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Numerical Study of a Stand-alone Flat Plate Solar Water Heater using Rectangular Flow Channel with Fin

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ABSTRACT

This paper presents a study of fluid dynamics behavior and thermal performance of a flat plate solar water heater. Flat plate solar collectors have lower efficiency since large heat losses occur from the collector surface by convection and radiation. This paper presents a model of a flat plate solar water heater having rectangular flow path with fin. In this study, the performance of a flat plate solar water heater having rectangular flow channel with fin is compared with the performance of conventional solar collector. The sole purpose of this study is to enhance the thermal performance considering the effect of enhanced turbulence of the working fluid. A CFD model is developed using Discrete Ordinate radiation model to solve radiation effect and model for analyzing fluid flow inside the systems Numerical simulation model solution is carried out using finite volumes method. Results showed that the flow behavior of the solar collector was approximately rotational type. The maximum thermal efficiency was 41.75%, which was 13.43% higher than a conventional one. The numerical results also showed that presence of fin inside the flow channels over the absorber plate provided an increase in the outlet temperature than the conventional one.

Keywords: Flat plate solar water heater, thermal efficiency, Fluid dynamics behavior.

1. Introduction

The use of the renewable energy especially the solar energy is continuously increasing and gaining popularity because of the high price of conventional energy resources and serious environmental pollution problem [1, 2]. One of classical way of using solar energy is to make hot water. Usually, the system consists of two main elements, i.e., a solar collector and a storage tank. Solar energy preservation is a topic of renewable energy has been the primary interest of many researchers for the last two centuries, because it can reduce the cost of domestic water heating up to 70%[3]. Solar energy collectors (solar water or air heater) are special kind of heat exchangers that transform solar radiation energy to internal energy of the transport medium [4].
A solar water heater (SWH) is an environmentally friendly device which absorbs renewable solar energy to produce hot water [4]. The solar thermal energy can be used in solar water-heating systems, solar pool heaters, and solar space-heating systems. Flat-plate collectors are the most common solar collector for solar water-heating systems in home and solar space heating [5].
The solar hot water system produces hot water of 50°C to 70°C depending upon the solar intensity and number of solar collector panels [6, 7]. Solar water heaters are characterized by its thermal performance that depends on the transmittance, absorption and conduction of solar energy and the conductivity of the working fluid [8, 9]. The requirement of hot water per day for industrial and commercial sector is around 2, 40,000 liters. The overall installed capacity of thermal collectors is capable of producing around 25 million liters of hot water per day at 60°- 70°C [8]. Therefore, its requirement is increasing day by day.
Flat plate collector thermal efficiency enhancement is now the interest of many researchers due to its low heat transfer characteristics
Reasons for low efficiency of flat plate collector are mentioned below:

i. Poor convective heat transfer between the collector working fluid and the absorber tubes.
ii. Collector plate temperature increases consequently as the thermal loss increases.

Methods to improve the efficiency are mentioned below:

i. Factors effect on convective heat transfer
ii. Commercial known method to improve the efficiency (area of heat exchanger, mass flow rate).
iii. Working fluids.

Most flat plate collectors have two horizontal pipes at the top and bottom, called headers, and many smaller vertical pipes connecting them, called risers. The risers are welded (or similarly connected) to thin absorber fins. Heat-transfer fluid (water or water/antifreeze mix) is pumped from the hot water storage tank (direct system) or heat exchanger (indirect system) into the collectors' bottom header, and it travels up the risers, collecting heat from the absorber fins, and then exits the collector out of the top header [10]. Solar collectors are of double pass or single pass; it may contain fin or other extruded parts for enhancing efficiency. Fluid flow phenomenon greatly affects the heat transfer in a thermal system[11]. Hence it is required to understand the flow characters of a solar collector in order to determine the thermal performance in an efficient way. A numerical model

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was developed to study the flow distribution in unglazed transpired plate collectors using TASC Flow-CFD code [12, 13] . CFD transient predictions were verified using indoor testing employing a solar simulator [14]. Effects of flow distribution through the absorber tubes are uniform under high mass flow rates [15].

The aim of this work is to study the effect of operating (change of mass flow rate) and design parameters (fins with rectangular channel) on the efficiency of standalone flat plate solar collectors. In this study, numerical analysis of the flat plate solar water heater is carried out with computational software named ANSYS FLUENT. The effect of adding ribs with rectangular fin with different mass flow rate was studied. Mesh independency test is carried out with different meshes of assured quality which yields the accurate prediction.. Velocity and temperature profiles of different zones of the flat plate are also observed.

2. Methodology

Geometry mainly describes the physical interpretation of the flat plate solar collector, shown in Fig. 1 and Fig. 2 with identifying the components and regions of the collector. The Fig. 1 shows the inlet and outlet sections of the collector which mainly indicates the change of temperature of the working fluid and this affects the efficiency much. The model studied in this project was built in aluminum absorber plate, which contains 2 risers, 12 rectangular flow paths; in every flow path it contains 5 rectangular fins at equal distance. These fins increase residence time as well as turbulence of the flowing fluid. These also increase roughness of the absorber plate. The inlet and outlet diameters are equal and it is 0.01905 m (0.75 inch).

Length of the collector plate is 0.9144 m (36 inch)
Width of the collector plate is 0.609 m (24 inch)
Width of the rectangular channel is 0.0254 m (1 inch)
Central distance of each successive channel is 0.0254 m (1 inch)
Length of each fin is 0.0127 m
Width of each fin is 0.00635 m
Distance of each successive fin is 0.1524 m (6 inch)
Area of the collector, A_c= 0.786 m^2

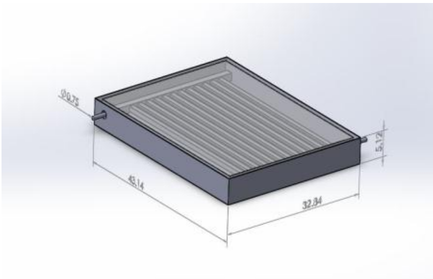

Fig. 1: Schematic of flat plate solar water heater (With rectangular flow path and fin)

Fig. 2: Fins inside the flow path

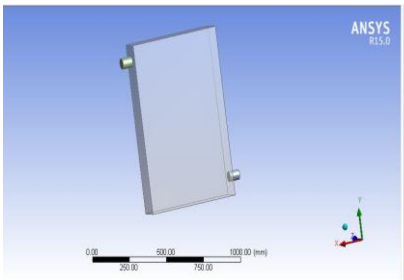

Fig. 3: Schematic of flat plate solar water heater (Without flow path and fin)

The geometry was exported to CFD software and meshing was generated with different face and edge sizing. The tetrahedrons elements in flow domain were adapted in flat plate meshing. Meshing is mainly the subdivision of the domain into a number of smaller, non-overlapping sub domains. Medium mesh size was used in this study. Two mesh models were generated separately which are shown in Fig. 3 and Fig. 4 respectively. For Orthogonal quality of mesh 1 the value is 0.787258 which has an ideal value of close to 1. Aspect ratio is a measure of the stretching of the cell. Generally, it is best to avoid aspect ratio excess of 5 in the flow.

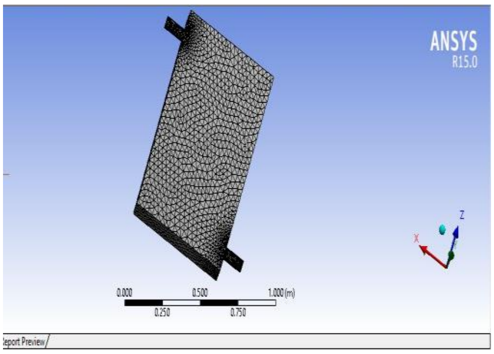

Fig. 4: Mesh model (With rectangular flow path and fin)

From the tests it is found that mesh quality is good. Numbers of nodes are 20836 and number of elements are 114690 for the mesh 1.

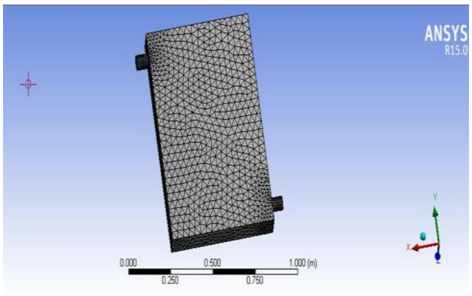

Fig. 5: Mesh model (Without rectangular flow path and fin)

For Orthogonal quality of mesh 2 the value is 0.84764 which has an ideal value of close to 1. In mesh 2 aspect ratio used is 1.90129. Numbers of nodes are 6250 and number of elements are 30215 for the mesh 2.

Modeling is the next step for CFD analysis after meshing is completed. It includes choosing various models for different criteria. Generally there are turbulence and radiation model. In turbulence flow the velocity field always fluctuates. As a result, the transported quantities such momentum, energy and species concentration fluctuate. Generally the FLUENT offers various turbulence models. The standard K-€ (epsilon) model was used to capture the turbulence flow in this study of a flat plate collector due to its suitability for a wide range of turbulence flows. The standard K-€ model for the simple scheme of turbulence used two equation models. In which the solution of two separate transport equation allows the turbulent velocity and length scales, which are to be independently determined. Standard wall function was taken as near-wall treatment. For standard K-€ (epsilon) turbulence model it is allowed to use standard wall function and this function works reasonably well for broad range of wall bounded flow like in flat plate solar collector in this study.

For radiation model, Discrete Ordinate radiation model was adopted in this project, which is more advantageous and used for a simpler radiation and for acceptable accuracy. For setting up the Discrete Ordinate radiation model the 3 steps are followed. These are: After choosing DO model, it provides options for Angular Discretization, Theta divisions and Phi divisions. These theta and phi divisions define the number of control angles used to discretize each octant of the angular space. The number of bands is set to be zero, indicating that only gray radiation is to be modeled. When a non-zero Number of Bands is specified, the radiation model provides options to show the wavelength intervals.

In this project, for Boundary condition (shown in Table 1) all the water inlet surfaces were defined as mass flow rate at inlet. The mass flow rate, temperature of the working fluid (water), mass fraction of all species, turbulent intensity is specified. Before FLUENT can begin solving governing equations, flow field guessed initial values, used as initial values of the solution, had to be provided. Once the initial values had been provided, the iteration was performed until a converged result is obtained.

Table 1: Boundary conditions for fluid flow

Domain	Water inlet	Water outlet	Glass plate	Absorber with fin
Type	Mass flow inlet	Pressure outlet	Wall	Wall
Flow direction	Negative Y direction	Negative Y direction	Positive Z direction	Negative X direction

At the inlet the working fluid is at ambient temperature and this is the lowest temperature of the collector. Working fluid temperature is highest at outlet section by absorbing heat from the solar radiation as passing over the absorber plate. The rectangular fins increase the surface area and residence time for the working fluid so that it can absorb more heat.

3. Results & Discussion

Fig.6 and Fig.7 show the velocity streamline of flat plate collector for model 1 and model 2 respectively. Model 1 and Model 2 represent the condition for mesh 1 and mesh 2. These contours show the fluid flow characteristic. These also show the effect of turbulence. The laminar sub layer on the lower part of the collector is responsible for lower efficiency of collector but the roughness of the collector helps to remove the layer and makes the fluid flow more turbulent.

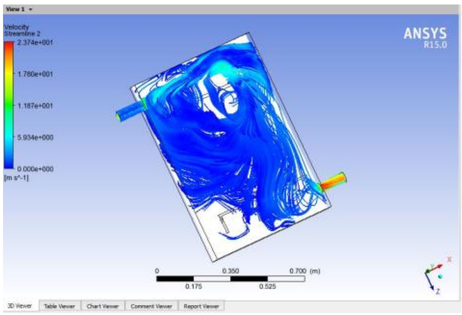

Fig. 6: Velocity streamlines (**For Model 1**)

The fins inside the rectangular flow passages designed in this study contribute to make the flow more turbulent (In Fig.7). Due to the hindrance to flow caused by fins, the residence time of fluid inside the collector increases. Turbulence in flow also increases. As a result outlet temperature rises and flow velocity decreases.

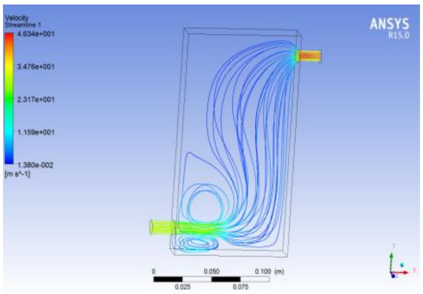

Fig. 7: Velocity streamlines (**For Model 2**)

Velocity was higher in flat plate collector without fin and flow channels (Fig. 7) as there was no hindrance to flow. And so there is more uniformity in flow streamlines.

Fig. 8 & Fig. 9 show the temperature contours of flat plate solar collector for model 1 and model 2. Scale beside the contours indicates the temperature of different zones. The working fluid (water) when enters to the collector with an ambient temperature then it passes over the absorber. Through glass plate heat from solar energy tracked in the collector and gradually the fluid become hot absorbing this heat. Lowest temperature is at inlet, comparatively higher at wall side of wooden box, then increases in the middle of the collector and the highest is at outlet.

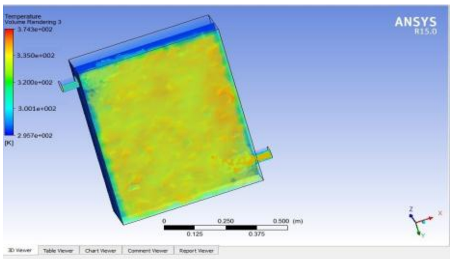

Fig. 8: Temperature contour (**For Model 1**)

Fig. 8 shows temperature contour of flat plate solar collector for model 1 i.e. with fin & flow channel. It shows that the temperature at inlet is 305 K and water passing through the rectangular flow channels with fin inside. Water exits at a temperature around 338 K. Here temperature rise is 33 K.

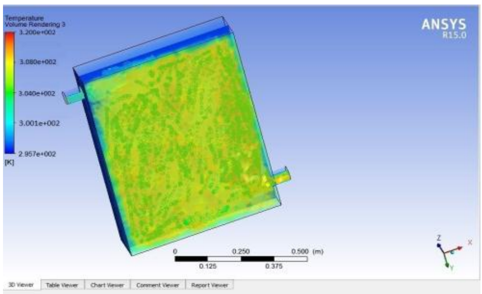

Fig. 9: Temperature contour (**For Model 2**)

Fig. 9 shows temperature contour of flat plate solar collector for model 2 i.e. flat plate solar collector without fin & flow channel. The scale on the side indicates the temperature distribution. It shows that the temperature at inlet is 299 K and water passing through the rectangular flow path it exits at a temperature around 307 K. Here temperature rise is only 8 K which is much lower than the model 1 analyzed in this study.

From the temperature contours, it can be said that flat plate solar collector with fin & flow channels is more efficient and satisfactory than the one which is without any fin & flow channel.

Fig. 10 shows the efficiency of experimental and numerical set up, the efficiency of designed model is higher than the conventional simple model without rectangular flow path and fin, and thus it validates the model. The numerical value of efficiency is 5% higher than experimental value.

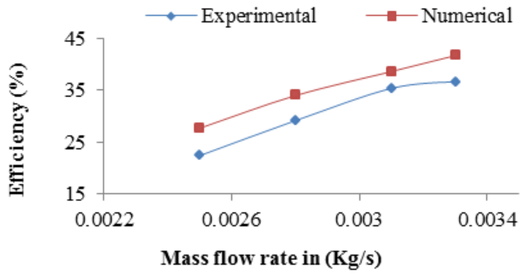

Fig. 10: Efficiency Vs. Mass flow rate curve

Fig. 11 shows the Heat transfer co-efficient for different mass flow rate, the value of heat transfer co-efficient increases with the increase in mass flow rate. Higher Mass flow rate and fin enhanced the turbulence results in enhanced the heat transfer coefficient.

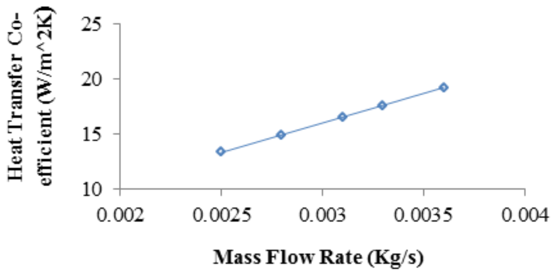

Fig. 11: Heat transfer co-efficient Vs. Mass flow rate curve

Fig. 12 shows the relationship between temperature and mass flow rate, fall in temperature with increase in mass flow rate. The difference between numerical and experimental value is within an acceptable range of variation that proof the validation of the model.

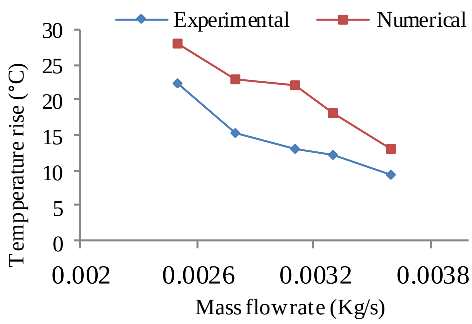

Fig. 12: Heat transfer co-efficient Vs. Mass flow rate curve

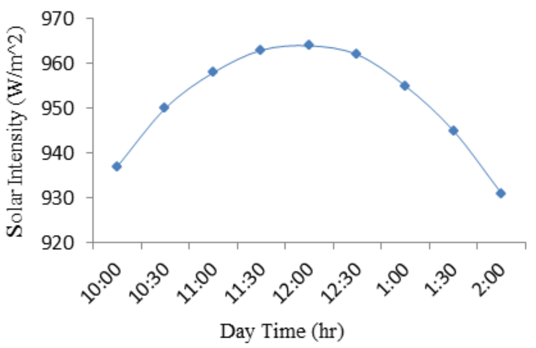

Fig. 13: Solar intensity Vs. Day time curve

Fig. 13 shows the change of solar intensity with respect to day time, the intensity increases to a highest value with day time and then decrease. The highest value of solar intensity was found at around 12.00 PM. The latitude and longitude of Rajshahi is 24.36˚ North & 88.62˚east respectively.

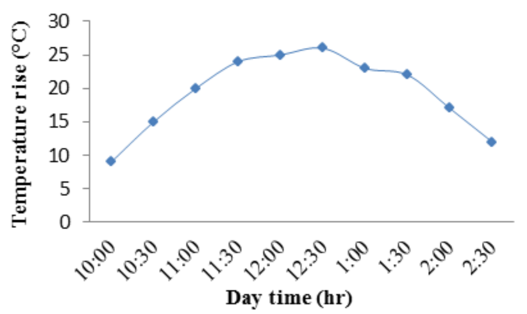

Fig. 14: Temperature rise Vs. Day time curve (clear weather)

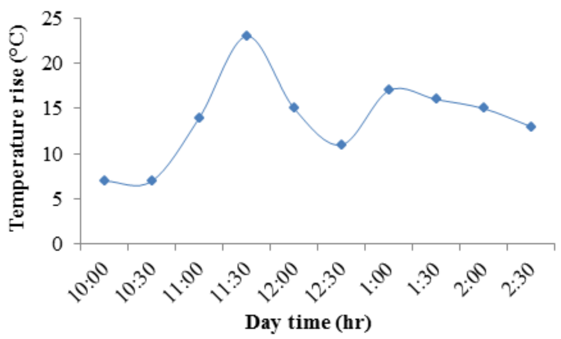

Fig. 15: Temperature rise Vs. Day time curve (cloudy weather)

Fig. 14 & Fig. 15 show the change of temperature with respect to day time in clear and cloudy weather respectively. In clear weather highest temperature obtained at 12:30 AM after then temperature decrease, on the other hand for cloudy weather the highest temperature was obtained at 11.30 AM and he minimum temperature was found at 10:30 AM and then at 12:30 PM due to cloudy weather.

4. Conclusion

A numerical model is developed to study the effect of rectangular channel with fin in a solar water heater. Considering different mass flow rate of water input, the flow behavior of working fluid was observed and the temperature and velocity at outlet were obtained. The mass flow rate was varied from 9 Kg/hr to 13 Kg/hr. The highest efficiency was obtained 41.75% (Numerically) and 36.7% (Experimentally). The highest efficiency is found at highest mass flow rate. It was also found that the temperature rise decreases with increase in mass flow rate, at the same time the heat transfer co-efficient increases with increase in mass flow rate.

From CFD results, it is concluded that-

i. The best result was obtained on clear sunny days.

ii. Collector outlet temperature during day varies depending on solar intensity and it is directly proportional to solar intensity.

iii. The value of heat transfer co-efficient increased with the increase in mass flow rate.

iv. From the numerical values of efficiency it was found that solar water heater with fin inside the rectangular flow path was 28% more efficient than that of without fin & flow path. From temperature contours it is seen that solar water heater with fin & flow path gave around 25 K more temperature rise than the solar water heater without fin & flow path.

v. Analyzing the thermal performances and flow characteristics it is seen that solar water heater with fin was more efficient than solar water heater without fin.

vi. Analyzing the flow characteristics it is seen that increase of turbulence in the flow channel gave better performances.

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