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Analysis of Evacuated Tube Collector and Its Impact on Cost Reduction Measure in Boiler House

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ABSTRACT

The impact of energy usage on the environment and the increase in the price of fossil fuel has led to the use of renewable energy sources such as solar energy. It has become a matured field over few decades, and has been a potential alternative to the fossil fuels. The simplest and most direct applications of this type of energy is the conversion of solar radiation into heat, which can be used in water heating or space heating applications. The need of renewable energy sources and the growing interest for solar energy has resulted in the need for investment for solar collectors. Solar collectors are the key components of solar systems for trapping of solar energy. They capture the Suns energy, transform into heat and then transfer this heat to the working fluid. A commonly used solar collector is the flat-plate solar collector and the evacuated tube solar collector. A lot of work has been carried out in order to analyze and improve the performance of these collectors. This work presents a three-dimensional mathematical model for simulating the complete solar collector system including the evacuated tube collector and the storage tank. The flow of water inside the evacuated tube is investigated by numerical analysis. The model is based on solving the energy conservation equations. The energy equations were solved using the finite-volume method and executed using the ANSYS-Fluent software. In order to verify the numerical results, an experimental analysis was conducted. The comparison between the computed and experimental results of the fluid temperature at the collector outlet showed a satisfactory convergence.

***Keywords*— Computational Fluid Dynamics, Collector performance, Evacuated tube, Numerical Analysis, .**

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I. INTRODUCTION

Rapid increased energy prices and the continuous reduction of the Earth's conventional fuels resources as well as the growing energy needs have been the motivation for the recent growing interest in alternative sources of energy, such as solar energy. Applications range from domestic solar water heaters (SWHs) to sophisticated solar farms for power generation [1]. The world market for solar water heaters has expanded significantly over the years. Solar domestic hot water systems (SDHWS) are widely used throughout the world and a large variety of systems are commercially available. A number of investigators have made extensive studies on different aspects of SDHWS (F.O.Gaa, 1992; G.L.Morrisson and M.Behnia, 2005; Vassilis Belessiotis, 2002; V.Ruiz, 2008; S.V.Joshi and J.K.Nayak) [2].

The basic elements of SDHWS are collectors (flat plate or evacuated tubes), connecting pipes, a water storage tank, and heating elements. It has been experimentally proved that the evacuated tube solar collector based solar water heating systems perform better as compared to flat-plate solar collector particular for high temperature operations because of the reduced convection heat loss from the tubes due to the vacuum insulation. The flow in the water-in-glass evacuated tube is driven by natural circulation of the fluid between the collector and the storage tank. However , this concept can be used for a low-pressure system, as the tubes can only withstand a few meters of water head [3,4]. The initial stage of this study involved the measurement of the daily performance of a typical water-in-glass solar water heating system, and was reported by Morrison et al. (2001). The system being tested (Fig. 1) consists of two water-in-glass evacuated tube collectors (120 tubes each) connected to a 1000 LPD horizontal tank. The tubes are 1.5m long, have absorber diameter of 37mm. Potential difficulties in heat extraction from the long single ended thermosyphon absorber tubes were reported by Gaa et al. (1996) and Morrison et al. (2001). Further experimental studies were presented in Budihardjo et al. (2002).

Fig.1.ETC Solar Water Heater installed at PCCOE's Boys Hostel

The tank could be installed either above the collectors (thermosyphon systems) or in a lower level (forced circulation).Worldwide, more than 90% of all solar domestic water heating systems (SDWHS) are based on the thermosyphon principle. A domestic thermosyphon system consists of a solar thermal collector interconnected with a water storage tank through insulated piping. A density difference is created by temperature difference, and there is natural circulation of water (thermosyphon effect), in which the warm water rises and the cold water flows down, as shown in Fig.2. At low collector flow rates, a thermosyphon tank can exhibit a large degree of temperature stratification since the cold inflow mixes only with the bottom layer. However, higher mass flow rate due to drawing off hot water from the tank will induce serious disturbances of the temperature stratification, and a fully mixed tank may result. Previous studies on thermosyphon SWHs were mainly on the performance of domestic systems. However, the connection of more thermosyphon SWHs might arise in an application when considerable hot water consumption is required, resulting in higher mixing and less temperature stratification inside each tank and between tanks [5,6].

There has been extensive work on the analysis of the performance of the thermosyphon solar water heating systems (SWHS) but very little has been published about the natural convection in and out of evacuated collector tubes. As a result, majority of them have failed to accurately represent the system. In the current work, both experimental measurements and computational modeling have been used in the investigation. Numerical simulations were performed to simulate the heat transfer and fluid flow in the evacuated tubes connected to the horizontal tank using Computational Fluid Dynamics (CFD) package, FLUENT 6.

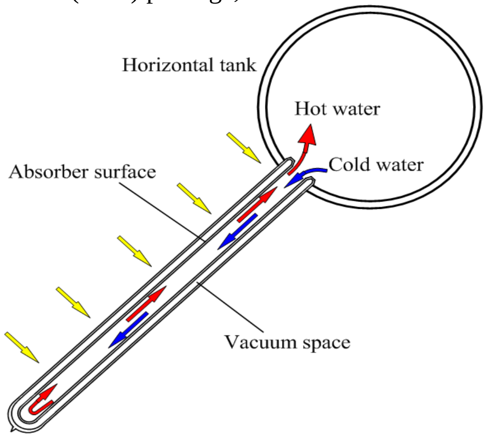

Fig.2.Natural circulation in evacuated tube solar water heater [7]

II. SYSTEM DESCRIPTION

a The solar water heating system shown in Figure 1 consists of following parts:

A. *Evacuated tubes*

The solar water heating system consists of two collectors of evacuated type. It consists of two glass tubes made from extremely strong borosilicate glass. The outer tube is transparent allowing light rays to pass through with negligible reflection. The inner tube is coated with a special selective coating (Al-N/Al) that has excellent solar radiation absorption and negligible reflection properties. The top of the two tubes are fused together and the air contained in the space between the two layers of glass is pumped out while exposing the tube to high temperatures. This "evacuation" of the gasses forms a vacuum, which is an important factor in the performance of the evacuated tubes [8]. The evacuated tube used in this system along with its cross section is shown in Figure 3. These evacuated tubes are filled with water for thermosyphon effect.

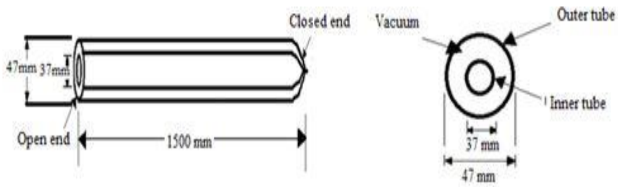

Fig. 3.Schematic diagram of one ended evacuated tube along the length and its cross-section [9].

B. *Header*

The header used in this system is shown in Figure 4. The outer body of the header and square pipe inside the header is made up of the steel. The header pipe contains thirty holes in which the evacuated tubes are attached. Open end of the evacuated tubes are fitted in these holes and the closed ends are supported by the frame.

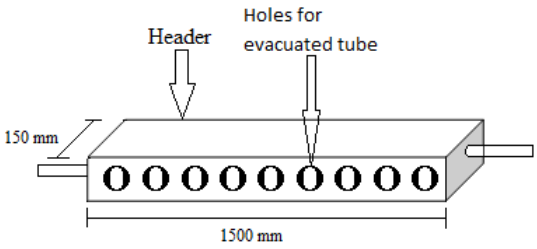

Fig.4. Schematic diagram of complete header

C. *Electric Back-up system*

The SWHS has electric backup for each individual system as shown in Figure 5. The 1000 LPD system is installed with Raccold 3 KW/ 70 Litre electric geysers for each floor bathroom block.

Fig. 5. Electrical back-up

D. *Storage tank*

The system consists of Honeywell make ETC Type 500 litre manifold (02 manifolds connected in series) with 500 litre Hot Water Storage Tank. Each 1000 litre system is independently connected to each floor of Wing A.

Fig.6. Hot water storage tank

III.EXPERIMENTAL ANALYSIS OF SWHS

In this work, the system configuration presented in Figure 7 is of particular interest and is referred to as the solar domestic hot water system (SDHWS). The system is comprised of the following major components:

- Hot water storage tank (1000 LPD)
- Evacuated solar collector
- Inlet and Outlet pipe
- Electric heater
- Stands

Fig.7. Experimental set up in PCCOE Boys Hostel

The details of the installed solar water heating system at PCCOE's Boys Hostel are as follows:
Occupancy: 197 students
Floors: 04 Floors
Life: 04 Years old installation

Table 1. Solar water heating system details

System Description	Capacity	Backup System
Honeywell Make ETC Type 500 x 02 litre Manifold with 500 Litre Hot Water Storage Tank (04 Systems)	1000 LPD	Raccold 3 KW/ 70 Litres Electric Geyser (04 Systems)

A. *System calculation*

Table 2.Electric heater calculation

1.	Electrical Geyser capacity (3 kW)	3*860 kcal= 2580 kcal/hr
2.	Electrical Geyser capacity (Assume 95%)	2580*0.95= 2451 kcal/hr
3.	Daily operation hours during winter and monsoon	2 hours
4.	Total Heat output per day	2451*2= 4902 kcal
5.	Water Heating Duty Condition (at 25^0C)	20^oC to 45^oC
6.	Max. Hot Water Output per Day	196.08 litres

7.	Electrical backup operation hours required	08 hours		@ Rs. 10.0 per unit (Rs. 24,840 per month)

Table 3.SWHS calculation

System Details	*Boys Hostel (A Wing)*	*Boys Hostel (B Wing)*
ETC Solar Make	Honeywell	Honeywell
ETC Capacity Configuration	500 x 02 = 1000 LPD (04 Nos.)	500 x 01 + 500 x 01 = 1000 LPD
Total Installed ETC Solar Capacity (LPD)	4000 LPD	1000 LPD
Electrical Back Up Heater Installed Capacity	03 kW x04 = 12 kW (Total)	02 kW x 03 = 6.0 kW 3.2 kW x 03 =9.6 kW Total = 15.6 kW
Electric Back Up Heater Operation	During monsoon and winter season 02 hours per day, 3 kW typical water heater can generate max. 65.6 litres hot water for 02 hours operation	
Electrical Back Up Heater Installed Capacity (LPD)	787 LPD	1023 LPD
Occupancy	149 Students	48 Students
Required Hot Water Capacity @ 25 ltr /45^{o}C per person	3725 Ltrs.	1200 Ltrs.
Electric Energy Saving Potential	Current system capacity shortfall approximately 60% will be taken care by modified system without additional electric consumption, saving equivalent of 82.0 kW per day	

B. *Observations*

Based on above mentioned site survey data, we can see shortfall in hot water capacity for most of the locations of Boys Hostel. As per MNRE guidelines, hot water system is designed on basis of 25 litres at 60 ^{o}C or 40 litres at 40 ^{o}C per person. We feel current system capacity needs to be increased by 5225-4000 = 1225 litres. Solar water heater is extremely efficient during summer but hot water requirement is little or none. During monsoon, solar water heater output is subjected to weather conditions and 3 kW typical water heaters can generate maximum of 65.6 litres hot water for 02 hours operation. Considering active monsoon and prolonged winter, electrical back up heater is active during both seasons. However, expected hot water output is still not guaranteed at cost of expensive electrical energy.

IV. NUMERICAL ANALYSIS OF SWHS

The objective of the present work is to numerically analyze the performance of the thermosyphon evacuated tube solar collector for solar water heating application. There are many numerical methods that can be used to solve fluid flow and heat transfer problems. These include finite element, finite difference, control volume, and the boundary element. The main goal of all these numerical methods is to transfer the complicated differential equations that govern the flow and heat transfer and which are not possible to solve analytically, into simple algebraic equations and are solved using the power of computers. These methods are called computational fluid dynamics, CFD. This chapter presents the mathematical equations that must be solved.

A. *The Governing Equations*

To evaluate the thermal performance of the indirect heating integrated collector storage solar water heating system, the velocity, temperature and pressure of the fluids involved in the system need to be evaluated. These fluids are water (in the storage tank and the service water in the pipe). The equations that govern the fluid flow and heat transfer are the continuity, momentum and energy equations. The equations for unsteady, turbulent and incompressible flow are presented below.

- The Continuity Equation [10]

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0$$

- The Momentum Equation [10]

In x-direction:

$$\frac{\partial(\rho u)}{\partial t} + \mathrm{div}(\rho u U) = -\frac{\partial p}{\partial x} + \mathrm{div}(\mu\ \mathrm{grad} u) + \left(-\frac{\partial(\rho u^2)}{\partial x} - \frac{\partial(\rho uv)}{\partial y} - \frac{\partial(\rho uw)}{\partial z}\right) + f(x)$$

In y-direction:

$$\frac{\partial(\rho v)}{\partial t} + \mathrm{div}(\rho v U) = -\frac{\partial p}{\partial x} + \mathrm{div}(\mu\ \mathrm{grad} v) + \left(-\frac{\partial(\rho uv)}{\partial x} - \frac{\partial(\rho v^2)}{\partial y} - \frac{\partial(\rho vw)}{\partial z}\right) + f(y)$$

In z-direction:

$$\frac{\partial(\rho w)}{\partial t} + \mathrm{div}(\rho w U) = -\frac{\partial p}{\partial x} + \mathrm{div}(\mu\ \mathrm{grad} w) + \left(-\frac{\partial(\rho uw)}{\partial x} - \frac{\partial(\rho vw)}{\partial y} - \frac{\partial(\rho w^2)}{\partial z}\right) + f(z)$$

- The Energy Equation [10]

$$\frac{\partial T}{\partial t} + \frac{\partial(VT)}{\partial x} = \frac{\partial}{\partial x}\left(\frac{\nu}{Pr}\frac{\partial T}{\partial x} - uT\right)$$

where;
u ,v and w = Fluctuating component of velocities.
f(x), f(y) and f(z) = Body forces in the direction of x, y and z direction.
p = Fluid pressure.
uT = Turbulent Heat flux.
Pr = Turbulent Prandlt number
ν= Fluid kinematic viscosity.

B. *Numerical model*

3D CFD models for the absorber with the double glass cover are developed to evaluate the radiation and convection losses. The geometry is generated using ANSYS 14.0-Workbench.

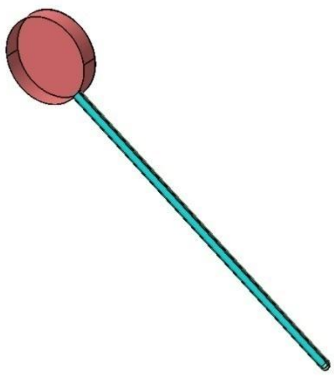

Fig.8. Cross section of Evacuated tube

The above geometry of the evacuated tube was generated using ISO9459-2 (1994).

The geometrical characteristics of the evacuated tube model are as follows:
Tank diameter = 350 mm
Tank width = 150 mm
Outer glass tube diameter = 47 mm
Inner glass tube diameter = 37 mm
Length of the absorber surface = 1500 mm
Inclination = 45^o

C. *Meshing*

Different models have been designed and the corresponding computational domains were meshed with grid fine enough to reach a mesh-independent solution.

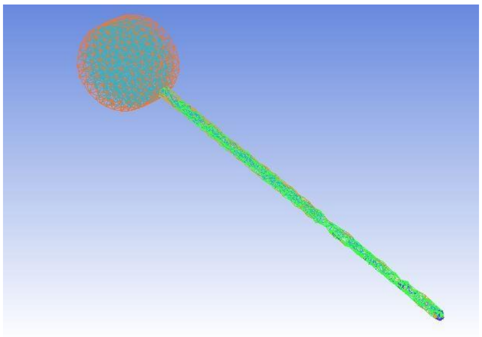

Fig.9. Mesh generation in evacuated tube collector

Note: A detailed investigation of the conditions prevailing at the boundaries of the computational domains is to be carried out, especially for the heat transfer mechanism.

V.RESULT & DISCUSSION

As per performance study conducted on 22nd April, 2015, following factors contributed towards solar water heater inefficient operation,

1. During summer season ETC Solar Water Heater can attain 59 ^oC temperatures around 14:00, there is possibility to achieve more thermal output with same set of ETC modules.
2. Damaged tubes 06 Nos. 1.25 % needs to be replaced.
3. Lost performance due to dirt/dust deposition on the exterior surface of ETC tubes equal to 3.89 %.
4. Building parapet wall and hot water storage tank shadow effect – 11.9% panels to be reposition to maximize solar exposure.

VI.CONCLUSION

Referring to above mentioned facts and calculations , we can conclude existing hot water system is consuming minimum 24 units of electricity, however calculation is indicating back up heater cannot provide hot water more than 266 litre per electric geyser which is sufficient for maximum 14 students. There is capacity shortfall for 38 students (equivalent of 760 litres).

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