Computational Fluid Dynamic Simulation and Experimental Testing of a Serpentine Flat Plate Solar Water Heater

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Abstract: The aim of the study is to improve thermal performance of passive serpentine flat plate solar collectors using striped technique. Striped mechanism was applied on absorber plate so as to diminish thermal fusion in the plate and investigation enhancing practice of energy conversion from the collector units to the working fluid. Study was conducted or carried out with numerical simulation and experimental testing to compare results for validation. Demand of domestic hot water has mostly been filling with conventional flat plate solar collectors. Conventional solar collectors are relevant for high flow rate that requires high operational costs. In the past, serpentine solar collector was ignored due to large pumping requirements at higher flow rates. However at low flow rate, serpentine collector is more economical and efficient. Therefore, striped absorber plate of the serpentine solar collector in varoius modes were designed by ANSYS 14.5 relase FLUENT and simulated using computational fluid dynamics. The effect of the configuration parameters of striped serpentine solar collector was investigated and good result was obtained.The anaysis was done by decoupling the last striped from whole system. So that the result of the second stripe became inlet boundary condition for the last of four segments. For the collector mass flow rate of 0.00285kg/s and solar radiation of 650w/m2, temperature of absorber plate(Tp) and water at collector exit (T0) became 360k and 338k respectively. The same collector model was manufactured and experimental investigation was carried on with similar conditions as did for simulation. Therefore, absorber plate (Tp') and water at exit of the collector (T0') during the experimental test attained maximum temperature of 353k and 336.9k respectively. There fore, numerically predicted temperature distribution on the striped absorber plates was agreed with experimental obtained data with little discrepancy. This inconsistency was due to variatiance of solar radiation and data measurement error. Collector heat removal factors obtained with both numerical study and experimental testing was similar in figures and remarkable with other research.

Keywords:,thermal breaking, serpentine flat plate solar collector, thermosyphone, CFD & Experiment

1. Introduction

Solar collectors are special kind of devices that transform solar irradiance into internal energy of the transport medium, and hence increases their thermal effects. They absorb and capture the incoming solar radiation, converts it into heat and transfers the heat to a fluid flowing through the collector[1]. Demand of domestic hot water has been satisfying with various heating application. However, solar water heating alone reduced domestic water heating costs by as much as 70% [2]. Owners of the collectors have found that solar water heating systems are cost-effective in meeting their hot water needs all over the year.
Flat-plate solar collector is the most common for residential water and space heating as well as for industrial application. Most of the flat plate collectors currently available on the market are of the parallel tube type known as conventional flat plate solar collector[3]. They are relevants for high flow rate that requires high operational costs. Moreover, conventional flat plate collector had been in service for a long

time without any significant changes in their design, shape and operational principles[4].

According to Matrawy & Farkas[5] configuration of a solar collector is an important factor that determines its thermal performance. Serpentine solar collector has the potential to perform better than a conventional parallel tube collector in low-flow systems due to the earlier onset of turbulent flow which enhances heat transfer application. Even for the same collector area, tube spacing and tube diameter, serpentine collector performer better than conventional collector[6]. According to Myrna & Beckman[7] the major reason for the difference in performance between conventional and a serpentine flat plate solar collector was the internal heat transfer coefficient. However in the past, serpentine flat plate solar collector was ignored due to large pumping requirements at higher flow rates.

Serpentine collector has geometry for which collector efficiency factor and heat removal factor cannot easily be expressed in a simple form. If thermal break is made midway between the serpentine tubes, then the collector can be analyzed as a conventional collector. If the break is not provided, reduced performance can be expected and more complicated analysis is necessary[8]. The heat removal factor for a serpentine collector is much more difficult to determine than for a conventional flat-plate collector[7]. Unlike analysis for conventional collector, there is heat transfer between the tubes for a serpentine collector.

Several paper with analytical solutions were published. All analytical solutions were done to treat the differential equations governing the heat transfer in a serpentine-tube absorber. Abdel-Khalik[9] found an analytical solution for heat removal factor of a serpentine tube bonded to the plate with two segments. He concluded that analytical solution for two segments was applicable for any number of segments with small error. Zhang and Lavan[10] showed that this conclusion was lead to much errors than predicted for a certain parameter range by obtaining analytical solutions for N=3 and 4. The solution ignores heat transfer application through its U-bend portion and assumes one-dimensional heat transfer in the plate.

Chiou & Perera[11] also analyzed the serpentine collector for any number of turns. As the number of turns increases, value of heat removal factor (FR) approach the values for turn N=1. In this case, the analysis for a long straight collector with no turns will hold. Therefore, the model is very close to the model for the flat plate collector, with the exception being that the internal heat transfer coefficient will be different [6].

There are only a few publications that report on experimental results of serpentine-flow solar collector. Eisenmann & Wiese[12] had conducted experiment on two serpentine collectors that have the same geometry and shape. In the first collector, serpentine tube was soldered to the absorber plate all through the collector, whereas in the second collector bends of the tubing was not thermally connected with the absorber. They put both over the sun under identical meteorological conditions and measured their performance. The efficiency of the collector that was soldered to absorber plate became about 2 to 2.5% superior in the experiment.

The experiment was conducted on the collector whose absorber plate was soldered to serpentine tube rather than striped plate that attached to tube. In fine and tube absorber collector arrangement, heat is normally transferred through absorber plate to tubes and then working fluids. As result, thermal diffusion due conduction mode caused throughout the system which reduces overall performance in the collector. Moreover, the experiment was unable to make predictions on the required parameters UL & F' of a serpentine-flow collector experimentally.

Unlike parallel flat plate collector, there is heat transfer occur between tubes for a serpentine collector resulting in two dimensional heat transfer problem. Thus, it requires thermal break midway between serpentine tubes, and then the collector can be analyzed as a conventional collector. Consequently, coarser approximations need to be made in order to achieve analytical solutions for the absorber and fluid temperatures (Lund, 1989)[13] as cited by Eisenmann & Wiese.

Since computational fluid dynamics analysis of the flow and heat transfer in flat plate solar collectors is computationally quite difficult and cost, number of research works on this subject is quite low[2,14]. However, there was no adequate simulation work has been done so far for a serpentine collector. Thus, it was designed to perform simulation and experimental testing of serpentine flat plate solar collector. It is obvious that there might be certain limitations for experimental results thus data at each and every point but computational fluid dynamics (CFD) handles complex situations where experimental is not applicable because of limitations and cost effectiveness problem[15].

2. Material and Methodology

Geometry model was designed using ANSYS and the model get transferred to mesh. In meshing section, parameters of geometry part was defined. For better thermal and flow analysis, under mesh sizing, fining was selected to discretize flow further in to many elements and updated to recognize the input. Similar model was designed, manufactured and assembled for the experimental test. Thermocouple sensors were provide on serpentine tube and the plate in order to gauge thermal and flow distribution through the collector. Collector site orientation was adjusted and temperature distribution through the plate as well as water in the tube recited with digital multi-meter reader.

2.1 Development of Geometry &Meshing

Basic serpentine flat plate solar water heater was developed and going to be investigated. Unlike conventional collector, there is a complicated heat transfer network present in between serpentine tubes in the collector which results the analysis into 2-D heat transfer problem. Therefore, it is not easy to do the analysis of flow and thermal character inside the tubes and absorber plate. Thus, it requires appropriate thermal breaking application in the system. Breaking in the midway was one of the option but using more breaking system cause further complication on the setup of the boundary condition for decoupling and/or coupling system.

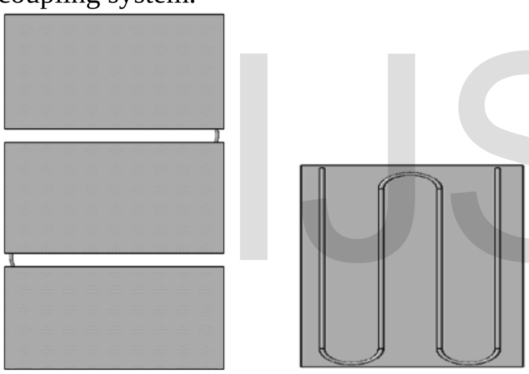

Figure 1.How designed striped geometry was decoupled from main system

Geometry employed for numerical investigation was illustrated as above and two thermal breaking lines were applied to simplify the analysis. The breaking lines are 20mm apart which separate adjacent plates adequately for possible losses occur due to heat conduction and moreover 20mm thick Styrofoam insulation was used in between two consecutive striped plates. Development of an exact computational mesh for the domain under investigation was paramount importance in CFD simulations. The accuracy of numerical results in CFD modelling was mesh dependent that means the finer mesh generally provides better results at the increased computational time [16]. Therefore the size of the mesh in the domain should be gradually increased to such level that the further raise in the number of control volumes does not result in considerable changes in theoretical or imaginary results obtained at the end of the exploration.

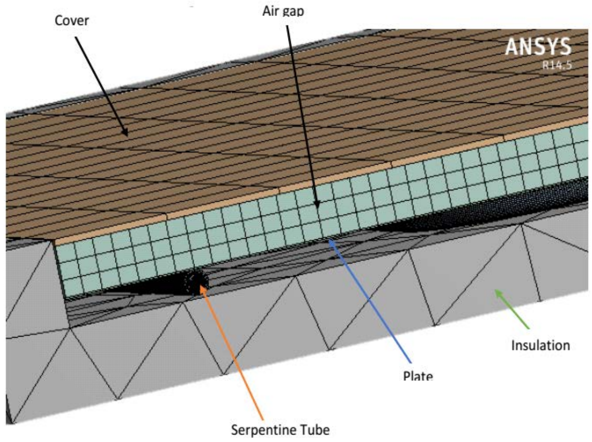

Figure 2. Computational grid of the system

Properties of materials employed for model were activated from the domain. The properties of water was used for a liquid domain in the computational mesh. Piecewise-linear functions were used to make into account the dependence of water properties upon temperature. The effect of gravity was taken into account along the vertical axis by specifying the negative acceleration value. Since flow was very small, laminar flow model with pressure-velocity coupling used.
The radiation heat loss to the sky was included in the boundary condition of the side wall and glass cover. The apparent sky temperature was calculated by using the equation from ASHRE hand book[15]. Heating of surfaces due to radiation and/or heat sources within the fluid phase can be included in this model. There are five radiation models which allow us to include radiation, with or without a participating medium in heat transfer simulations.
Solar load model are used to calculate radiation effects from the sun's rays that enter a computational domain. The model includes a solar calculator utility that can be used to construct the sun's location in the sky for a given time-of-day, date, and position. Solar load is available in the 3D solver only, and can be used to model steady and unsteady flows.

2.2 Prototype Manufacturing

Similar model of serpentine solar collector was manufactured with striped techniques where the plate was attached to serpentine shaped tube for separated segments. Striped mechanism prohibited or minimize intensity of thermal losses through the collector active part without doing the required work. Thermocouple sensor was provide on serpentine tube and the plate in order to gauge thermal and flow distribution through the collector.
Heat losses to neighbor or adjacent side of the collector system with conduction and convection processes. To interact with losses, thermal breaking line was formed between two adjacent plates with about 20mm part. That thermal line was covered with Styrofoam material which serve as insulator for heat to minimize air circulation in the collector. Since the collector rely on natural circulation system, significant amount of heat can be gained due to unique property of low flow rate.

Figure 3. Physical feature, how serpentine tube bend to required shape & kept in collector system

2.3 Experimental setup

Experiment setup was established in Jimma Agricultural Mechanization Research Center Lab and testing was conducted for over one month with outdoor condition. The collector was designed with two thermal breaking lines that divided the collector into three striped real model. And all the collector units were kept over the sun to trap incident radiation. Serpentine tube was soldered to the absorber plate to enhance thermal flow in favor of contact with aluminum sheet that has 0.8mm thickness. They are used to establish good heat transfer application between absorber plate and the tube and also insist heat transfer process from plate to transport fluid.

2.4 Collector Orientation

The collector position was adjusted to best performing angle of orientation. This should be as close as possible to Due South (0º) in the Northern Hemisphere for absorption of maximum solar irradiation. The surface orientation leading to maximum output of a solar energy system may be quite different from the orientation leading to maximum incident energy. The total annual energy received as a function of slope is maximum at approximately $\beta = \emptyset$ where $\emptyset$ is the latitude. For maximum annual energy availability, a collector tilt angle equal to the latitude is considered [8].

The performance of the solar water heater depends on prompt exposure to incoming solar radiation. Therefore, the solar collector should be far from block obstacles like tall buildings, trees or hills positioned in front and back side that hindered them to gain substantial solar energy.

Table 1. Collector Specification

No	Parameter	Symbol	Magnitude
1	Length of one serpentine segment	L	0.96m
2	Distance b/n tubes	W	0.14m
3	Plate thickness		0.8mm
4	Tube outside diameter	D	12.7mm
5	Tube inside diameter	Di	11.28mm
6	Plate thermal conductivity	k	46 w/m0c
7	Mass flow rate of water		0.0028kg/s
8	Collector area	Ac	1.52m^2
9	Collector slope angle		100
10	Space b/n plate & glass	-	20mm

11	Thickness of back insulation	L_b	0.046m
12	Back insulation thermal conductivity	Kb	0.02w/m 0c
13	Thickness of collector	-	0.085m

3. Result and Discussion

3.1 Introduction

Under computational fluid dynamics case, solution was found and the required parameters were displayed in post-processing. Here by using CFD software temperature distribution inside flow tube and absorber plate of serpentine collector were predicted thereby to estimate collector efficiency factor and other parameters that express collector performance. Here flow characteristics and thermal performance of the serpentine solar collector was examined by experimental testing. Temperature distribution through the plate and working fluid has been followed with K-type thermocouple sensors. The sensor displayed the input in the form of voltage and the voltage was translated in to temperature using standard table.
Eventually, the result obtained with computational fluid dynamics simulation analysis was compared with experimental testing outcome for validation purpose.

3.2 CFD simulation

The numerical results obtained from CFD modelling of a serpentine solar collector model is presented as follow. As it was tried to explain in earlier, the collector system was divided in to three stripes because of thermal breaking system. Each striped model was engaged with detail operational and boundary condition considered for best simulation purpose. The properties of copper, aluminum and glass were applied for tubes, absorber plate and cover system respectively.
The properties of water were temperature-dependent and piecewise-linear functions were used to take into account dependence of water properties upon its temperature.
On top surface of absorber plate, equivalent heat fluxes of 650W/m^2 was applied. Providing that the side and the bottom part of the plate was set to be at adiabatic condition. This heat flux was calculated from average based of solar radiation collected on June 30, 2014. For both CFD and experimental testing, heat fluxes of 650W/m2 was used to simulate temperature distribution though out absorber plate and water flow through the tube.
Collector thermal analysis was generally performed in the following ways. The first striped model was simulated with a given boundary conditions and output condition of this model coupled and decoupled to become input for the next stripe. Again the output of the second striped model was coupled and again decoupled to the last striped. In such away the solution for serpentine flat plate collector was analyzed until the result obtained become dissimilar. Figure5a demonstrated the temperature distribution pattern of the water in the tube for the last decoupled striped model.
This methods may works or be easy for fluid flow in the collector tube but might be difficult or may has limitation concerning with air, cover and insulation material that were thermally broken for analysis. For this case, uniform boundary conditions for air, cover and insulation were used for all stripes. For instant, wall boundary conditions with convection heat transfer coefficient of 20 w/m^{2}k was applied for air in all stripes.
Because of the serpentine solar collectors was set to be inclined to horizontal, the effect of gravity was taken into account along the vertical axis by specifying the negative acceleration value of cosine 10^o multiplied by the gravitational forces constant[16]. Collector angle was established based on recommendation made with literature. Experimental site has latitude of 7.7^0 and collector angle was made to be 100 for best annual solar radiation collection option without applying tracking system.

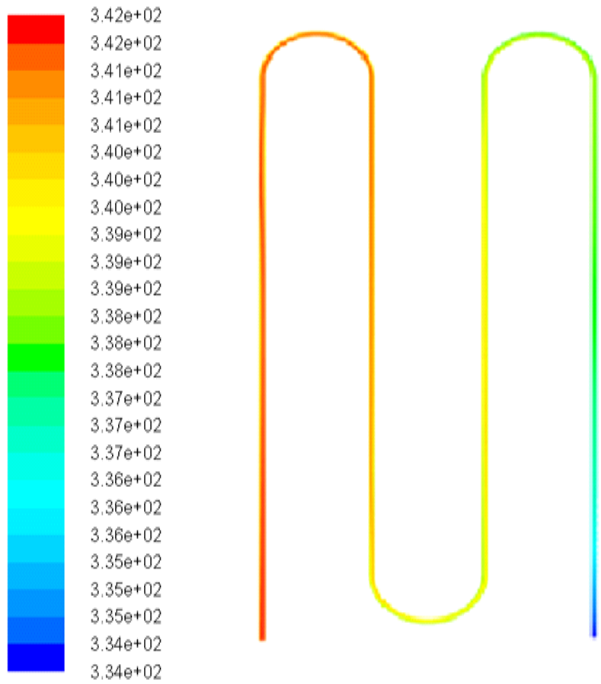

Figure 4. Temperature contour of the last striped serpentine tube

Figure 4 presents the temperature contours of water in the tube. As it can be seen from the graph, the water entered the serpentine tube of the last striped at an inlet temperature of 334k (which is exit temperature of second striped). Gradually as the flow passes through the tube, the temperature of the fluid at the exit of the tube became 342k.This result showed that there was better heat transfer process in the system. The numerical results obtained clearly demonstrate that the proposed design of the solar collector provides a considerable improvement of the performance.

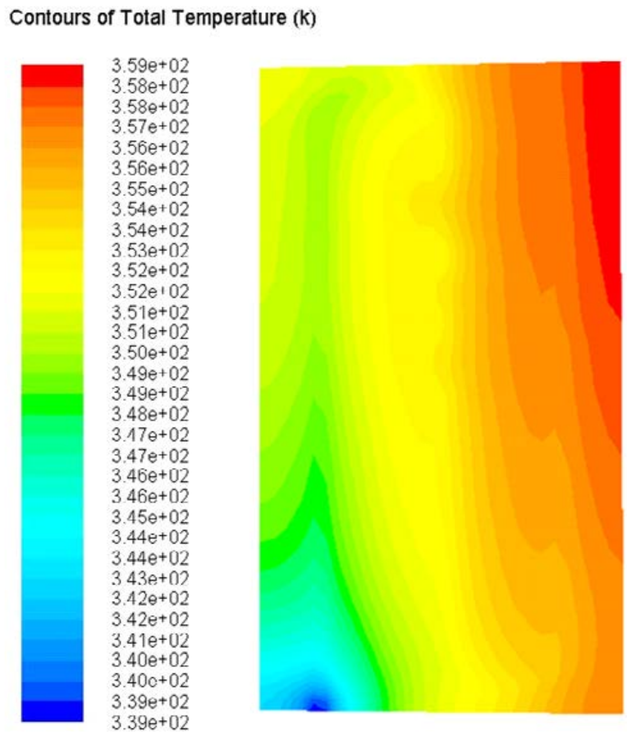

Figure 5. Temperature contour of the last striped absorber plate

Absorber plate has achieved maximum temperature of 360k that was small as compared with some literature. This was because solar radiation available during the time of experimental testing was of the smallest of the all months. In general, the test was conducted during the summer season when availability of constant solar radiation was inconvenient. Meanwhile as you increase the heat flux more and more, thermal distribution through the system became higher.

The same amount of solar heat flux was used to examine collector performance thoroughly for both numerical and experimental test activities. Since the main aim of this research is to investigate thermal performance characteristic of the serpentine flat plate solar collector with CFD simulation and experimental testing, similar condition has to be applied to perform comparison.

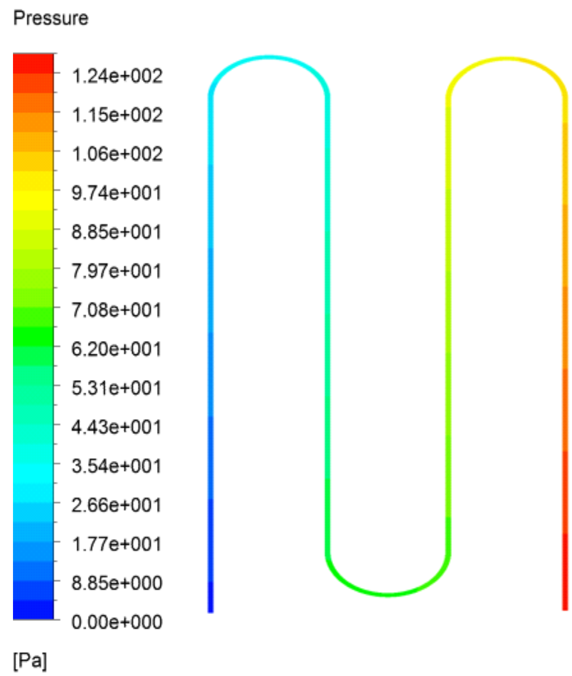

Figure 6. Pressure drop of water flow in serpentine tube of the last striped

As it can be seen from the Figure 6, high pressure drop was seen at collector inlet. Water moves down from the storage tank to the collector due to gravity but as soon as it leaves tanker and reach the inlet section, it faces the bend that become obstacle to flow.

As result it losses energy which causes pressure drop at the section. In general, pressure drop seen was an order of 124 Pascal. Only the last decoupled four segmented striped was analyzed here, in fact pressure drop through serpentine tube is higher when compared to conventional one.

The flow in the collector was induced by the density gradient, which in turn was caused by the heating of the working fluid. The figure in general shows the typical variation of the density inside the collector.

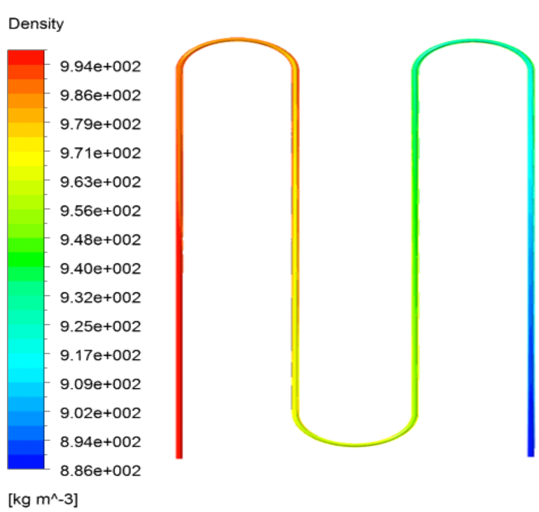

Figure 7. Density contours of water in serpentine tube

It can be seen that for the given boundary conditions the density of water changes from 886 kg/m³ at the top after heating process to 994 kg/ m³ at the bottom where the temperature is the lowest. Also from numerical results the water is cold more at the collector inlet section since higher water density results represent a lower water temperature in collector tube.

- **3.3 Leak test result**

On the serpentine tube hole was prepared and the thermocouple sensor was attached with help of epoxy materials. Unless the sensors were attached with drilled holes tightly to tube, leak probably occur. Therefore to minimize the tendency of the leak, leak test was conducted with water-immersion methods. Leak was general omitted from water flow through the tube in whole collector system.
The smallest bubble an operator could detect has 1 mm radius and that the waiting time is 30 seconds [17]. Assuming that the pressure inside the bubble is at atmospheric pressure, it can be stated from the previous equations that the bubble volume is and therefore the minimum detectable leak rate at Jimma atmospheric condition become

3.4 Estimation of Solar Irradiance

The thermal performance of natural circulation solar water heating was tested on June 30, 2014 at Jimma Agricultural Mechanization Research Center using serpentine flat plate solar collector setup with batch type water tank. An estimation of solar insolation of that experimental site was made by employing engineering equation solver (EES) software. A program that compromised important parameters of air with non-dimensional units was developed. Data's were collected on the temperature of air, sky and black body with ten minute intervals. Since once the program was developed, the collected data was inserted in the program and manipulated
Figure 8 shows the profile of solar radiation available that was calculated based on data of the test day. Since season was summer, it has been difficult to get a clear day to do performance test and several trials have been done to get good daily solar curve. This data was one of the best clear days for performance test.

Figure 8. Solar radiation on June 30, 2014 at Jimma Agricultural Mechanization Research Center

Due to decreases in solar radiation, the ambient temperature also starts to decrease. Ambient temperature variation of the experimental site also has the following pattern.

Figure 9. Ambient temperature variation of the experimental site

3.5 Experiment result

Temperature distribution through the plate and water in the tube were measured using k-type thermocouple. Since the thermal breaking system was applied, absorber plate was detached from each other and fixed to tube with soldering techniques. On the serpentine tube, this temperature sensors were attached on holes so as to read temperature distribution through the flow. In addition, the sensor was attached on the surface of plate to measure how hot could absorber surface be.
Table 2 below displays temperature of water flow in the serpentine tube. The collector system was divided into three stripes as result of thermal breaking application and on each strip as per the thermocouple sensor allocated, data has been registered with in 20 minute intervals. Different reading of temperature was recorded at every hour and average values of water temperature are considered. Here temperature was read in terms of voltage induced caused due to temperature difference between conducting wires in sensor. Using this induced voltage, corresponding temperature was read using standard table including ambient temperature.

Table 2. Temperature of water in the tube at various points

Z(m)	0.09	0.16	0.30	0.42	0.56	0.83	0.97	1.12	1.26	1.48	1.47	1.52
X(m)	-	0.48	0.93	0.03	0.93	0.48	0.03	0.48	0.93	0.48	0.03	0.93

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Tw (K) 295	298.2	302.5	317.4	317.6	319.3	320.7	322.9	323.3	323.5	336.9	317.4

Table 3 displayed average plate temperature distribution in the absorber plate. Temperature of the plate was computed on average based and displayed here at every ends of the strips. Four temperature values were shown as per the stripes.

Table 3. Absorber plate temperature at various points

Z-axis(m)	0.295	0.68	1.15	1.55
X-axis (m)	0.45	0.57	0.35	0.48
Plate temp(k)	334	345	351.5	348

Heat removal factor of the collector (FR) can also be calculated for the experimental testing. Collector inlet temperature of the water was estimated from experimental testing and become 293k and collector exit temperature is 336.9k as well as mean temperature plate is 351.5k from collector experimental data. Therefore, UL becomes 4.98w/km^2 and F_R becomes 0.780878.

Table 4. Collector removal factor at solar heat flux of 650w/m^2

Parameters	CFD	Experimenta	Analytical
Heat removal (F_R)	0.8783	0.7809	0.8190 (Al)
Efficiency factor (F’)	0.7476	0.5879	-

Figure 10 indicated that how temperature of the flow was varied with location. This figure displays temperature distribution of water flow in tube along z-axis. Water was admitted to the inlet of collector at temperature value of 20 ^{0}C. As it passes through the tube, heat transfer takes place so that water start gaining considerable heat from the process. As it can be seen from the graph, the water in the tube extract little amount of heat in first strip since it goes short distance to complete loop.

Figure 10. Temperature variation of water in the collector

In the above diagram, the maximum temperature of the water in the first strip was 310k but as it passed to the next strip, considerable amount of heat was enabled to be gained. Due to possibility of long contact time with the tube surface that causes good heat transfer process in the system. As result, water in the tube gained significant amount of heat. The water in the tube attained maximum temperature of 337k throughout the system.

Figure11 displayed below demonstrated collector plate temperature distribution in whole strips. Temperature variation is taken in average based at each end of the strips. In second and third strips, collector plate temperature was sharply increasing and attain maximum temperature of 351k at the middle third strips. Here solar radiation directly fallen on the absorber plate and there was no apparent shading effect.

For last strips, there is possibility of self-shading effect for time before noon. Even though water storage tank was suited above the collector, it affected thermal performance of the last strip. The graph is drawn using result obtained at 14hr.

Figure 11. Temperature distribution in absorber plate

Table 5 below has displayed the summary of water of temperature at tube exit obtained by CFD simulation and experimental testing .The data’s were kept here to comparison the result obtained with both simulation and testing.

Table5. Summary of comparison of water temperature in tube obtained by Computational Fluid Dynamics & experimental result

Time (hr)	Solar Intensity (w/m2)	Amb Temp (k)	Water tempby CFD(K)	Water temp by experiment (k)
9:00	396	295	315	305
10:00	497.6	296	320	317.73
11:00	552.2	298.5	322	313.73
12:00	641.8	299.4	326	322.77
13:00	648.6	300.3	328	323.38
14:00	700.5	299.2	338	336.9
15:00	562.5	298	320	318.43

Figure 12. Comparison of temperature of water at collector exit with CFD & experimental

Collector instantaneous efficiency was found to vary according to the external conditions i.e. solar radiation, ambient temperature and mean tanker temperature. The efficiency curve of experimental results agreed with model. The collector system showed higher efficiency at low tank temperature and the efficiency decreases as the tank temperature increases. An average tank temperature was 322k and $F_R\tau\alpha$ is the y-intercept in the efficiency line and F_RU_L represents the slope of the curve. The higher the slope, the higher is the sensitivity to external conditions. Both experimental and model collector curves have high slope value which indicates the efficiency is very sensitive to external condition. The heat transfer coefficient U_L also depends on the mean plate temperature.

Figure 13. Collector Instantaneous efficiency during test hours

Khalifa[18] experimentally investigated the impact of mean plate temperature on the total and collector top heat transfer coefficient. It was found the total and collector top heat transfer coefficient varies during the test hours due to the increase solar radiation and the mean absorber temperature. Higher collector inlet temperature increases the mean plate temperature and increases the collector total heat transfer coefficient which reduces the efficiency of the collector.

4. Conclusion

Thermal performance of flat plate solar collector can be improved by altering its configuration of heat transport system from solar absorber to heat storage system. Solar collector size, shape and flow rate in general affect system performance. Serpentine flat plate collector was designed based on thermal breaking system that was recommended by different literatures. Unless thermal breaking was applied, it is difficult to model formulae that enable to analysis as conventional collector. The performance of this collector was investigated by numerical simulation methods. Collector model was designed applying ANSYS 14.5-FLUENT software. The software was used to identify the optimum configuration of the most economical serpentine flat plate solar water heating systems.

For the collector mass flow rate of 0.00285kg/s and solar radiation of 650w/m^2, temperature of absorber plate(Tp) and water at collector exit (T_0) became 360k and 338k respectively. The same collector model was manufactured and experimental investigation was carried on with similar conditions as did for simulation. Consequently,absorber plate (Tp’) and water at exit of the collector(T_0’) during the experimental test attained maximum temperature of 353k and 336.9k respectively.

Collector model has three stripes and while both CFD simulation and experimental test was taking over, all strips exhibited varies temperature distribution in the collector system. For experimental session, solar radiation is directly fallen on the absorber plate and there is no apparent shading effect seen especially for the time before noon in second strips whereas in third and last strips, there is possibility of self-shading effect observed for time before noon. Even though water storage tank was suited above the collector, it affected thermal performance of the last strip. Consequently, such temperature variation was happened in the strip.

In general, numerical and experimental results obtained were found with good agreement with some deviation. In numerical case, serpentine flat plate solar collectors outperformed better when compared to experimental due to some experimental imperfectness during data collection and instant variation of solar insolation. Numerical results obtained demonstrated that striped absorber plate design would improve the heat transfer from the walls of tubes to the liquid which results hot water production of the solar collector good.

5. Recommendation

Serpentine solar collector requires further study to model the science exist behind the collector. So far different studies were conducted on the collector to model collector's important parameters using analytical methods for several turns. Yet modelled collector heat removal factor (FR) formula was invalid for all materials.

As we all know that serpentine solar collector has geometry for which collector efficiency factor and heat removal factor cannot easily be expressed in a simple form. Unlike the analysis for the parallel flat-plate where the fins between the tubes are assumed adiabatic at the center of the tube spacing, there is heat transfer occur between the tubes. However no analytical modelling was formulated for collector efficiency factor for serpentine solar collector. It is unable to make predictions on the thermal output of a serpentine-flow collector with experimental.

Thermally breaking the collector system in to more than two stripes requires serious attention in settling required boundary conditions. In this research, two thermal breaking line was applied and each stripe was analyzed separately and later coupled. Accordingly, output of the first stripe became input for the second stripe and output of the second stripe became input for the third stripe. In such manner, analysis of collector system was done and finally coupled together to become the collector system. This methods may works for fluid flow in the tube but might be difficult with air, cover and insulation material that were thermally broken for analysis. Therefore, more effort is required to model (F') to analyze the thermal behavior of the tube bends. Moreover, detailed numerical investigations should also be taken into consideration.

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