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Parametric Analysis of Inclined Flat Plate Collector: A Review with Case Study

Bandana Swain[1], Shebaz A Memon[2] and A. Madhusudan Achari[3,*]

[1]*Mechanical Engineering Department, Indus University, Ahmedabad, Gujarat, 382115, India;*

[2]*Mechanical Engineering Department, School of Engineering, Institute of Technology, Nirma University, Ahmedabad, Gujarat, 382481, India;*

[3]*Mechanical Engineering Department, School of Engineering, Institute of Technology, Nirma University, Ahmedabad, Gujarat, 382115, India*

**Correspondence Author*

Abstract

The solar energy, as an alternative to fossil fuels, is the need of the hour. The use of solar energy, especially for water heating, remains critically low in India. It is observed after an extensive review of studies on the solar energy collector that the parameters affecting the efficiency of flat plate collector need an empirical study to establish the location specific values. This work presents the experimental investigation of a solar water heater in technical collaboration with Welson Energy Systems, where variable water flow rate in the range 0.001 to 0.02 kgs^{-1} is used. The aim of the research is to establish the dependence of first law efficiency, second law efficiency (exergy efficiency) and average temperature rise on the mass flow rate of water, the orientation of flat plate collector and the greenhouse effect. The results show that the instantaneous efficiency increases with the increase in mass flow rate and second law efficiency decrease with the increase in mass flow rate. The instantaneous efficiency and second law efficiency are significantly more with greenhouse effect than it is without the greenhouse effect. The exergy loss is found to be more without greenhouse effect than it is with the greenhouse effect.

Keywords: Solar flat plate collector, greenhouse effect, instantaneous efficiency, second law efficiency

1. INTRODUCTION

The amount of energy used by society has been one of the important yardsticks to gauge the development of nations. Energy usage is closely intertwined with almost all human activities of importance. The huge leap forwards, in human history, can be traced to the shifts in the energy paradigms, be it usage of coil, petroleum or electricity.

Highly dense resources of energy, fossil fuels, are essentially subdued carbon deposits in the crust of the earth. The release of this carbon into the atmosphere has serious consequences on the fine-tuned global ecosystem. The environmental concerns and non-infinite nature of fossil fuels have necessitated the exploration of renewable energies.

Being at low latitudes, India is highly blessed with abundant amounts of solar radiation fairly distributed over large swaths of the subcontinent size county. Most areas of the nation receive solar radiation more than 5 kWh per day for most of the year.

The energy received from the sun far exceeds the total human energy requirements. The dilute nature of solar energy is one of the major obstacles. In addition to that, solar energy is not available at night times and cloudy days. This creates a huge mismatch between energy supply and demand patterns. Large range of thermal applications for the use of solar energy is conceived, developed and implemented. One of the promising application of solar energy is its heating of the water for domestic and commercial purposes.

The first law of thermodynamics provides the law of conservation of energy, which will be conserved for closed system anyway. The second law of thermodynamics talks about the quality of the energy, which can be a helpful tool to study and identify the areas of improvements in the complex thermal system. The utility of the second law comes from its ability to benchmark the quality of heat using the temperature of the fluid stream with respect to the dead state surrounding temperature.

2. OVERVIEW OF SOLAR COLLECTOR LITERATURE

The quality of energy has become increasingly important to get the idea of available energy. Exergy analysis of the system is necessary to identify the gap between available energy and system performance. Farahat et al. [1] have optimized the second law efficiency of flat plate collector (FPC) using the sequential quadratic program in MATLAB. A parametric study is also performed, where it is found that exergy efficiency of FPC is very sensitive to the ambient temperature, wind speed and optical efficiency of the collector. Bahrehmand et al. [2] have studied the single glass and double glass collectors from the first law and second law point of view. It was observed that double glass collector comes out to be better. They have done analysis, where triangular fins are more effective in comparison to rectangular fins. Mortazavi et al. [3] have executed the advanced exergy analysis of simple air heater, which identifies the areas for potential curtailment of exergy destruction in the process

The literature survey shows some previous studies that deal with the exergy analysis on various types of systems such as solar air heater, concentrating solar collector, integrated solar roof collectors, vapor compression system, gas power, and vapor cycles etc. Manfrida et al. [4] studied of a Rankine Organic cycle powered by a low temperature flat plate solar collector where the 2nd law analysis of the system was done that include several exergy flows, which determine the overall balance. Eldighidy [5] used on Otto air standard cycle with ideal regeneration to determine outlet temperature of solar collector for maximum work output.. Yeh et al. [6] have investigated theoretically and experimentally the effect of parallel barriers that were placed with uniform spacing and in parallel, thereby dividing the air channel (collector) into parallel sub channels (sub collectors) of the same size on the collector efficiency of flat-plate solar air heaters. Also, the experimental studies were performed for different locations of the barriers. Yeh et al. [7] have investigated the effects in collector efficiency for air flowing between two parallel-plate channels with the absorbing plate inserted for conducting recycle-flow, and with fixed mass flow rate.

Kaushik et al. [8] have carried out the basic energy and exergy analysis for the system components (viz. parabolic trough collector/receiver and Rankine heat engine etc.) for evaluating the energy and exergy losses as well as exergy efficiency for typical solar thermal power system under given operating conditions. Karwa et al. [9] investigated experimentally the performance of solar air heaters with chamfered repeated rib-roughness on the airflow side of the absorber plates. The study shows substantial enhancement in thermal efficiency (10 to 40%) over solar air heaters with smooth absorber plates due to the enhancement in the Nusselt number (50% to 120%). They also presented a mathematical model for thermal performance prediction of solar air heaters with absorber plate having integral chamfered rib-roughness. Torres et al. [10] have done The thermodynamic method for designing dryers operated by flat plate solar collectors. Hasan et al. [11] have analyzed a binary ammonia-water mixture thermodynamic cycle that produces both power and refrigeration. The analysis includes exergy destruction for each component in the cycle as well as the first law and exergy efficiencies of the cycle and also the optimum operating conditions are established by maximizing the cycle exergy efficiency for the case of a solar heat source.

Kurtbas et al. [12] presented the results of their experimental study on the four newly developed flat plate geometries in an attempt to increase the heat transfer coefficient. Heat transfer grew at the expense of pressure drop in the collectors. Ozturk et al. [13] improved the first law and second law efficiency solar air heater using Raschig rings of PVC material on the air side with the black painted aluminum absorber. This extended surfaces enhanced the heat removal factor. Luminous et al. [14] did an experimental analysis of a solar air heater for varying air flow rates and performed thermodynamic analysis for that. Naphon [15] has studied the extended fin double pass solar air heater for entropy generation and found the optimum flow rate of working fluid by the experimental investigation. Ucar et al. [16] have used five different geometries in solar air collector to improve the performance of the heater using passive heat transfer enhancement techniques. The collector with absorber surface at 2° angle was found better among the tested collectors. Tiwari et al. [17] experimented on the solar distillation system for the better portable water output, second law efficiency and first law efficiency on an hourly basis.

Toh-ching et al. [18] have done exergy analysis with various local point and global maximum points. Further the develop the exergy analysis of a flat plate solar collector by out6line the coloration between the exergy efficiency of flat plate solar collector with outlet and inlet fluid temperature variation with respect to the influence of fluid flow rate and collector area.

Examination of the relevant literature reveals few prior theoretical (analytical and numerical) and experimental study relating to second law analysis and optimization of flow parameter on an inclined plate collector i.e. inclined plate water heater with or without the greenhouse effect.

When working fluid temperatures higher than 100 ^{0}C are required, it becomes necessary to concentrate the radiation. This is achieved using focusing or concentrating collectors such as, cylindrical parabolic collectors in which rotation about a single axis is required. Fluid temperature up to 400 ºC can be achieved by cylindrical parabolic focusing collector systems. The generation of still higher working temperature is possible by using paraboloid reflectors which have point focus and these required two-axis tracking.

Evacuated parabolic trough plate collector uses a vacuum inside the transparent tubes, containing the absorber tubes carrying working fluid so that the heat loss from the fluid being heated to the surrounding is minimized. Odeh et al. [19] have proposed the direct use of water as working fluid in contrast to specially made synthetic heat transfer oil used at the time. They have shown that water-based collector system has less thermal losses and one can sustain optimal scenario by changing the flow rate with change in radiation. Ravelli et al. [20] have implemented their athematic model for direct steam generation power plant in three different programs. It was found that TRANSYS results in the best match with the data of the real plant installed.

The tilt angle of solar collector is a crucial parameter for solar radiation availability for absorption of energy. If we adjust tilt angle as per solar path on a particular day, we may end up losing a lot of solar energy, because the zenith angle changes through the year. The search for the tilt angle, which can yield the maximum radiation collection in the entire year, has occupied the attention of many researchers. Yadav et al. [21] have surveyed the literature related to the optimization of tilt angle and they have elaborated upon parameters affecting it and different methodologies used to optimise the tilt angle. Hafez et al. [22] have reviewed the literature in detail for the tilt and azimuth angle of solar energy collectors. Danandeh et al. [23] have done the comparative study of different models for the estimation of solar irradiance on the horizontal surface. It was observed that different models are better suited for different types of geographies and climate as shown for the sites in Iran.

Shariah et al. [24] have studied the tilt angle for natural circulation flat plate water heater for two sites in Jordan using TRANSYS software. The optimum angle for these collectors was different from the latitudes of the sites. The optimum angles also depend upon the collector area. Gunerhan et al. [25]

have studied the optimum tilt angle for Izmir, Turkey using FORTRAN program and have compared the results with other models available. They have recommended that tilt the angle should be changed once every month to get optimum solar radiation absorption. It can be observed that optimum angle is not necessarily as per latitude of the location.

Chang [26] has used the Julian date system to calculate the optimum tilt angle of the solar collector in the northern hemisphere. It was found that this dating system help improve the search for an optimum tilt angle at a given location. It is also affected by the clearness index as well, increase of which will tend to flatten the optimal tilt angle. Skeiker [27] has studied the optimum tilt angle for Syrian regions and has proposed the twelve angles to be adjusted monthly along with simple methodology to find the angle. It has been estimated that readjustment of the tilt angle of the solar collector has the potential to increase the solar energy collection by 10%. Moghadam et al. [28] have developed the model for the optimum tilt angle for the sites in Iran using MATLAB, where the optimum angle for any specific time period can be determined. It was emphasised that daily change of tilt angle can yield better results.

Matthew et al. [29] have searched for the optimal tilt and azimuth angles for the continental United States for the grid 10 km. It was found that optimum tilt angle is not the same as of latitude angle and optimum azimuth angle is not due south. It was observed that the readjustment of the tilt to optimal value can increase the available solar radiation on the flat plate substantially. Siraki et al. [30] have explored the reasons for the deviation of the optimal angle from the latitude of the location. They observe that apart climatic conditions and clearness index, one needs to consider the surrounding conditions. They have proposed minor modification in HDKR model to make it compatible with urban settings.

Bakirci [31] has derived the general model for the optimum tilt angle for all the provinces of Turkey. The angle from °0 to 90° with the step size of 1° was calculated for available solar insolation to search for the optimal point. Rizal et al. [32] have utilised the solar position algorithm to ascertain the solar zenith and azimuth angle for the Indonesian island. They have also proposed to use of the central computer to adjust tilt of all the collectors accordingly.

Kittler et al. [33] have traced the long history and evolution of time keeping using solar dial and geodetics, where trigonometry has replaced the old methods of calculations. They advocated for the modifications in the different solar geometric angles in compliance with the ISO 19115. E.g. to consider the azimuth angle clockwise for 360°. Jafarkazemi et al. [34] have employed an empirical correlation of Erbs to find the optimal tilt angle for Abu Dhabi and have suggested to change the tilt angle at least semi-annually. Difference between annual average optimal tilt angle and latitude is 2-3° and azimuth is suggested close to the due south.

Handoyo et al. [35] have developed the equation for optimal tilt angle using calculus based optimisation and have validated it with several literature models and experimental data. Their model requires the latitude, time and other relevant information for the calculation of optimal tilt angle. Darhmaoui et al. [36] have optimised the tilt angle for the Mediterranean area using Reindl's anisotropic model by feeding the actual data of 35 sites of the region. Regression analysis renders that quadratic relation between attitude and optimal tilt angle best fits the data.

Stanciu et al. [37] have used three models for the computation of solar radiation Hottel and Woertz model, Liu & Jordan model and HDKR model for different location on the globe. They have given empirical correlations based on the study, which can be used for different locations around the globe.

Aung et al. [38] have performed the numerical analysis two-phase closed-loop natural circulation solar collector for parametric study of the tilt angle and riser diameter using MATLAB. It was noted that optimum tilt angle changes with the change in the riser diameter. Armstrong et al. [39] have described GPU based software developed for sun position calculation, which is supposed to give very high speed results for years for solar radiation directions. Khorasanizadeh et al. [40] have used several diffused radiation models to find the optimal tilt angle for the site in Iran using long term solar radiation data availed. It was calculated for monthly, seasonal, semi-annual and annual time periods. Semi-annual readjustment of surface tilt was recommended, as further readjustment does not yield significant increase in the efficiency. Despotovic et al. [41] have done search for optimal tilt angle and have come up to a similar conclusion.

Soulyman et al. [42] have derived the general correlation for mid latitudes to find out the optimal tilt angle of solar collector. It was observed that optimal tilt angle is not exactly as of the latitude and should be adjusted for the collector at least semi-annually. Kaddoura et al. [43] have optimised the tilt angle for the several cities of Saudi Arabia by implementing the model in the MATLAB. They have suggested the six readjustments annually. More frequent adjustments are suggested in the months near equinox, because of rapid change in the sun path near equinox in comparison to solstices. Jamil et al. [44] have found the optimal tilt for the solar collector for two sites in India using measured solar radiation data. They have recommended altering the tilt angle at least seasonally, if not monthly.

Sidak et al. [45] have developed an automatic dual axis solar tracking system based on open loop control system along with accessories such as the controller unit and GPS unit. It is shown that this system can accurately track the sun at any location, increasing the available solar energy substantially. This system requires a tiny amount of power to operate itself.

Ozbay et al. [46] have done the experimental investigation of the tilt angle using number of panels at different angles and have connected the system with tiny single board computer called Raspberry pie. This system can be tracked online through the internet.

Montoya-Márquez et al. [47] have studied the important heat transfer parameters using non-dimensional numbers using ANSI/ASHRAE 93-2010 standard. This study gives an idea of the effect of the tilt angle in these factors. Lu et al. [48] have proposed the method to find the optimum tilt angle based on the concept of effective solar radiation. For low temperature climates, especially at the time of sun rise and sun set, the heat gain from solar radiation will be lower than heat loss by convection. This is termed as ineffective solar radiation. For the site of Lhasa, Tibet, the optimum tilt angle comes to be different by 5° with only effective solar radiation considered for the calculation.

Gao et al. [49] have used the heat pipe in the FPC for low temperature application, where heat transfer enhances due to latent heat involved. Effect of tilt angle on the start-up conditions are also investigated.

The detailed literature review shows that the optimum tilt angle for the solar collector is not necessarily equal to latitude, if the solar tracking system is not integrated with the system. The optimal value the tilt angle is influenced by many factors like the local climate, radiation amount, usage of solar energy, obstruction in the way of radiation etc. The literature does not suggest any definite model to find the optimal tilt angle which can be applied globally. This leads to need of the effort to find the value and desired frequency of adjustment of tilt angle for the location under study.

3. EXPERIMENTAL SETUP

The study presents a detailed experimental work on solar water heater/inclined flat plate collector. It describes the design of various components of the experimental setup and also enumerates in details the optimization of flow parameters with or without greenhouse effect. The basic attempt of the work is to measure the variation of average outlet temperatures at different intervals of time and at different orientations as well as with different flow rates at different clear sky days and hours. All the Experiments have been conducted at Bhubaneswar (20.2591 Latitude, 85.792 Longitude).

3.1. Description of physical problem

The main focus of the work is to measure the variation of average outlet temperatures on the absorber plate when it is kept at various orientations with different flow rates. In order to achieve the objective, the model has been selected accordingly. Fig. 1 represents a schematic sketch of the physical problem.

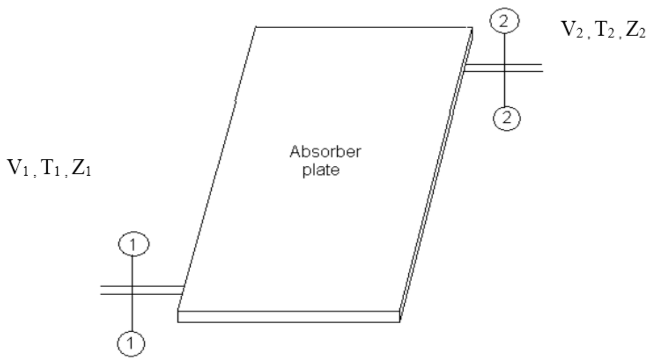

Fig. 1 Assembly of experimental setup

The physical problem consists of an absorber plate of length 2.1 m and width 0.97 m within which tubes are fixed. The diameter of the tubes is 0.018 m with the pitch ranging from 0.012 m. The absorber plate is connected to a storage tank, which is being located above the level of absorber plate/collector. Also the absorber plate is being attached with glass cover of 5 mm thickness to achieve the objective of greenhouse effect.

Here,

Discharge flow rate of water,

$Q = \frac{\pi}{4} d^2 v$ m3 /sec

Where, d is the diameter of the pipe and v is the average velocity of fluid.

Angle of incidence,

$$\cos\theta = \sin\emptyset\,(\sin\delta\cos\beta + \cos\delta\cos\gamma\cos\omega\sin\beta) + \cos\emptyset\,(\cos\delta\cos\omega\cos\beta - \sin\delta\cos\gamma\sin\beta) + \cos\delta\sin\gamma\sin\omega\sin\beta$$

Where,

Declination angle,

$\delta = 23.45° \times \sin[(360/365)\times(n+284)]$,

n is no of day in the year.

β = slope angle

∅=latitude of the location

γ=surface azimuth angle

ω=hour angle

Local apparent time (LAT) = Standard time ± 4(Standard time Longitude -Longitude Of location) + (Equation of time correction)

Tilt factor for beam radiation

$$rr_b = \frac{\cos\theta}{\cos\theta_z}$$

$$\cos\theta_z = (\sin\emptyset \times \sin\delta) + (\cos\emptyset \times \cos\delta \times \cos\omega)$$

Radiation shape factor for the diffuse radiation,

$$R_d = \frac{(1+\cos\beta)}{2}$$

Tilt factor for reflected radiation,

$$r_r = \frac{\rho(1-\cos\beta)}{2}$$

Total radiation flux on tilted surface,

IT = Ibrb +Idrd+ (Ib+Id) rr

Instantaneous efficiency, $\eta_i = \frac{\dot{m}C_p(T_2-T_1)}{I_t\times A_p}$

Exergy, $e = (h-h_0) - T_0(s-s_0) + \frac{V^2}{2} + gz \qquad kJ/kg$

Irreversibility, $I = T_0(s_2 - s_1) = T_0\Delta s$ kJ/kg (Gouy-Stodola equation)

Second law efficiency,

$$\eta_{II} = 1 - \frac{\left(\frac{T_a}{T_0}\right)}{\left(\frac{T_a}{T_s}\right)}$$

3.2. Design and fabrication of the experimental setup

3.2.1. Flow loop

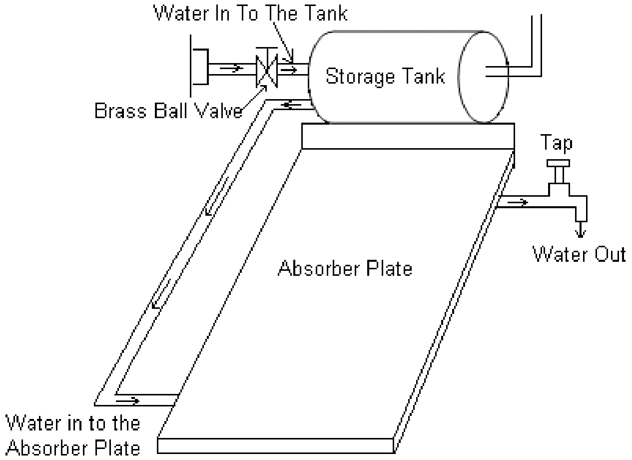

Fig. 2 Schematic of flat plate collector

The Fig. 2 represents schematic diagram of the flow loop. It consists of a tap (supplying water) connected to storage tank by means of a flexible pipe with brass ball valve arrangement. The brass ball valve regulates the flow of water to the storage tank. The storage tank is connected to absorber plate by means of a flexible pipe. The water then flows through the tubes that are fixed within the absorber plate. This water in turn is drained out through the top outlet.

3.2.2. Complete assembly of experimental setup

Fig. 3 Solar water heater experimental setup

The experimental apparatus consists of a storage tank, stand, pipes and a target absorber plate as shown in Fig. 3. The copper tubes are fixed within the absorber plate through which the fluid (water) flows. The storage tank is placed on the stand and the absorber plate is then kept on the frame. The flow line consists of an inlet tap for supplying water, a brass ball valve for flow control and an outlet tap for discharging and collecting the hot water in a graduated beaker after flowing through the absorber plate for the purpose of flow measurement.

3.3. Experimental procedure

3.3.1. Temperature measurement

The experimental setup was placed in the sun facing south-west location. The water was allowed to enter into the storage tank, and then to the absorber plate through flexible pipe. Then both inlet and outlet tap were kept closed. With this condition, the setup was kept in the sun for one hour. Both inlet and outlet taps were opened after one hour and the temperature of hot water collected at outlet tap was noted down simultaneously, at the interval of 3 minutes. In this way, fifteen observations were noted down. This process was continued for six different flow rates. Then, the position of experimental setup was changed and kept facing due-south and the same procedure was continued and another fifteen observations were noted down for six different flow rates. This process was done without using any glass covers i.e. “without greenhouse effect”. After noting down the readings without greenhouse effect, the experiment was again conducted with greenhouse effect by using one glass cover. The glass cover of thickness 5 mm was attached to the absorber plate and same procedure was repeated, as it was already conducted for “without greenhouse effect”.

3.3.2. Flow measurement

The water coming out of the outlet tap is collected in a graduated beaker. The time is noted down for collecting 100 ml of water by means of a stop watch and the rate of flow is measured.

4. RESULTS AND DISCUSSIONS

The results have been summarized for two different cases, viz. “without greenhouse effect” and “with greenhouse effect”. The results cover exergy loss at various stages of collector caused by irreversibility for both the cases considered and the effect of water flow rate on various parameters such as second law efficiency, instantaneous efficiency and increase in temperature of water (heating effect) over the solar thermal system.

4.1. Without greenhouse effect

In this study, the outlet temperature of water at various water flow rate situations were noted down. The various outlet temperature data were collected using experimental apparatus and methods already described to find out the instantaneous efficiency and second law efficiency with variation in mass flow rate of water.

4.1.1. Effect of water flow rate on instantaneous efficiency

Fig. 4 depicts a typical plot of instantaneous efficiency versus water flow rate for the cases of solar plate collector facing south-west and due south. It is evident from the figure that instantaneous efficiency increases with increase in water flow rate. This is due to the fact that increase in useful heat gain by the water with increase in water flow rate causing the various losses accounted such as, top loss, bottom loss and side loss etc. to decrease. Nusselt number plays a significant role in determining the heat transfer rate as the flow in the solar collector is mainly governed by convection. Increase in mass flow rate gives rise to increase in Nusselt number, which ultimately leads to increase in the instantaneous efficiency. However, for a particular mass flow rate, the efficiency is higher when the solar collector plate faces due south than that when it faces due south-west. It is evident that the slope of the graph obtained for due-south location more than that for south-west direction. Therefore, it can be concluded that the increase in instantaneous efficiency for due-south location is more effective than that of south-west location of solar collector. It is also observed that the rate of increase in first law efficiency is more with higher mass flow rate, which is more significant in the case of solar collector plate facing due-south.

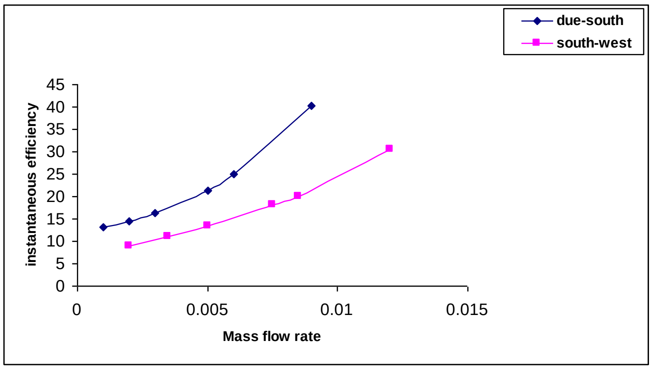

Fig. 4 Variation of Instantaneous efficiency with Mass flow rate

4.1.2. Effect of water flow rate on second law efficiency

The Fig. 5 depicts a typical plot of second law efficiency versus mass flow rate of water with the solar plate collector facing south-west and due south. It can be observed from the figure that second law efficiency decreases with increase in mass flow rate of water. This is due to the fact that exergy loss, due to increase in entropy, increases due to increase in mass flow rate of water. More exergy loss causes less exergy recovered and ultimately more becomes the irreversibility.

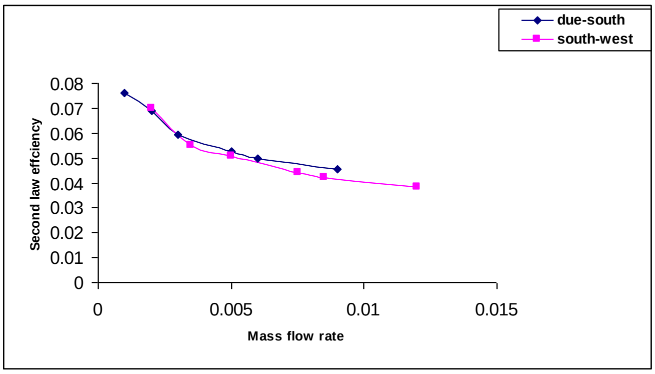

Fig. 5 Variation of Second law efficiency with Mass flow rate

Though, the difference between the two curves is very small, the difference between the second law efficiency for a particular value of mass flow rate of water increases with increase in mass flow rate. However, the second law efficiency has a marginally lower value for the case of solar collector plate facing south-west when compared with that of due-south. It can be concluded from the figure that the solar collector plate becomes more effective when it faces due-south compared to when facing south-west.

4.1.3. Effect of water flow rate on average temperature rise.

The Fig. 6 shows a typical plot of average temperature rise versus water flow rate for the cases when solar plate collector faces south-west direction and due-south. It is observed from the figure that the average temperature rise decreases very slightly with water flow rate in the first phase of the mass flow rate of water range.

At a particular narrow water flow rate range the decrease of average temperature rise is not significant. But beyond that, the decrease of average temperature rise is quite significant. Therefore the curve at that particular range, where the average temperature rise is not significant, slightly flattens i.e., the slope of the curve slightly decreases indicating the water flow rate is optimum within this particular range.

The average temperature rise remains nearly same (decreases very slightly) in the range of 0 to 0.008 kg/s for the case when the solar collector plate faces south-west. However, the above mentioned range for the case when the solar collector plate faces due-south is 0 to 0.005 kg/s. Beyond the ranges mentioned above for both the cases, there is significant decrease in average temperature rise. Though the instantaneous efficiency and second law are higher for the case when the solar collector plate faces south direction, the average temperature rise is lower than the case when the solar collector plate faces south-west. This may be due to the fact that the solar collector plate receives more solar radiation when it faces south-west.

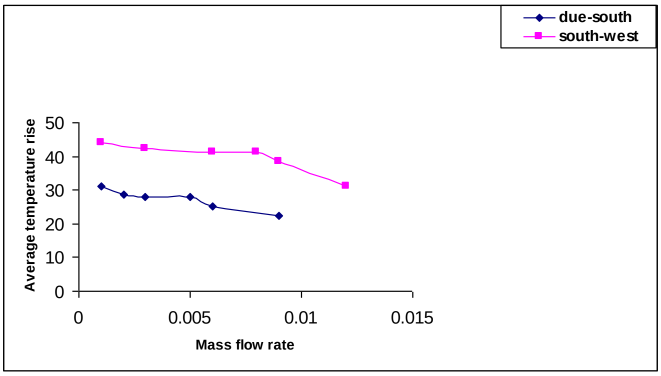

Fig. 6 Variation of Average temperature rise with mass flow rate

4.2. With greenhouse effect

In this investigation, a glass plate of 5 mm thickness is selected and is made to fix over the absorber plate. Similar to the case, when there is no glass plate over absorber plate, outlet temperature data were collected using experimental apparatus and methods already described to find out the instantaneous efficiency and second law efficiency with variation in mass flow rate of water.

4.2.1. Effect of water flow rate on instantaneous efficiency

The Fig. 6 depicts a typical plot of instantaneous efficiency versus water flow rate when the solar collector plate faces south-west direction for the cases of without greenhouse effect and with greenhouse effect. The instantaneous efficiency for both the cases of without greenhouse effect and with greenhouse effect increases with increase in mass flow rate of water, when the solar collector plate faces south-west direction. The profiles have the same trend, but the increase in instantaneous efficiency with greenhouse effect is more significant than that of without greenhouse effect. It is because of using glass cover in case of with greenhouse effect, helps in reducing the losses by convection and re-radiation than that of without greenhouse effect resulting more heat gain by the water. Therefore, the curve is somewhat steeper in case of with greenhouse effect than that of without greenhouse effect.

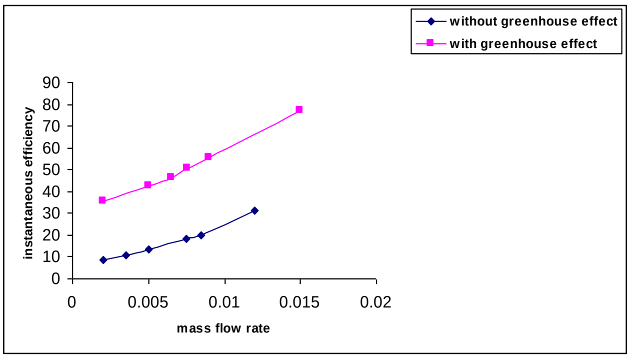

Fig. 7 Variation of Instantaneous efficiency with Mass flow rate (South-west)

Similar to Fig. 7, instantaneous efficiency versus water flow rate when the solar collector plate faces south-west direction for the cases of without greenhouse effect and with greenhouse effect has been shown in Fig. 8. It also shows similar trend as depicted in Figure 4.5 for the reasons as already discussed.

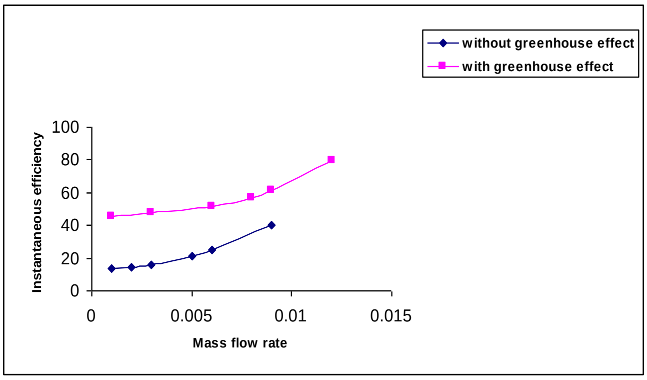

Fig. 8 Variation of instantaneous efficiency with mass flow rate (Due South)

4.2.2. Effect of water flow rate on second law efficiency

The Fig. 9 depicts a typical plot of second law efficiency versus mass flow rate of water when the solar collector plate faces south-west direction for the cases of without greenhouse effect and with greenhouse effect.

It can be seen that the second law efficiency has a higher value for a particular mass flow rate of water for the case of with greenhouse effect when compared to without greenhouse effect when the solar collector plate faces south-west. However, the decrease of second law efficiency is significant in both the cases. Higher second law efficiency in the case of with greenhouse effect is due to the fact that using glass cover with greenhouse effect helps in decreasing the outlet average temperature which lessen the exergy loss than that of without greenhouse effect and causes more increase in entropy, resulting more exergy recovered than that of with greenhouse effect. Therefore the curve is somewhat flat for the case of “with greenhouse effect” than that for “without greenhouse effect”.

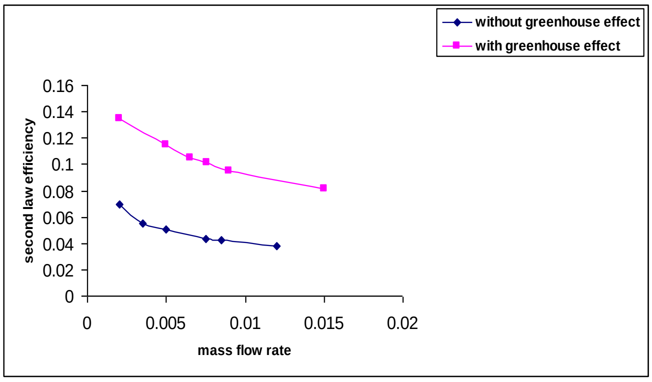

Fig. 9 Variation of second law efficiency with mass flow rate

Similar to Fig. 9, second law efficiency versus mass flow rate of water when the solar collector plate faces due south direction for the cases of without greenhouse effect and with greenhouse effect has been shown in Fig. 10. It also shows similar trend as depicted in Figure 4.6 for the reasons as already discussed.

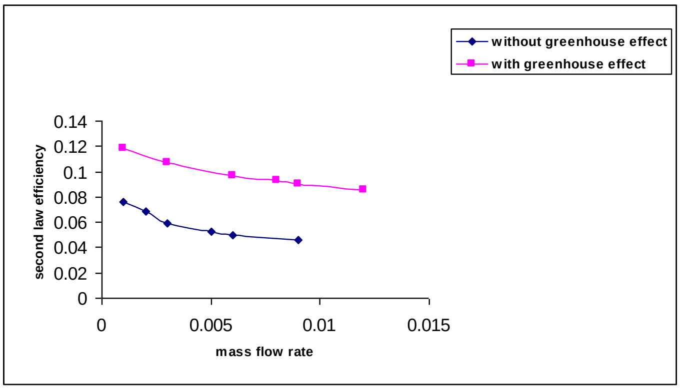

Fig. 10 Variation of second law efficiency with mass flow rate

4.2.3. Effect of water flow rate on average temperature rise.

The Fig. 11 depicts a plot of average temperature rise versus mass flow rate of water when the solar collector plate faces south-west direction for the cases of without greenhouse effect and with greenhouse effect. The average temperature is higher in case where the glass plate is covered over the solar collector plate (creating greenhouse effect) as compared to that without glass cover (without greenhouse effect). It is because of using glass cover with greenhouse effect, the losses due to the convection and re-radiation decreases causing higher average outlet temperature thereby increasing the temperature rise. It can also be observed that the variation in average temperature rise is very small for the range of 0 to 0.008 kg/s of water flow rate. Beyond this value, the average temperature rise decrease significantly with increase in mass flow rate.

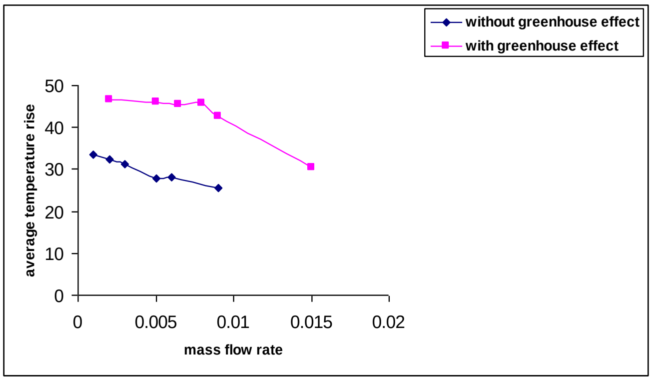

Fig. 11 Variation of Average temperature rise with mass flow rate

Similar to Fig. 11, average temperature rise versus mass flow rate of water when the solar collector plate faces due south direction for the cases of without greenhouse effect and with greenhouse effect has been shown in Fig. 12. It also shows similar trend as depicted in Figure 4.8 for the reasons as already discussed.

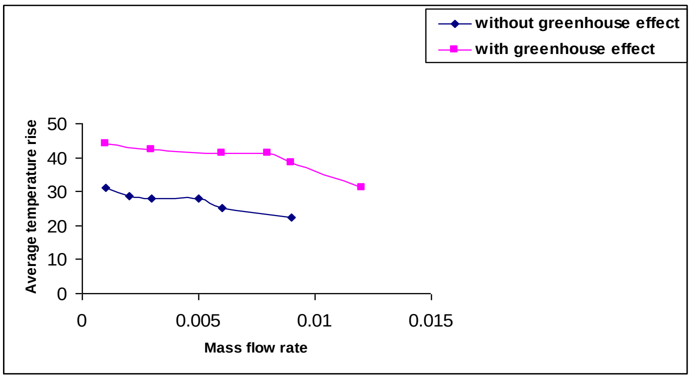

Fig. 12 Variation of Average temperature rise with mass flow rate

5. CONCLUSIONS

A series of experiments were conducted and observations were carried out both for "without greenhouse effect" and "with greenhouse effect" to investigate the characteristics of instantaneous efficiency, second law efficiency and average temperature rise for different water flow rate. The problem parameters were investigated with different orientations such as south-west and due-south. Based on the exhaustive measurements and the data derived, the following conclusions may be drawn.

5.1. For the case of "without greenhouse effect":

1. The instantaneous efficiency profile is slightly steeper in case of due-south location than that for south-west location of solar collector indicating more useful heat gain in the case of due-south location of solar collector, because of more intensity of solar radiation, causes due to more angle of incident.
2. The second law efficiency profile is slightly flattened in case of due-south location than that for south-west location of solar collector concluding that more exergy gets recovered. The intensity of solar radiation is more in case of due-south location.
3. With increase in water flow rate, the average temperature profile flatten which describes the decrease in average temperature rise is not significant for a particular region. Beyond that, it again decreases. Therefore, the profile can be attributed to optimum water flow rate at that particular region.

5.2. For the case of "with greenhouse effect":

1. The conclusions for all the parameters such as instantaneous efficiency, second law efficiency and average temperature rise, follow the same trend just like for the previous case i.e., for "without greenhouse effect".

2. The instantaneous efficiency is more for the case of "with greenhouse effect" than that for "without greenhouse effect" because of using glass covers "with greenhouse effect" the reduction of losses due to convection and re-radiation than that of "without greenhouse effect" resulting more useful heat gain by the water. The instantaneous efficiency can be increased by using extra cover plates i.e., maximum of two cover plates. But by using more cover plates, the maximum efficiency will decrease due to low intensity of radiation reaching the solar collector.

3. The decrease of second law efficiency is less significant with greenhouse effect than that of without greenhouse effect, because of the increase in average outlet temperature by using glass cover in case of with greenhouse effect, thereby increase in entropy causing less exergy loss than that of without greenhouse effect and ultimately resulting in increase of exergy recovered.

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