Asian Journal of Scientific Research

ISSN 1992-1454

science alert
http://www.scialert.net

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Asian Journal of Scientific Research 6 (3): 445-455, 2013
ISSN 1992-1454 / DOI: 10.3923/ajsr.2013.445.455

Comparative Study of Single Pass Collector and Double Pass Solar Collector Filled with Porous Media

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ABSTRACT

This research reports a comparative study of the conventional single pass flat plate collector and the double pass solar collector filled with porous media such as gravel and metal chips at the lower channel of absorbing unit. The component materials, design, performance efficiencies, capabilities and the application of the solar collectors are presented to show various disparities that exist between the collectors. Emphasis was laid on the multi-pass approach as a gate way to future development on solar collectors.

Key words: Solar energy, collector, single pass collector, double pass collector, porous media

INTRODUCTION

The research on solar collector has gained its popularity over the years due to the increase in demand for the utilization of solar energy. Series of research have been done to improve the means of converting solar energy to other forms of energy that would meet the needs of human being. This as called for a concerted effort of scientists and engineers, who came out with the classification, different approaches of designing and evaluation of the efficiency of solar collector, that would be economically viable and technically effective.

Energy is vital input for economic growth in agriculture and industry. Fossil fuels are depleting at a faster rate due to over exploitation, besides increasing in cost of environmental sustainability. Search for sources of green energy and their technological development is of paramount importance to have a balanced and buoyant environment for better quality of life (Kothari *et al.*, 2009).

Amer *et al.* (2012) proposed solar power and wind energy as adjunct renewable energy sources for due to increase in consumption of fossil fuel which poses a threat on environmental sustainability. Joseph *et al.* (2011) emphasized the future of solar energy supplying the whole energy needed in facilities such as building with cheap cost of production and environmental friendly.

The single pass collector is also known as flat plate collector. It was said by Garg and Parkash (2006) that it forms the hearts of any solar collection system designed for operation in the low temperature range, from the ambient to 60°C or the medium temperature range, from ambient to 100°C. A well engineered flat plate collector delivers heat at relatively low cost for a long duration. The most important part of the collector is the absorber plate along with the pipe or duct to pass air in thermal contact with the plate to transfer heat from it.

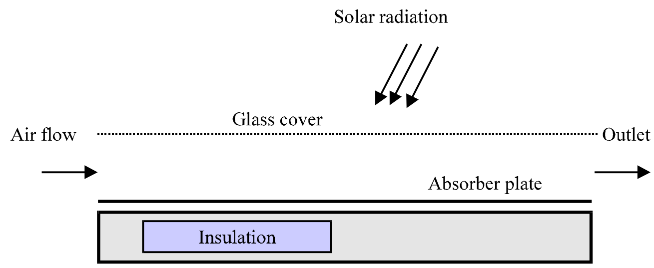

Fig. 1: Cross-sectional view of single pass solar collector (Languri and Ganji, 2011)

The single pass flat plate collectors as shown in Fig. 1 have the following advantages over other types of solar energy collector: They absorbed diffuse, direct and reflected components of solar radiation. Tracking of the sun is not required but they are fixed in tilt and orientation. They are easy to construct with cheap cost. They require low maintenance cost and long life. They operate at high efficiency (Garg and Parkash, 2006).

It was emphasized by Sen (2008) and Karatasou *et al.* (2006) that it is necessary to have tilted surfaces for the maximum collection of solar energy but the angle of tilting depends on both the latitude and day of the year.

An analytical program, suitable for use on a digital computer was developed by Test (1976) for the purpose of studying the hourly behaviour of a flat plate solar collector. The data for the past ten years were studied to determine the average diffuse radiation on clear days, ambient temperature, average cloudiness and effect of cloudiness on global radiation. The quantities were then put in the form of empirical equations so that they would predict the proper input for a computer programme. The results indicated that the energy absorbed by a collector and its efficiency are strongly dependent on collector temperature and cloudiness. Test (1976) warned that a good report of collector efficiency must contains the conditions under which a collector was operated and its geometry.

A theoretical model and experimental setup were carried out by Sopian *et al.* (2009). It was confirmed that the effect of using porous media in the lower channel of the solar collector provides a higher outlet temperature compare to the conventional single pass collector. This improves the thermal efficiency of the collector. The effects of mass flow rate, solar radiation, temperature and variation of the depths of the upper and lower channels on thermal efficiency were established. In addition, the heat transfer and pressure drop relationships was developed for air flow through the porous media. It was concluded that the typical efficiency of the double pass solar collector with porous media is about 60-70%.

It was reported by Rabadi and Mismar (2003) and Chamolia *et al.* (2012) that the instantaneous efficiency of collector is increased when using porous media. Al-Hadidi and Ibrahim (2008) divided the daily solar time into four T_1 (between sunrise and 9.30 a.m.), T_2 (9.30 a.m.-12.00 p.m.) T_3 (12.00 p.m.-2.30 p.m.) and T_4 (between 2.30 p.m. and sunset).

The collector efficiency of upward type double pass flat plate solar air heater with fins attached and externally recycle was investigated theoretically by Ho *et al.* (2011). A double pass device was constructed by inserting the absorbing plate into the air conduit to divide it into two channels (upper and lower). The double pass device introduced in this research was designed for creating a solar collector with heat transfer is double.

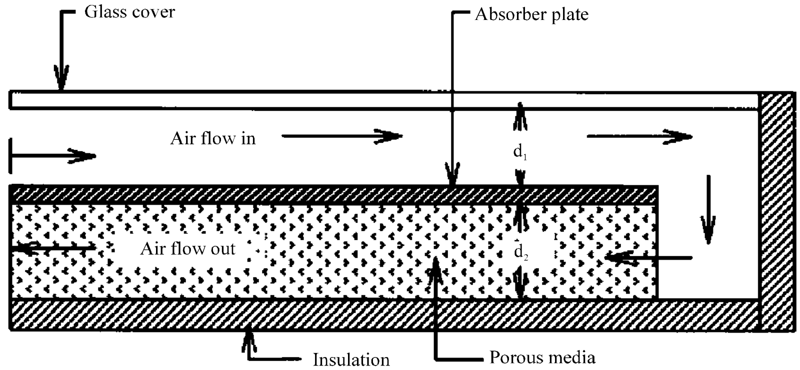

Fig. 2: Cross-sectional view of double pass solar collector (Sopiana *et al.*, 1999)

The mathematical and experimental study conducted by Ramani *et al.* (2010) emphasized the inclusion of porous material in the second air passage of double pass counter flow solar collector as a means to improve the thermal performance. The mathematical model was based on the volumetric heat transfer coefficient. It was revealed that the thermal efficiency of double pass solar air collector with porous absorbing material is 20-25 and 30-35% higher than that of double pass solar air collector without porous absorbing material and single pass collector, respectively.

An experimental study was performed by Karim and Hawlader (2004) which shows that the efficiency of the collectors is a strong function of air flow rate. Efficiency increases with flow rate and tend to be saturated beyond a flow rate of about 0.056 kg m^{-2} sec. A flow rate of about 0.35 kg m^{-2} sec was considered optimal for solar drying of agricultural products. Since the v-corrugated collector shows better efficiency in both single and double-pass operation and is also structurally stable, this collector was considered predominantly useful for drying applications.

It was recorded by Aldabbagh *et al.* (2010) that the efficiency increases with increase in flow rate between 0.012 and 0.38 kg sec^{-1} was used and for the same flow rate the efficiency of the double pass was found to be higher than the single pass by 34-35% and concluded that the maximum efficiencies obtained for the single and double pass air collectors are 45.93 and 83.65%, respectively for the mass flow rate of 0.38 kg sec^{-1}. The enhanced collector was reported by Herrero Martin *et al.* (2011) that it increases the thermal efficiency value by 4.5%. The double pass solar collector is shown in Fig. 2.

Attempt has been made in this paper to show the differences between the single pass collector and the double pass solar collector with porous matrix based on the material requirement, design and theory of heat transfer within the collector system and its surrounding. The relationship between efficiency with reduced temperature parameter $(T_p\text{-}T_{srd})/G$, power output with mass flow rate and efficiency with increment in temperature were illustrated with the aid of graphs.

MATERIALS AND METHODS

Analysis of various parts of the single pass collector and double pass solar collector filled with porous media were considered and the heat transfer within the system and its surrounding were looked into. This reflected the disparity in heat loss of both systems which implies different performance efficiency value when exposed to the same solar radiation.

Glazing with a plane glass: A plane glass is usually installed on the single pass flat plate absorber while two planes are used on the double pass solar collector with porous matrix. The glass material has transmission allowance for the short wavelength radiation from the sun which range between 0.25 and 3.0 μm (Duffie and Beckman, 2006) and it disallows the passage of long wavelength radiation. But the flat plate emittance is of long wave length (Hollands *et al*., 2001). Therefore, it seals the heat energy within the space between the plane glass and the collector. This sealing is more effective in double pass collector with two planes as glazing material.

However, part of the long wavelength radiant heat emitted by the absorber escapes to the atmosphere, some are re-radiated onto absorber mostly double pass that has double plane, while the rest are loss to the surrounding through convective heat transfer. Therefore, a plane glass usually used for glazing of single pass solar collector cannot eliminate the heat flow beneath the glass cover to the surrounding. Hence, there is need for further reduction of heat loss to the environment.

The following equations (Hollands *et al*., 2001) are used to evaluate the values of absorptance α, reflectance ρ and transmittance τ solar energy on a plane glass:

$$r(\theta) = \frac{r_1(\theta)}{2} + \frac{r_2(\theta)}{2} \tag{1}$$

$$\tau(\theta) = 1 - \alpha(\theta) + \rho(\theta) \tag{2}$$

Two plane glasses: The two plane glasses are more efficient than one glass. They are usually applied to double pass solar collector with porous media. Since the glasses are made of the same material and assumed symmetry of each plane, they are bound to have the same value of reflectance ρ and transmittance τ. In this case there would be a pair of reflectance and one transmittance. The following Equations are used to evaluate two plane glasses (Hollands *et al*., 2001).

$$C_{g,in} = (1-\rho-\tau)\left(\frac{\tau}{1-\rho^2}\right) \tag{3}$$

$$C_{g,out} = (1-\rho-\tau)\left(1+\tau\frac{\rho}{1-\rho^2}\right) \tag{4}$$

Therefore, the transmittance and the reflectance of centre glass would be estimated by:

$$\tau_{g2} = \tau^2\frac{1}{1-\rho^2} \tag{5}$$

$$\rho_{g2} = \rho + \tau^2\frac{\rho}{1-\rho^2} \tag{6}$$

The following equations (Tiwari, 2002) reflect the heat flow around the two plane glasses, in which four temperatures are very relevant in the process of evaluating the quantity of heat flow within this region. The temperatures are: Air temperature T_{out}, outer glass temperature $T_{g,out}$, inner glass temperature $T_{g,in}$, inner air temperature T_{in} and thermal resistance R. The Equations required are of forms:

$$q_{in} = \frac{T_{g,in} - T_{in}}{A_{cg} R_{in}} \quad (7)$$

$$q_{int} = \frac{T_{g,out} - T_{g,in}}{A_{cg} R_{int}} \quad (8)$$

$$q_{out} = \frac{T_{out} - T_{g,out}}{A_{cg} R_{out}} \quad (9)$$

where, q_{int} is the quantity of heat transfer internally with two the glasses.

The absorbed solar radiation per unit area of each plane glass, $S_{g,in}$ and $S_{g,out}$ can be calculated from:

$$q_{int} = q_{in}\text{-}S_{g,in} \quad (10)$$

$$q_{out} = q_{int}\text{-}S_{g,our} \quad (11)$$

Flat plate solar collector: This is the energy conversion unit that absorbs the solar radiation. It does not concentrate the incident radiation energy before absorption. Therefore, it collects both the direct and diffuse parts of radiation.

The following features distinguished the flat plate collector from others:

- It has high transmission cover
- The absorber plate is usually coated with high solar radiation absorptance and low infrared ray emittance
- It has high heat conductivity
- Ability to release the absorbed heat to the flowing fluid that has contact with it

At this juncture, a point of divergence set in for both the single pass and double pass solar collector with porous matrix as far as flat absorber is concerned.

The single pass flat plate has a good insulating material at the lower side of the plate. The insulation of the single pass collector usually consists of a reflective foil with a fiberglass material that will not allow out-gas at elevated temperature. Though, polyester fiber material is becoming popular due to health and safety concerns with regard to usage of fiberglass.

Heat loss from a plane glass: The Eq. 12 below reflects the summation of radiation and convective heat transfer between the absorber plate and the cover:

$$q_1 = h_1 (T_p - T_c) + \frac{\alpha(T_p^4 + T_c^4)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1} \quad (12)$$

$$h_2 = \frac{\sigma(T_p + T_c)(T_p^2 + T_c^2)}{\varepsilon_p^{-1} + \varepsilon_c^{-1} - 1} \quad (13)$$

where, h_1 and h_2 are the inner convective and plate to cover radiative heat transfer coefficients, ε_p and ε_c are the wavelength of the plate and cover emissive radiations and the temperatures of the plate and cover are T_p and T_p, respectively.

The convective heat transfer correlation at tilt angle up to 60° is stated below:

$$Nu = \frac{h_1 L}{k} = 1 + 1.446\left(1 - \frac{1708}{Ra\cos\theta}\right)\left(1 - \frac{(\sin 1.8\theta)^{1.6} 1708}{Ra\cos\theta}\right) + \left[\left(\frac{Ra\cos\theta}{5830}\right)^{1/2} - 1\right] \tag{14}$$

$$Ra = \frac{\beta\rho^2 g C_p}{k\mu}(T_p - T_c)L^2 \tag{15}$$

where, C_p, $\boldsymbol{\beta}$, μ and k are fluid properties at mean temperature 0.5 (T_p, T_p), θ is angle of inclination of collector, L is distance between absorber and glass.

Heat loss from double plane glass: The convective heat transfer correlation is of the same form with the single plane except the constant 1.466 that changed to 1.7 as shown below:

$$Nu = \frac{h_1 L}{k} = 1 + 1.7\left(1 - \frac{1708}{Ra\cos\theta}\right)\left(1 - \frac{(\sin 1.8\theta)^{1.6} 1708}{Ra\cos\theta}\right) + \left[\left(\frac{Ra\cos\theta}{5830}\right)^{1/2} - 1\right] \tag{16}$$

Heat loss from glass: The sum of convective and radiative heat loss from glass cover of a single pass collector to the surrounding on a clear day is depicted in the following Eq. 4.

$$q_2 = \sigma\varepsilon_c (T_c^4 - T_{srd}^4) + h_2 (T_c - T_a) \tag{17}$$

where, T_{srd} is the temperature of the surrounding.

The ambient and surrounding temperatures are the two vital functions that determine the effective radiation heat transfer coefficient (h_4):

$$h_4 = \sigma\varepsilon_c (T_c^2 - T_{srd}^2)(T_c + T_{srd}^2)\frac{(T_c + T_{srd}^2)}{(T_c + T_a)} \tag{18}$$

Heat loss from lower side of the collector: This heat loss from the lower side of the absorber is a major deficiency of the single pass solar collector. The working fluid that passes through the porous material at the lower channel of the double pass has saved heat loss. The heat transfer coefficient for loss of heat through the lower channel from the collector plate 13 is as stated in Eq. 19:

$$U_{low} = \frac{1}{\frac{t_{low}}{k_{low}} + \frac{1}{h_{out}}} \tag{19}$$

where, h_{out} is the external heat transfer coefficient t_{low} is the thickness of the insulator at lower channel and k_{low} is the conductivity of the insulation.

Similarly, loss at the edge of the collector is as shown in Eq. 20:

$$U_{edg} = \frac{1}{\frac{t_{edg}}{k_{edg}} + \frac{1}{h_{out}}} \quad (20)$$

where, t_{edg} and k_{edg} are the thickness of the insulation and the conductivity of the insulation, respectively.

Heat loss from upper side of the collector: In order to simplify the equation involved, the ambient temperature T_a is assumed to be equal to the surrounding temperature (T_{srd}).

Therefore, the heat loss coefficient can be valued in terms of collector plate and ambient temperature difference:

$$Q_L = U_{upp}\,(T_p\text{-}T_a) \quad (21)$$

Therefore, the summation of heat losses is U_T 4:

$$U_T = U_{low}+U_{edh}+U_{upp} \quad (22)$$

Factor of heat removal by fluid: The working fluid circulates round the collector system as it pass through the absorber plate, it gains heat from the collector. The loss of heat from collector earlier discussed is to the surrounding but this is crucial, since it is the determinant of the collector efficiency. Therefore, the heat gain factor is calculated in the following form Eq. 19:

$$UG = \frac{\dot{m}C_p\,(T_{out} - T_{in})}{U_{use}} \quad (23)$$

$$\eta = \frac{U_{use}}{AG} \quad (24)$$

where, G is solar radiation intensity, A is area of plate:

$$\eta = F_R\,(\tau a) - F_R U_T\,(\frac{T_p - T_{srd}}{G}) \quad (25)$$

The heat removal factor F_R is low in value for single pass collector when compare with double pass solar collector because of porous media and additional pass of the fluid below the absorber.

Effects of porous material: Porous media are solid materials that have good absorptivity and emissivity properties. They are loosely filled into the lower channel of the double pass solar collector. This reduced the porosity of the lower channel and the flow rate of the working fluid also reduced. The solid matrix acts as energy storing material. The energy that would have crossed the boundary of the system is retained. This is dissipated to the working fluid flowing across it. Hence, it improves the efficiency of the collector system as reported by Sopian *et al.* (2009) and Rabadi and Mismar (2003). Cheap material such as rock samples and metal chips are used as porous media.

Working fluid path: The channels of flow of working fluid in a single pass solar collector are of two types:

- The collector in which the working fluid flow past the top surface of the absorber
- The collector that working fluid flow beneath the flat plate solar collector

However, the working fluid flows past through the both sides of the double pass solar collector, this make it more efficient because of increase in fluid rate of heat removal from the absorber compare to the single pass solar collector that has contact with one face of the absorber only. Through, the flow direction may be reversed in double pass by starting of fluid flowing from lower channel to the upper surface of the collector.

RESULTS AND DISCUSSION

Here, we used the literature values to show major differences between the single pass collector without porous media and double pass collector that has gravels at the lower channel of the absorber plate.

Figure 3 shows the Single Pass Solar Collector (SPSC) and Double Pass Solar Collector with porous matrix (DPSC) in which various efficiencies in relation with the reduced temperature parameter $(T_p-T_{srd})/G$. It can be deduced from the graph that single pass is effective at low value of reduced temperature parameter but totally inactive at higher value. When the efficiency is 40%, the value of reduced temperature parameter is about 0.03 and 0.08 for single pass and double pass collector with porous media, respectively.

The temperature parameter indicates that the temperature within the confine of absorber is higher in double pass with porous media. This behaviour of the collectors was confirmed by Duffie and Beckman (2006) and Tiwari (2002).

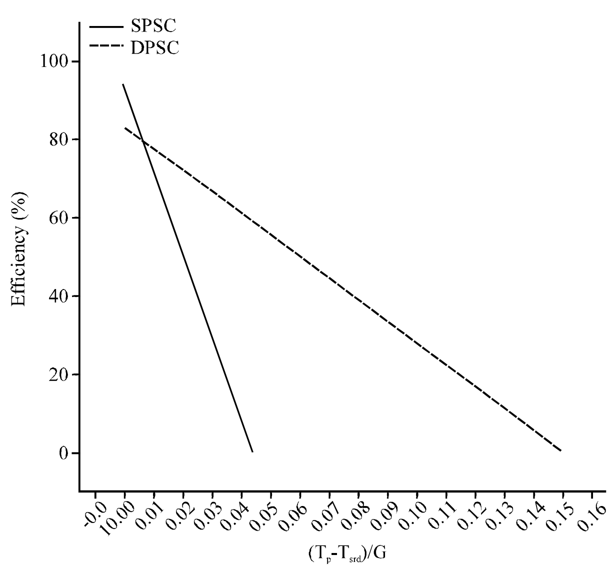

Fig. 3: Typical solar collector efficiency characteristics, $(T_p-T_{srd})/G$: Temperature difference function of the collectors

The output power of the solar collectors against the mass flow rate of the fluid is shown in Fig. 4. It can be seen from the graph that, when the mass flow rate is 0.1 kg sec^{-1} about 340 Watt of power can be generated from single pass while double pass reflected close to 880 Watt.

This shows clearly that the output of the single pass solar collector is low compared with the double pass, even increase in fluid mass flow rate cannot make any meaningful improvement in the power out-put of single pass solar collector.

The thermodynamic efficiency against mass flow rate has the same pattern of curves in Fig. 4 as reported by Sopian *et al.* (2009).

The ambient temperature is the temperature in the neighborhood of flat plate collector. Therefore, when the increment on ambient was about 15°C, 49 and 67% was recorded for both single and double passes, respectively. It can also be deduced from Fig. 5 that the efficiency

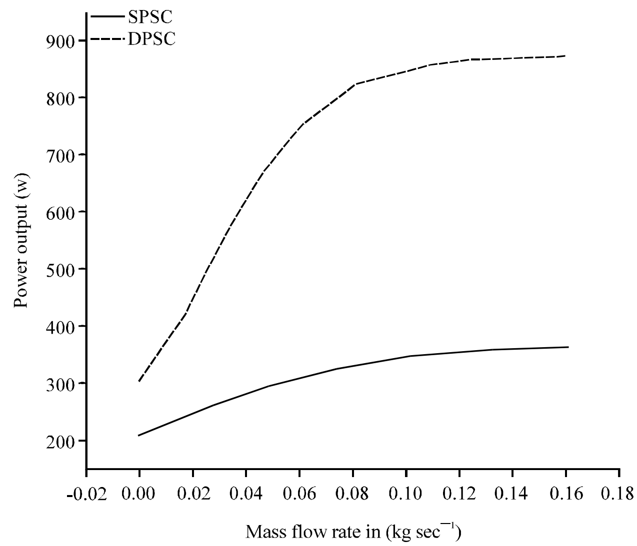

Fig. 4: Effect of mass flow rate on thermal output power

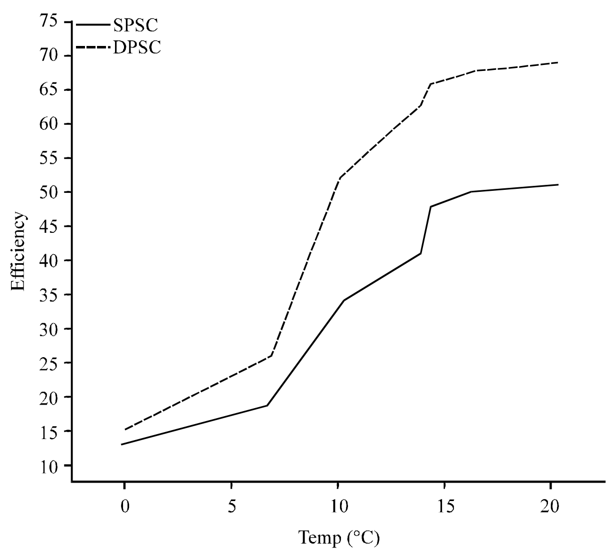

Fig. 5: Variation of performance efficiency with increment in ambient temperature

of the single pass solar collector may not exceed 52% efficiency despite increment of about 20°C from the ambient temperature of 31°C. But double pass solar collector can reach around 70% of efficiency within this range of increment in temperature.

This is due to the fact that the double pass collector retains some of the heat loss by single pass solar collector through the cover, absorber and insulating material. Furthermore, the presence of heat retaining material, the porous media has added more to the efficiency of the double pass. This is similar to the report of Aldabbagh *et al.* (2010).

Future development: It was observed that improvement can be made on the solar collectors if the heat loss can be reduced or brought to negligible value. This is the idea that is behind the study of a collector in which the working fluid would be able to have more than two pass called multi-pass as reported by Karim and Hawlader (2004).

CONCLUSION

The study has tried to reflect the basic differences between the conventional single pass solar collector with a plane of glass as a glazing material with the double pass solar collector with porous media, gravel at the lower channel of absorber plate. It was shown that enormous amount of heat is loss at various boundaries that surrounded the absorber plate. Therefore, heat loss is greatly reduced in the double pass and the gravel assisted in heat retention. Suggestion of multi pass solar collector was also made for further improvement on performance efficiency.

ACKNOWLEDGMENTS

The conducive environment that aids research activities established by PETRONAS and the authorities of the Universiti Teknologi PETRONAS are highly appreciated.

NOMENCLATURE

α = Absorptance
ρ = Reflectance
τ = Transmittance
$C_{g,in}$ = Inner glass cover
$T_{g,in}$ = Temperature of the inner glass (°C)
T_{srd} = Temperature of surrounding, sky (°C)
h = Convective heat trans. coefficient(W m^{-2} °C^{-1})
q = Heat transfer (W m^{-2})
$\dot{m}$ = Mass flow rate (kg m^{-2} sec^{-1})
A = Absorber surface area (m)
η = Collector efficiency (%)
t = Thickness (mm)
Nu = Nusselt number
L = Distance between the glass and plate (m)
F_R = Heat removal factor from plate
U_T = Plate total loss coefficient (W m^{-2} °C^{-1})
k = Conductivity (W m^{-1} °C)
C_p = Specific heat capacity at constant pressure
β = Tilt angle, vol. heat expansion coefficient
θ = Angle of incidence, collector tilt angle
G = Solar radiation intensity (W m^{-2})

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