Design and CFD Simulation of Solar Water Heater Used In Solar Assisted Biogas System

Lemi Negera Woyessa , Basam.Koteswararao, Balewgize A. Zeru, P.Vijay

Abstract: Difficulty in collecting conventional energy sources as well as their economic benefits including saving of time ,money, fertilizer of higher nutrient value, availability of waste easy and comfortable cooking, health benefits including the reduction diseases and environmental benefits such as saving of forest, clear surrounding were the main motivational factors for this research. However, climate temperatures in areas are too low to enable enough biogas production in small unheated digesters to meet the energy requirements of the institute, so the objectives of were to overcome the problem of energy by solar assisted with the hot water storage tank. In this research mathematical modeling of the solar water heater was designed and the analysis of heat transfer coefficient (losses) through the flat plate collector was done and the techniques that used to reduce these losses also mentioned. From the simulation results; the effect of mesh type on flat plate collector, temperature rise, and pressure drop were characterized including flow type in the laminar and turbulent using CFD approach. The FPC was needed for the preparation of the hot water for the heating of the waste food for the selected fixed dome digester with 2m^2 was designed. The effect of water mass flow rate 0.01-0.05kg/s on flat plate collector, temperature rise, pressure drop, and velocity was characterized including the variation of flow types intensity using CFD approach. The optimal temperature to this process was 37$\pm$2 °C.The results obtained have been validated with analytical results.

***Index Terms**: CFD simulation, flat plate collector; Solar assisted; solar water heater; Solar radiation.*

I. INTRODUCTION

Ethiopia is one of the developing countries among those with initiatives to promote biogas technology to reduce the severe energy problem faced especially in the household energy sector and in different institutions. The demand of energy for human life is increasing time to time as the standard of living increase, thus it extended with the use of fossil fuels for cooking, lighting, and industrial purposes and as far as in turn its combustion results contribute global warming effect [1], [2].

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A solar assisted biogas system has been suggested to meet the difficulties in biogas yield due to climate change conditions. Solar flat plate collectors have been considered in the current research for providing the required amount of heat energy, absorbed from solar radiation to the biogas plant digester to maintain an optimum slurry temperature. This research will aim at providing a solution to the difficulty in the production of biogas in varying weather conditions especially during climate change season where the temperature remains low throughout the year and assesses solutions by design of solar assistance biogas production from waste food. Because the left food from the cafeteria, the sun is a free renewable energy source and the heat can be captured by solar collectors for digester heating system with storage tank. Therefore, in this research, it is necessary to design a solar assisted biogas digester with an efficient process, which allows optimal uses of available resources and optimal of biogas productions with optimal temperature.

II. LITERATURE REVIEW

Biogas as a source of renewable energy is produced by biotechnology and used widely on a residential scale. The biogas was produced for the very first time in 1814 by Davy from organic wastes. Biogas technology was introduced on October 12, 1966, Gregorian Calendar. (October 2, 1959, Ethiopian Calendar), when the first batch type floating digester was constructed in Ambo University to generate the energy required for the purpose of welding. During the last two and half decades above one thousand digesters were installed in various parts of the country such as in households, community, and governmental institutions ranging in size from 2.5 m^3 to 200 m^3. However, the awareness and practices didn't disseminate to society. But currently due to the renewed interest on renewable energy to achieve Millennium Development Goals (MDGs), governmental and nongovernmental organizations are participating to widely disseminate the technology [2]. Various Biomass [9] experiments conducted to get energy instead of simply waste.

2.1. Heating System of Anaerobic Digestion System

There are two methods of heating the digester by solar energy i.e. passive and active. In the case of passive heating, for example, the digester's body can absorb solar energy as a receiver through a lid or dome.

2.1.1. Solar Energy

Solar energy is the energy that sustains life on earth for all plants, animals, and peoples. It provides a compelling solution for society to meet their needs for clean and abundant sources of energy in the future. Solar radiation has been utilized for centuries by people for heating and drying [12][13].

Solar energy has two major advantages:
1. It is an environmentally benign source of fuel
2. Free and available in adequate quantities in most regions of the world.

Incoming solar radiation of the incoming radiation a part is reflected, absorbed and diffracted depending on the wavelength. According to research [3] the efficiency of PV cell will increase by various cooling methods.

2.2. Types of Solar Collectors

Four types of solar collectors are used for residential applications:

1. Flat-plate collector
2. Integral collector-storage systems
3. Batch system
4. Evacuated-tube solar collectors

1.Flat-Plate Collector

Flat plate collector (FPC) is a special kind of heat exchanger that transforms solar radiation energy into heat energy which is transferred through a working liquid [12]. The absorber absorbs the solar radiation and transfers the heat to the flowing water (solar water heater). It can increase the temperature of the fluid up to 100℃ above ambient temperature. By considering Characteristics flat plate solar collector was selected.

- ✓ Flat-plate collectors will absorb the energy coming from all directions above the absorber (both beam and diffuse solar irradiance), due to this reason, it can work effectively on cloudy days.
- ✓ They are widely available and low-cost.
- ✓ In climates with lots of snowfall, they have the advantage that the hot water in the panel can be used to melt the snow off the panel, thus reducing downtime and increasing overall production time.

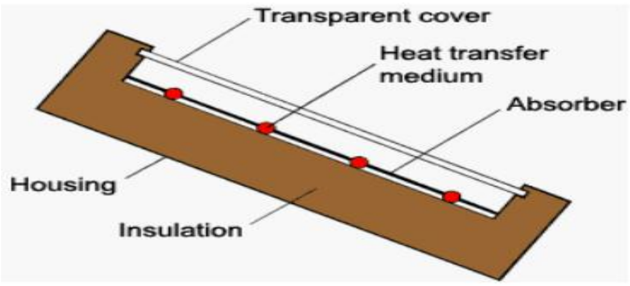

Figure 1. Flat-plate solar collector model (9)

- ✓ Their designs are robust and therefore less prone to damage.
- ✓ simple in design, requires little maintenance and has no moving parts and therefore one of the most used and important types of solar collector.
- ✓ Additionally, a flat-plate collector can be constructed using local materials and skills, For the reasons, simple technology, popularity, and the relatively low price.

III. METHODOLOGY AND MATERIALS

3.1. Physical descriptions of the Research

Jimma university branch of the institute of technology is one of the Ethiopian University located at the Jimma zone, southwestern Ethiopia that is in the Oromia region and 335km distance from Addis Ababa. The geographical coordinate is between 7° 13'- 8° 56N latitude and 35°49'-38°38'E longitude with an estimated area of 19,506.24Km^2.

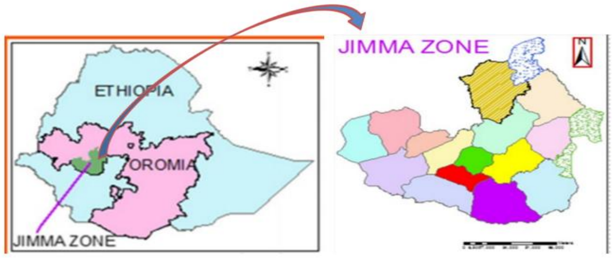

Figure 2. Map of Jimma zone

3.2. Data Collection

Both primary and secondary data were instrumental in informing this study. Primary data was collected through observation, structured personal interviews with cafeteria heads and key informants, and focus gather food waste data. Menu of the food in the day and lastly cooking system they used. Secondary data was meteorology data from metrology agency, collected data through desktop research and review of relevant literature from the internet and publications.

3.3 Solar radiation of meteorology data collection

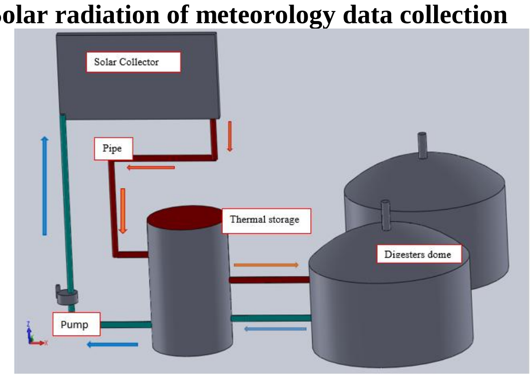

Figure 3. Layout of the main parts included in this paper

Solar radiation data and temperature distribution data were taken from Meteorology agency in the Addis Ababa, Ethiopia , Bole for five and six-year data for the design and CFD simulation of solar assisted biogas system of this project. This all data where the key used for this project as the raw material to fulfill the analytical design and CFD analysis of design of solar assisted biogas system in the Jimma institute of technology at all.

System description: -The system mainly consists of three subsystems heating system, heat storage system and fermentation system. The heat storage device accumulates the surplus heat and supplies heat when there is not sufficient heat-collecting capacity.

IV. CFD SIMULATION OF SOLAR WATER HEATER

4.1 CFD Simulation of solar water heater

Computational fluid dynamics (CFD) is the analysis of systems involving fluid flow, heat transfer and associated phenomena such as chemical reactions by means of computer-based simulation. A numerical model was first constructed using a set of mathematical equations that describe the flow. These equations are then solved using a computer programmed in order to obtain the flow variables throughout the flow domain.

Discrete Transfer Radiation Model (DTRM) to simulate the solar collector for better understanding of the heat transfer capabilities of the collector.

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In order to provide easy asses to their solving power, all commercial CFD packages include sophisticated user interfaces to input problem parameters and to examine the results. Hence all code contains three main elements:

Pre-processor

Solver

Post-processor

A. Geometry: The geometry for this problem is constructed on Solid Works 2013 and imported to ANSYS Fluent.

Table 1 Specification of flat plate collector

The specifications of the flat-plate solar collector	
Specifications	Details
External dimensions	2000 × 1000 × 100 mm
Tubes material	Copper
Quantity	9 tubes, 23 mm in diameter
Absorber Absorptivity	0.95
Absorber Emissivity	0.05
Glass	4 mm
Glass Transmissivity	0.88
absorber and glass	25mm

Note: The full geometry of collector was created in the solid work Software using the various features available in solid work to create various parts of the collector with the help of specifications given in table 1 to get the model of the collector which is shown in figure 4.

The assembled FPC model was imported to ANSYS fluent for simulation.

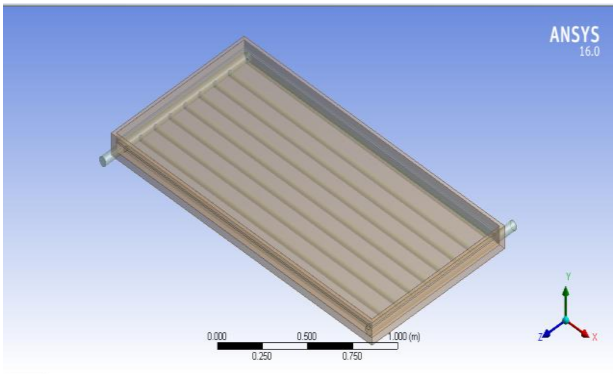

Figure 4 Imported flat plate collector to ANSYS

Figure 4. was the model of flat plate collector imported to Ansys fluent prepared for the CFD simulations procedure and all the geometry was for preparations of the CFD simulations. The computational mesh is used as a pre-processor for the CFD solver and post-process geometry was prepared as indicated in figure 5.

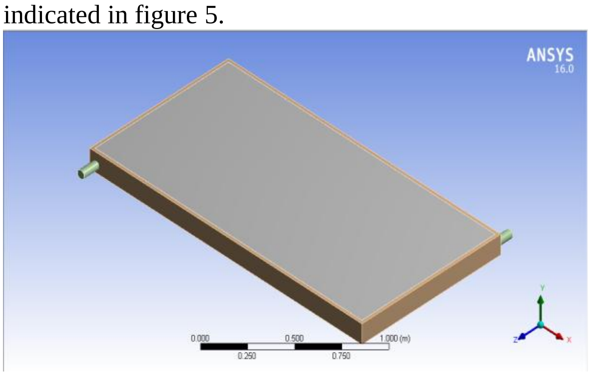

Figure 5. Geometry for Meshing

B. Mesh

The domain was broken down into a set of control volumes, with a node at the center of each volume.

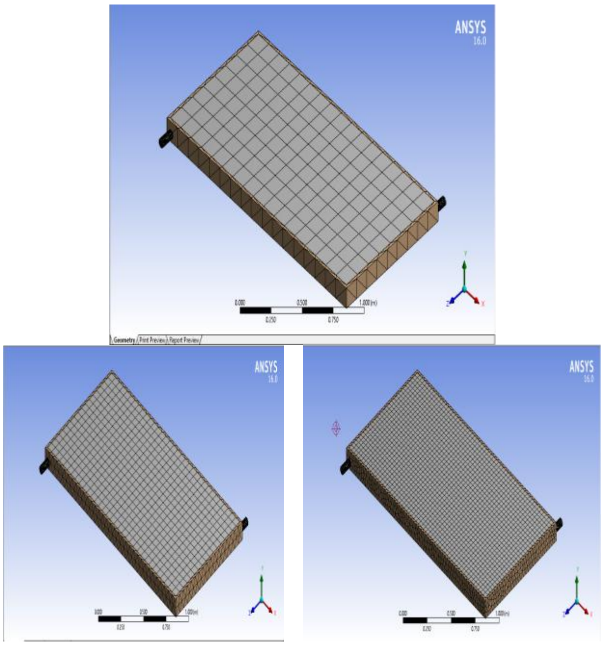

Figure 6. Types of meshing by using ANSYS FLUENT

The total number of nodes N in the resulting grid is limited by constraints on computer memory and by CPU time [11]. Initially, a relatively coarse mesh is generated. It is meant to reduce numerical diffusion as much as possible by structuring the mesh in a good manner, particularly near the wall region. Later, a fine mesh is generated. The computational time and accuracy depend on grid size. The high number of the grid will lead to good accuracy and vice versa. Figure 6 was different types of mesh for the preparation's solutions such as coarse, medium and the fine type mesh. The result was done on the three types of mesh and selected the preferred types of mesh based on the results of the simulations.

4.1 Solver

The computational domain has been solved as a steady state conjugate heat transfer problem and the solution process is performed until convergence and an accurate balance of mass and energy are achieved. In the iterative scheme, all the equations are solved iteratively, for a given time step, until the convergence criteria are met.

4.1.1 Boundary Condition

The collector plate boundary conditions mainly include solar radiation intensity, ambient temperature and mass flow rate of water in inlet and outlet. The specified boundary conditions are as detailed here.

In this analysis, a mass flow rate of 0.01-0.05kg/s was applied for the riser inlet.

A heat flux of 565.9 w/m^2 was applied to the top glazing thereby simulating a solar heat input.

The side and bottom walls of the system were treated as adiabatic, which means insulating materials to protect the loss in the collector.

Table 2 material properties which used for ANSYS FLUENT

No	Thermal conductivity(w/m k)	Density (Kg/m^3)	Specific heat (KJ/kg*k)
Water liquid	0.6	998.2	4182
Copper	386	8978	381
Rockwool	0.4	48	840
Glass	1.14	2230	750

V. RESULTS AND DISCUSSION

5.1 CFD Simulations of Flat Plate Solar Collector

After all stages of this thesis, some results are observed and presented in analytical and simulation results. The analytical results contain the energy required for the biogas system and produced by the solar water heater was calculated. The simulation result has been expressed in the figure bellows and the figures contain temperature contour, pressure contour, velocity stream, velocity contour, velocity vector and volume rendering profile values of the flat plate collector, and direction of water flow between outlet and inlet at the same and different mass flow rate. After giving all the necessary inputs properties of various volumes of the collector to the software as shown in table and figure was performed the calculations inside it and gives the related output in the form of contours for distribution of parameters, reports which include data at various faces and graphs.

5.1. Simulation Results of Flat Plate Collector

The simulation was carried out pressure profiles, velocity profiles and temperature profiles inside the solar collector. The result was analyzed with the different mesh type and the same parameter and in different types of flow in the laminar and turbulent flows described in the below.

5.2 Turbulent type fluid flow CFD simulation of flat plate collector

Turbulence model Realizable k-ε was used as the model of these types flow to simulate flat plate collector. The performance of a flat plate can be understood certainly by observing the Velocity contours, temperature profiles.

5.3 Simulation of flat plate collector by coarse mesh

Table 3. Mesh information from the report

Domain	Nodes	Element
Part1(glass)	324	136
Part2(absorvour)	324	136
Part3 (fluid domain)	142435	605874
Part4(insulation)	465	1235
All domains	143548	607381

5.4 Pressure contour profile of flat plate collector at course mesh

The pressure contour shows the pressure drop in the collector and decreases from input to the output as indicated bellows and the average values of the pressure drop 0.202pa for course type mesh simulation.

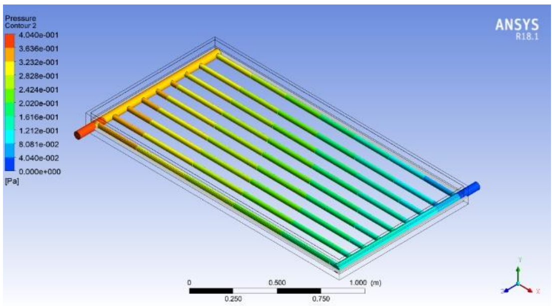

Figure 7. Pressure contour in the fluid domain of flat plate collector in all parts of the fluid

This pressure drop was in all parts of the fluid domain by select all the parts of the fluid domain in the collector and the value of the pressure drop almost equal as indicated from both figure 7. and the average pressure drop was the same as indicated from both of the legend results.

5.5 Temperature contour profile of flat plate collector at course mesh type

Temperature distribution in riser and header is progressively increased from the inlet of the pipe to outlet in the collector. The cold water enters to inlet at ambient temperature and output temperature was 325.5K as indicated from the figure 8.But the average temperature from all legend display was 311.1K because the color displayed was not exact visualize the value.

Note: -This temperature contour was at the plane selection or at the center of the fluid domain based on the dimension of the collector. But in all fluid domain, the variations of the temperature were varied because the location variable determines the temperature due to the heat exchanger from absorber to the fluid domain parts of the collector.

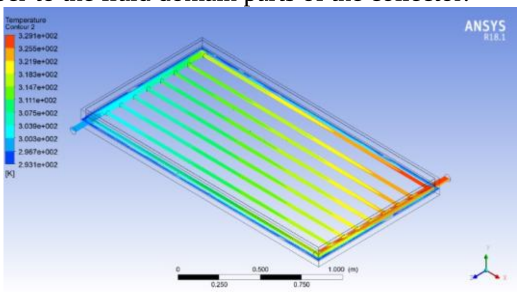

Figure 8. Temperature contour at the plane selection in the CFD post

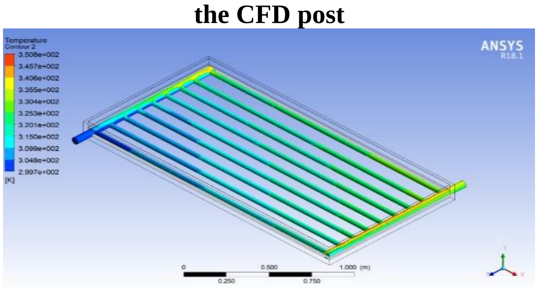

Figure 9. Contour Temperature variation at all fluid domain

As indicated in figure 9. color displayed the output contour temperature of the fluid domain parts were 330.4K the color indicated, and the displayed value was varying by variations of the locations of the place to show the variations of the temperature contour. But the average value from the legend was 325.25K.

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5.6 Velocity contour of water in the flat plate collector at course mesh

From this type of flat plate collector, the simulation result at (0.03kg/s) mass flow rate inlet to the collector, velocity profile has a maximum 0.011m/s. This was the velocity of the value in the tube from input to the output and the maximum value was described as indicated from legend displayed.

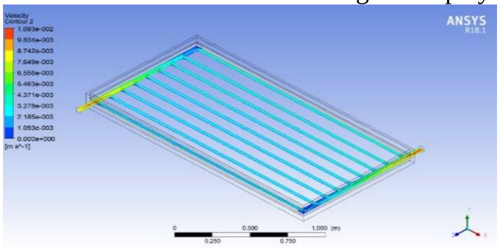


Figure 10 Velocity contour of flat plate collector

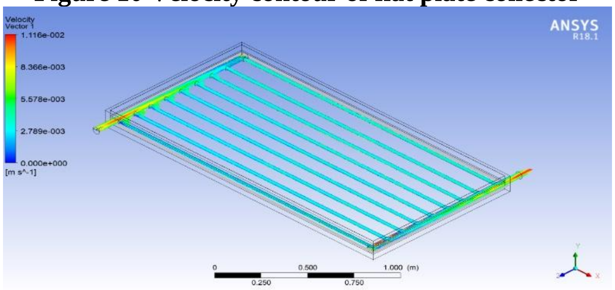


Figure 11 Velocity vector of flat plate collector

This vector is the velocity direction of water in the collector from the input to the output of the hot water in the collector. The velocity vector shows the vector of the velocity in the turbulence flow of fluid from inlet to the outlet.

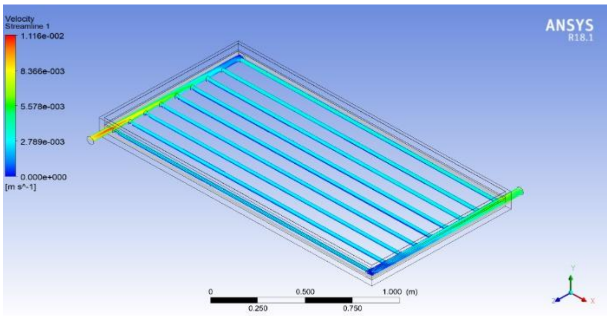


Figure 12. Velocity streamline for water flow inside the FPC

This velocity streamline was clearly shown the direction of fluid flow as well and the magnitude of velocity. This streamline velocity is stream flow of the water in the collector from input to output and shows the line in which the velocity varies from cold to hot output is varied.

5.7 Simulation of flat plate collector by a medium-mesh type

Table.3. mesh information of medium mesh type

Domain	Nodes	Element
Part1(glass)	1224	561
Part2(absorvour)	1224	561
Part3 (fluid domain)	142360	605513
Part4(insulation)	1763	4972
All domains	146571	611607

5.8 Pressure contour of flat plate collector at medium type mesh

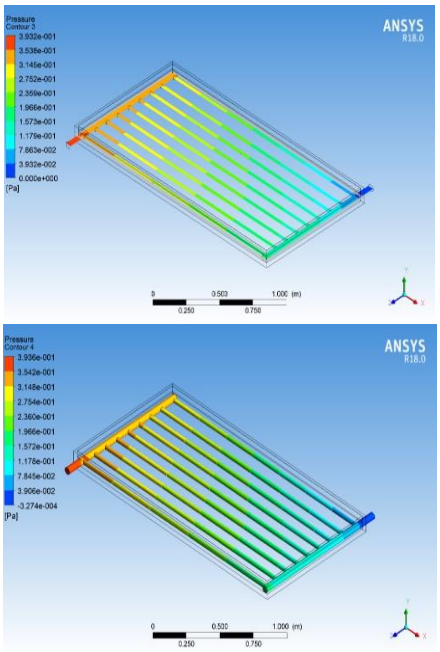


Figure 13. Pressure contour in the fluid domain at plane location (A)and at all domain (B)

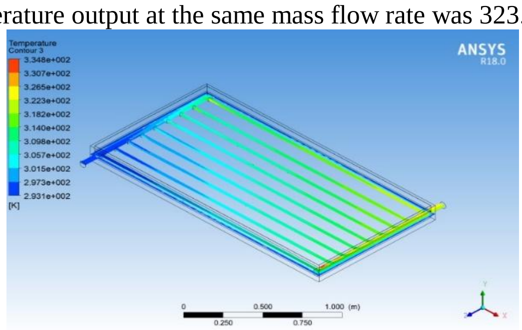
The pressure contour shows the pressure drop in the collector and decreases from input to the output as indicated bellows and the average values of the pressure drop at same mass flow rate was 0.1966pa for medium type mesh simulation. This pressure contour was varying from input to the output as described from color and indicated by the value in both location display of the CFD post indicated in figure 13 of A & B.

Note: - This pressure variation or drop was in all parts of the fluid domain by select all the parts of the fluid domain in the collector and the value of the pressure drop almost equal as the indicated legend of both.

5.9 Temperature contour profile of flat plate collector at medium mesh type

As shown the figure 14. The temperature was increased from input to the output and the output temperature was maximum 326.5K. As indicated from the result the value of the temperature at output increase from course mesh type to fine mesh type output. The average value from color displayed in the cross-section of the FPC was 313.95K.

This temperature variation from inlet to outlet was in all fluid domain to indicate the value of temperature in all parts of the flat plate collector fluid domain. From Figure7.9 of B maximum temperature was 329.8K but the average temperature output at the same mass flow rate was 323.6 K.



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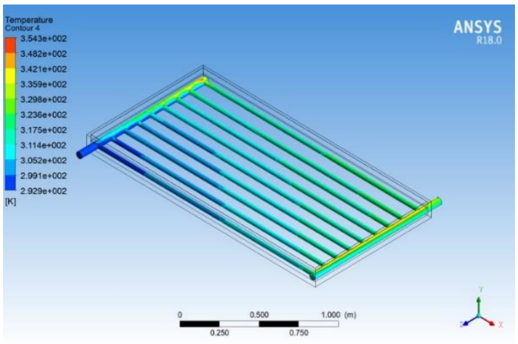
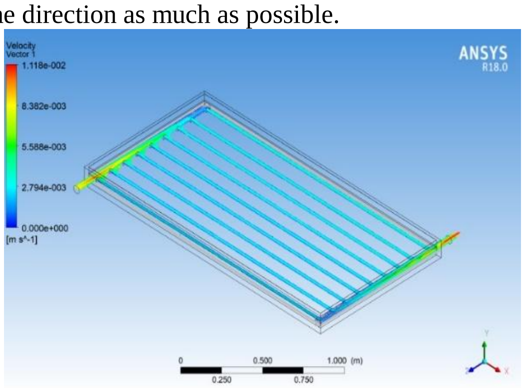


Figure 14. Temperature contour for the FPC at plane location (A) and at all domain(B)

5.10 Velocity contour of water in the flat plate collector at medium mesh type

As indicated below vector shows the direction of velocity water from inlet cold water to output hot water in the flat plate collector. In the vector velocity, it's possible to read the value and the direction as much as possible.



This contour is the velocity value of fluid flow in the collector variation as indicated in the Legend of the figure and the maximum of the velocity contour is 0.012m/s. but the velocity variation is depending on the structure of the collector in the header the velocity is higher and in the riser it's almost similar value as indicated in figure 15.

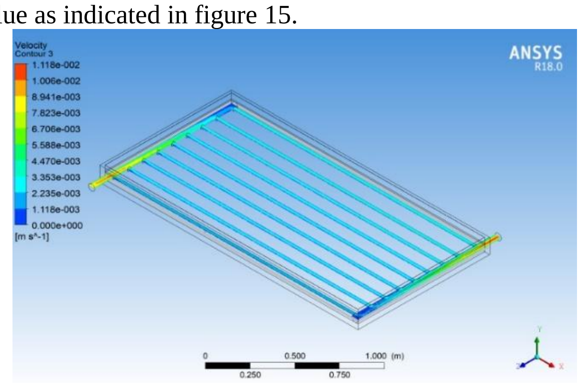


Figure 15. Velocity vector (A) and contour(B) at the medium mesh of the collector

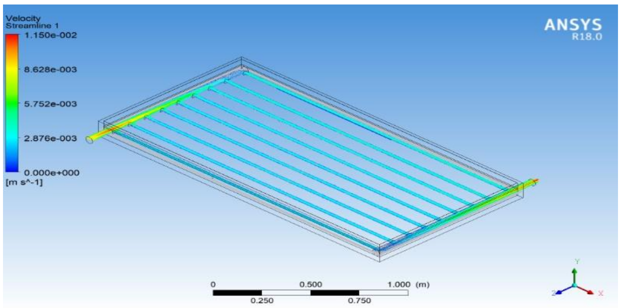


Figure 16. Velocity streamline for water follow inside FPC

This was the streamline velocity from input to output of fluid in the collector in the riser and in the tube of the flat plate collector.

5.11 Simulation of flat plate collector by a fine mesh

Table 4. Mesh information from the report

Domain	Nodes	Element
Part1(glass)	3480	1653
Part2(absorvour)	3480	1653
Part3 (fluid domain)	142432	605857
Part4(insulation)	4917	14172
All domains	154309	623345

5.12 Pressure contour of flat plate collector at fine mesh type

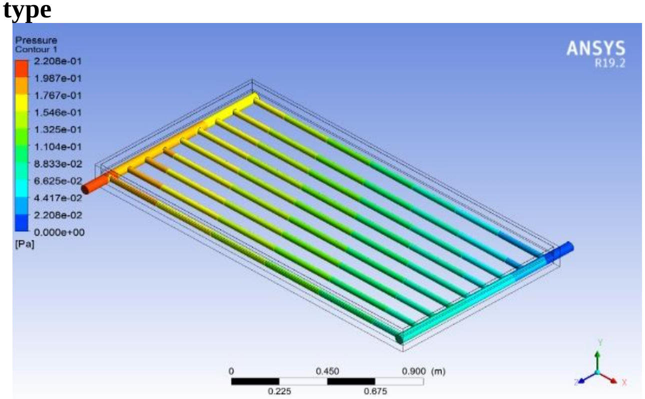


Figure 17 Pressure contour of the collector

This shows the pressure drop on the flat plate collector. From those figures at (0.03kg/s) mass flow rate, the average pressure drop was 0.1104pa and this pressure drop was in the all fluid domain of flat plate collector such as header and riser parts of the collector. This pressure contour is in all fluid domain to show the pressure drop from input to the output of flat plate collector but also it's possible to show the pressure contour in the midplane of flat plate collector by select the location of the collector as shown in figure 18

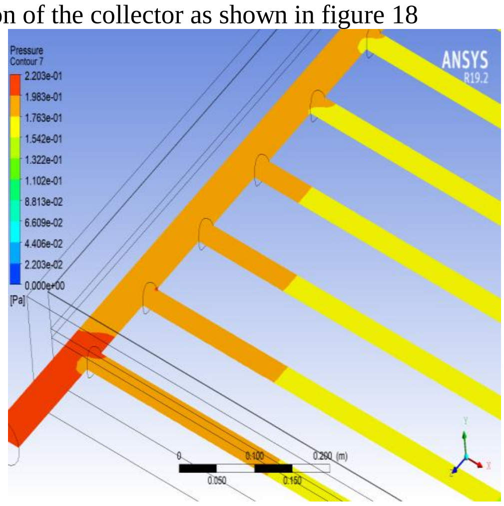


Figure 18 Pressure contour at the selected locations of the plane

Here to indicate the pressure drop at the plane location and at the all the fluid domain are equal as its shown from all simulation in all type of the mesh.

5.13 Temperature contour profile of flat plate collector at fine mesh type

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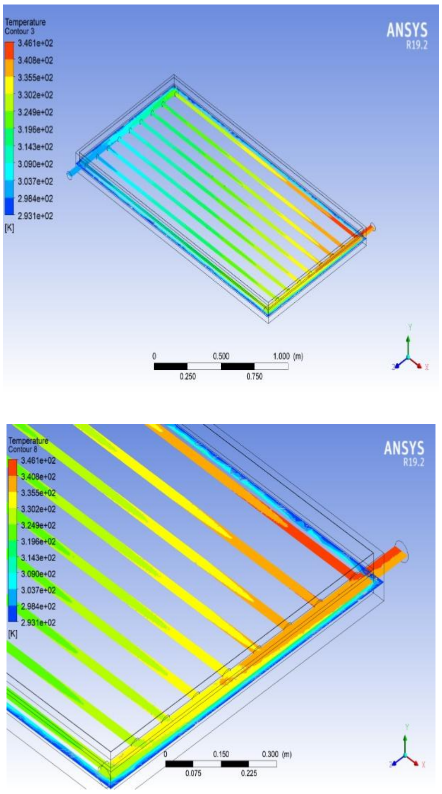


Figure 19 Temperature contour at the fine mesh of the collector

Temperature variation in the collector from the inlet to outlet in the fine the mesh result was described in the temperature contour below. Temperature contour on flat plate collector from the legend at (0.03kg/s) mass flow rate was 340.8K. according to the color displayed in the collector. but the average temperature output from the two was 320.8K.

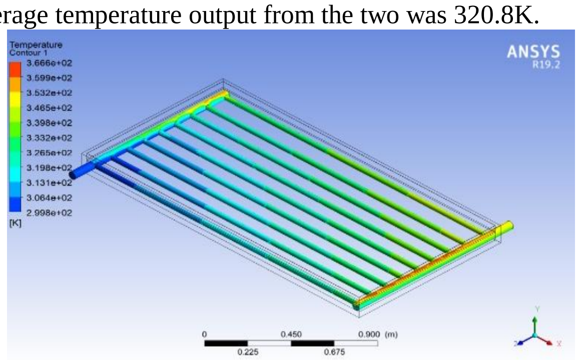


Figure 20. Temperature contour at all domain of fluid domain at fine mesh type

The temperature contour of the collector was varied from cold water input to hot water output temperature as shown in the specific locations of the fluid domain of the collector in figure 20. but the value of the temperature from the legend and the color displayed in the figure was not visible so its value was average. this temperature variation on all the fluid domain and at the center plane to show the value was quite different in the CFD post as shown all simulation from all type of the mesh. From the figure 20 the average temperature was the 333.2K which was the temperature needed from the design.

5.14 Velocity of water in the flat plate collector at fine mesh type

This vector shows the direction of velocity from inlet cold water to output hot water in the flat plate collector and the magnitude of velocity in the fluid domain was clearly shown.

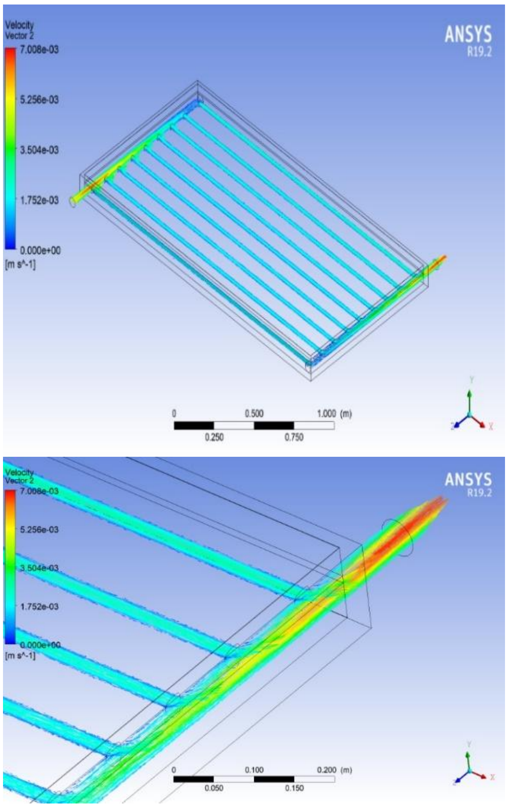
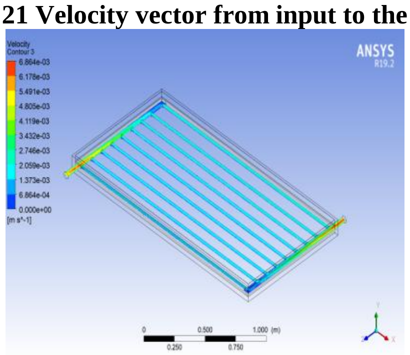


Figure 21 Velocity vector from input to the output



The above figures 21-22 show the velocity profile for flat plate collector when water flows through the fluid domain of header and riser plate. From this simulation result type at (0.03kg/s) mass flow rate inlet to the collector, the velocity profile has a maximum 0.0762m/s. The streamline of water from input to the output was clearly indicated and possible to show the velocity streamline by the animation as indicated in figure 24.

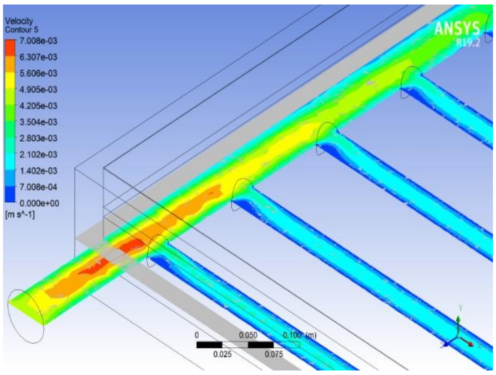


Figure 22 Velocity contours of fine mesh type of the collector

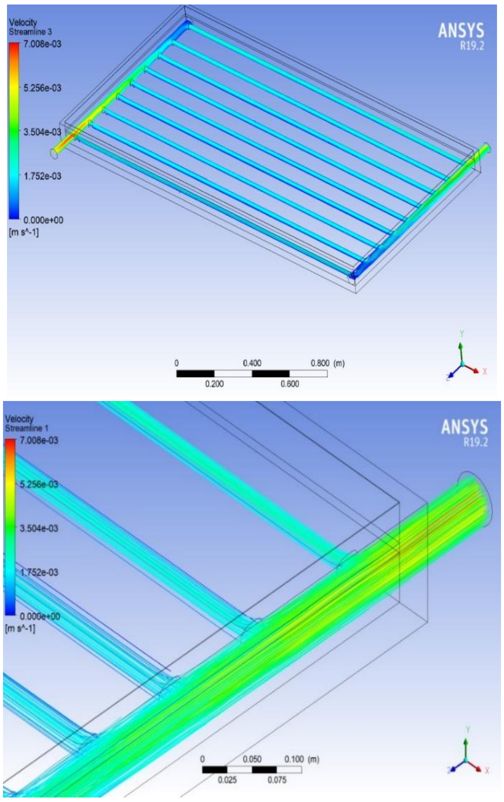


Figure 23 Velocity streamline of water flow inside the FPC

Animation of the streamline was shown in the below figure to show the line movement of fluid from input to the output at different flow type. Note: This is the movement of the water in the collector from the cold-water inlet to hot water output for the purpose of heating. Generally, this animation shows the movement of water in collector tubes and the velocity of the fluid in the collector.

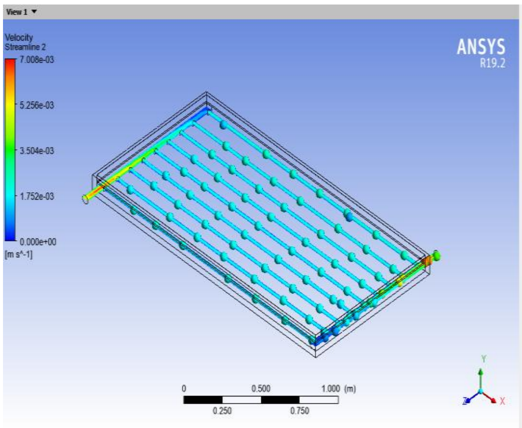


Figure 24 Velocity streamlines for water flow inside the FPC in an animation

Based on the grid sensitivity study the fine mesh was the best for the required based on the output temperature and pressure drop in the collector.

5.15 Laminar type fluid flow CFD simulation of flat plate collector

Pressure contour in the laminar flow: - This laminar type simulation took place with the same type geometry and input parameters but the output results of the contour temperature, velocity, and the pressure are different. Additionally, the simulation was done in the fine mesh.

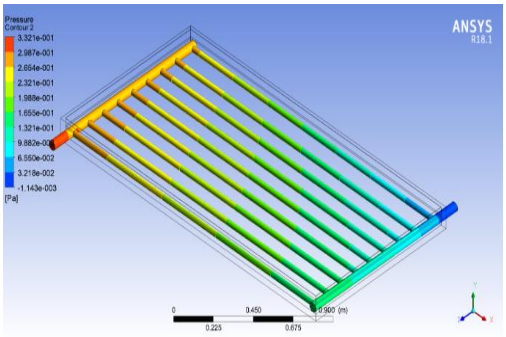


Figure 25 Pressure contour of flat plate collector

Pressure drop in the laminar flow is quite different from the turbulent flow and the value of the average drop pressure in the same mass flow rate was 0.10895pa.

Temperature contour in the laminar flow: -The contour temperature in laminar flow types was also displayed as flows as simulated in the turbulent flow. The average temperature at the 0.03kg/s was 321.5K. This simulation was defined with the same boundary conditions with the turbulent conditions, but the temperature distributions were different according to the result of the simulations.

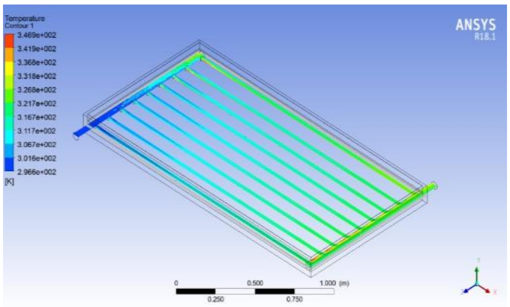


Figure 26 Contour temperature in laminar flow

Velocity contour in laminar flow type: - Velocity vector shows the magnitude and the direction of flow of the fluid and the streamline show the line of the velocity in the risers and the headers of the flat plate collector in the laminar flow types and are different from the turbulent flow. The maximum velocity was 0.0116m/s.

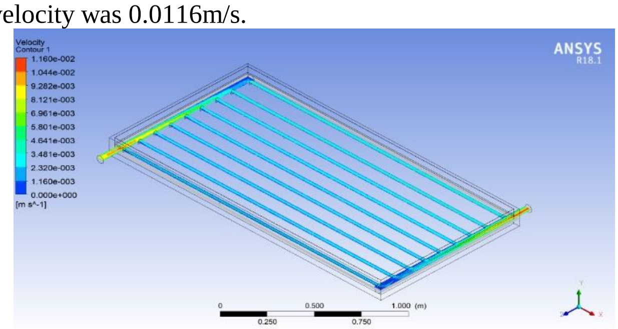
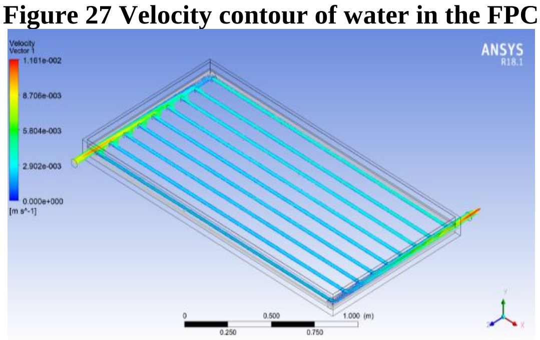


Figure 27 Velocity contour of water in the FPC



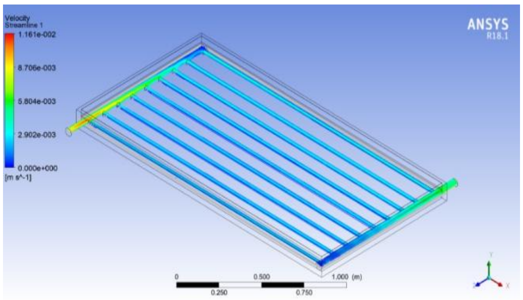


Figure 28 Velocity vector(A) and velocity streamline (B) of water flow inside the FPC

5.16 Graphical analysis and comparisons of a different result

The graphical representation was used to analysis the design in the accurate number and comparisons of the different parameters in this design.

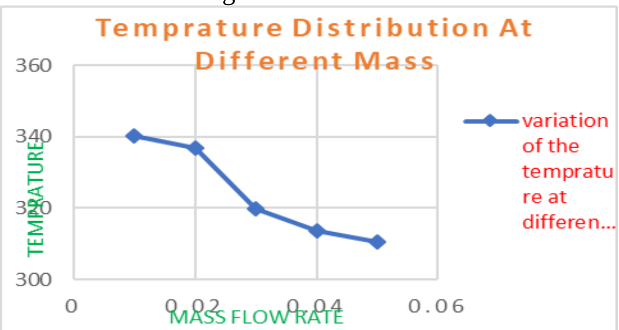


Figure 29 Average temperature hot water with varying the mass flow rate

Note: Simulation results of different turbulence flow and laminar flow with a mass flow rate of water through flat plate collector of fine type mesh of the results.

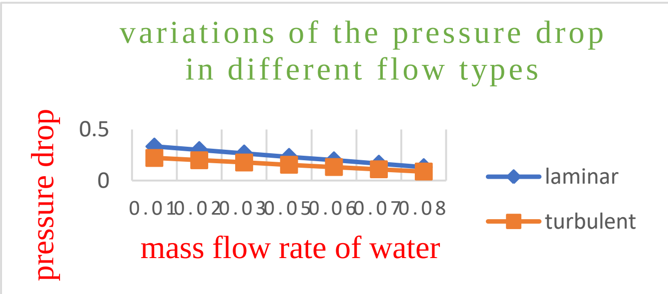


Figure 30 Variations of the pressure drop in the different types flow

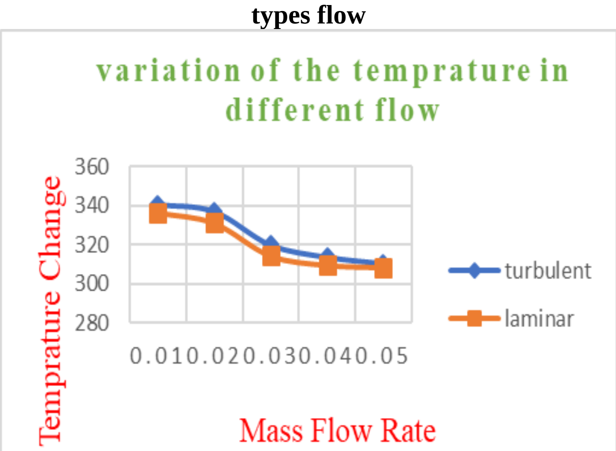


Figure 31 Temperature distributions in the laminar and turbulent flow

Figure 31 Temperature outlet comparing the two flows qualitatively, temperature outlet for turbulent flow is better than laminar flow type when the mass flow rate of water was the same. both temperature outlet and pressure drop at unit change comparing the two flows, then the turbulent flow is more than laminar flow, so turbulent flow was more acceptable.

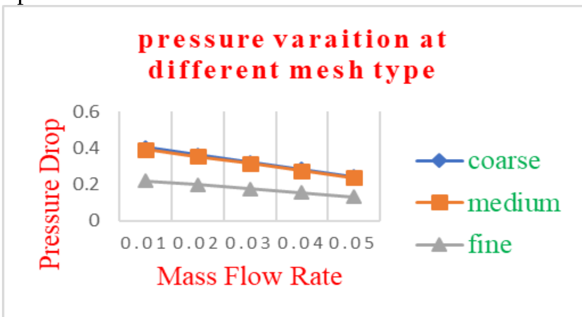


Figure 32 pressure drop variations in the different types of mesh type

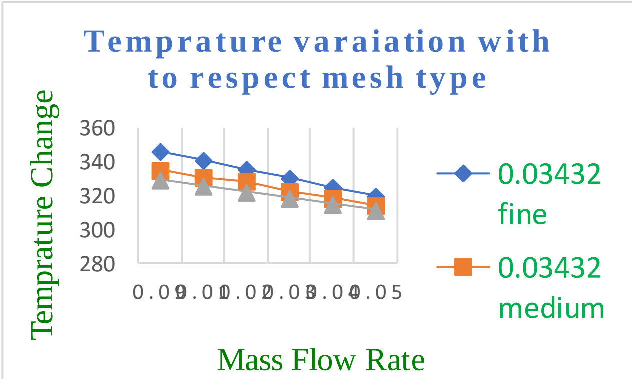


Figure 33 Temperature distributions in different mesh types

From figures 32 to 33 it can be concluded that the pressure drop and maximum outlet temperature variations through different flow direction of water through the fluid domain, at a different mass flow rate of water results. Comparing the three mesh types and different mass flow rate results, when hot water flows through the collector plate. It's possible to select the mesh types possible for the design.

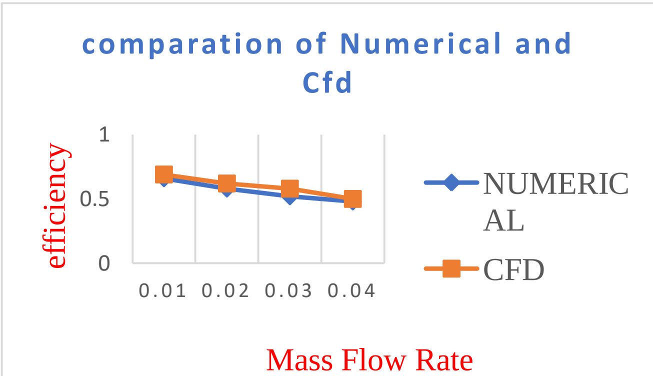


Figure 34 Comparisons of efficiency of numerical and CFD simulations.

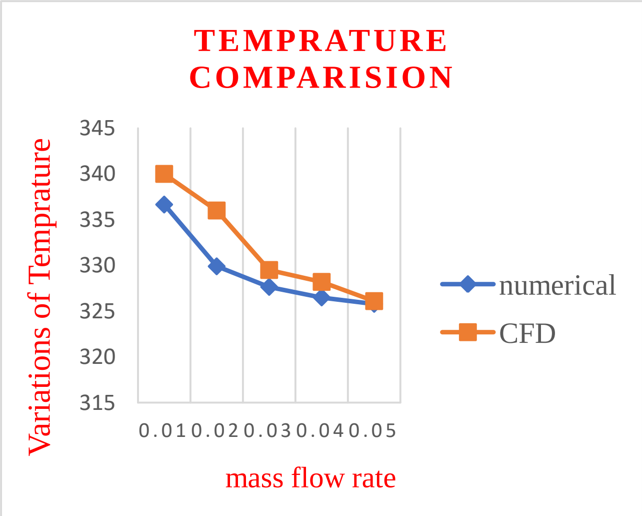


Figure 35 Temperature variation with mass flow rate in both numerical and CFD

From fig 34-35 the validation of the numerical value of the output temperature and efficiency of the two was compared and the CFD was more efficient based on the required output. This was depending on the same mass flow rate and material selected for the design, the above figure shows the variation of the analytical and CFD simulation in the short ways.

V. CONCLUSIONS

At present, our country is facing various problems, among that energy crisis has become more serious. Both energy crisis and pollution problems could be controlled by adopting an alternative method of distributed energy systems. This article presents the design and CFD simulation of solar assisted biogas system, to overcome the above problem.

The main point covered under this research was putted as follows in general: -

A detailed mathematical calculation for the flat-plate solar collector cross sections and thermal storage tank. Specifically, a mathematical model was developed to estimate the heat demand and thermal dissipation of a pilot fermentation system at 35°C temperature with 44.7m^3 biogas production per day under the local metrological data.

CFD simulation of flat plate collector was done for preparation of hot water used to produce biogas system by the solar water heater.

The detail study was done in an average of solar radiation heat absorbed by 2m^2 flat plate collectors and 122 number of the collector needed for heat needed for the fermentation according to mathematical calculation design.

A CFD simulation to predict the effect of different parameters on solar collector heater system to validate thermal performance, pressure drop, flow velocity water and temperature output for different type of mesh and flow types in the collector has been conducted. From this simulation the fine mesh and turbulent flow was optimized. The maximum outlet water temperature of 333.2K. Additionally based on the output temperature the efficiency of the flat plate collector was validated.

RECOMMENDATION

The following points can be recommended for future work. The results solar assisted biogas system contributes a significant energy save if implemented at the specified site. More experimental investigations are needed to confirm the performance and efficiency of the proposed design. The same work can also be done using other types of collectors and other types of solar water heater typeParametric studies can be done using the vacuum tube or concentric type solar collectors. Optimizing of the system with using a different type of heat exchanger optimization of thermal storage tank using CFD.

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