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Numerical Study on Temperature Distribution of Water-in-Glass Evacuated Tubes Solar Water Heater

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***Abstract*— This A numerical study on water-in-glass evacuated tube solar collector using Computational Fluid Dynamics (CFD) is presented in this work. The water-in-glass evacuated tube is an integral part of evacuated tube solar water heater. The water-in-glass collector is the mostly used form of evacuated tube collector because it has higher thermal efficiency and simple construction requirements and hence low manufacturing cost. The usage of evacuated tube collectors is increasing day by day. Thus, several works have been published for representing the stratification of the fluid inside the tubes and the reservoir, as well as analytical modelling for the heat flow problem. Based on recent publications, this paper proposes the study of solar water heating with evacuated tubes, their operation characteristics and operating parameters. To develop this work, a computational tool will be used-in this case, the application of computational fluid dynamics (CFD) software. The commercial software ANSYS-CFX® was used for the CFD simulation of the temperature distribution of water-in-glass evacuated tube solar water heater, which uses the Finite Volume Method (FVM). The objective of this work is to complement the studies cited earlier, approaching the transient analysis of an evacuated tube collector with different inclinations geometries and different tube dimensions geometries , to allow better heat removal from the tube and to evaluate the behaviour of the fluid within this solar collector and possible improvements to be applied in the model. In this work, the model with three different inclinations (30°, 45°, 60°)and same tube dimension (47D1800L) is described and then the model with different dimension(47D1200L, 34D1400L) for same inclination is also simulated. According to the simulation results, length and diameter (47D1800L) and inclination angle 45° model is the best.**

***Index Terms*—water-in-glass evacuated tube, computation fluid dynamics, solar water heater, numerical analysis.**

I. INTRODUCTION

Solar energy is one of the alternative energy sources. Solar energy can be converted into a more useful form by either an electrical, chemical or thermal process. Water heating systems are provided by solar energy (sunlight) directly to thermal energy. Hot water is required for many purposes and the sun can be used effectively, and economically to provide this heat. The warming effect of solar radiation is obvious and it is well known that a container of cold water, left exposed to the sun will be raised in temperature. Solar water heating systems are designed to make convenient use of this phenomenon [1]. In this paper, the utilization of solar energy through solar water heating systems plays a big role in the quantity of conventional energy required. Solar water heaters therefore have significant potential to reduce environmental pollution arising from the use of fossil fuels [2]. Water heating is one of the simplest applications of the solar heat and one of the expensive. The operation of a solar thermal collector is based on the absorption of solar heat, and its circulation through the system, in order that a working fluid (water for instance) can be heated. Evacuated tube solar collectors exhibit better performance than flat-plate solar collectors, in particular for high temperature operation. Therefore, the glass evacuated tube is gradually becoming the key component in solar thermal utilization such as the solar water heating system. [3]

But only in recent years that interest in renewable energy sources acquired a global importance due to the intensification of the problems from the Greenhouse Effect and progress in studies related to Climate Change In this field, is inserted the solar energy and its various applications.

Solar energy plays an important role for sustainable development in coming years and represents a large-scale alternative energy employment, especially regarding the use in water heating for domestic use. It should be noticed that the profile of energy consumption comprises demand peaks at certain times of day, particularly at about 7 pm, when most of the population are coming home and have a chance to take a bath. [4]

Meeting this demand requires a large energy capacity and able to meet this peak consumption. However, with the use of decentralized solar collectors in domestic usage, this peak would not be so pronounced and public investments needed in energy sector could be shifted to other uses, as example, incentive policies for purchasing such systems and taxes reducing. [5]

The current research in renewable energy indicates a growing interest for solar collectors with evacuated tubes, which has as basic characteristic: low heat loss by convection resulting from the vacuum isolation. With researches focused on developing models that represent the problem of heat transfer of this type of collector, the calculation of performance, and emphasis on numerical simulation of water flow inside the tubes and improvements to increase efficiency. The system is drafted in Fig. 1.

Previous works were performed concerning the various ways to extract heat from vacuum enclosed cylinder, including the possibility of developing more realistic methods for calculation of the performance of these collectors. Numerical analysis models were also evaluated for the internal flow of water inside the tube, using the software FLUENT® for the fluid-thermal solution, allowing the verification of preferential water flows inside the tubes and a stagnation region at the end of large length pipes; which could directly influence the efficiency of the collector.[6]

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Fig.1.Experimental set-up of evacuated tubes

In additional studies, the natural circulation rate within an evacuated tube was analyzed by using a numerical model and Computational Fluid Dynamics software (CFD), in this case FLUENT®. The modeling of the system consisted of a tube attached to the thermal reservoir. As for the distribution of radiation along the circumference, it was applied the condition of 82 [W] of total energy inserted into the system through uniform or variable heating between the top and bottom of the tube. In conclusion, experimental tests allowed validating the numerical model. [7]

Analysis of an evacuated tube solar collector with single opening and mounted on a reflective system were also evaluated. This system would allow the concentration of the reflected radiation on the collector. The study was conducted by means of numerical model and experimental apparatus. It was also studied the effects on the internal flow by varying the heat flux distribution along the pipe circumference. [8]

A different geometry was also discussed through an evacuated tube collector with two opened ends, arranged vertically and the collector subjected to solar radiation from all directions [9]. Other studies concerning the analysis of solar collectors must be pointed out, such as [10], [11], [12] and [13]. In this context, the evacuated tube collectors are interest systems whose low heat loss by convection and high efficiency along the day allow the installation of a few units to meet a family necessity for hot water. Therefore, any research that seeks improving the technology and knowledge in such equipment should be encouraged. [14]

For the fluid-thermal analysis of the system, Computational Fluid Dynamics (CFD) and Computational Heat Transfer (CHT) – adopting the ANSYS-CFX® software – will be applied.

II. Numerical Simulation Approach

The water-in-glass evacuated tube solar water heater that is studied in this research consists of 10 evacuated tubes with direct connection to a 120 L storage tank. Modeling heat transfer and fluid flow inside a 10-tube-and-tank system would require high computational power which at this stage is not possible to perform. An attempt has been made to simplify the solar water heater by modeling only a single evacuated tube and the corresponding tank section to which the tube is connected. Investigation using CFD simulations indicated that the flow and heat transfer in the tube is not significantly influenced by what happens in the adjacent tubes. Therefore, there was a need to develop a simpler computational domain which could be used to investigate the effect of varying operating conditions on the natural circulation flow rate through the tubes. [15]

The commercial software ANSYS-CFX® was used for the CFD simulation of the temperature distribution of water-in-glass evacuated tube solar water heater, which uses the Finite Volume Method (FVM). Three-dimensional models were developed considering only the water in the shape of the storage and pipe. Since the modeling of glass and other components would result in increased computational cost without adding considerable accuracy to the solution. The heat transfer by radiation was modeled by applying a heat flux incident on the lateral surface of the tube. Other approach used was considering only a part of the storage tank and one tube, instead of the entire solar collector. [16] [17]

A. *Geometry of Water-in-Glass Evacuated Solar Water Heater*

The geometry of the water-in-glass evacuated solar collector used in the simulations contains, as main components: a manifold and internal tube. The first standard model geometry characteristics are: tube diameter 47 [mm], tube length 1800 [mm] (47D1800L), tank diameter 400 [mm] and tank width 120 [mm] with three different tilt angles were evaluated; 30°, 45° and 60°.

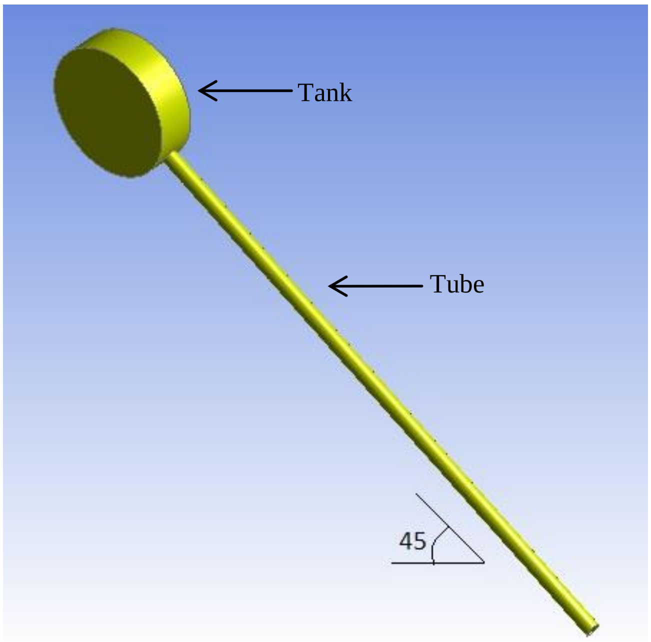

Fig.2. Model of water-in-glass solar water heater at 45° inclination

And then two different models geometry were also discussed by changing tube dimensions such as tube diameter 37 [mm], tube length 1400 [mm] (34D1400L) and tube diameter 47 [mm], tube length 1200 [mm] (47D1200L). The geometry is represented in Fig. 2.The geometries are modeled with tetrahedron elements. Tank-tube connection is presented in Fig. 3.

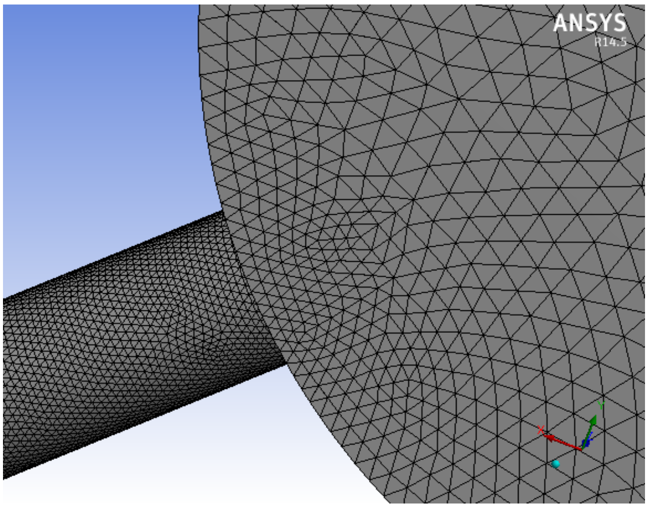

Fig.3. Mesh of water-in-glass solar water heater

B. Boundary Conditions

The boundary conditions on ware-in-glass evacuated solar water are described on Fig.4. In this study, the initial temperature of the water in the models was set as 300 [K]. For solar irradiation of 1 kW/m^2 Cabanillas' results show that the average absorbed around the tube circumference is approximately 600 W/m^2 and three different tilt angles was evaluated; 30°, 45° and 60°. The analysis consists in a transient state, so that 1 hours of operation was considered. The gravitational acceleration was set as 9.81 [m/s²], absolute pressure 1 [atm] and heat losses was neglected in the models. The fluid motion was considered as laminar flow, since water velocity didn't achieved greater magnitudes.

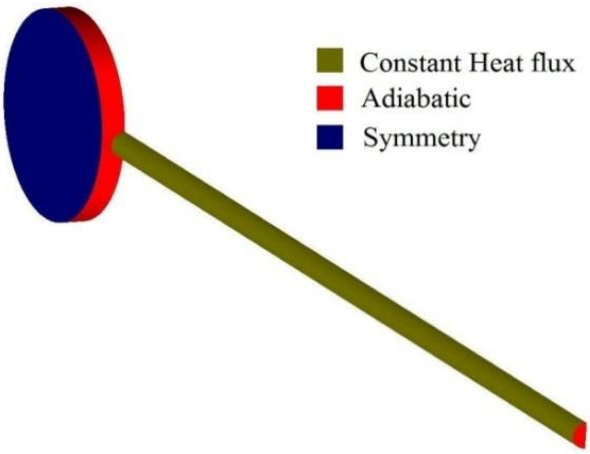

Fig.4. Boundary condition of water-in-glass evacuated solar water heater

C. Mathematical Model

The problem presented in this fluid-thermal analysis consists in solving the combined equations of Navier-Stokes and energy equation for incompressible fluid and subjected to density variation with temperature. For this case, ANSYS-CFX® uses the finite volume method for modeling the constitutive equations of the system in their conservation form.

D. Boussinesq approximation

For buoyancy calculations, a source term is added to the momentum equations as follows:

$$S_{M,buoy} = (\rho - \rho_{ref})g \tag{1}$$

For buoyancy flows where the density variation is driven only by small temperature variations, the Boussinesq model is used. The buoyancy source term by appling Boussinesq approach is expressed from the simplified equation (2).Which considerers the independence of the fluid density with respect to temperature and pressure, and applies gravitational acceleration gradients on each finite volume as a linear function of the material thermal expansivity; this approach gives good results when used in most incompressible fluids, such as water.

$$\rho - \rho_{ref} = -\rho_{ref}\beta(T - T_{ref}) \tag{2}$$

Eq. (2) is combined with the pressure gradient (hydrostatic pressure) and the body force to have a final term in the Boussinesq approach y-momentum Eq.(5) that is expressed as g_y $\beta(T-T_{ref})$ for the buoyancy effects. Eq. (5) couples the temperature field and the flow field.

The conservation equations adapted to the Boussinesq approach model are given below:

Continuity equation

$$\rho\left(\frac{\partial U_x}{\partial x} + \frac{\partial U_y}{\partial y} + \frac{\partial U_z}{\partial z}\right) = 0 \tag{3}$$

Momentum equations

Component x

$$U_x\frac{\partial U_x}{\partial x} + U_y\frac{\partial U_x}{\partial y} + U_z\frac{\partial U_x}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{\mu}{\rho}\left(\frac{\partial^2 U_x}{\partial x^2} + \frac{\partial^2 U_x}{\partial y^2} + \frac{\partial^2 U_x}{\partial z^2}\right) \tag{4}$$

Component y

$$U_x\frac{\partial U_y}{\partial x} + U_y\frac{\partial U_y}{\partial y} + U_z\frac{\partial U_y}{\partial z} = g_y\beta(T - T_{ref}) + \frac{\mu}{\rho}\left(\frac{\partial^2 U_y}{\partial x^2} + \frac{\partial^2 U_y}{\partial y^2} + \frac{\partial^2 U_y}{\partial z^2}\right) \tag{5}$$

Component z

$$U_x\frac{\partial U_z}{\partial x} + U_y\frac{\partial U_z}{\partial y} + U_z\frac{\partial U_z}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial z} + \frac{\mu}{\rho}\left(\frac{\partial^2 U_z}{\partial x^2} + \frac{\partial^2 U_z}{\partial y^2} + \frac{\partial^2 U_z}{\partial z^2}\right) \tag{6}$$

Energy equation

$$\rho c\left(U_x\frac{\partial T}{\partial x} + U_y\frac{\partial T}{\partial y} + U_z\frac{\partial T}{\partial z}\right) = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{7}$$

For the buoyancy case, the equations of momentum neglect the hydrostatic gradient from the pressure term, called in this case as "movement pressure" which is responsible for the fluid motion and corrects the absolute pressure to evaluate the material properties.

III. Validation of Numerical Simulation

Although CFD techniques are widely accepted such numerical models need to be validated against experiments in order to gain some confidence in the results. The experimental setup was designed and installed at Mandalay Technological University, Mandalay (96.1°E, 21.98°N). Fig.1 gives the view of experimental set-up of evacuated solar water heater. This system consists of 10 water-in-glass evacuated tubes coupled to a120-litre horizontal tank for hot water. In water-in-glass evacuated tubes, the outer tubes and the inner tubes are made of Borosilicate glass with 58mm outside diameter and 47mm inner diameter with 1800mm length. The angle of the evacuate tubes is mounted at 45° with respect to the horizontal surface so as to receive the maximum solar radiation. . The cylindrical tank is diameter 400mm and 1200mm length. The water temperature at inlet and outlet and the ambient temperature are measured by the type-C thermocouples. The measurements are taken for one hour from 11a.m. to 12.00 noon. At that time inlet temperature is 304K and the heat flux is about 600w/m^2. Fig.5 shows the temperature distribution of water-in-glass evacuated solar water heater as determined by experimental measurements and simulation model. Temperature was measured in various positions in the collector via thermocouple type K with numerical display and resolution 1˚C, the ambient temperature was measured by normal mercurial thermocouple. All of these works presented good agreement with experimental data for simplified geometry of the solar collector. The error percentage is 12% between experimental and simulation.

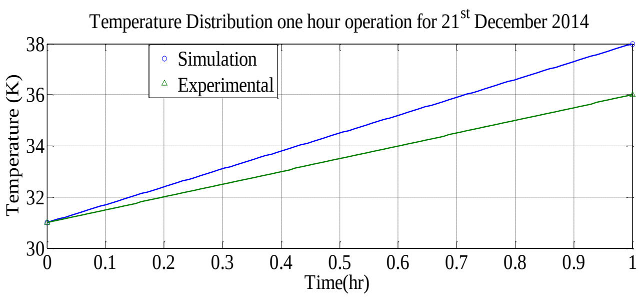

Fig.5.Comparison of simulated temperature distribution with experimental measurement

IV. Results and Discussion

In this paper, three different collectors and different inclination angles are simulated.

A.Solar water Heater Model with 47D1800L

After simulating one hour of operation, it is already possible to visualize the temperature distribution in a water-in-glass evacuated solar water heater with 30°,45° and 60° inclination angles in Fig. 6,7and 8 respectively. In these figures, the blue region represents lower water temperature and the red region indicates the highest temperatures of the system, close to the tube wall which receives the heat flux. For 30°, 45° and 60° of inclinations, the temperature of water in the top portion of the tube is higher than that of middle and bottom. This is because of buoyancy effect produced due to density difference.

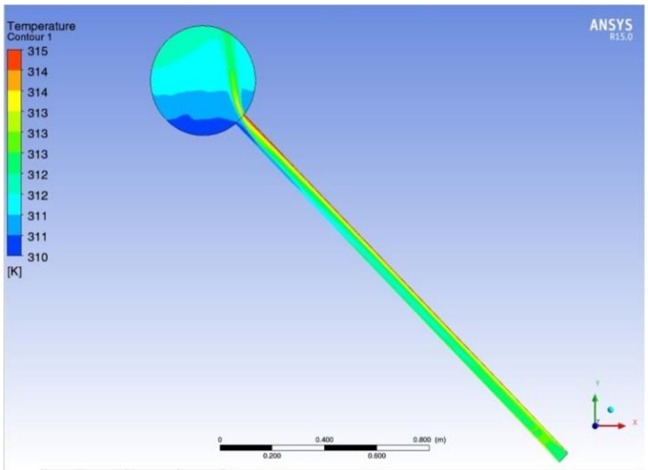

Fig.6. Temperature distribution of solar water heater with 45˚ inclination after one hour of operation

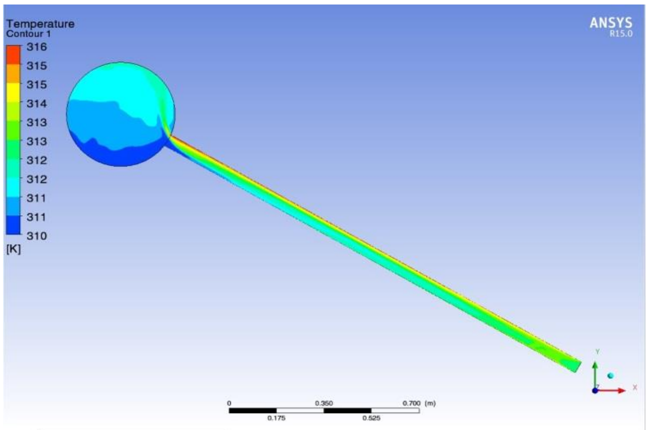

Fig.7. Temperature distribution of solar water heater with 30˚ inclination after one hour of operation

As seen in Fig. 6,7and 8, the stagnation zone was reduced and the lower temperature observed in the simulation of 1 hour of operation was approximately 310 [K], indicating that there was not water at 304 [K] in the system.

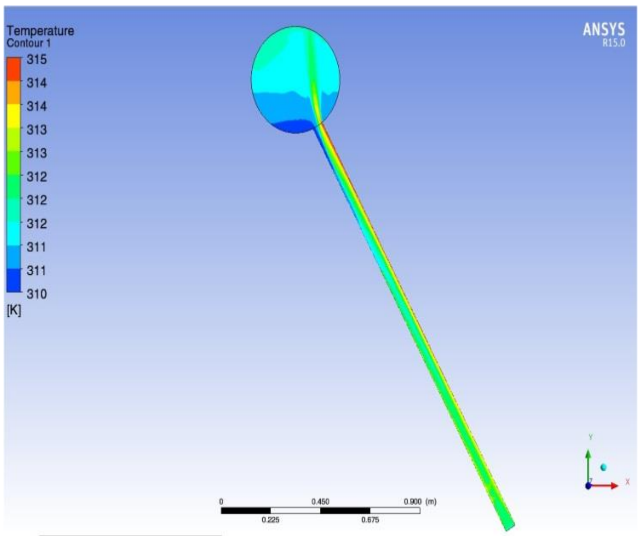

Fig.8. Temperature distribution of solar water heater with 60˚ inclination after one hour of operation

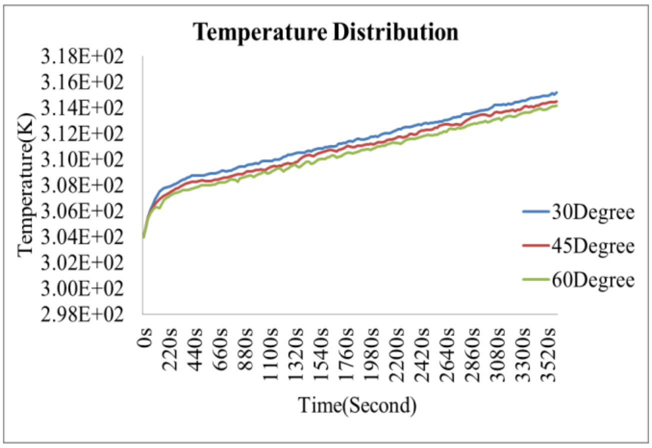

Fig.9.Temperature development for different inclinations

The temperature development for different inclination can be seen in Fig.9. At 45˚ of tilt angle (figure6), the lower temperature region is less than at 30˚. At 60˚ the lower temperature area is lowest. Comparing the thermal performance of the model (47D1800L), subjected to different collector inclinations, the results showed little difference between the temperatures development achieved on each analysis (as can be seen in Fig. 9).

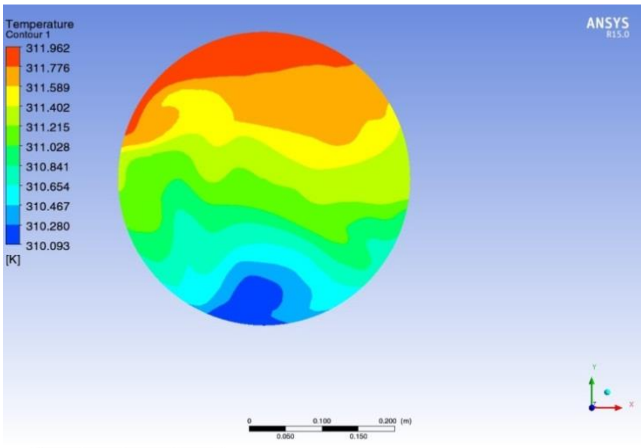

Fig.10. Temperature Stratification in the tank for 45˚inclination

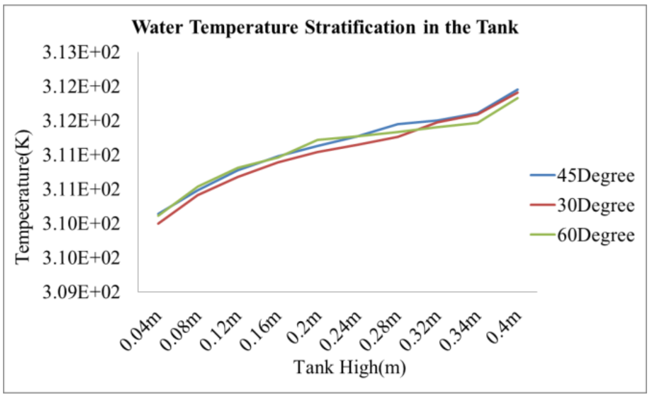

Fig.11.Temperature Stratification in the tank for different inclinations

The temperature distribution of the water on a vertical plane in the tank is shown in Fig. 10. It can be observed that the water with a lower temperature goes to the bottom, whereas the water with higher temperature circulates along the top of the tank due to the buoyancy effects. The temperatures were measured at the tank and tube connection. The temperature stratifications in the tank for different inclinations are described in Fig.11. At 45˚inclination, the temperature is slightly higher than 30˚ and 60˚.

B. Two Different solar Water Heater Models with Two Tube Dimensions 47D1800L and 34D1400L

The temperature distribution of the two different models with (47D1200L) and (34D1400L) dimensions at 45˚ inclination through one hour operation are shown in Fig. 12 and 13.

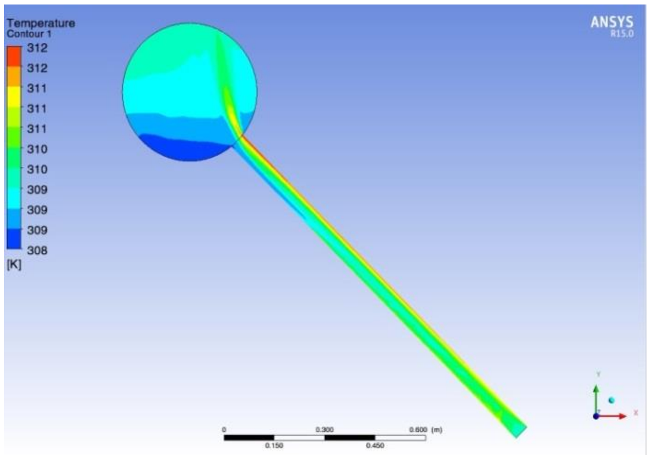

Fig.12.Temperature distribution of solar water heater (47D1200L) with 45˚ inclination after one hour of operation

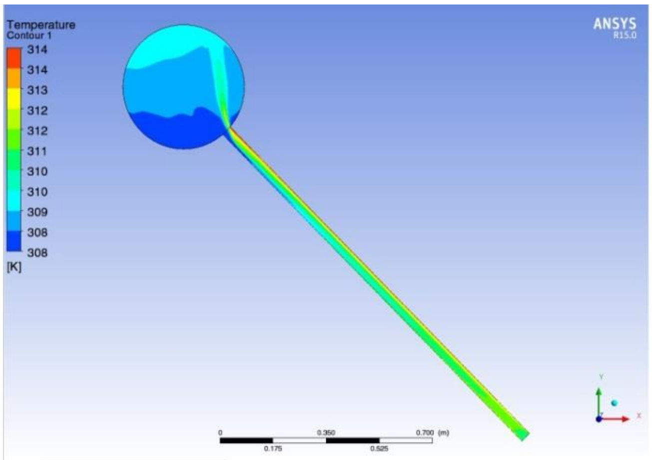

Fig.13.Temperature distribution of solar water heater (34D1400L) with 45˚ inclination after one hour of operation

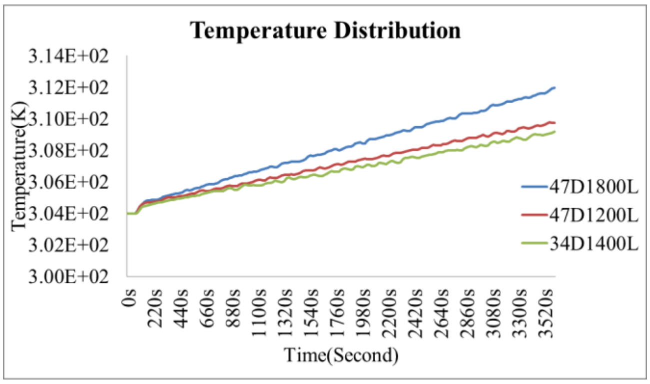

Fig.14. Temperature development for different geometries with 45˚ inclination

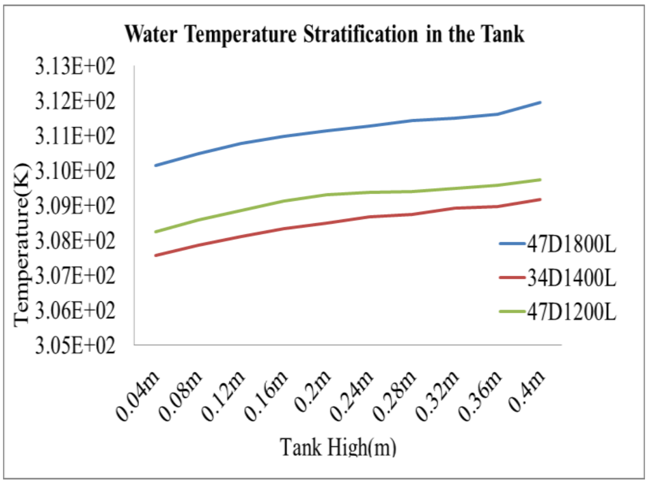

Fig.15. Temperature Stratification in the tank for different tube dimension

Analyzing the temperature for the three models, the conventional collector acquired higher temperature values as in Fig.14. For the tilt angle of 45°, the maximum temperature in the first model (47D1800L) was of 315 [K], the model with (47D1200L) achieved 312 [K] and the model (34D1400L) 314 [K].The simulation of water-in-glass evacuated tube solar water at various diameters and lengths is showing in Fig.15, the effect of increasing in diameters and lengths will increase the temperature in solar water heater, it means there is more heat transfer in the tube.

V. Conclusion

In this paper, three different collectors and different inclination angles are simulated. The thermal performance of water-in-glass evacuated tube solar water heater is obtained via CFD numerical simulation. In this paper, there is no significant variation in the temperature because of inclination angles. Because of the round shape of the evacuated tubes, they have the capability of receiving major amount of solar radiation. The heat losses are minimized in the tubes to a larger extent. So, the inclination angle does not produce significant changes in the temperature characteristics. In these models (47D1800L, 34D1400L, 47D1200L), the behaviour the temperature in the tank were different. Also, in these models the increment of the water temperature in the tank was in the range from 310K to 311.949K for the (47D1800L) model, while for the (34D1400L) model and the (47D1200L) model the increment of temperature was in a range from 307.5 K to 309 K and 308.25K to 309.7K. A better prediction of the water temperature in the tank was observed for the model with (47D1800L) than for other two models. Experiment results are successfully verified with simulation results with maximum error within 20%. From this work, better understanding and useful information are provided for water-in-glass evacuated solar water heater. It is concluded that CFD numerical simulations are useful in identifying ways to improve on efficiency of solar collectors and it can be used for optimizing the geometrical configurations.

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Nomenclature

$S_{M,buoy}$- the source term,
g - the gravitational acceleration,
ρ - the corrected density,
ρ_{ref} - the reference density used in all terms related to the density except the above source term,
β - the thermal expansivity,
T - the studied temperature and
T_{ref} - the reference temperature set as an average value of the problem domain.
μ - dynamic viscosity
k - conductivity
c - specific heat
U_x ,U_y, U_z -velocity component

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