 25:75, 0:100 [2]. Parabolic reflector is at the tube centre line and the tubes are positioned at a distance of 3 absorber diameter. only 29% of the radiation received by the top half of the absorber surface. 80% of radiation of result obtained when the position of tubes apart increases.

2.2.3 Effect of varying circumferential heat distribution

Uses of an evacuated tube collector with a concentrating reflector so that increase the radiation on each tube. A number of reflector geometries have been developed because the various reflector used. The reflector used of parabolic shape, CPC and involute reflector. A most of solar radiation is absorbed through the bottom half of the tube circumference when a concentrating reflector used.

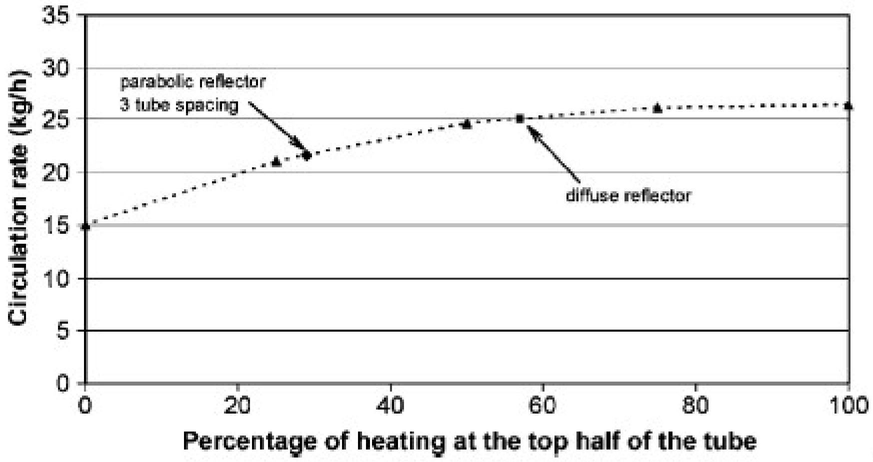

Figure 2.4: Circulation rate through a single tube in constant heat input of 82 W and the heat distribution is shifted from extreme bottom heating to top heating [2].

In simulation results the flow rate increases because the heat distribution shifts from the bottom to top half of the tube shown in Fig. 2.4 [2].

As shown Fig. 2.4 the heat input is concentrated on the bottom of the tube circumference so that the heat distribution is varied and the change of circulation rate. The change of circulation rate is observed between uniform heating and extreme top heating condition. Uses of diffuse reflector and parabolic reflector with tube spaced of three diameter apart. In Concentrating reflector need of different mass flow rate correlation developed. The constant heat input is 82 W and the heat distribution is varied shows the simulation results of velocity counters at different positions [2]. As shown in Fig. 2.5 [2] when heating is concentrated on the top half of the tube, there is fast stream near the top half and shows that the hot fluid stream is clearly separated from the cold fluid. Cold fluid stream entering the tube when it is drawn into the heated layer on the top. But when heating is concentrated in the bottom half of the tube, the hot stream leaving from the tube is slow in space of larger cross sectional area.

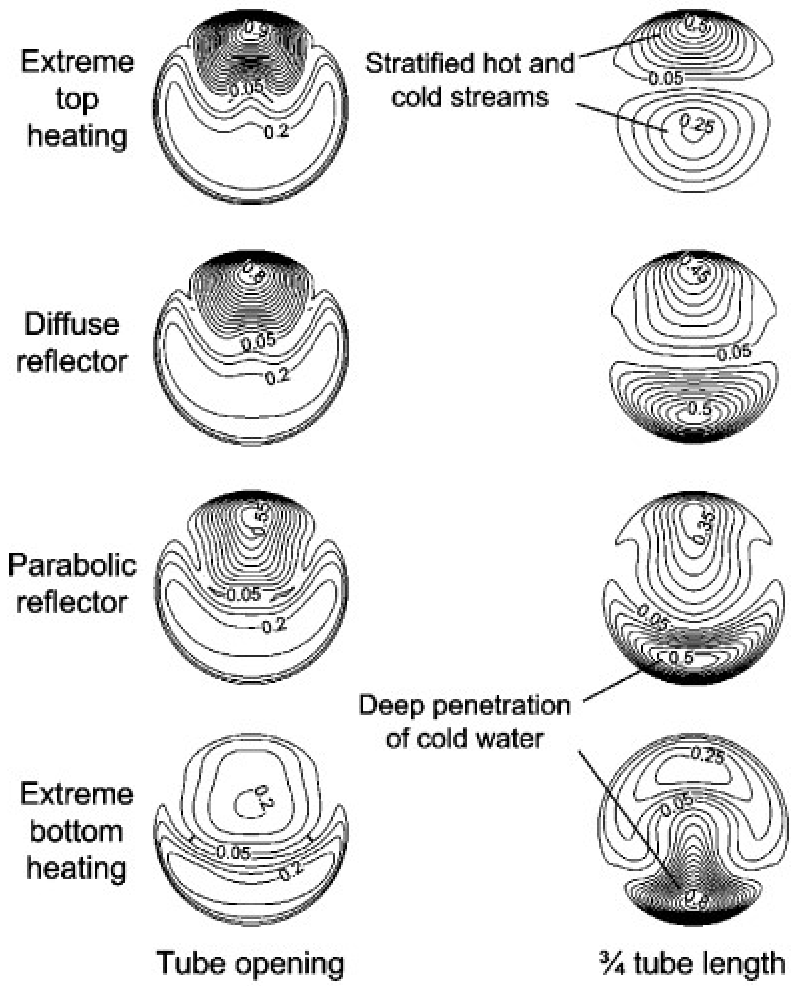

Figure 2.5: Velocity contours across tube opening and 3/4 tube length under various circumferential heat distribution and constant heat input (Vmax = 60mm/s)[2].

Assuming symmetrical circumferential heat flux distribution which take place when the radiation is perpendicular to the collector plane [4]. The collector optical configuration and the transverse incidence angle are main factors that determine the heat flux distribution around an evacuated tube and these two factors are inter-related. For example, when the radiation is incident at an angle to the tube array that time the angular orientation of heat flux distribution change and also change the shape of the radiation profile around the tube. The heat flux distribution around the tube depends on the geometry reflector, the distance between the collector and reflector and also the inner tube separation. To find the varying effect of heat input distribution on circulation flow rate through the tubes. For simplified top-bottom heat input ratios of 100:0, 75:25, 50:00, 25:75 and 0:100 were simulated at constant total heat input of 75 W on a tube at inclined of 45 degree. Length of tube is 1420 and diameter of 34 mm [3].

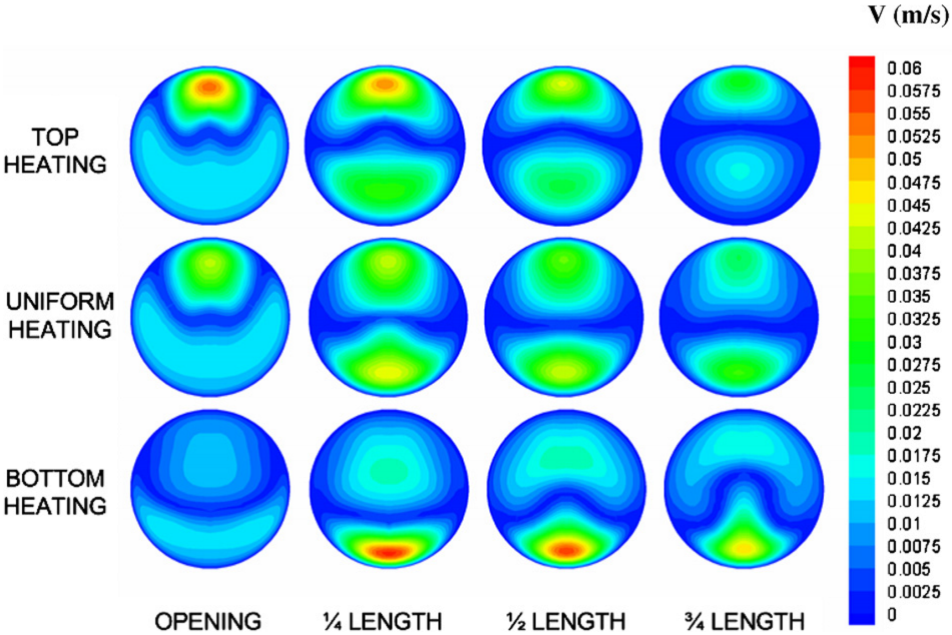

Figure 2.6: Velocity contours at various axial locations in an evacuated tube (length = 1420 mm, diameter = 34 mm, inclination angle = 45^o) for circumferential heat flux distributions of top heating, uniform heating and bottom heating [3]

I. Budihardjo et al. [3] studied the ETC for velocity contours at various axial locations in an evacuated tube. As shown in Fig. 2.6 determined the contours of velocity magnitude at four axial locations in a single-ended tube using the simulation in fluent for top, uniform and bottom heating conditions. When heat input on the top of the tube, a thin and fast hot stream is observed along the top of the top of the tube. The hot stream occupies a larger portion of tube cross-section when the heat input is concentrated on the bottom half of the tube. And the out-flow velocity is much lower than the top heating condition.

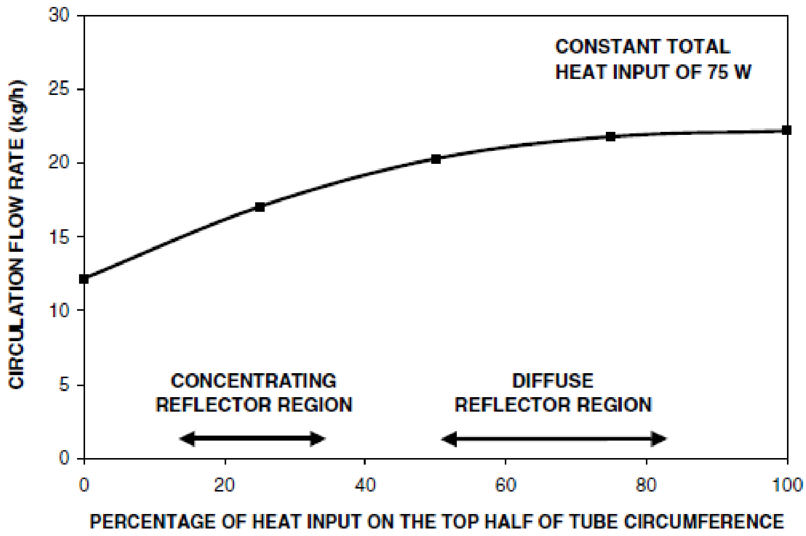

Figure 2.7: Variation of natural circulation flow rate with circumferential heat flux distribution in a tube with L/d ratio of 1420/34 and inclination of 45^o for constant heat input of 75 W [3]

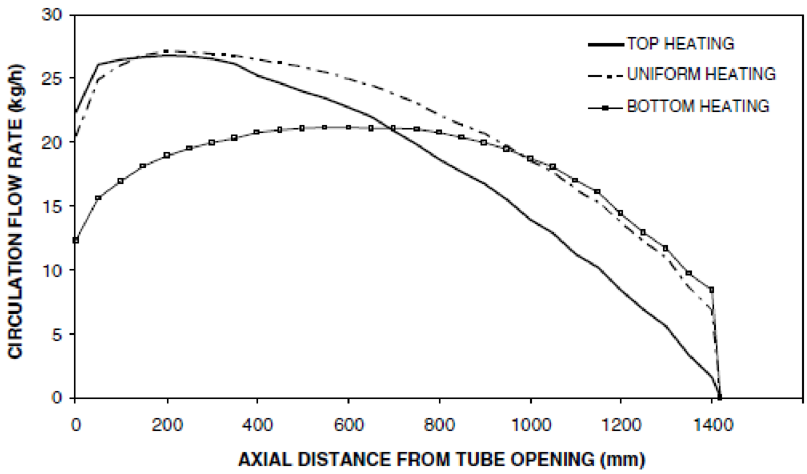

Figure 2.8: Variation of natural circulation flow rate with axial distance from the tube opening for top heating, uniform heating, and bottom heating conditions; total heat input = 75 W, tube L/d ratio = 1420/34, inclination angle = 45^o[3]

As shown in Fig. 2.7 that the heat input is varied from bottom heating to top heating the natural circulation flow rate through the tube increases. 10% approximately variation in circular flow rate between the uniform heating and top heating. As shown in Fig. 2.8 that natural circulation flow rate near the sealed end of the tube is smaller than the uniform heating and bottom heating under the top heating. For bottom heating condition the maximum flow rate occurs in the middle of the tube and the out flow circulation rate is half of the highest flow rate within the tube [3].

2.3 Transverse Incidence Angle

I. Budihardjo et al. [3] studied the ETC for three transverse incidence angles were simulated, 30^o, 45^o and 60^o to the normal.

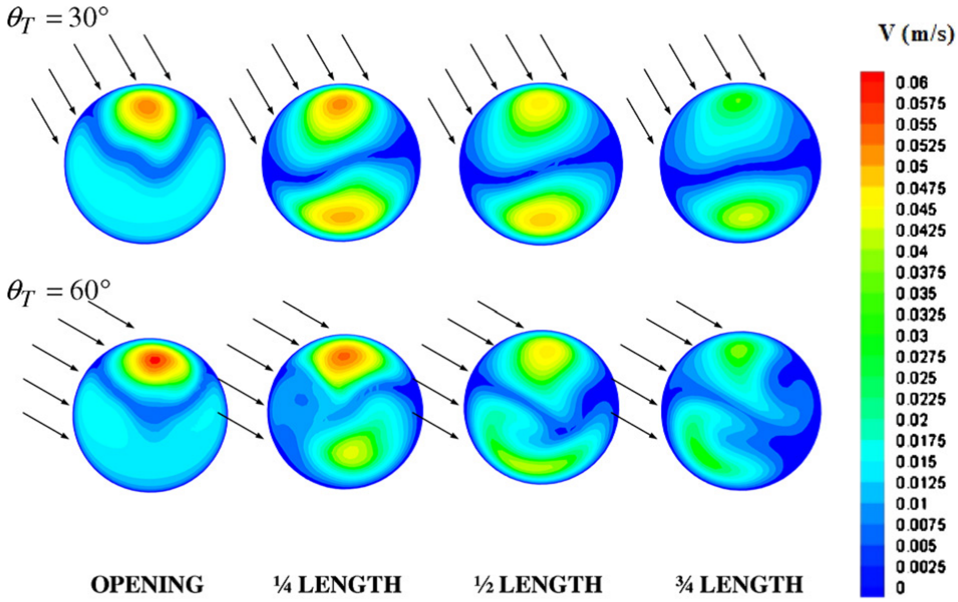

Figure 2.9: Velocity magnitude on transverse incidence angle [3]

The flow structure is change inside the tube as a variation of transverse radiation angle. When the radiation is incident at 30^o, the hot and cold stream are clearly separated by a shear layer and the flow structure is similar to the flow structure during normal incidence radiation. At 60^o transverse angle, the shear layer becomes unstable in flow structure is observed during the tube. But near the opening of two stream are still separated. For same total heat input, the circulation flow rate is constant for transverse angles between the 0^o and 30^o. At 60^o incidence angle the natural circulation flow rate is 4% less than the normal incidence radiation. Incidence angle does not significantly affect the circulation flow rate through the tube [3].

2.4 Numerical Simulation

Johane Bracamonte et al. [11] performed a CFD analysis for ETC. The equation system consisted on the mass, momentum and energy balance for laminar flow and incompressible Newtonian fluid. The boussinesq approximation was used and all water physical properties are considered constant but the density in the momentum source terms which was allow to be a function of temperature. The reference temperature is 300 K and density is water at 300 K temperature and 100 KPa pressure. Transient simulation was used and consider the time step is 0.5 sec. Nodes of mesh is

3,19,890 nodes and 1,474,140 tetrahedral elements was used to get mesh-independent solution.
Initial and boundary condition : Water flow is not exist before the collector was exposed to solar radiation. So stationary fluid was considered as initial condition for the velocity field. Water in thermal equilibrium with the ambient before the heating process being. Concerning the momentum boundary condition, the non-slip condition applied on the all surfaces of the solution domain. Domain is closed –box type so that it is not possibility to set the pressure clearly on any surface. Selected the lower node as a reference node for a pressure level. Take heat transfer coefficient value is 0.6 $Wm^{-2}K^{-1}$. The tilt of the collector was considered by modifying the orientation of the gravity respect to the global coordinate frame used in simulation [11].
G. L. Morrison et al. [2] performed the CFD analysis on ETC. In this simulation discretisation scheme is used to second order upwind and method of pressure-velocity coupling is SIMPLEC used. In simulation tube wall thickness is considered 1mm and no considered the wall condition in any of the CFD parametric studies. The grid used of 5,00,000 elements and tank heat loss coefficient assumed to be 5 W/m^2K on bottom walls and 10 W/m^2K on the top. In simulation heat flux applied on top is 500 W/m^2. The transient simulation was initialised with the tank and ambient temperature of 300 K. The 0.2 sec time step used at the start of simulation and then after the flow structure was developed sine the time step was increased to 0.5 sec. By the simulation 32.5 mm/s velocity predicted that is nearest velocity of 32 mm/s velocity obtained from the PIV measurement [2].
I . Budihardjo et al. [3] Computational Fluid Dynamics (CFD) package, fluent used in analysis. In CFD model consist of 70,000 mesh point with structured grid and it is near the wall. The core of the tube is covered with the quad-shaped mesh. The orifice of the tube was modelled as an open surface with constant pressure boundary condition and the in-flow and out-flow through the tube are assumed to be normal to the opening. The model can be treated as a steady-state problem. The Reynolds number in the range of 10^2 to 10^3 as the diameter based, so that a laminar flow was used in the simulations. The CFD model was used of the data for heat input of 125,250,375 and 500 W/m^2 and tank temperature 17, 27, 40, 50, and 60^{o}C and the inclination angels of 30^o, 45^o, and 70^o from vertical [3].
J. A. Alfaro-Ayala et al. [10] performed on CFD analysis on ETC. Finite volume method used in this simulation. The flow and energy eqation solved for the coupling of the velocity and pressure through SIMPLE algorithm. For momentum and energy eqation second order upwind discreitization scheme used and for pressure standrad scheme used. Steady state and laminar model used in this simulation [10].
Boundary condition : Mass flow rate at water inlet and pressure outlet at water

exit. Constant heat on the top half of the tube and adiabatic as bottom half of the tube [10].

2.5 Development of flow rate correlation

The workdone by I. Budihardjo et al. [3] studied heat transfer correlation that were developed for forced convection system cannot be used. Because in system where heat transfer create by means of natural convection, the heat transfer and the natural circulation flow rate are coupled. As heat transfer the density variation along the thermosyphon loop is shown in Fig. 2.10.

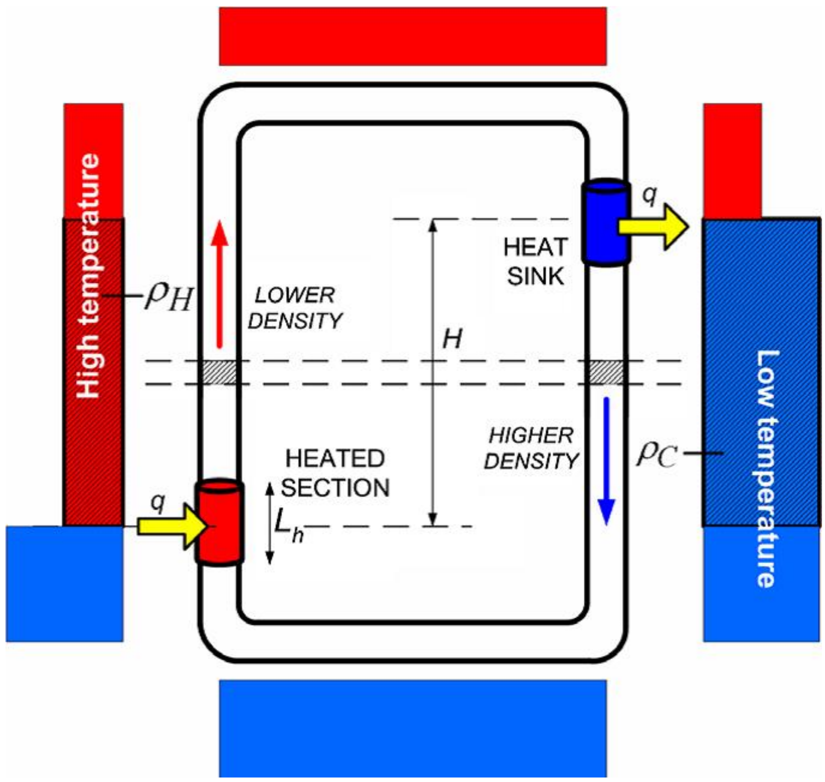

Figure 2.10: Thermosyphon loop [3].

If we consider that a horizontal slice of the loop, the difference between the weight of fluid on either side of this slice of the loop is

$$dF = (d\rho)\, g\, (dv) \tag{2.1}$$

Where dv is the volume of the each tube section. The density difference between the cold and hot fluid can be related to the temperature difference as,

$$d\rho \approx -\rho\beta\, (dT) \tag{2.2}$$

The pressure difference ,

$$dp = dF/Ac = -\rho\beta g\,(dT)\,(dh) \tag{2.3}$$

The heat transfer in the heated section is related to the circulation flow rate and temperature increase through the section :

$$dq = \dot{m}CpdT = \rho u\pi d^2 CpdT/4 \tag{2.4}$$

From equation (2.3) and (2.4)

$$dp = 4g\beta dqdh/u\pi d^2 Cp \tag{2.5}$$

Integrated to total driving pressure head

$$\Delta p = \int dp = 4g\beta qH/u\pi d^2 Cp \tag{2.6}$$

For steady state condition , the total driving pressure head is balanced by the frictional pressure drop in the loop. Using the Darcy equation as,

$$\Delta pf = 2f\rho u^2 Lp/d \tag{2.7}$$

Where Lp is the total length of the loop. For laminar flow in pipe friction factor is,

$$f = 16/Re \tag{2.8}$$

Put the value of friction factor in equation (2.7)

$$\Delta pf = 32\mu uLp/d^2 \tag{2.9}$$

From the equation (2.6) and (2.9)

$$q = 8\mu u^2 \pi CpLp/\beta gH \tag{2.10}$$

The heat transfer coefficient

$$\bar{h} = q/As(Tw - T)avg \tag{2.11}$$

Tw is the tube wall temperature , T is the fluid temperature and As is the area of heat transfer,

$$As = \pi dLh \tag{2.12}$$

Equation (2.10) and (2.11) can be used to relate the heat transfer coefficient of temperature to tube geometry, fluid properties, and the temperature difference

$$h = 8u^2CpLp/\beta gHdLh(Tw - T)avg \tag{2.13}$$

Equation (2.13) can be non-dimensionalised as

$$Re = X(Nu.Gr/pr)^{0.5} \tag{2.14}$$

Where X is the function of loop dimension i.e. pipe diameter length of loop, vertical separation between heat source and heat shink and the heater [3].

2.6 Flow structure

In the workdone by I. Budihardjo et al. [3] the flow rate the opening of the tube for bottom heating was less than the uniform and top heating.

2.6.1 Top heating

The flow in the tube is bi-filament. The hot stream settled at the top edge of the tube. The cold stream enter from the tank towards the sealed end of tube. The cold stream is gradually drawn in the boundary layer, spiral around the tube circumference and reverses direction near the opening of tube. The natural circulation flow rate decreases towards the sealed end because of the flow reverses before reaching the sealed send of tube. The hot stream and cold stream is interact in the recirculation zones at near opening of the tube as it is shown below Fig. 2.11 [3].

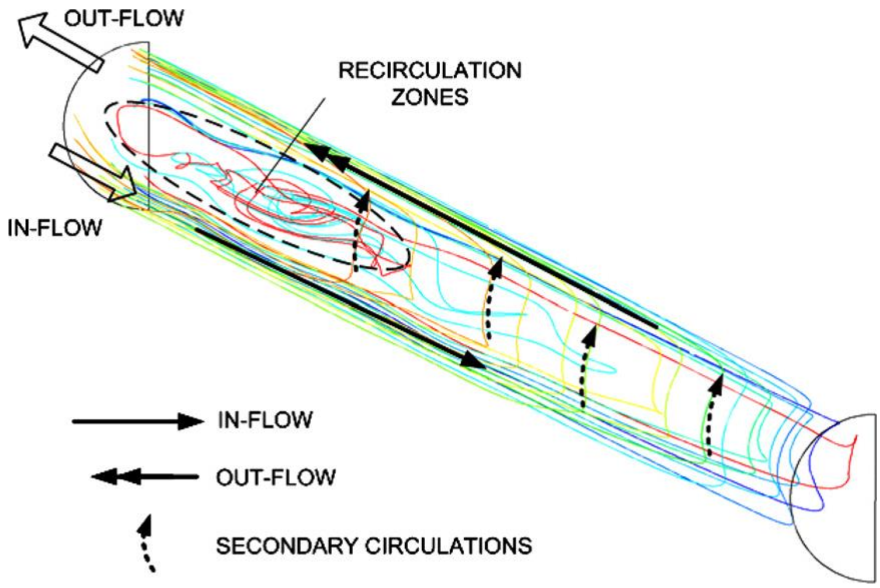

Figure 2.11: Flow structure in a single-ended tube heated from the top and recirculation zone at the near of the opening tube [3].

2.6.2 Bottom heating

The heat input applied on the bottom half of the tube than high velocity stream enters the bottom edge of the tube towards the sealed end. As the flow is heated around the circumference of tube the flow rises to the top because of the its lower density. Heat applied on the bottom of tube so that unheated water in top of tube is falls in bottom of tube and than recirculates into the cold fluid moving towards sealed end as it is shown below Fig. 2.12 [3].

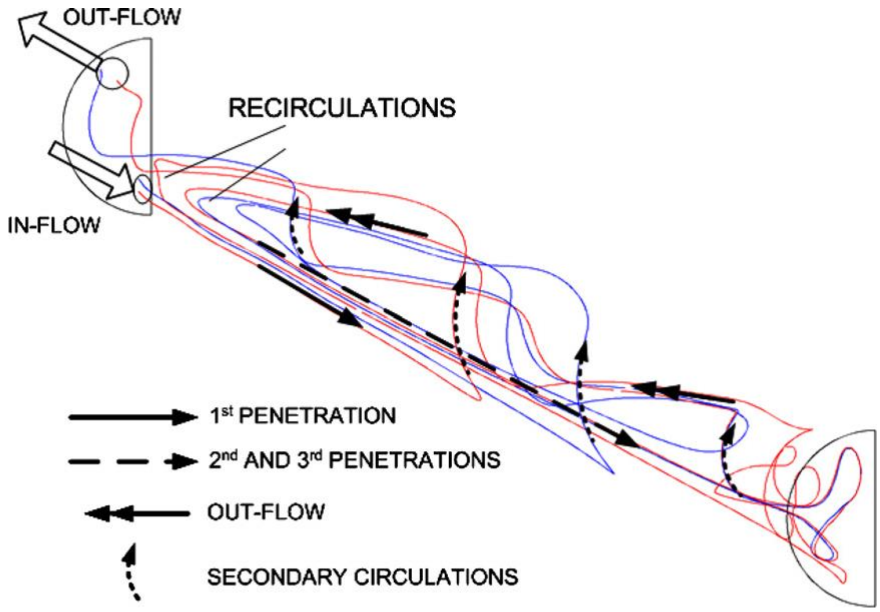

Figure 2.12: Flow structure in a single-ended tube heated from the bottom and recirculation of stream zone [3]

2.6.3 Uniform heating

The tube is heated uniformly, but the top circumference has more influence than the bottom circumference of tube. The hot stream move towards the opening of the tube by driving force, So that avoid the recirculation zones. The natural circulation flow rate through the tube for uniform heating is more similar to the top heating condition [3].

2.6.4 Flow within tubes

In the work undertaken by Johane Bracamonte et al. [11] as the water heats up so that the density decreases and the water mass flow up toward the storage tank by the buoyancy force. Velocity increases with the tilt angle due to the increased projection of the buoyancy forces on the way of flow direction. For 10^o tilt there was no difference found between the velocity profile in tube 1 and tube 4. But when the tilt angle increases the flow patterns in both tube is very and larger velocity found in tube 4. At 45^o tilt angle a 5% mean relative difference velocity obtained in both the tubes 1 and 4. So by this effect Tube 1 and tube 8 nearest to the boundary wall of the storage tank that produce a larger resistance to the flow and this resistance increases with the square of flow velocity. So that highly sensible to the tilt angle. As a result when reduced the velocity, the temperatures at the extremes tubes of 1 and 8 higher than the other tubes [11].

2.6.5 Flow within the storage tank

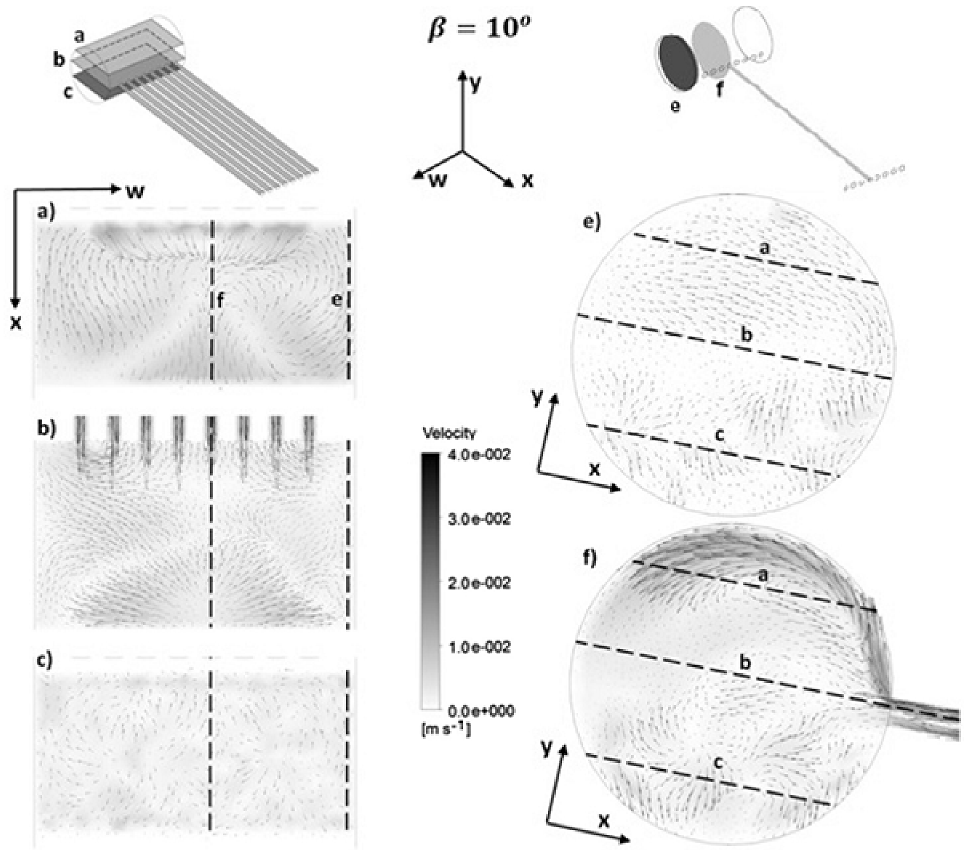

Figure 2.13: Velocity magnitude and vector projection on planes located at: (a) 0.085 m above the tube opening centerline. (b) 0.085 m below tube opening centerline. (c) 0.001 m above the tube opening centerline. (e) Symmetry plane of tube 4. (f) 0.01 m from lateral wall [11]

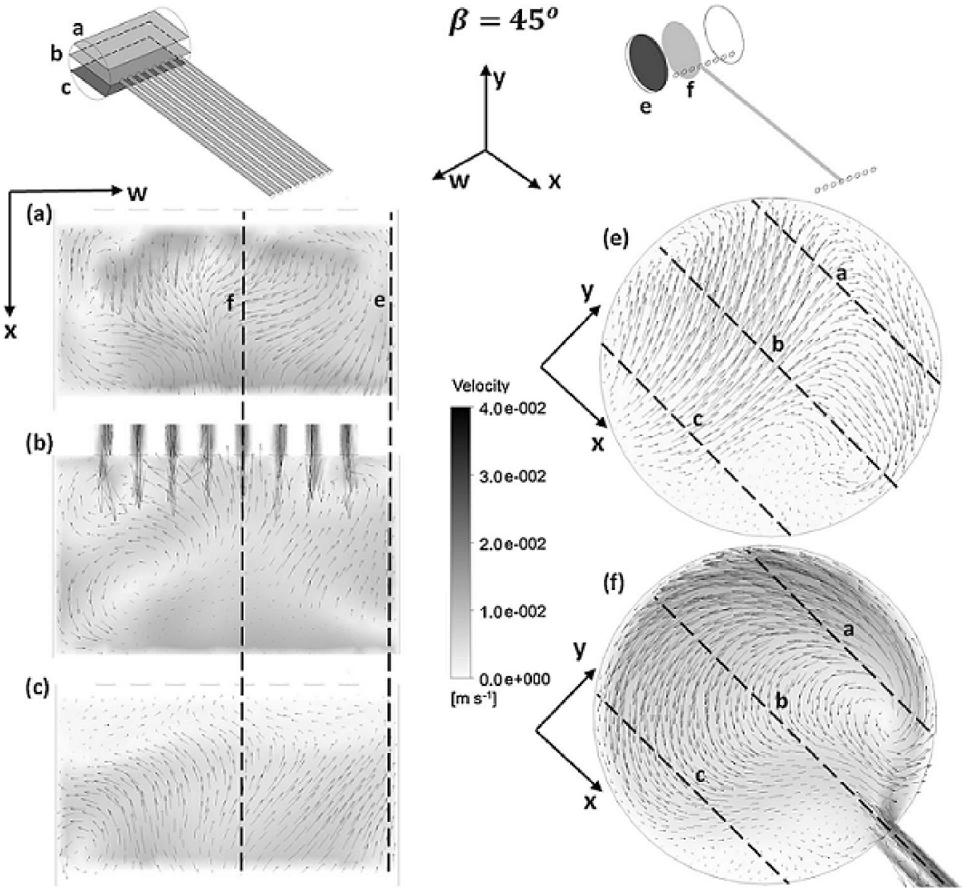

Figure 2.14: Velocity magnitude and vector projection on planes located at: (a) 0.085 m above the transversal symmetry. (b) 0.085 m below tube opening centerline. (e) 0.085 m above the tube opening centerline. (f) Symmetry plane of tube 4. (f) 0.01 m from lateral wall [11]

As shown in Fig. 2.13 for 10^o tilt the warm water leaves from the evacuated tubes staying close to the storage wall. So that the momentum of this flow is separated before it reaches the lower level of tank. as shown in Fig. 2.14 for 45^o tilt warm water has a larger penetration on the storage tank and generating a vortex that reaches lower level of the storage tank due to the larger momentum of flow [11].

2.6.6 Temprature and Velocity distribution in the manifold

J. A. Alfaro-Ayala et al. [10] had studied the effect on velocity contour and vector at the manifold in three cases: 1) flow at no heat condition 2) heat transfer using the BA model and 3) heat transfer using the VPT model. In no heat flux condition the water flows across the manifold in straight direction to the exit without the interacting with water of the tube and no backflow obtained in the manifold as shown in Fig. 2.15 . In BA model certain degree of backflow obtained across the manifold. The water at the bottom flow towards exit, the water flow in top of the manifold is slowed by the water coming from the tube. When the VPT model using the water flow towards exit at the bottom, the velocity distribution permit more interaction between the warm water at top and cold water at bottom [10].

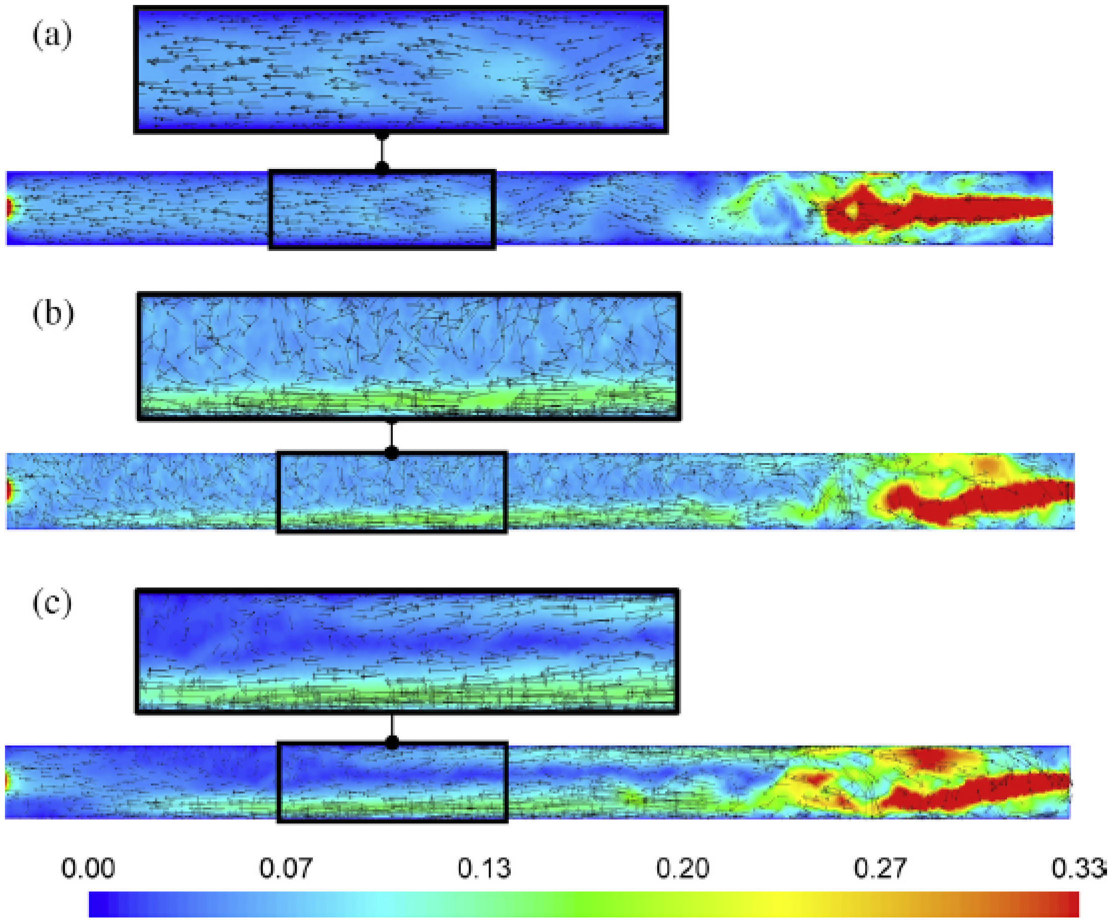

Figure 2.15: Velocity contours and vectors in the manifold (a) no heat (b) BA model (c) VPT model [10]

2.7 Thermal stratification

Johane Bracamonte et al. [11] had studied higher temperature and thermal stratification obtained with the lower tilt angles.

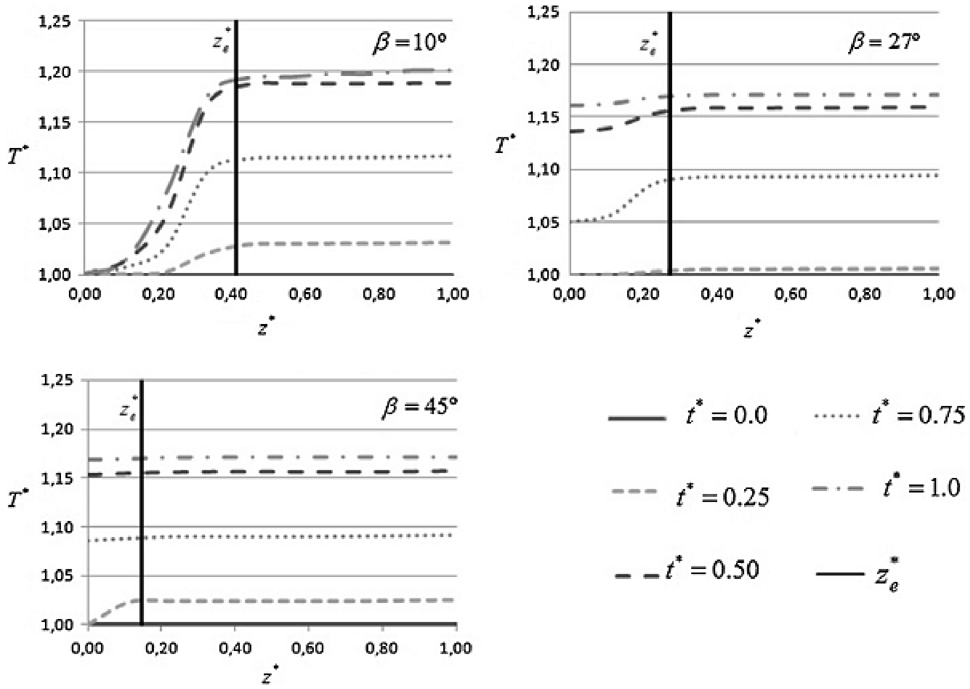

Figure 2.16: Non dimensional temperature profile [11].

As shown in Fig. 2.16 at lower tilt angle 10^o remains the stratified in the storage tank through all the heating process but at larger tilt angle the storage tank fully mixed at half of the heating process. For 27^o tilt angle the stratification decrease and the lower temperature increases with time. For all tilt angle homogeneous temperature above the tube opening point so that the warm water fully mixed above the opening of tube. The opening of tube located higher inside the tank, the thermal inactive region of water build up below that point. So that tube prolongation inside the tank take minimum to reduce to thermal inactive region. The thermal inactive region clearly found in the 10^o tilted angle. But cold region is not found at 45^o angle [11]. In the work undertaken by J. A. Alfaros-Ayala et al. [10] the comparison between the outel temprature at the of solar collector manifold for the experimental result, BA model and the VPT model. The percentage diference between experimental result and BA model is less than the percentage difference between the experimental result and VPT model. Inlet temprature of the manifold is affect on the ability of the solar collector to rise the temprature at exit of the exit manifold of the solar collector [10].

Chapter 3

Heat transfer in an evacuated tube collector

The methodology to simulate the heat transfer and flow in an ETC is provided in this chapter.

3.1 Methodology of ETC

Investigation natural circulation flow rate in water-in-glass evacuated tube solar collector with apply the various heat distribution and constant heat input. Two kinds of collector are widely used. One is flat plate collector which can used in limited temperature, another is evacuated tube collector which can be used in high temperature without limitation.
Simulation of ETC system, it is important to understand the heat transfer in the tube and the storage tank of water. With this objective in mind, will simulate of ETC in FLUENT ANSYS 14.5, which include of type of tube material, material of tank, and constant heat input, various ratio of percentage heat flux on the bottom half and the top half of the tube. The combination of simulation for tube and tank material, heat input and heat flux allows studying the heat transfer in ETC.

3.2 ETC geometry model description

2D geometry made in design modular. The tube length is 1400mm and the 400 diameter of tank. The diameter of tube is 34 mm. The geometry positioned at various tilt angle to normal of ground. 30^o , 45^o and 60^o tilt angle used as shown in Fig. 3.1, 3.2 and 3.3. And another geometry is that the twisted tape inserted in the tube as shown in Fig. 3.4. The twisted tape length is 1350 mm and width is 25 mm. Pitch of twisted tape is 25 mm and 50 mm respectively. The ratio of width and pitch is 1:1 and 1:2.

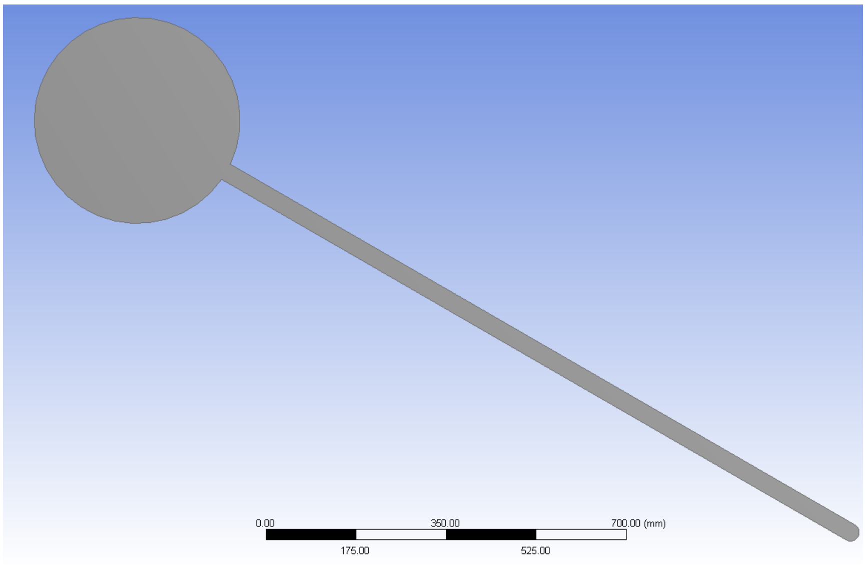

Figure 3.1: Geometry at 30^o tilt angle

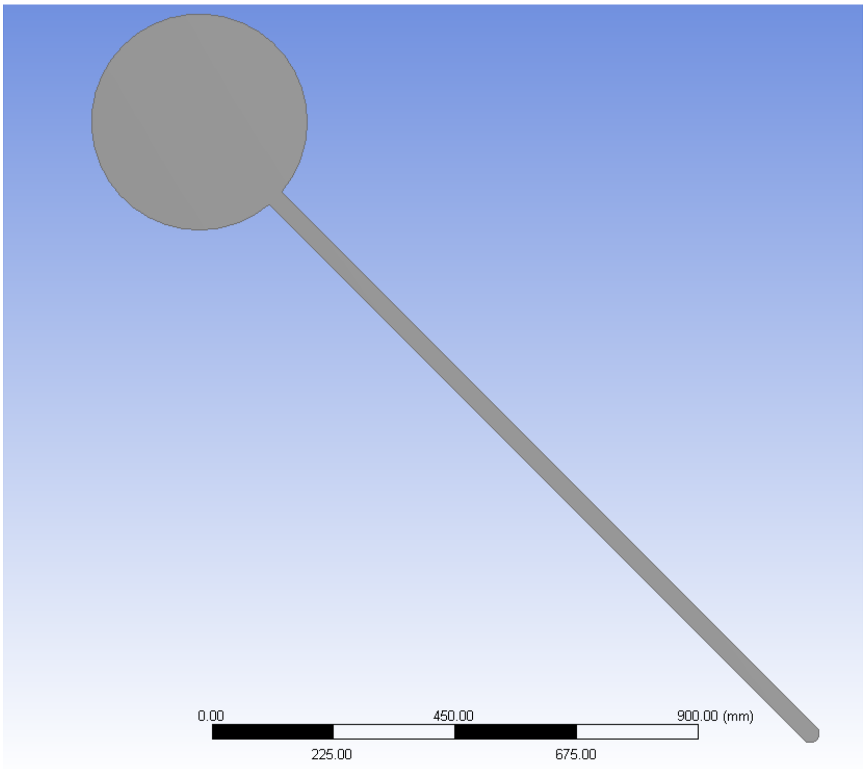

Figure 3.2: Geometry at 45^o tilt angle

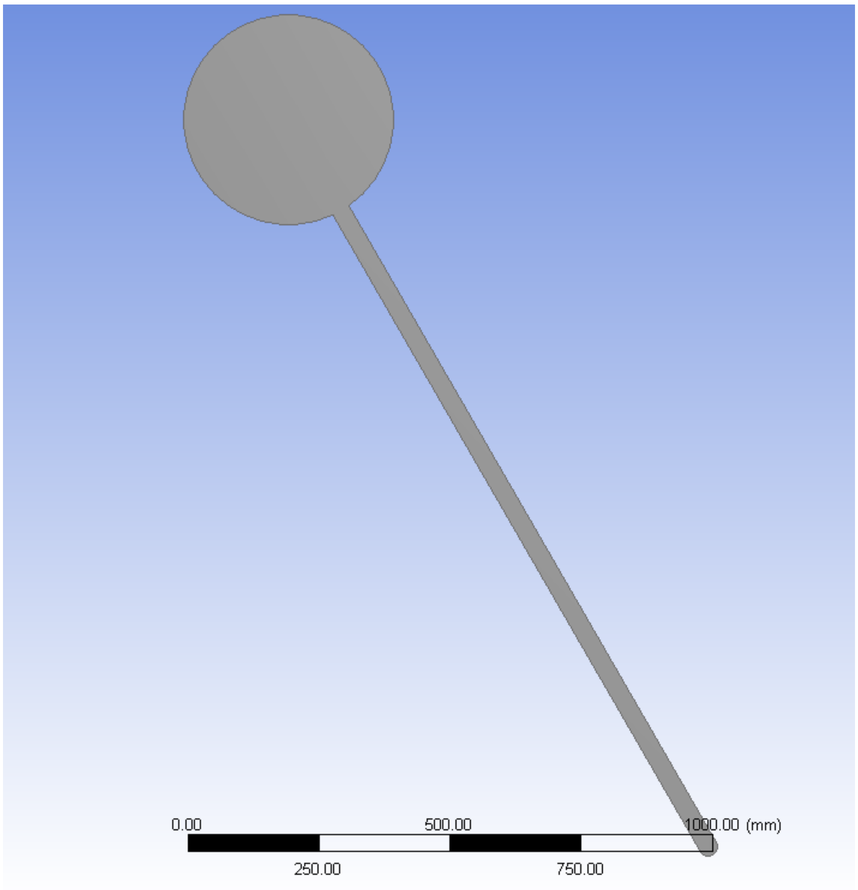

Figure 3.3: Geometry at 60^o tilt angle

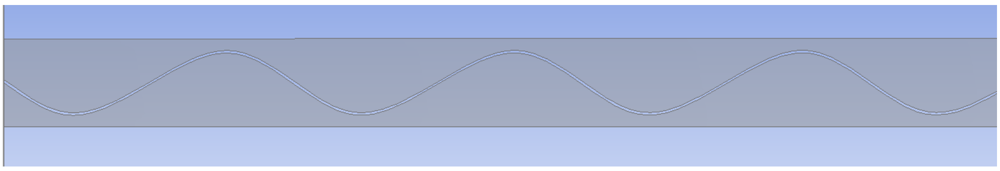

Figure 3.4: Twisted tape inserted in tube

3.3 Mathematical Model

For incompressible Newtonian fluid and laminar flow the eqation system solved exist on the mass, momentum and energy equations [10].

3.3.1 Governing Equations

The governing equations for continuity, momentum, and energy equations for the fluid region are as follows:

3.3.1.1 Mass Conservation (Continuity) Equation:

$$\frac{\partial u_i}{\partial x_i}=0 \tag{3.1}$$

3.3.1.2 Momentum Conservation Equation:

$$\rho^{'}(\frac{\partial u_i}{\partial t}+\frac{\partial u_i u_j}{\partial x_i})=-\frac{\partial p}{\partial x_i}+\frac{\partial p}{\partial x_i}+\mu(\frac{1}{3}\frac{\partial^2 u_j}{\partial x_i x_j}+\frac{\partial^2 u_i}{\partial x_i x_j})+(\rho-\rho^{'})g \tag{3.2}$$

3.3.1.3 Energy Conservation Equation :

$$\rho^{'}(\frac{\partial h_{tot}}{\partial t}+\frac{\partial h_{tot} u_i}{\partial x_i})-\frac{\partial p}{\partial t}=k\frac{\partial T}{\partial x_i x_j} \tag{3.3}$$

where $\rho^{'}$is a reference density and $h_{tot}=h+\frac{1}{2}\|u\|^2$is the total enthalpy.

3.4 Computational Domain and Boundary Condition

The computational domain of an evacuated tube collector model has contains boundary conditions which listed below;
Closed end of tube: adiabatic
Tank wall: adiabatic
Fluid cell zone condition: water
Solid cell zone condition: copper, steel, glass (Depend on analysis condition).

3.5 Mesh Generation

Mesh generation is often most important and most consuming part of CFD analysis. The quality of the grid plays a direct role on the quality of the analysis. The solver will be more robust and efficient when using a well-constructed mesh. For the best Quality of mesh generation of the ETC geometry, fluent meshing requires the following parameter input: Relevance, Use Advanced Size function Spam Angle Centre Min size, Proximity MIN size, Max face size, Max size and Min edge length, Meshing Method, Refinement. Change the following parameter and check the quality of the mesh generated into geometry. Number of quality parameter available for checking the quality of the mesh for better and efficient analysis. Change the meshing input parameter and check the quality of the mesh and select the most efficient and well-constructed mesh for analysis of the ETC geometry as shown in Fig. 3.5, 3.7. 129942 nodes and 256484 elements used in mesh of ETC for without inserted twisted tape in tube. 84059 nodes and 163266 elements used in mesh of

ETC for inserted twisted tape in tube. The mesh matrics skewness as shown in Fig. 3.6 and 3.8.

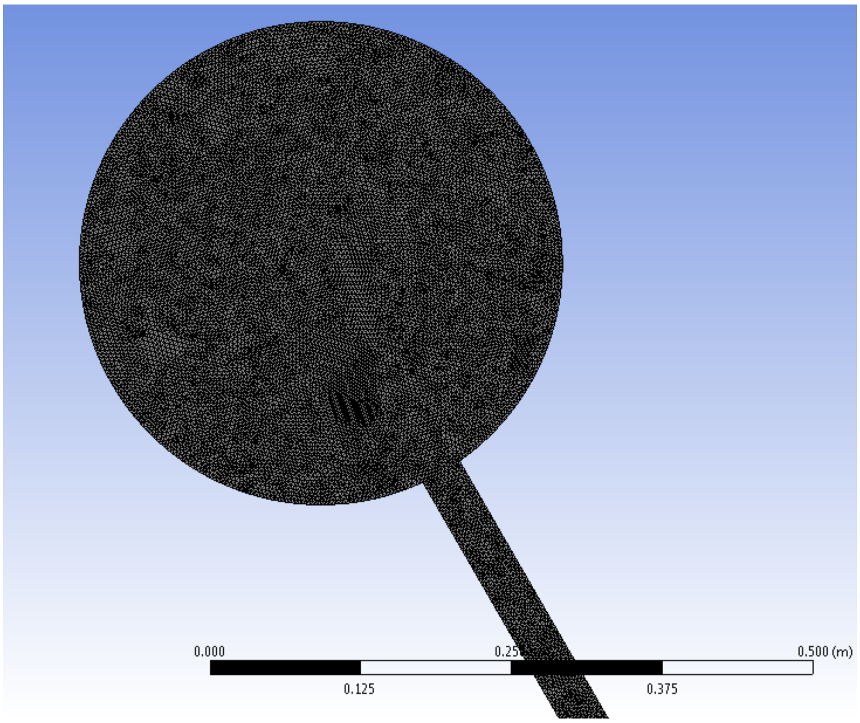

Figure 3.5: Mesh of an evacuated tube collector without twisted tape

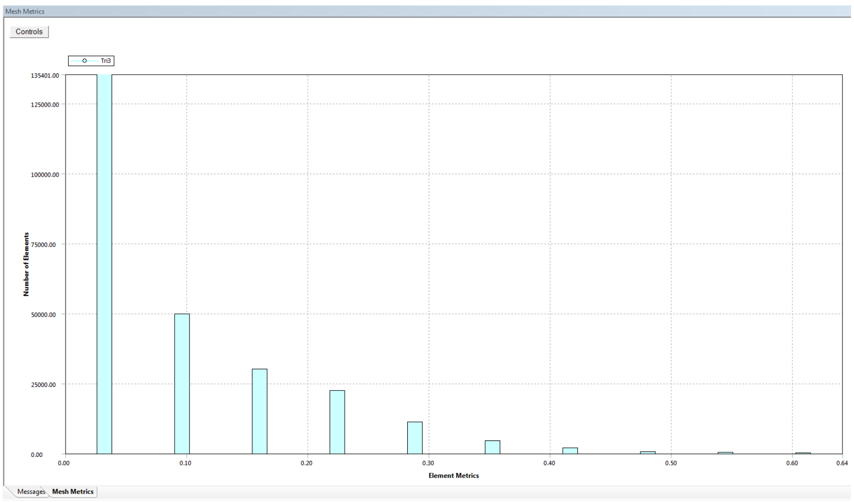

Figure 3.6: Mesh metrics skewness of an evacuated tube collector without twisted tape

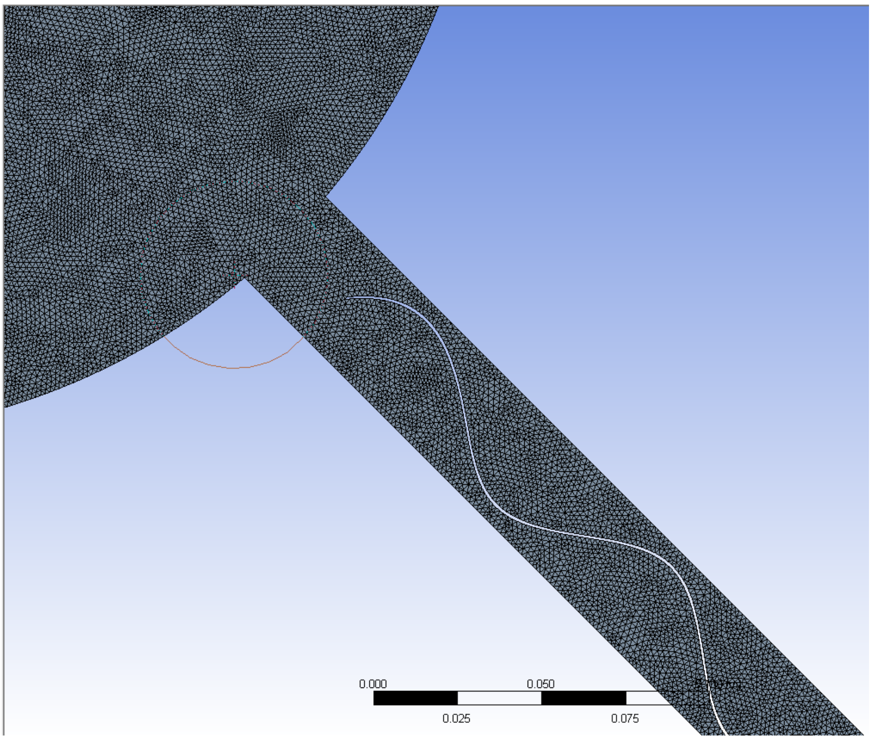

Figure 3.7: Mesh of an evacuated tube collector with twisted tape

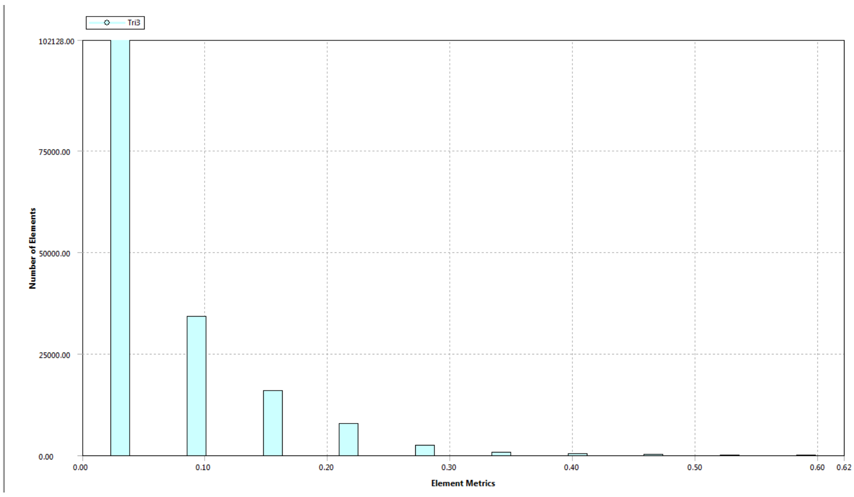

Figure 3.8: Mesh metrics skewness of an evacuated tube collector with twisted tape

3.6 Computational Procedure in FLUENT ANSYS

3.6.1 Setup for simulation analysis

After meshing, apply all setup condition to the ETC geometry. First activate the model which is correlated the simulation like energy model and viscous model etc.

In this project the flow is laminar in viscous model. The heat transfer between the solid and fluid so that only energy model is selected for this analysis. Than after select the material which will be used for the ETC as well as heat transfer fluid. All types of fluids and solid available in the ANSYS database. Whenever some time new material which is not already defines by ANSYS, that material properties also define by user defined database (UDD) or by user defined function (UDF). Consider the properties of water is that the density of water 998.4 kg/m^3 very to use of boussinesq approximation. Take a constant specific heat and thermal conductivity 4182 J/ kg-K and 0.9 W/m-K respectively. Consider the constant thermal expansion coefficient at 300 K is 0.0002748 k^{-1}. And take a viscosity is 0.001003 kg/m-s. Double precision used and pressure based type solver used in transient simulation. In simulation consider atmospheric pressure condition and 9.81 gravitational acceleration. In Boussinesq set the temperature 300 K and 998.4 kg/m^3 at operating condition. The constant 700 W/m^2 heat flux applied on the top of the tube and 200 W/m^2 constant heat flux applied on the bottom of the tube.

3.6.2 Solution method of evacuated tube collector

Several discretization schemes are available for steady and unsteady analysis i.e. PISO, SIMPLE or SIMPLEC. Coupled scheme is used in this project. When the flow is alignment with the grid the first order upwind discretization may be acceptable. For the triangular and tetrahedral grids, since the flow is never aligned with the grid, generally more accurate results were obtained using second order discretization scheme. For quad/hex grids, better results obtained using second order discretization, for complex flows. In this project the first order Implicit Transient Simulation technique is used. Second order upwind momentum discretization scheme is used in this project. The least square cell based gradient and body forced weighted pressure used in discretization scheme. In solution control for momentum and pressure explicit relaxation factor is 0.75 consider. In solution initialization the standard initialization method is used in this numerical model.
This study consider time step size T = 0.1 sec with total number of time step 15000. Time step method is fixed and max iteration is 1000.

Chapter 4

Results and Discussion

This section presents results and observation from the CFD simulations carried out in this project. When the constant heat flux is applied on the top and bottom of the tube, it is important to understand the heat transfer phenomena taking place in the tube. There are some characteristics derived and compared at various tilt angles to find out the optimum tilt angle of evacuated tube collectors as listed below.

- Flow within the storage tank
- flow within the tube
- Thermal stratification and mixing
- Consideration about the use and design of ETC
- Flow structure when the twisted tape is inserted in tube
- Mean temperature in storage tank at various tilt angle with and without twisted tape inserted

The simulation was carried out for an ETC at tilt angles of 30^o, 45^o , 60^o respectively. Also simulation was undertaken for an ETC with twisted tape inserts of width/pitch of 1:1 and 1:2 for an inclination of 45^o. The length of the twisted tape was 1350 mm and constant width of 25 mm. The thickness of twisted tape was 1 mm.

4.1 Simulation of an evacuated tube collector at different tilt angles without twisted tape

The temperature distribution in solar water heater at 30^o is shown in Fig. 4.1.

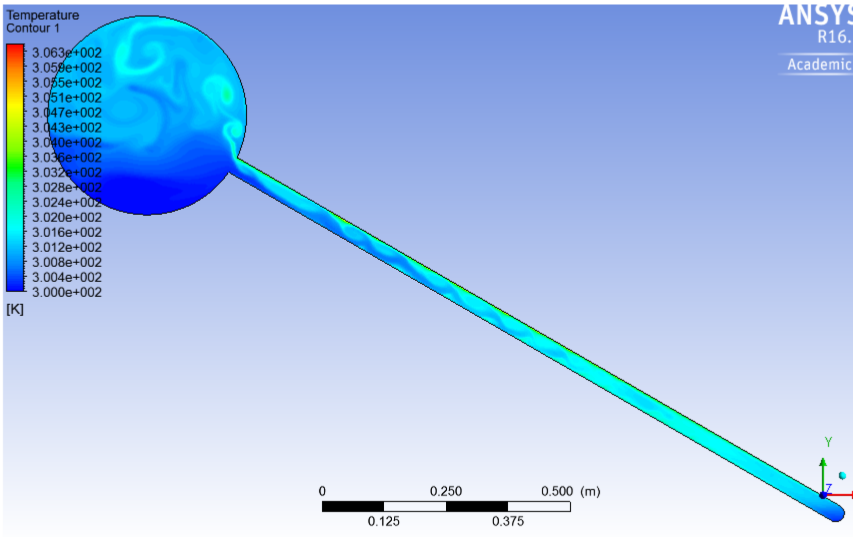

Figure 4.1: Temperature contour at 30^o tilt angle

The temperature distribution in solar water heater at 45^o is shown in Fig. 4.2.

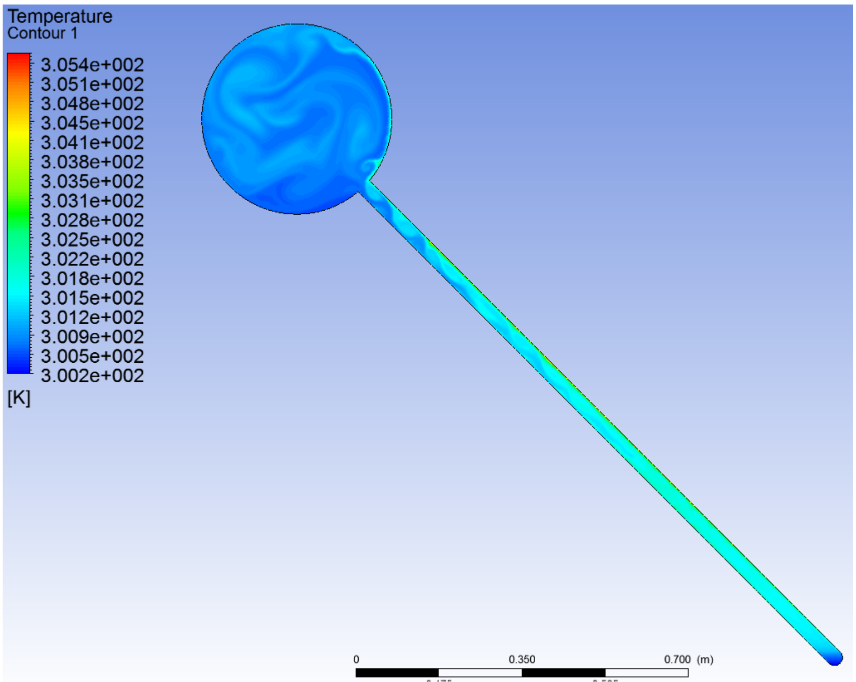

Figure 4.2: Temperature contour at 45^o tilt angle

The temperature distribution in solar water heater at 60^o is shown in Fig. 4.3.

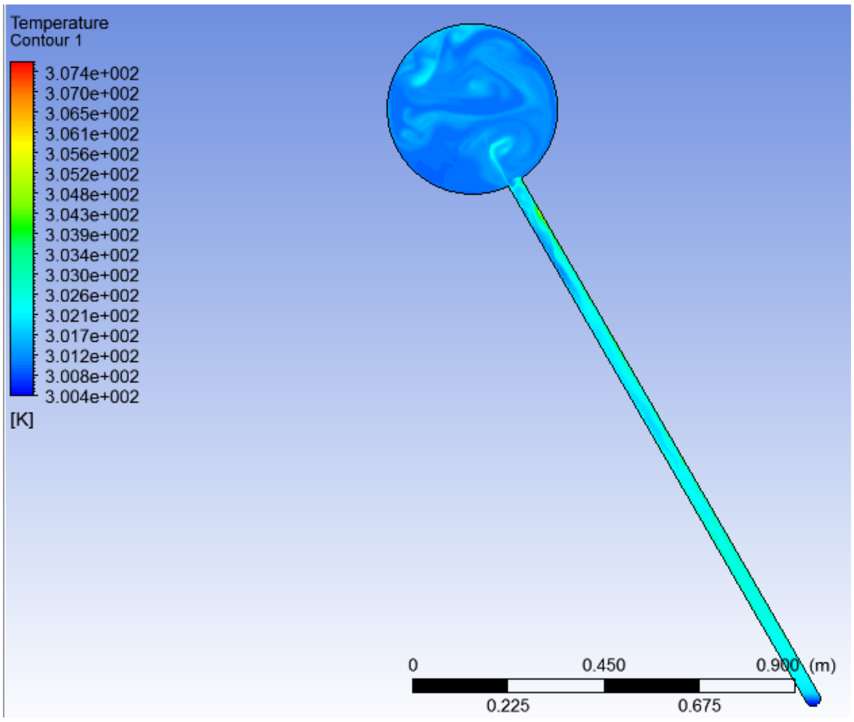

Figure 4.3: Temperature contour at 60^o

The velocity profile in solar water heater at 30^o is shown in Fig. 4.4.

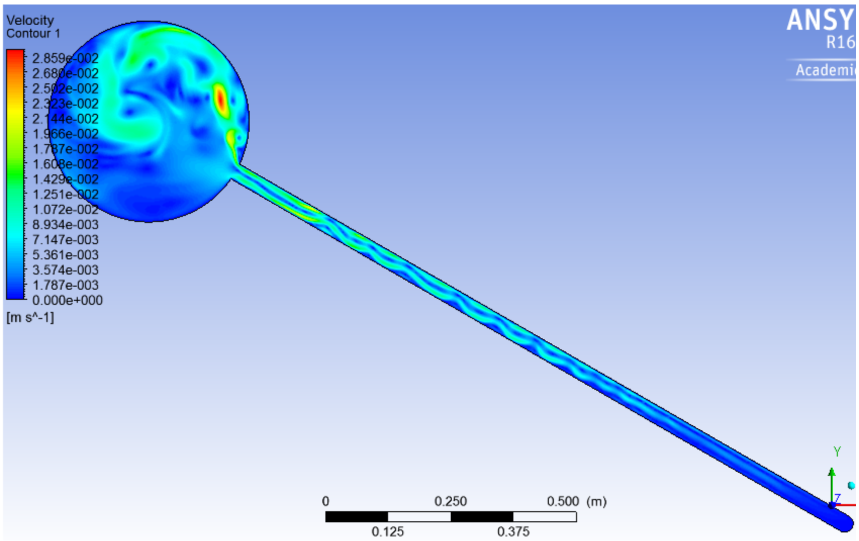

Figure 4.4: Velocity contour at 30^o

The velocity profile in solar water heater at 45^o is shown in Fig. 4.5.

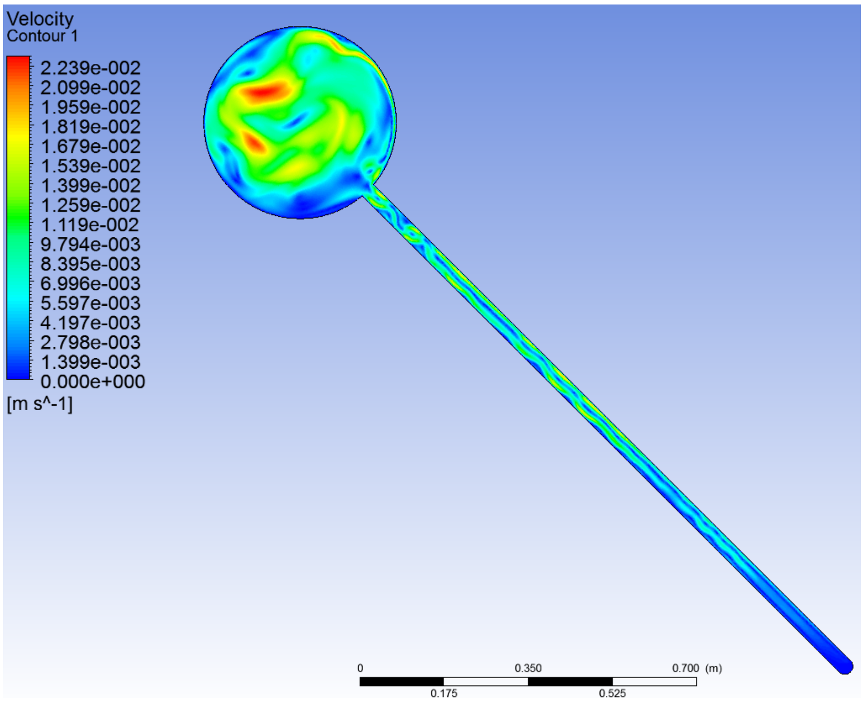

Figure 4.5: Velocity magnitude at 45^o

The velocity profile in solar water heater at 60^o is shown in Fig. 4.6.

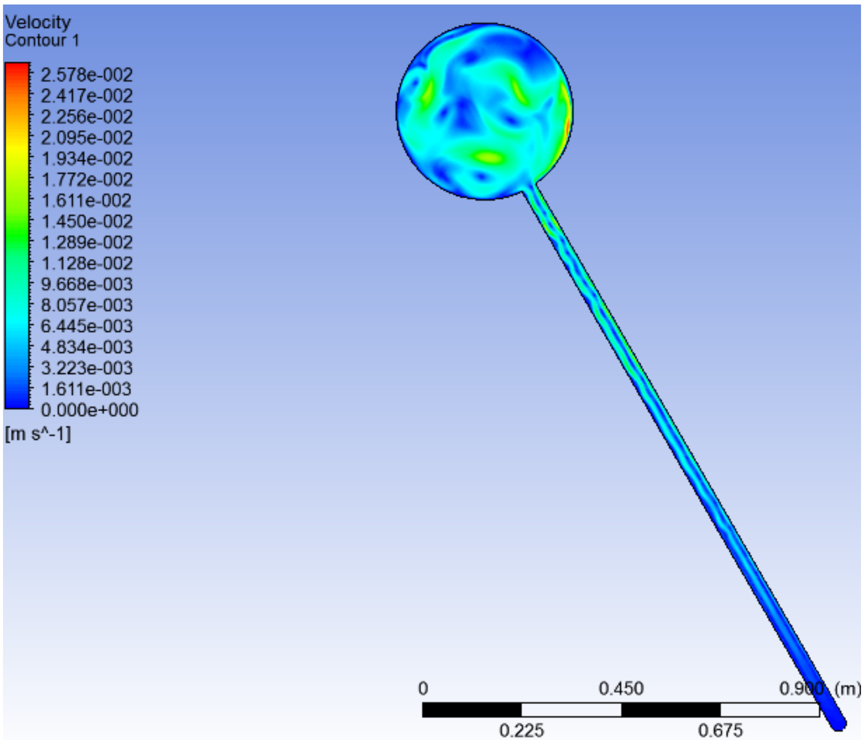

Figure 4.6: Velocity magnitude at 60^o

4.1.1 Flow within storage tank

As shown in Fig. 4.4 4.5 4.6 the velocity magnitudes are showed at different tilt angles. It is seen that for 30^o tilt angle the hot water flow exits from the evacuated tubes remaining close to the wall of storage tank. For all that the momentum of this flow is dissipated before it reaches the lower region of the tank as shown in Fig 4.4. For the 45^o tilt, the warm water flow has a larger penetration in the storage volume generating a vortex that reaches the lower region of the storage tank, because the flow has larger momentum and the lower location of the tube opening thereby leading to the full mixing of the water.

4.1.2 Flow within tubes

By the buoyancy driven flow within the tubes consists in a cold water from the storage tank to the lower region of tube. As density decreases due to water heats up and water flow up towards the storage tank by buoyancy forces. As shown in Fig. 4.4 4.5 4.6, the velocity within the region increases with the tilt angle because of the projection increases of the buoyancy forces along with the direction of flow. At the same time water flow downward by driven gravity due to larger density at the bottom half of tube. Water flow near the top and bottom half of the tube in opposite direction, it is built up between them by shear layer. Shear layer has smallest velocity. Stratification of temperature in tube as shown in Fig. 4.2. For 30^o tilt angle the cross sectional area fill by the flow towards and from the storage tank remains unaltered in process.

4.1.3 Thermal stratification and mixing

From simulation the greater temperatures and thermal stratification obtained with lower tilt angles as shown in Fig. 4.1, 4.2, 4.3, 4.4, 4.5 and 4.6 that the thermal stratification for the three studied angles. For the lower tilt angle of 30^o the storage tank remains stratified and for larger tilt angle the storage tank is fully mixed. For the tilt angle of 30^o the stratification decreases and the temperature increases with time in shown in Fig. 4.1. For all tilt angle it is found that the temperature above the opening of tube point is equivalent. So that the hot water us fully mixed above the opening of tube. The thermal inactive region is found in the 30^o angle. But this cold region is not found for 45^o tilt angle. It is important to consider the mixing effect of the water flow through the opening of tube and in to the storage tank.

4.1.4 Consideration about the use and design of ETC

As at low tilt angle to increase the solar occurrence on the thermal collectors. But in this condition it leads to a large thermal inactive region on the bottom of the storage tank as shown in Fig. 4.1. As a result the effective amount of available hot water is reduced in low tilt angle. But it is not considered as negative feature, when the thermal inactive region could work as buffer zone for the charging of fresh water without the mixing with previously heated water, while the hot water is obtainable at higher temperature.

4.1.5 Mean temperature in storage tank at various tilt angles without twisted tape inserted

Table 4.1: Average temperature in tank at various tilt angle without twisted tape

Tilt angle	Average temperature in tank after 5 min	Average temperature in tank after 10 min	Average temperature in tank after 15 min	Average temperature in tank after 20 min	Average temperature in tank after 25 min
30^0	300.9 K	301.7 K	303.6 K	305.2 K	306.6 K
45^0	301.5 K	305.1 K	304.8 K	306.0 K	304.6 K
60^0	300.6 K	301.1 K	302.4 K	301.9 K	302.4 K

As observed from Table 4.1 the maximum average temprature is attained an inclination of 30^o as compared to that at 45^o and 60^o. Also there are fluctuations in temprature for inclination of 45^o wherein the temperature initially increases and than decreases. For an inclination of 60^o, the fluctuations are almost steady. For 30^o inclination, the temperature are steadily increasing.

4.2 Simulation of an evacuated tube collector with twisted tape

The simulation done for the an evacuated tube collector with twisted tape, temperature distribution in solar water heater at 45^o tilt angle is shown in Fig. 4.7

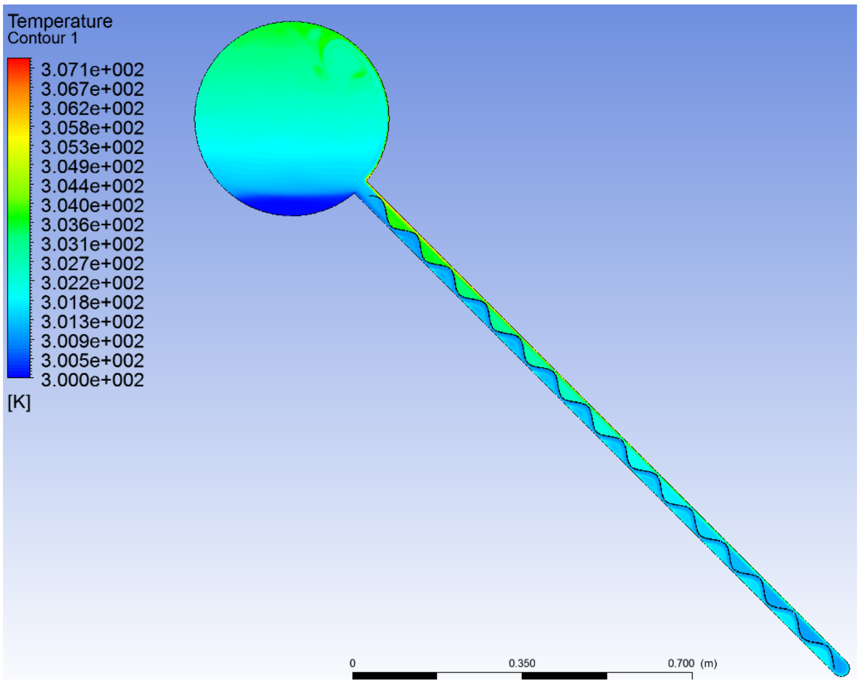

Figure 4.7: Temperature contour with twisted tape

The velocity profile in solar water heater at 45^o tilt angle is shown in Fig. 4.8.

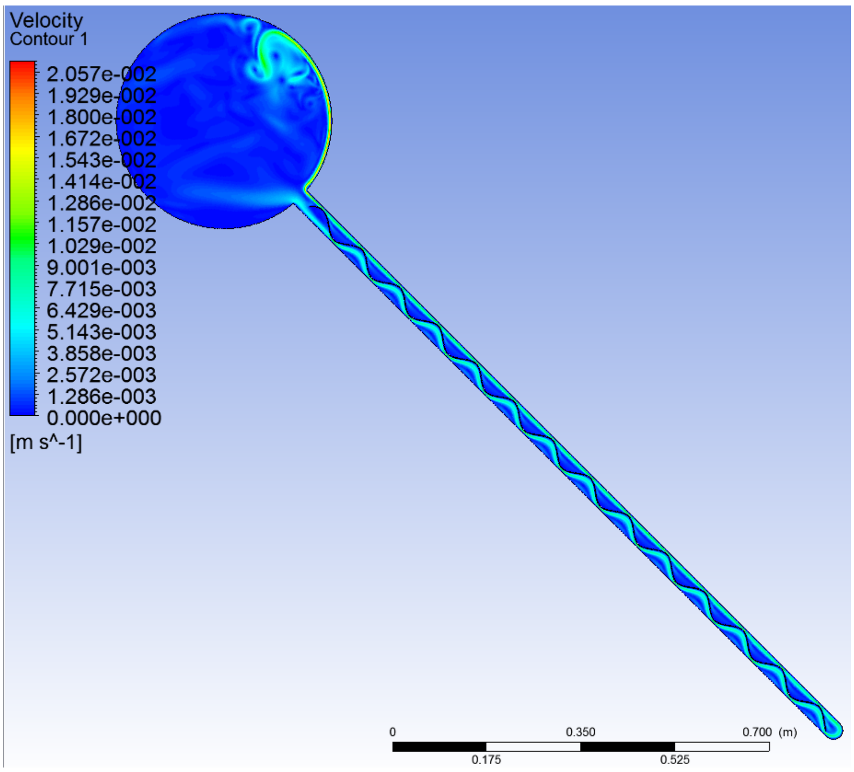

Figure 4.8: Velocity magnitude with twisted tape ratio 1:2

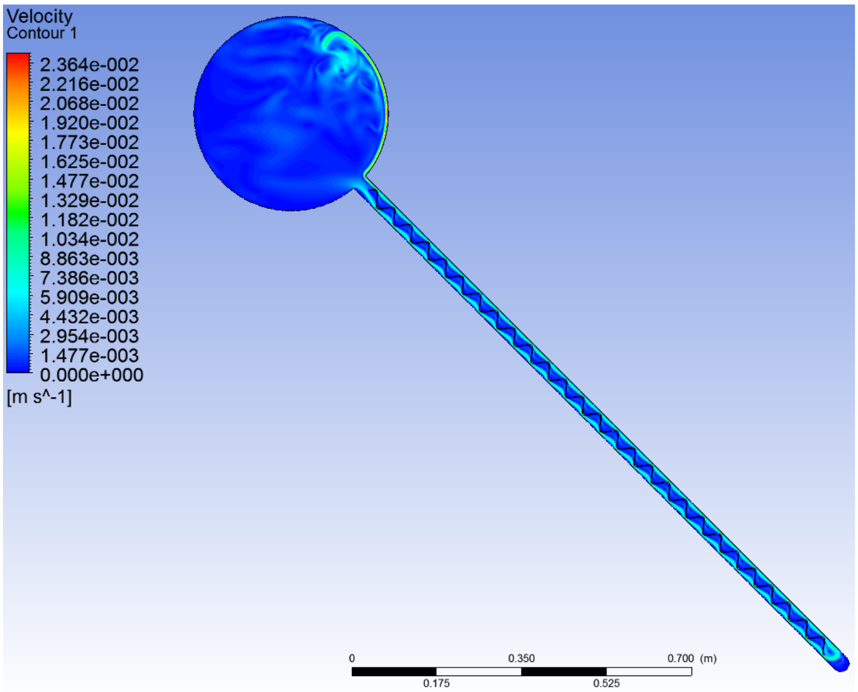

Figure 4.9: Velocity magnitude with twisted tape ratio 1:1

4.2.1 Flow structure with the twisted tape inserted in tube

Water flows toward the tank at near the top half of tube by driven force due to density decreases. The temperature profile and velocity profile disturbed by the inserted tape is as shown Fig. 4.7 and 4.8. Velocity decreases when the twisted tape inserted as shown Fig. 4.7. This is because the twist tape inserts makes the mixture of the water near the top and bottom half of the tube more intense, which destroys the original orderly flow and generates more eddy, and thus leads to a higher dissipation of mechanical energy. The w/p ratio of 1:2 disturb the flow in tube more intense. The velocity magnitude decreases as the pitch double as shown in Fig. 4.8 and 4.9.

4.2.2 Mean temperature in storage tank at various width/pitch ratio with twisted tape inserted

Table 4.2: Average temperature in tank at various width/pitch ratio with inserted twisted tape

w/p ratio	Average temprature in tank after 5 min	Average temprature in tank after 10 min	Average temprature in tank after 20 min	Average temprature in tank after 25 min
1:01	313.3 K	315.5 K	317.8 K	320.5 K
1:02	312.7 K	314.0 K	317.5 K	320.8 K

As observed in Table 4.2, with twisted tape w/p ratio of 1:1, higher tempratures are achieved in the storage tank at first five minutes compared to a ratio of 1:2. These results are obtained for a tilt angle of 45^o. The temperatures are however nearly equal after 15 minutes.

Chapter 5

Conclusions and Future work

5.1 Conclusions

1. As per the numerical simulation, it is proved that the solar collector tilt angle has a significant effect on solar energy gain, the flow patterns inside tube and storage tank, and the stratification of flow.

2. Larger flow velocities are achieved for configurations with larger tilt angle since the buoyancy forces have a greater component on the flow direction. With higher velocities the mixing effect increases in the storage tank leading to heating of the water at the bottom of the tank.

3. The simualtion results show that at 30^o tilt angle, higher temperatures are achieved in the storage tank. Also at a tilt angle of 45^o, there is proper mixing of water observed in the tank.

4. The CFD study of ETC revealed that for a 30^o tilt angle, the temperature profile in the storage tank provided the maximum temperature gain due to a reduced gravitational head.

5. The numerical study done using twisted tape inserts in an ETC collector revealed that there is an appreciable increase in storage tank temperature as compared to a simple ETC collector. Considering a width/pitch ratio of 1:1 for the twisted tape insert indicated the fastest temperature rise in the storage tank.

5.2 Future work

The present study may be extanded for future work such as :

- The effect of monthly solar variation over a location on the performance of ETC may be considered.
- The effect of inclination of the twisted tape insert on the ETC performance may be studied in 3D analysis.
- The influence of tube surface characteristics (radiation properties) on the ETC performance may be considered for future analysis.

Bibliography

[1] Hottel and Whillier,https://en.wikipedia.org/wiki/Solar thermal collector Flat plate collectors

[2] Morrison. G.L., Budihardjo. I., Behnia. M., 2004. Measurement and simulation of flow rate in water-in-glass evacuated tube solar water heater.

[3] Morrison. G.l., Budihardjo. I., Behina. M., 2007. Natural circulation flow through water-in-glass evacuated tube solar collector.

[4] Cabanillas. R.E., Estrada. C.A., Avila. F., 1995. A device for measuring the angular distribution of incident radiation on tubular solar collectors. Renewable energy 6 (7), 843-847.

[5] Window. B., 1983. Heat extraction from single ended glass absorber tubes. Solar Energy 31 (2), 159-166.

[6] Lighthill. M. J., 1953. Theoretical consideration on free convection in tubes. Quart. J. Mech . Appl. Math. 6 (4), 398-439.

[7] Leslie. F. M., 1959. Free convection in the tilted open thermosyphon. J. Fluid Mech. 7, 115-127.

[8] Japikse. D., Winter. E.R.F., 1971. Single-phase transport processes in the open thermosyphon. Int. J. Heat mass transfer 14, 427-441.

[9] Gaa, F.O., Behnia, M., Morrison, G.L., 1996. Experimental study of flow rates through inclined open thermosyphons. Solar Energy 57, 401-408.

[10] J. Arturo Alfaro-Ayala et al., Numerical study of a low temperature water-in-glass evacuated tube solar collector., Energy conversion and management 94(2015) 472-481.

[11] J. Bracamonte et al., Effect of the collector tilt angle on thermal efficiency and stratification of passive water in glass evacuated tube solar water heater. Applied energy155 (2015) 648-659.

[12] Yao. keguang et al., Performance evaluation of all-glass evacuated tube solar water heater with twist tape inserts using CFD. Energy procedia70 (2015) 332-339.