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Theoretical Analysis of Performance of Concentric Glass Tube Solar Air Collector Connected in Series

Vishal Dabra*
Mechanical Engineering Department
Panipat Institute of Engineering & Technology (P.I.E.T.), Haryana, INDIA
*Corresponding author. Tel.:+919416259010,
E-mail address: vishaldabra16787@gmail.com

Ranjan Choudhary
Mechanical Engineering Department
P.I.E.T., Haryana, INDIA

Rajinder Kumar
Mechanical Engineering Department
P.I.E.T., Haryana, INDIA

Abstract— This research work aims to provide warm air for household and industrial applications of the temperature as high as 65 °C. Total 12 concentric glass tubes are connected in series, allowing air to pass through them on after the other and gradually raising the temperature of the air. To assess the collector's thermal performance under stable working conditions, an experimental investigation was carried out for validation of theoretical data.
The findings reflect that in the low to moderate temperature range, the CTSAC performs exceptionally well thermally. At 50°C for the exit air, the measured thermal efficiency is 0.55. The thermal efficiency changes with air temperature, reaching 0.45 at 40°C and increasing to 0.68 at 62°C. These findings prove that the suggested CTSAC is an extremely effective solar air heating system appropriate for uses needing a medium-temperature air supply.

Keywords: Collector; Concentric; Efficiency; Series; Solar

I. INTRODUCTION

The role of energy resources in the progress of a Nation from developing to develop Nation is very crucial. It is the prime resource and primary need to live our daily life on the earth [1-2]. The maximum energy is obtained from the conventional resources but they are limited and will be depleted after few years. Use of conventional resources may lead to pollute the earth's climate, but also threats to human life [3].
To fulfill the upcoming energy needs, the role of replacement of conventional resources is very crucial. Out of different energy resources, solar energy is best alternative for replacing the conventional resources. It has been broadly used in several domestic and commercial purposes to overcome the future energy crisis [4-5]. Solar energy is a clean and abundant source of energy available on the earth. The potential of this energy directly depends on the climatic conditions, position of sun and wind speed etc.
Solar energy is converted into useful energy by means of device which is commonly known as "collector". They are mainly classified into two major types on the basis of heat carrying medium. This may be liquid or gas, depending upon the applications which solar collector is installed and used.

Solar air collectors (SACs) are extensively used collector because of their design simplicity. They are used in numerous applications of low and reasonable temperature requirements [6]. Generally, they have low thermal efficiency due to low heat interaction between the absorber surface and flowing air. The overall performance of SAC could improve by aggregating the value of convective heat transfer coefficients and reducing the heat losses to the environment. The influence of several factors like absorber material, absorber surface roughness, absorber surface area, tilt angle, collector design, mass flow rate and environmental conditions on the performance of SAC was studied and evaluated the performance of a SAC by using basics of 1st and 2nd law of thermodynamic by means of energy and exergy analysis. By changing the design specification and working operation, such as the collector surface area and mass flow rate etc. could help to improve the performance of SAC [7-8]. The thermal performance of SACs has been maximizing by improving the quality of absorber surface and artificial roughness can significantly enhance the fluid circulation and heat carrying ability. Also, different types of roughness modes were discussed in previous studies [9]. Previous works different types of fins and ribs were shown to enhance the performance of SACs. Fins and ribs were provided in smooth passages in to improve the heat transfer coefficient and technically durability [10]. The performance of a twin pass finned SAC was studied and analyzed [11]. Shah and Furbo [12] investigated the collector with parallel-connected evacuated double glass tubes [12]. EVT based solar collector integrated with parabolic concentrator was designed and reported the significant increase in the performance of the EVT solar collector [13]. In winter season, the highest exit air temperature reached at 170°C. Latent storage energy based SAC was studied and optimized [14]. The day-to-day energy efficiency varied between thirty two percent and forty five percent. The heater provides steady heat flow during the energy releasing process. Besides, SAC can also be worked as a cooling system [15]. More collector area helps to increase the performance of the collector with maximize the investment in the capital cost of the SAC. Likewise, at highest mass flow rate helps to improve the performance and diminish the process air temperature [16]. Dual end open evacuated tube based collector could overcome

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the shortcoming of one end open evacuated tube based collector and obtained better thermal performance because of the direct contact between the working fluid and the absorber surface [17].

In the literature, many researchers focused on improving the performance of SAC by using geometrical and parametric variations. But still there are few existing problems need to be resolved for getting best performance of SAC. In case of flat plate SACs, the direct heat exchange between the air and the absorber leads to a poor thermal efficiency and an irregular heat exchange. In case of evacuated tube based SACs, the pressure drop increases due to their complex structure. In this research work, the performance analysis of CTSAC was reported and their feasibility was checked and tested. For that a mathematical model was developed in computer programming language for solving four coupled equations. Computer program in JAVA script was initiated to obtain the results. It is novel approach to analyze the CGT connected in series and checked out the feasibility of CTSAC.

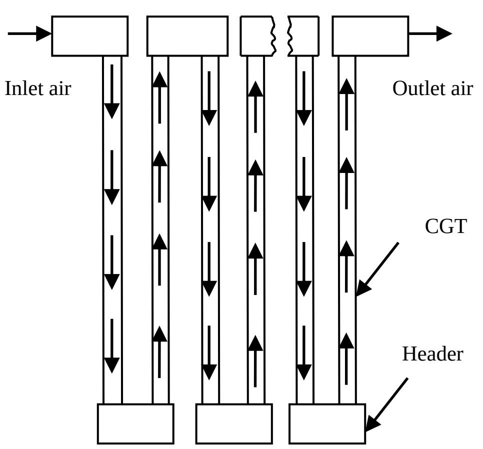

Figure1. Schematic diagram of CTSAC

II. MATHEMATICAL MODEL

For development of mathematical model, A CGT is considered which is basically made up of two glass tubes of different diameters with atmospheric air in vacant space between tubes and a black paint layer on the external surface of the inner tube. CGT is open at both end and inserted in the headers. The air flows inside the tube become warm after absorbing heat than warm air enters to the succeeding tube as inlet air.

The objective of a CTSAC is to raise the temperature of flowing air by the absorption of thermal energy converting from solar radiation. The highest exit air temperature can be determined by the geometry, atmospheric conditions, the inlet air temperature, and mass flow rate. To fix the operating conditions and number CGT connected in series are used to further raise the temperature of the flowing air. Such an arrangement of CGT reaches a point where increase in the number of CGT, raise in temperature does not justify the investment. So, design point of view, it is convenient to limit the numbers of CGT. In case of a series arrangement, the outlet temperature form the first tube is used as the inlet temperature for the second tube and so on as shown in Figure 1.

The following assumptions are made to develop a mathematical model of CTSAC:

1. Atmospheric air is taken as working fluid.
2. No leakage of air.
3. Operate under steady state condition.
4. Uniform cross-sectional area of flow.
5. Uniform air flow inside the CGT.
6. The temperature varies only along the length of CGT.
7. Neglect the temperature gradient in radial direction.
8. Uniform and constant coefficients of heat transfer.
9. Uniform solar radiation impinges on the CGT

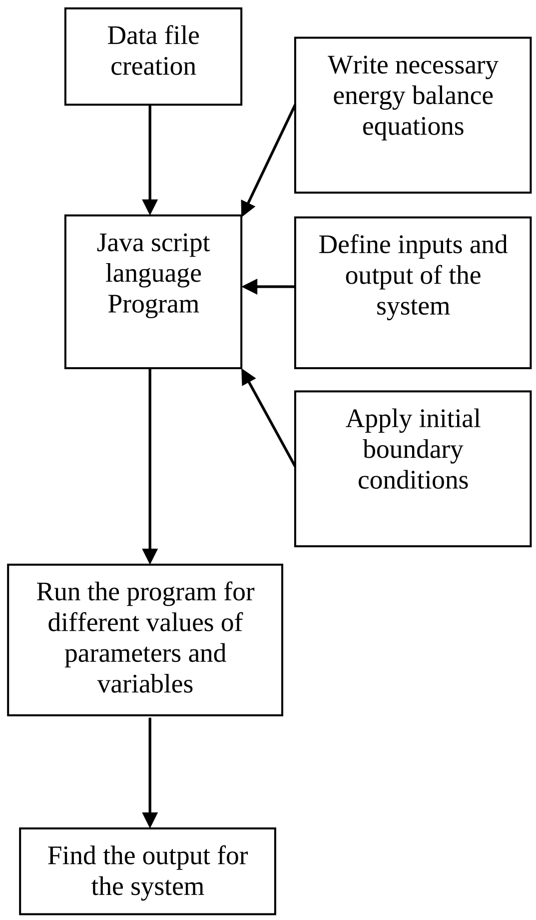

Figure 2. Flow chart of Java program for CTSAC

The following equations of conversation of energy for each component of CTSAC:

1.2.1 For transparent glazing

$$\alpha_1 \theta_1^4 + \beta_1 \theta_1 + \gamma_1 \theta_2^4 + \delta_1 \theta_2 + g_1 = 0 \qquad (1)$$

1.2.2 For absorber coating

$$\alpha_2 \theta_1^4 + \beta_2 \theta_1 + \gamma_2 \theta_2^4 + \delta_2 \theta_2 + \tau_2 \theta_3 + g_2 = 0 \qquad (2)$$

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1.2.3 For glass absorber tube

$$\delta_3\theta_2 + \tau_3\theta_3 + \epsilon_3\theta_4 = 0 \quad (3)$$

1.2.4 Heat transfer fluid

$$\frac{d\theta_4}{dx} = h_4(\theta_3 - \theta_4) \quad (4)$$

Where, θ_1, θ_2, θ_3 and θ_4 are temperatures of components of CGT. These temperatures are function of CGT length and α_i, β_i, γ_i, δ_i, τ_i, ϵ_i, g_i and h_i where i=1,2,...........4.
A computer program in JAVA script has been developed and advance numerical methods based solution is executed. The flow diagram of computer program is described in Figure 2. Through this program, above discussed equations are solved and results are obtained.

III. RESULTS AND DISCUSSION

The result and discussion about the CGTs connecting series are elaborated below for most selecting cases.
Deviation of exit air temperature difference by varying the number of CGTs (1-12) connected in series for air mass flow rates of 0.0053kg/sec, 0.0074kg/sec, 0.0095 kg/sec and 0.0118kg/sec, are shown in figure 3. This shows that for mass flow rate 0.0053kg/sec, 0.0074kg/sec, 0.0095 kg/sec and 0.0118kg/sec the exit air temperature difference increases from 28.3°C to 82.9°C, 22.7°C to 81.7°C , 18.9°C to 79.9°C and 16.1°C to 77.4°C, respectively, as the number of CGT increases from 1 to12.

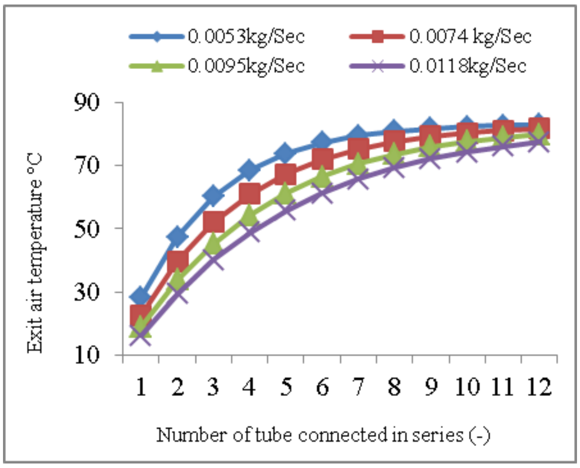

Figure 3. Deviation of exit air temperature difference by varying the number of CGT connected in series at different mass flow rate

Figure 3 shows that when the air mass flow rate increases, the exit air temperature difference diminishes. This is due to the resistive time of the air inside the CGT decreases as the mass flow rate increases, which causes the temperature increment to decrease. Additionally, figure 3 illustrates how the temperature differential increases quickly up to eight CGTs connected in series, after which it increases to extremely modest values before becoming nearly constant. This is because there was initially a significant temperature differential between the air and the absorber surface, and as that difference decreased, the air flow direction decreased.

This is because when using this curve, mass flow rates and the number of CGTs can be fixed for a desired exit air temperature difference. When developing a CTSAC for a specific capacity, this is helpful.

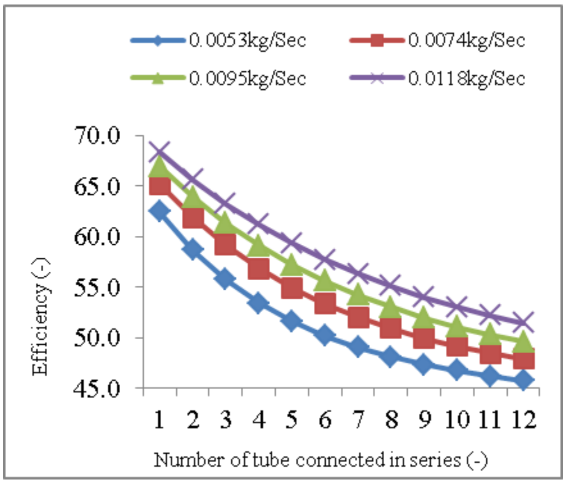

Figure 4. Deviation of efficiency of CTSAC *by varying the number of CGT connected in series at different mass flow rate*

Deviation of efficiency of CTSAC by varying the number of CGTs (1-12) connected in series for air mass flow rates of 0.0053kg/sec, 0.0074kg/sec, 0.0095 kg/sec and 0.0118kg/sec, are shown in figure 4. This shows that for mass flow rate 0.0053kg/sec, 0.0074kg/sec, 0.0095kg/sec and 0.0118kg/sec the efficiency decreases from 62.5% to 45.8% , 65.1% to 47.9%, 66.9% to 49.6% and 68.3% to 51.4%, respectively, as the number of CGT increases from 1 to12. It is observed from the figure 4 efficiency of CTSAC rises with increase in air flow rate. This shows that the series arrangement of CGTs can improve the efficiency of CTSAC. Air passes through the CGTs and is progressively heated in each tube. Exit of one tube is inlet of next tube. This arise the condition that the inlet temperature of the air is increased to the next tube.

With increase in the mass flow rate, the resistant time of the air inside the CGT decreases. This is due to decrease in the temperature enhancement of flowing air. Figure1 also show that the temperature difference increases at rapid rate upto 8 CGTs are arranged in series but after that temperature difference increases very small values then almost constant. This is because of initially the temperature difference between the air and absorber surface is large and decrease in the direction of flow of air due to decrease in temperature difference between the air and absorber surface. CTSAC is designed to provide high temperature air for various domestic and industrial processes.

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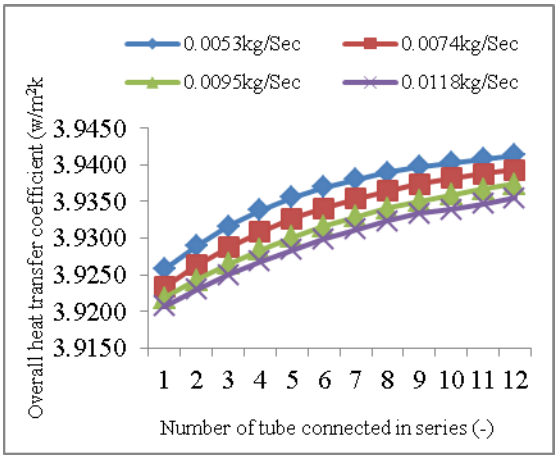

Figure 5. Deviation of overall heat loss coefficient of CTSAC *by varying the number of CGT connected in series at different mass flow rate*

Figure 5 displays the deviation of the CTSAC's overall heat loss coefficient (U_L) when number of CGT increases. As observed from figure 5, the U_L is not linearly related to the temperature of the absorber coating and its surroundings. The value of U_L reaches to 1.23 when the surrounding temperature is 303 K and the temperature difference between the absorbing coating and surrounding is 110 K. At different surrounding temperature, the expression of the U_L is different.

IV. CONCLUSIONS

On the basis of various parameters of CTSAC were presented in this theoretical study. The findings show that in the low to moderate temperature range, the CTSAC performs exceptionally well thermally. At 50°C for the exit air, the measured thermal efficiency is 0.55. The thermal efficiency changes with air temperature, reaching 0.45 at 40°C and increasing to 0.68 at 62°C. These findings show that the suggested CTSAC is an extremely effective solar air heating system appropriate for uses needing a medium-temperature air supply.

V. CONFLICT OF INTEREST

The authors have no conflict of interest.

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