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MATHEMATICAL MODELLING AND ANALYSIS OF CORRUGATED BLACK COATED SOLAR FLAT PLATE COLLECTOR

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Abstract— **Solar flat plate collector is one of the valuable heat sources with variety of applications such as space heating and cooling, industrial process heating and drying process etc. The major heat losses from a normal solar flat plate collector are through the top cover which reduces the thermal efficiency; also the heat transfer coefficient is low between the air and the absorber plate in solar flat plate collector. Many experiments had been conducted to increase the thermal efficiency of flat plate collector. Based on literature review, it is concluded that few studies carried out on corrugated absorber plate. It will increase the heat transfer rate. Improvement of thermal efficiency of solar flat plate collector is to be obtained by enhancing the rate of heat transfer. In this article experimental setup is evaluated and compared with fins and without fins. Analysing the flat plate collector using Ansys Workbench will give theoretical solution for solar flat plate collector.**

*Keywords— **Solar flat plate collector; corrugated surface; Ansys Workbench***

I. INTRODUCTION

Energy is available and used in many forms and plays an important role in worldwide economic growth and industrialization. The growth of population and rising industrialization need large amount of energy. Environment degradation with use of fossil fuels is a danger to life in this earth and threat to the environment. Development of renewable energy sources is important reducing the environmental pollution. Considering many renewable energy sources, solar energy is huge energy source for meeting the demand. [1] The available solar radiation provides an infinite and utilising solar energy for heating applications is to convert it into thermal energy by using solar collectors.

Flat-plate solar collectors are mostly used in low temperature energy technology and have attracted the attention of a large number of investigators. [2], [3] Several designs of solar air heaters have been developed over the years to improve their performance. There are two types of solar flat plate heating collectors; water heating collectors and air heating collectors. [4], [5] The pace of development of air heating collector is slow compared to water heating collector mainly due to low thermal efficiency. Conventional solar air collectors have low thermal efficiency due to high heat losses due to top and bottom covers and low convective heat transfer coefficient between the absorber plate and flowing air stream. [6], [7] Attempts had been made to improve the thermal performance of conventional solar flat plate collectors by providing various design and flow arrangements.

Extensive investigations had been carried out on the optimum design of conventional and modified solar flat plate heaters, in order to search for efficient and inexpensive designs suitable for mass production for different applications. [8], [9] The researchers have given their attention to the effects of design and many parameters like type of flow passes, number of glazing and type of absorber flat, corrugated or finned plate, on the thermal performance of solar air heaters. Theoretical parametric analysis of a corrugated solar air heater with and without cover, they obtained the optimum flow channel depth, for maximum heat at lowest collector cost. It was found that there exists an optimum mass flow rate corresponding to an optimum flow channel depth. This result has been concluded that, after conducting a study on 10 different designs of solar air heaters. [3] They reported that the V-corrugated collector having high efficiency compared to conventional solar flat plate collector. For improving the performance of solar air heaters, few studies had been conducted on the effect of the air flow passage dimension and pressure drop and hence the cost-effectiveness of the system.

Thus, more studies were being done to improve the thermal efficiency of the solar flat plate collector systems by proposing the various techniques for improving the heat transfer coefficients. [10], [11], [12] Few studies carried out a performance analysis to investigate the thermal performance of cross-corrugated solar air collectors. Many studies had been

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done in both experimental and theoretical to improve the performance of solar heaters systems. [13], [14] Modelling and analysis was considered as fast and cheap analytical tools by engineers while developing optimal solar energy systems for a given application before their construction. This study involves experimental investigation and analysis of a solar air heater system with corrugated absorber plate. The model will be evaluated using the experimental values obtained from a model built and tested outdoors.

II. THERMAL ANALYSIS

In a solar flat plate collector, heat transfer rate is depends upon the mass flow rate of the air [5], [15].

To simplify the analysis, following assumptions should made:

- Uniform mass flow rate of collector.
- One-dimensional heat transfer through the system layer.
- There is no heat transfer in the direction of flow, the exergy transferred in the flow direction by mass transfer.
- The heat transfer from the collector edges is negligible.
- Properties of glass and insulation are independent of temperature. (Constant)
- All thermo-physical properties of the fluid, air gap, and absorber are temperature dependent.
- The sky radiation and ambient conditions are time dependents.
- Loss through front and back are to the same ambient temperature.
- The sky can be considered as a black body for long-wavelength radiation at an equivalent sky temperature.
- Dust and dirt on the collector are negligible.

A. Solar flat plate collector

Various types of solar air-heaters are being used for different applications; among them flat-plate collectors are extensively used in low-temperature solar energy, because they are relatively simple, easy to operate and have low capital costs. Solar air heaters have many advantages over liquid heaters regarding the problems of corrosion, boiling, freezing and leaks. [16], [17] Solar air heater without thermal storage is extensively used for drying agriculture products. Basically many agriculture products are getting dried at low temperature (50–60 ◦C) and this can be easily achieved in solar air heater. Hot air generated by air heater can be delivered by natural convection or force convection.

A bare plate roof air heater was fabricated from corrugated aluminium sheet roof in farm shed to provide hot air for agricultural use. [11], [18] The performance efficiency of such a roof air heater is observed to be strongly influenced by the design parameters of the system. It was reported that higher air temperature can be obtained in low air mass flow rate through air heater and longer air channel. [19], [20] During experiments in solar absorber solar air heaters with and without fins, it was found that air heaters with fins are seen more efficient in comparison to the air heater without fins for air flow rates ≤0.0388 kg/s/m2.

Solar flat plate collector designed cost effective, where the gap between the absorber plate insulation material over 50 mm is useless. [9], [21] A part of solar radiation is absorbed by the covering glass and the remained is transmitted through the absorber plate and it is transmitted to the working fluid. Therefore, the conversion factor indicates the percentage of the solar rays penetrating the transparent cover of the collector and the percentage being absorbed in the collector.

III. EXPERIMENTAL ANALYSIS

A. Experimental analysis

The collector consists of a glass cover and absorber plate with a well insulated parallel bottom plate, forming a rectangular duct profile. The corrugation of the absorber plate is equilateral triangle in shape and the air is made to flow into the corrugation. The theoretical solutions of the thermal performance of the solar flat plate collector system involve the formulation of the energy balance equations that describe the heat transfer mechanisms at each component of the solar flat plate collector. The heat distribution through the solar flat plate heater is as shown in Fig.1.

The selected collector has single glass cover, black coated aluminium absorber plate, glass wool insulation enclosed in a metallic frame. [18], [23] Outlet temperature of air was predicted for specific mass flow rate of air for entire day. Various losses will be calculated. Useful heat gain of the collector will be estimated. Finally thermal efficiency of the collector will be calculated. Mass flow rate of the air flowing through a collector is one of the important parameter improve the performance of the collector. Outlet temperature of air from the collector at various flow rates will also calculated using the model. Effect of change in mass flow rate, intensity of solar radiation, absorber material on collector performance will be predicted using the model and then comparing it with experimental data.

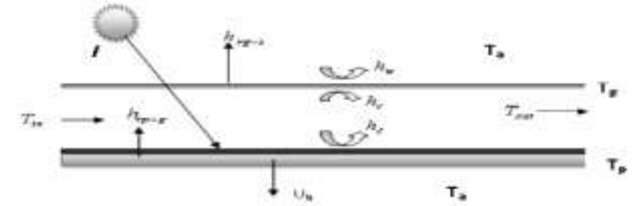

Fig. 1**:** Schematic diagram of flat plate solar collector with heat transfer parameters

The energy balance equations obtained are as follows [7], [24]:

On the glass cover:

$$h_{rp-g}(T_p - T_g) + h_c(T_g - T_f) = U_t(T_g - T_a)$$

On the absorber plate:

$$(\tau\alpha)AI = Ah_c(T_p - T_f) + Ah_{r.p-g}(T_p - T_g) + AU_b(T_p - T_a)$$

The air flow:

$$\dot{m}C_p(T_{out} - T_{in}) = Ah_c(T_g - T_f) + Ah_c(T_p - T_f)$$

Depends upon the design of experimental setup the heat transfer parameters will varied. Fig.2 shows the corrugated black coated solar flat plate collector.

Fig. 2 corrugated black coated Solar flat plate collector

In this collector absorber plate contains equilateral triangular fins to improve the heat transfer rate of the collector. Fins provided in the absorber plate will increase the contact area of air to the absorber plate. Also it increases the friction in between air and absorber plate. That collector design is showed in Fig.3.

TABLE I. Design and dimension of corrugated solar flat plate collector

Sl.No.	Parameters	Value
1	Collector type	Flat plate collector
2	Material	Mild steel
3	Dimensions of collector	1000 mm x 500 mm x 100 mm
4	Area of absorber plate with fins	0.5929 m^2
5	Area of absorber plate without fins	0.4851 m^2
6	Volume of the collector with fins	0.02377 m^3
7	Volume of the collector without fins	0.024255 m^3
8	Size of equilateral triangle	10 mm
9	Distance between two fins	30 mm
10	Absorber plate material	Aluminium
11	Fin material	Aluminium
12	Insulation material	Glass wool
13	Glass cover material	Low iron glass

IV. ANALYSIS OF CORRUGATED COLLECTOR

CFD is a science that is helpful for studying fluid flow, heat transfer, chemical reactions etc by solving mathematical equations by using numerical analysis. It is equally helpful in designing a heat transfer system from scratch and troubleshooting/optimization by suggesting design modifications. CFD employs a very simple principle of changing the entire system into small cells or grids and applying governing equations on these discrete elements to find numerical solutions for pressure distribution, temperature gradients, flow parameters in a shorter time at a lower cost because of reduced required experimental work.

Modelling of 3D model of collector is done in workbench. Further this model is converted into step format before importing it into ICEM CFD. For this purpose ICEM was used as preprocessor. There was a need to place very fine mesh of the plate. Quality of the mesh was checked and it was found in acceptable limit. The boundaries and continuum as inlet, outlet, heated wall, insulated wall and the fluid zones were defined as per the experimental conditions. It is basically called a postprocessor for analyzing the CFD problems.

As the flow was turbulent, k–e model was selected as turbulent model for further analysis of the problem. Energy equation is kept ON as a heat transfer model. Air was selected as working fluid with its standard properties. [10], [19], [25]

According to the models selected earlier the equations which were considered for the solution are continuity equation or energy equation or momentum equation or equation for turbulence. The above equations have been solved under-relaxation factors.

After setting all necessary input conditions the problem was iterated for 300 iterations within which it gives well converged solution so that accurate results were displayed. The results obtained with the CFD are of acceptable quality. In the current work, various problems encountered in the design of solar flat plate collector and their solutions with the help of CFD have been reviewed.

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A. Temperature distribution of Solar Collector with Fins

Analysis of solar collector with fins is conducted for various days reading taken from corrugated solar collector. The readings are taken at kumaraguru college of technology, Coimbatore. In this report temperature distribution from glass cover and absorber plate is showed on 28.01.2016, 01.02.2016. Here the distribution is showed at various times from 11am to 3pm. Fig.5, 6, 7, 8 shows the temperature distribution of collector with fins.

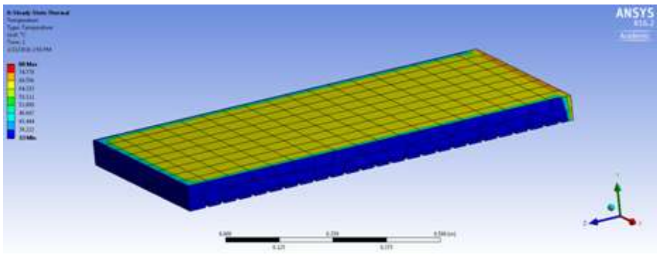

Fig.5. Temperature distribution from glass cover on 28.01.2016 at 11am

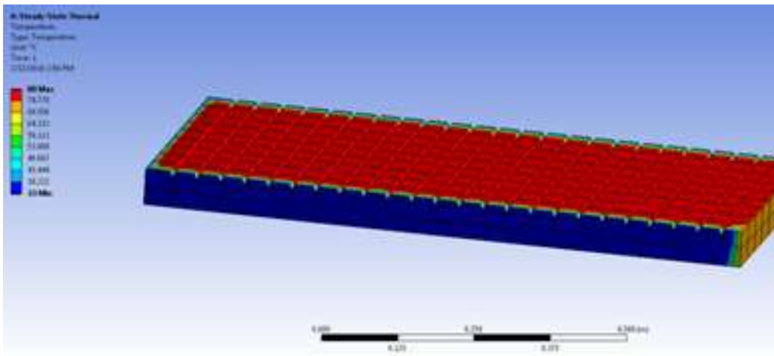

Fig.6. Temperature distribution from absorber plate on 28.01.2016 at 11am

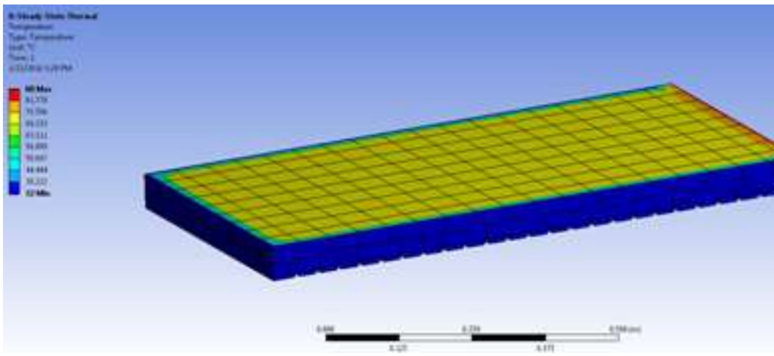

Fig.7. Temperature distribution from glass cover on 01.02.2016 at 1pm

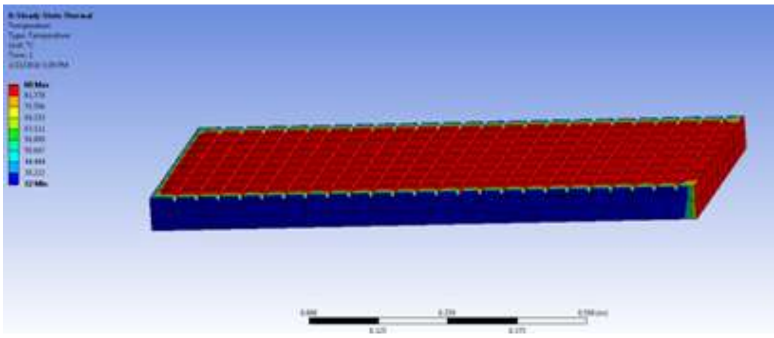

Fig.8. Temperature distribution from absorber plate on 01.02.2016 at 1pm

B. Temperature distribution of Solar Collector without Fins

Analysis of solar collector without fins is conducted for various days reading taken from solar flat plate collector. The readings are taken at kumaraguru college of technology, Coimbatore. In this report temperature distribution from glass cover and absorber plate is showed on 02.02.2016, 09.02.2016. Here the distribution is showed at various times from 11am to 3pm. Fig.9, 10, 11, 12 shows the temperature distribution of collector without fins.

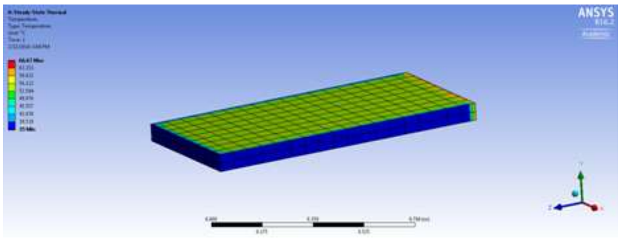

Fig.9. Temperature distribution from glass cover on 02.02.2016 at 11am

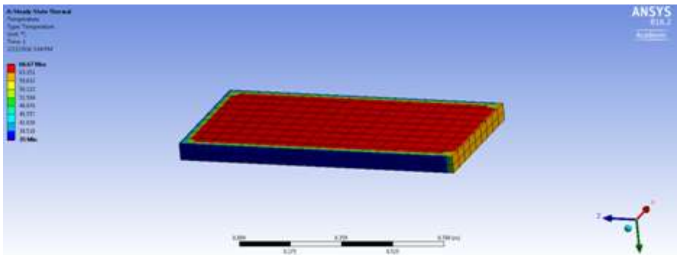

Fig.10. Temperature distribution from absorber plate on 02.02.2016 at 11am

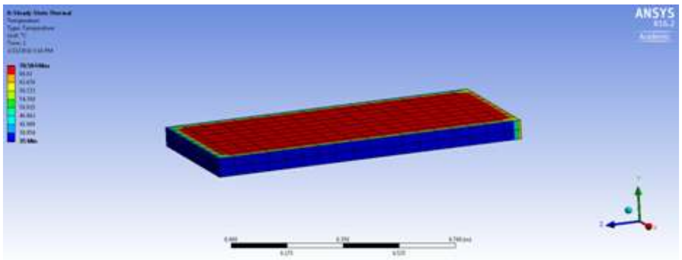

Fig.11. Temperature distribution from glass cover on 09.02.2016 at 2pm

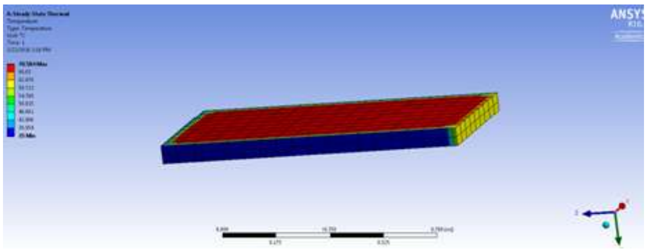

Fig.12. Temperature distribution from absorber plate on 09.02.2016 at 2pm

VI. CONCLUSION

Solar flat plate collector is a device which captures the solar energy. Producing hot air by using solar air heater is a renewable energy technology used to produce heat for many applications. Such systems produce heat at using sun as energy source and it is freely available during day time. It requires minimum maintenance like cleaning of collectors only is required. Solar air heater having equilateral triangular sectioned rib roughness on the absorber plate has been proposed. An experimental investigation will be conducted to compare with predicted results. Using CFD thermal performance of collector, heat transfer rate, mass flow rate of air will be studied. Corrugated surfaces created zigzag motions. Because of this heat transfer parameter increases and also efficiency of the total system is increases.

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