Journal of
Fundamentals of Renewable Energy
and Applications

Rahman et al., J Fundam Renewable Energy Appl 2018, 8:1
DOI: 10.4172/2090-4541.1000253

Review Article Open Access

Experimental and Numerical Analysis of a Stand-Alone PV/T System to Improve its Efficiency

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Abstract

A lot of re-usable thermal energy within industrial processes is emitted into the environment every year in the world as energy waste. The aim of this paper was to study the estimating of maximal available heat flow rate using different temperature driving forces by a mathematical surface technique. This technique is based on the usage of pinch analysis principles. The maximal available heat flow rate with different temperature driving forces can be calculated by using a trapezoid surface area within a grand composite curve. This technique can be applied by upgrading large quantities of available heat for steam or electricity generation within industrial processes. The research idea, which is presented using a mathematical surface technique, is founded on increasing the available heat flow rate with different temperature driving forces by using the excess and available heat flow rates regarding waste streams. This technique was tested on an existing formaldehyde process that allows for efficient and additional steam production of 1.2% with a higher outlet temperature for steam generation.

Keywords: Flat plate collector; PV panel; ANSYS simulation; Concave lens

Introduction

The PV/T system is one of the promising ways to extract solar energy from the sunlight. Solar air and water heating system is used mainly for tap water heating (39%), residential air heating (45%), solar cooling (7%), industrial heating (6%), drying (3%) and pool heating (0.2%) [1-4]. Since solar energy is the most plight form of clean energies, development of new technologies to enhance the solar system efficiency is the main concern now a day. To improve that efficiency; elemental analysis of solar system and theoretical efficiency calculation is the new era for solar scientists.

In all solar hybrid system the electricity is generated from the PV panel as well as a heating fluid is passed above the collector plate to extract heat from collector also gives the thermal performance of the system. The flat plate heaters can absorb both direct and diffuse solar radiation while the concentrating heaters in the main can absorb only direct solar radiation The flat plat solar collector, its heat flow paths, way of losses have been reported, Fabio Struckmann [5]. In which the reflection (10%) and absorption (5%) loss of glass cover and the collector plate reflection (5%) loss etc. are shown. So heat absorbed by the collector is 80%. But most of which i.e., about 45% heat is lost to surrounding due to poor insulation. So, most solar collectors have maximum thermal efficiency which is around 35%. By proper designing if any of these factors is minimized then higher thermal efficiency is obtained.

The efficiencies for varying mass flow rate have been reported by Omjara APO et al. where they depicts that the efficiency increases with increasing mass flow rate where external electrical source is needed [6]. So in order to make a self-sufficient system some solar panels are required to combine with collector system. These panels provide electricity to the blower to flow air through the collector. Heating of both air and water simultaneously with electricity have been offered a complicated design but gives maximum efficiency 65% which required expensive transparent cell [7,8]. Saleh AM represents the mathematical expression to determine air gap between the absorber and the cover. He also determined the equations for glass plate thickness, absorber thickness, insulation thickness, heat transferred by the working fluid and other heat transfer co-relations in his thesis report [9]. Alfegi EMA et al. worked on transient mathematical model of both side single pass and double pass photovoltaic thermal air collector. They found that the efficiency of combined photovoltaic thermal system is increasing from 26.6% to 39.13% as the mass flow rate varies from 0.0316 to 0.09 kg/s [10].

The case study of grid connected PV System at Northern Part of Bangladesh gave the average value of solar intensity for every month of a year. In which it was mentioned that the solar intensity is the lowest at December [11]. M Srinivas and S Jayaraj gave different curves of cell efficiency vs. temperature where they show that the cell efficiency decreases with increase in temperature. They also indicated that the thermal efficiency of a PV/T dual fluid collector with metal absorber was nearly 80%, and electrical performance of the system was satisfactory, and still scope for further improvement of cooling the photovoltaic panels was noted [12]. A numerous number of research work was done on the elemental and thermal analysis of flat plate solar air heater to know its fluid flow behavior, heat transfer phenomenon, effects of radiation and other variables [13-16]. The simulation of a concentrated solar receiver was studied by Islam MRI et al. in where the comparison of efficiency and temperature ratio were done between the experimental and numerical observation [17]. The flow behavior and the thermal characteristics along the length of the collector was studied by Khelifa A et al. [18] where the RNG k-epsilon and discrete orientation (DO) were recommended as the flow model and radiation model respectively. The comparative analysis between numerical and experimental observation of outlet temperature and thermal efficiency

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Received January 15, 2018; **Accepted** January 31, 2018; **Published** February 08, 2018

Citation: Rahman MS, Sarker MRI, Mandal S, Beg MRA (2018) Experimental and Numerical Analysis of a Stand-Alone PV/T System to Improve its Efficiency. J Fundam Renewable Energy Appl 8: 253. doi:10.4172/20904541.1000253

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of a flat plate collector was observed by Manilal KM [19].

This work presents a noble concept of PV/T system to utilize optimum solar irradiation exposing more collector area on the sunlight. This system emphasizes to place the solar panel at a different rack whereas all previous workers had placed the PV panel above the collector plate for hybrid PV/T system. Concave lens are used for lightening the PV panel which are placed at the same surface of the collector and takes very little area on the collector plate rather than placing of PV panel directly. In this system two major benefits are depicted clearly one of them is the more heating effect due to more collector area utilization and another is the improvement of PV panel efficiency by placing it at a sufficient temperature condition. A simulation work was also done for the thermal system of entire model which gives competitive results with the experimental one. Influences of other variables on thermal performance were also conducted including mass flow rate, flow behavior, temperature distribution etc.

Solar PV/T Concept

Design of photovoltaic-thermal collector

In all traditional photovoltaic thermal system, the PV panel is placed above the collector plate [1,4-9] where the panel covers an estimated area of absorber plate causes the reduction of heating effect due to radiation absorption. Whereas the present concept assure the maximum area of solar collector exposed to the sunlight that provides comparatively more heating effect to produce hot air.

In this system the main modification is done by replacing the solar panels from the collector surface by concave lens shown in Figure 1. In modified design the solar panels are placed on a separate rack. Due to small lens area instead of PV panel, more collector surface is exposed to sun light produces more heating effect which is estimated by balancing the energy of traditional design and current designed solar air heater. By balancing the absorption energy with estimated additional collector surface area it is calculated that up to 20% overall efficiency improvement is achieved if proper lightening of cell can be made possible.

Measuring distance between upper and lower racks

Since the lenses are placed at collector plane and the panels are placed at a rack below the collector plate, the light refracted through the lens and fall on the panel. So, in order to proper lighting of panel, the lenses are placed at a specific point which is measured by follows:

The lens dimensions are 7.5 × 5.75 cm²

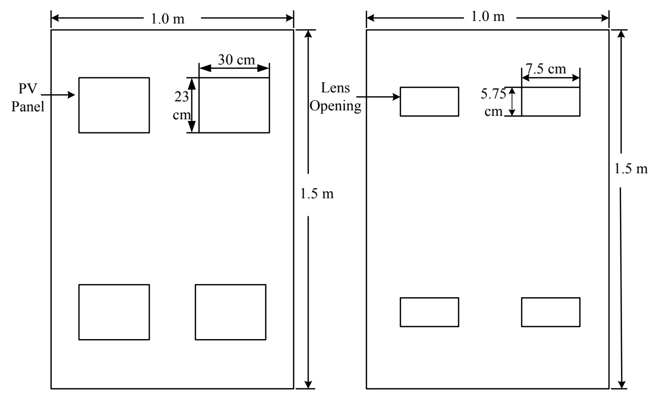

Figure 1: Top view of setup with PV panel and with lens at the collector surface.

The panel dimensions are 30 × 23 cm²

So, from Figure 2, if focal length of the lens, C_f =15 cm

Then, angle θ=tan^{-1} (3.75/15=14.0362)

So, by similar triangle method,

The distance, A_f=(AB/tanθ)

=(15/tan14.03)

=60 cm

Then, the distance between the lens and the solar panel,

$$AC = A_f - C_f$$

=60-15=45 cm

So, in order to proper lighting, the lens should be placed at 45 cm height from the panel.

The solar air heater of modified setup has been designed which is shown in Figure 3. The materials used for the design are mainly: Wooden box: (1.5 × 1 × 0.12) m³=1 piece, Glass: (1.46 × 0.96 × 0.005) m³=1 piece, Aluminum plate: (1.5 × 1 × 0.001) m³=1 piece, Concave lens : (0.075 × 0.0575) m²=4 piece, Solar cell: (0.30×0.23) m²=4 piece, Black paint: 1.5 kg, Stand: Angle bar, Cork board: (0.5 inch thick)=2 piece. Area: 1m², others: Wood, screw, brush, gum etc.

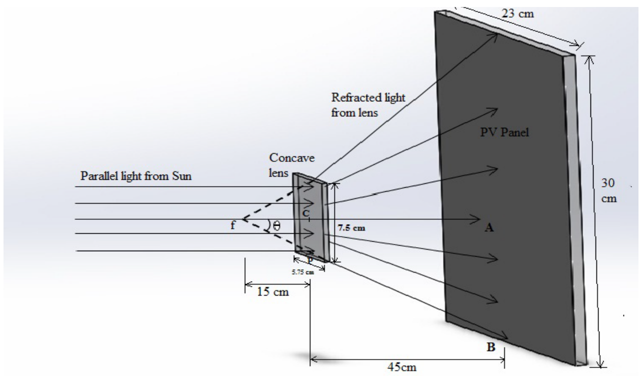

Figure 2: Ray diagram to measure distance between lens and solar panel.

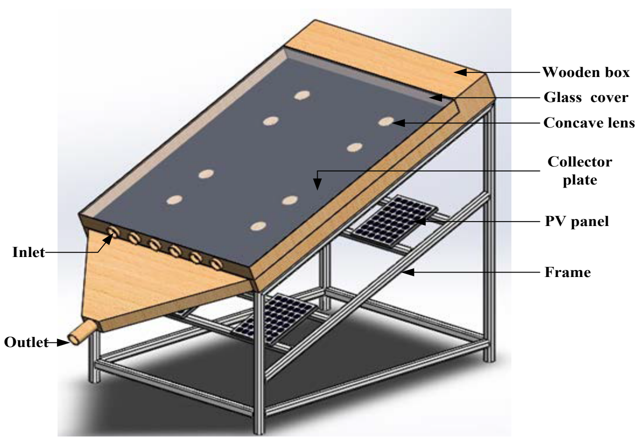

Figure 3: Isometric view of solar air heater with PV panel.

Experimental Setup

At first, a wooden box is made whose base is covered by partex of 1.5 m². The box is sufficiently rigid to take the load of cover glass, collector sheet and other arrangements [8,9]. After making the box, the stand is made by angle bar according to the size of the box. In stand, there are two racks that are made to support air heater box and solar panel. Then the box is covered by insulator for which cork sheet of 3 in is used and four opening are cut to pass light through it from lens to the panel which is closed by transparent glass. Next, the G.P. sheet is coated by black paint in order to make it a good radiation absorber and 8 small holes are made to set lens at that opening. After drying the paint, the lens are placed on the sheet opening and adjusted by pudding. Then, this collector sheet with lens is set on the box and total arrangement is covered by transparent glass. After preparing the box, a convergent section is adjusted with the box which contains both the inlet & exit port for the flowing of air. The exit port also contains the arrangement to hold the blower (Figure 4).

Finally, the box with the convergent section is set on the frame and the solar panels are set on the lower rack according to the lens and the opening of the box. The total system is made at a 23° inclined angle to receive solar radiation to the normal plane with the collector plate.

Performance Evaluation

Air inlet and outlet temperatures were measured by using thermometer. From thermometer, those data are directly noted to data table with the help of anemometer. The velocity of flow is measured directly from the outlet of the heater [10]. For measuring mass flow rate, the anemometer propeller was placed at the outlet of the blower. The velocity was measured for several times and finally the average velocity was fixed to take reading. The known outlet area was used to calculate mass flow rates according to the formula $\rho = m / v$ (where, $\rho =$ density of air, A=cross sectional area, v=velocity of air). A rate of mass flow was fixed for a particular day. The velocity was adjusted to keep the mass flow rate constant, since the density of air changes with changes in temperature.

The current and voltage was measured by multi-meter directly. To get the voltage reading the multi-meter is calibrated to voltage part and circuit is connected to voltage knob. Similarly, to get current reading the multi-meter is calibrated to current part and circuit is connected to current knob. From multi-meter those data are directly used to calculate efficiencies. The current and voltage are also measured by changing the circuit in series and parallel. The readings were taken at various intervals (15 min, 30 min or 60 min). The top of the heater was not always placed normal to the sun because the tilt angle of sun varies from time to time but our heater tilt angle is kept constant. The day which gives intensity of irregular value was neglected from investigation [11].

Computational Model

A CFD model was developed to analysis the flow behavior and thermal analysis of the solar air heater. The geometry of the modeled solar air heater is shown in Figure 5. In that air heater an aluminum plate with black coating is used as collector absorber plate. The receiver coating had 2 mm thickness with 1.5 m^2 rediated area exposed to sunlight. A glass of 4 mm thickness was used as transparent cover which is placed at 10 cm above the absorber plate to entrapped radiation within the heater box. A small DC blower is used to flow the air throughout the setup with different flow rate. The inlet and outlet were placed at the same side. ANSYS 15 software is used for this simulation. Particularly the thermal side of total setup is studied by the simulation. The setup was designed by ANSYS design modeler. Hence, the mashing hexahedral mesh grid was done precisely with 103683 numbers of nodes as shown in Figure 5. The grid independence test was also done to get the sufficient number of cells which validate with 561101 numbers of cells. The convergence criterion was set at 10^{-5} for all the variables and 50000 iteration was done to get full convergency.

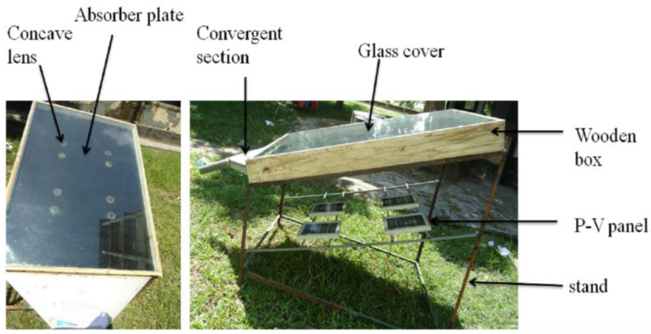

Figure 4: Final assembly of solar air heater.

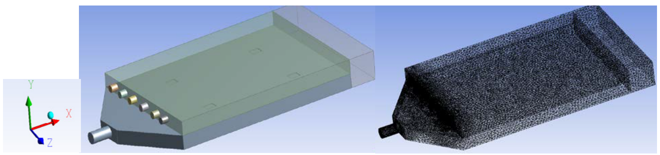

Figure 5: Double pass solar air heater with adopted mess.

Steady state RNG $k-\varepsilon$ Turbulence model used as flow model, the viscous heating was also used to get temperature dependent viscosity by the combination of energy and momentum. The turbulent $k-\varepsilon$ provides the analytical formula for the turbulent prandtl number whereas the standard $k-\varepsilon$ model provides constant value of prandtl number. So, RNG $k-\varepsilon$ model expected to provide better performance for double pass flow and boundary layer.

Results and Discussion

Thermal performance of solar air heater

The thermal performance of solar air heater was investigated with different working condition also with different mass flow rate. The velocity vector represents the flow distribution and the temperature contour shows the temperature distribution at the lower channel and above the collector plate. From Figure 6, it is seen that the flow distribution is not properly uniform throughout the absorber plate as result of pressure fluctuation and viscous effect. A vortex type lopsided flow is shown where the more air flow through one side of absorber plate then another side. This vortex type flow is able to increase the heat transfer phenomenon with the increasing force convection heat transfer co-efficient.

The temperature distribution above the absorber plate and the surface below the absorber plate is shown in Figure 7 respectively. The temperature above the collector plate is distributed by maintaining an inverse relation with the air flow rate, i.e., the highly heated zone is found at negligible air flow region of the collector plate. But that temperature distribution does not affects the efficiency of solar air heater which can be concluded from the temperature distribution of

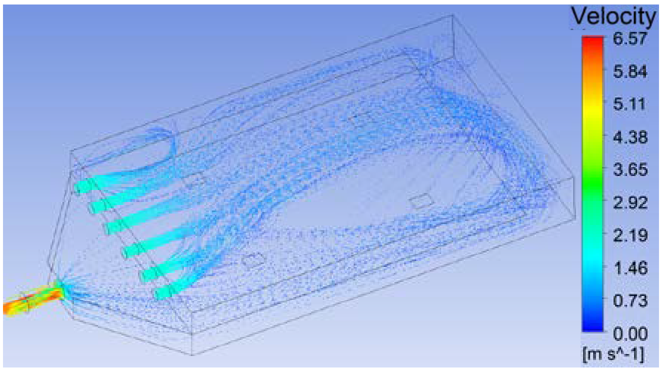

Figure 6: Velocity vector of flowing fluid within the double pass solar air heater.

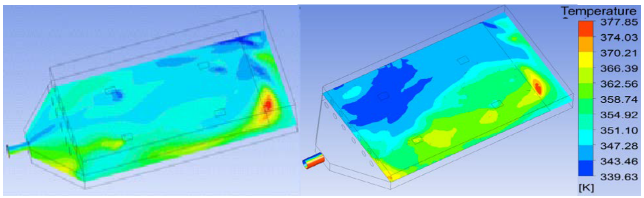

Figure 7: Temperature distribution on the surface plane below and above the collector plate of double pass solar air heater.

lower surface of collector plate. The unevenly heated air is mixed when passes from upper to lower channel that results a uniformly heated air at the lower portion of collector plate as shown in Figure 7. Uniformly distributed and maximum temperature of output air is often extracted from the system as well.

The double pass solar air heater combined with photovoltaic panel by concave lens is investigated experimentally under Rajshahi weather condition. The readings are taken at the bright sunshine day. The performance of double pass solar air heater is studied. The mass flow rate is varied from 0.0012 kg/s to 0.02816 kg/s. where the intermediate mass flow rates are 0.016 kg/s, 0.0181 kg/s, and 0.02112 kg/s (Figures 8 and 9).

From Figure 8, it is seen that the collector efficiency slightly increases with the day time. In 1st and 2nd day, the collector gives lower efficiency due to lower flow rate, running and leakage problem. By overcoming the leakage problem and by increasing the mass flow rate, the maximum efficiency of 55.3% is obtained at day-5. For a single day the efficiency is varied due to the solar intensity variation on the collector plate.

From Figure 9, it is observed that, the cell efficiency is also independent of day time but the efficiency varies slightly due to incident angle of light to the lens. The maximum efficiency is obtained when the solar ray is approached to perpendicular with the concave lens. The cell efficiency varies from 4.38% to 5.85%. The day time and mass flow rate have very little effect on cell efficiency but with increasing the total radiated surface of panel causes the efficiency improvement (Figure 10).

From Figure 5, it is obtained that the effect of cell efficiency is very low on overall efficiency because the cell produce maximum power 4.26 watt with 5.85% efficiency but the collector produce the maximum power 880.09 watt with 55.3% efficiency. So, in order to get maximum overall efficiency, more concentration is given to increase the collector area. By sacrificing small amount of cell power, a large collector power

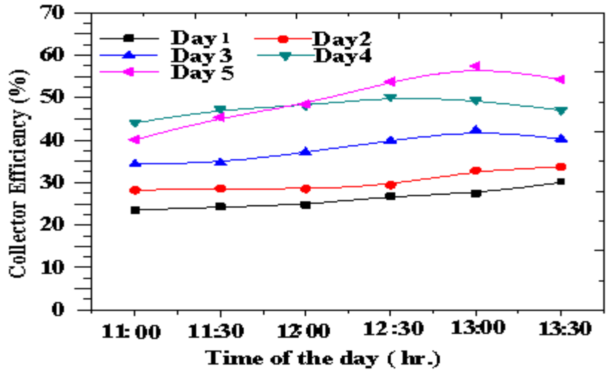

Figure 8: Time of the day vs. collector efficiency curve.

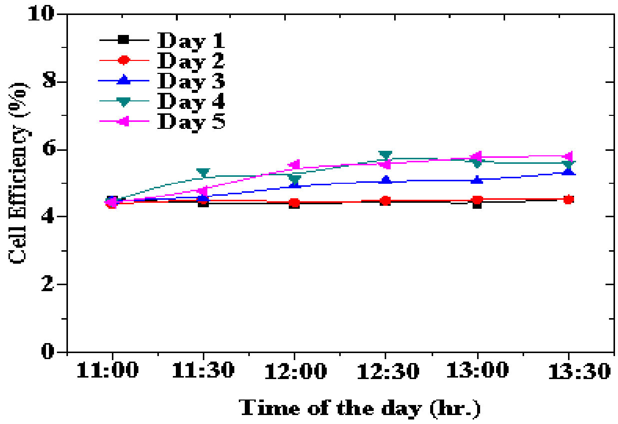

Figure 9: Time of the day vs. cell efficiency curve.

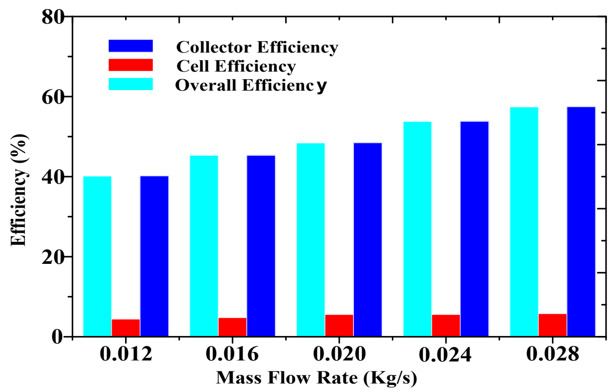

Figure 10: Effect of cell efficiency on overall efficiency.

can be achieved for which the overall efficiency of this system is too higher (Figure 11).

Effect of mass flow rate

From Figure 11 it is clear that the collector temperature is decreased with the increase of flow rate. The high flow rate of air takes more heat from the collector plate. The collector plate had the normal temperature of 350°C at the entering point of the air. Hence, the temperature gradually increased to 409°C and 372°C for the mass flow rate of 0.028

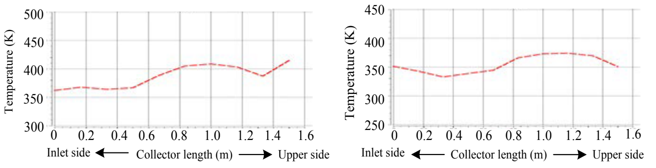

Figure 11: Temperature distribution above the absorber plate for lower and higher mass flow rate.

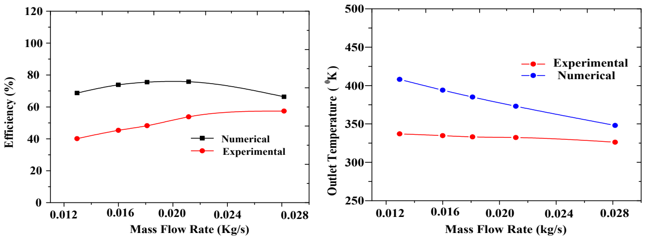

Figure 12: Variation of efficiency and outlet temperature due to mass flow rate.

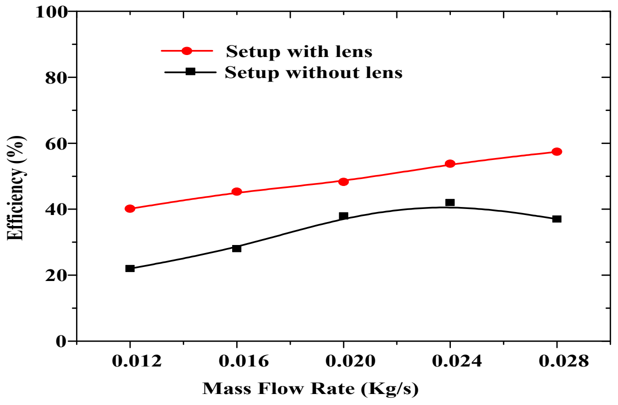

Figure 13: Comparison curve of mass flow rate vs. overall efficiency.

kg/sec and 0.012 kg/sec respectively. The air above the collector takes the largest amount of heat at the point of entering then the air decreases its heat absorption capacity so that the temperature is raises from the entering to the top part. The last point of the top parts contains a gap for the passage of next channel which cause the fall of temperature from its maximum.

It is observed from Figure 12 that the efficiency is increased with an increase in mass flow rate for both simulation and experimental measurement whereas; output temperature is gradually decreasing with increasing mass flow rate. This is due to the improvement of heat carrying capacity of air from the absorber plate surface. Consequently, lower amount of heat get the chance to lose from the collector as reflection, radiation or other means due to higher flow of air around the absorber by double pass system. Figure 12 also depicts a good agreement between the numerical and experimental result for both the outlet temperature and the efficiency of double pass solar air heater.

In Figure 13, it is clear that the overall efficiency of modified setup is very higher than the previous. The maximum efficiency of previous setup where the panel was placed above the collector surface as traditional one is 42.12% for mass flow rate of 0.024 kg/s and if the mass flow rate improves further, the efficiency is decreasing gradually. Whereas, the new modified setup where the solar panel is placed at a different rack and lighted by the concave lens gives maximum efficiency is of 57.43% at 0.028 kg/sec mass flow rate. So, the improvement in efficiency is of 15.31% which is a great improvement of solar radiation utilization in a PV/T system.

Conclusion

A noble concept of a PV/T of double pass solar air heater is developed and analyzed in this paper. This concept assists to improve the thermal as well as overall efficiency of PV/T system. Comparative analysis is made to investigate the flow behavior and thermal performance of double pass solar air heater. The impact of flow rate, placement of solar panel, lightening area and lens effect were investigated. The thermal efficiency is increased with the increase of mass flow rate. It is found that for the same mass flow range from 0.012 kg/s to 0.028 kg/s about 15.31% efficiency improvement is obtained. Ignoring a small amount of panel lighting problem, this new system declared as most effective way of solar energy utilization.

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