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Evacuated tubular or classical flat plate solar collectors?

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Abstract

Evacuated tubular solar collectors are increasingly used all over the world due to their low coefficients of heat losses to the environment. They are presented as devices that collect much larger quantities of solar energy than are usually obtainable from typical flat collectors. However, they suffer from the poor radiation transmissivity characteristics of the transparent shield covering the absorber. This makes the profits in terms of energy gain in the operating conditions of a typical solar power system in Poland only slightly dependent on the nature of the solar collectors used. This article seeks to explain this phenomenon through theoretical considerations.

Keywords: solar energy, solar collector, domestic hot water.

1. Introduction

Classic flat-plate solar collectors have met competition in recent years from various forms of vacuum tube collectors. As regards new installations, evacuated tube solar collectors have outstripped classic flat plate collectors in terms of total power installed since 2008 [1].

Vacuum solar collectors are typically used in DHW (Domestic Hot Water) systems. Vacuum tube solar collectors are commonly viewed as devices having significantly higher performance than ordinary flat plate collectors. This reputation may well generally be true for specific collector operation conditions when the ambient temperature is very low and solar radiation falls at a near right-angle to the collector plane. The advertising materials of commercial dealers usually provide only the performance of collectors at a solar radiation incident normal to the plane of the collector, when the equipment reaches its maximum energy potential. Under normal operating conditions this angle is variable, which may effect a radically different collector performance from the one expected. Recent investigations demonstrate that during typical operation evacuated tube collectors show an advantage over flat collectors mainly at operating temperatures exceeding an ambient temperature of 40°C [2].

2. Solar vacuum collectors

There are several designs of vacuum solar collectors [2, 3]. The most widely used types of evacuated tube collectors are shown in Fig. 1. Vacuum collectors certainly have much lower rates of heat loss to the environment than flat plate collectors.

However, the poor solar radiation transmissivity of their cylindrical glass envelopes causes much smaller values of solar energy to be accumulated in certain ranges of radiation incidence angles compared to the energy obtained by flat plate collectors working in

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the same conditions.

In all solar energy collectors there are three characteristic energy processes: absorption of solar radiation, energy loss to the environment and the useful energy extracted from the collector. These last two processes are coupled to each other and the energy received from the collector by the user closes the energy balance of the collector for specific conditions of its operation.

In particular, the collector yield increases with the rate of absorption of solar radiation reaching the collector face, but is reduced by energy losses to the environment from the hot absorber surface. Therefore, the construction of solar collectors strives to maximize absorption of solar radiation (high values of the absorber cover absorptance for the solar radiation spectrum in the wavelength range $0.3<\lambda<3.0$ μm) and simultaneously minimize heat losses to the environment.

There are two possibilities to reduce heat losses: application of selective absorber covers (low absorber layer emissivity for infrared radiation $\lambda>3$ μm reduce radiation losses) and minimizing or sometimes even eliminating convection and conduction losses through the layer of gas filling the space between the absorber and the transparent cover of the collector. Vacuum solar collectors have the lowest rates of convection/conduction heat losses to the environment. The overall coefficient of heat loss U_L for flat plate solar collectors is usually in the range 3.9–5.5 W/m^2/K, and for evacuated collectors 1.5–2.5 W/m^2/K.

To ensure the required physical robustness, in a vacuum system the solar collectors are usually composed of cylindrical shape glass elements with the absorber placed inside a glass shield. The glass tube is usually made from borosilicate glass.

There are two basic designs of vacuum collectors. The first, shown in Figures 1A and B, are evacuated tubes with a flat absorber placed inside. Removal of collected solar energy is by heat pipes/Field tube heat exchangers (Fig. 1A) or a U-tube (Fig. 1B) fastened to the absorber plate. Tubular elements are generally arranged in parallel without spaces between the pipes.

In the design shown in Figure 1C and D the collector is simply an elongated tubular Dewar vessel with an absorbing layer sputtered on the surface of the inner vessel glass wall. Reception of the absorbed energy can be realized by the direct flow of the energy carrier (water) through the inner vessel space, Fig. 1D, or by the U-tube with cylindrical fins made of copper or aluminum foil inserted in the element, Fig. 1C. This second way of removing useful energy from the collector, due to the inevitable heat contact resistance between the metal foil and glass, decreases the efficiency of the collector by about 5 to 6% compared with the direct-flow system [4]. Generally, C and D varieties of collectors have an approximate maximum performance of 60% compared to 80% for flat plate collectors [5]. However, they are the most widely used because of the increasing reliability of construction.

Since these collectors have an absorbing layer surface around the circumference of the inner glass tube, the cylindrical glass pipe elements are not placed directly next each to other, but spaced at a distance of 1–2 diameters of the elements with diffuse reflectors placed at the bottom [6].

3. Transmission of solar radiation through the collector transparent covers

The useful collector energy gain Q_u received within a specified time (day, week, month, etc.) can be described by the Hottel-Whillier-Bliss equation [7, 8]:

$$Q_u = A_k F_R \left[H\left(\overline{\tau\alpha}\right) - U_L \left(\overline{T}_{w,avg} - \overline{T}_a \right) \right] \qquad (1)$$

In the above equation the transmissivity – absorptivity product $(\tau\alpha)$ is a strong function of the radiation incidence angle and collector material properties, namely the glass cover transmissivity τ and the absorber surface absorptivity α.

For the flat plate collector, radiation incidence angle θ is the same for each point of the glass cover, so each point of the absorber achieves the same amount of solar energy. The functional dependence of $(\tau\alpha)$ on incidence angle θ is one-dimensional and usually is presented in the form:

$$(\tau\alpha)_\theta = K(\theta) \cdot (\tau\alpha)_{\theta=0} \qquad (2)$$

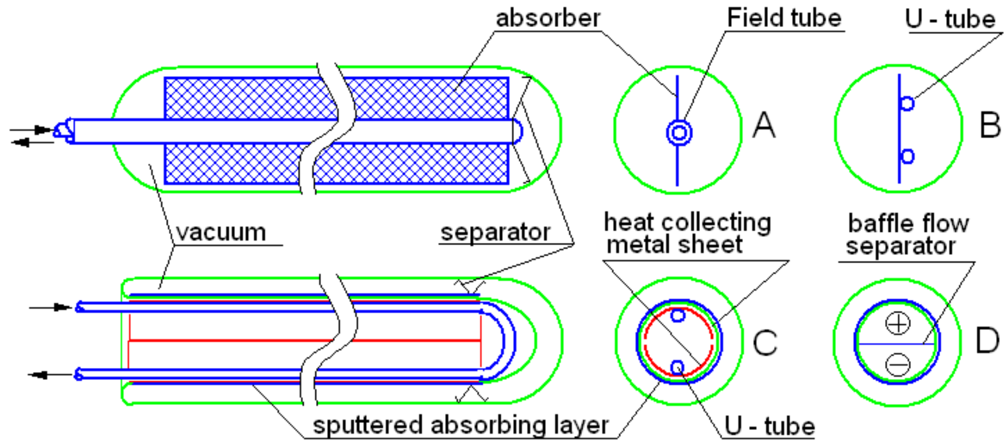

Figure 1: Two basic vacuum solar collectors design. A and B types are sometimes named as "Dornier-type" collectors, while C and D types are known as "Sydney type" or "all-glass vacuum tube"

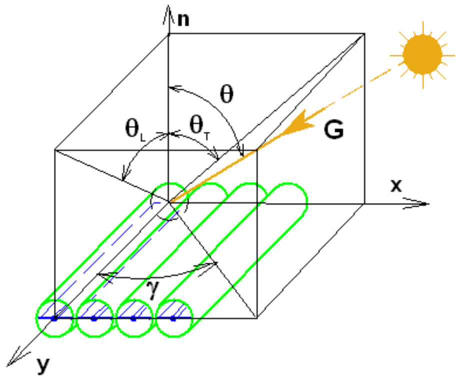

Figure 2: Solar radiation incidence angles (in collector face plane) for a sloped solar tubular collector facing south. θ - normal incidence angle, θ_T - transverse incidence angle, θ_L - longitudinal incidence angle

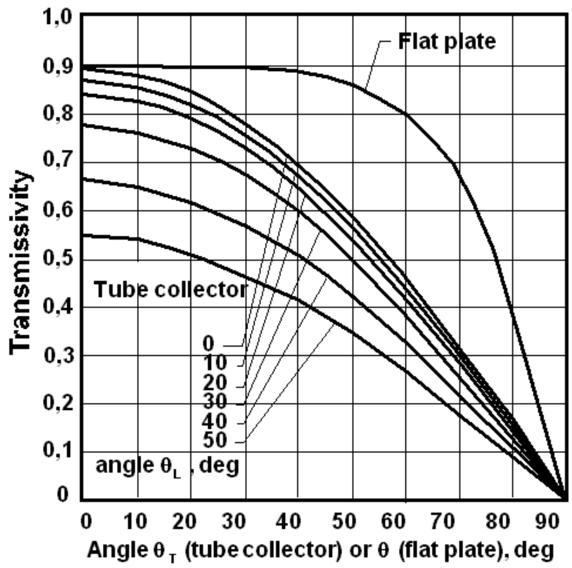

Figure 3: Dependence of cover transmissivity on the solar radiation incidence angle, for the flat plate collector [8] and evacuated tube, types A and B [3]

where $(\tau\alpha)_{\theta=0}$ is transmissivity - absorptivity product for the incidence angle equal to 0 (radiation direction perpendicular to the collector plane). Typical value of $(\tau\alpha)_{\theta=0}$ for single glassed flat solar collector is 0.75–0.82.

$K(\theta)$ is an incidence angle modifier. The angular dependence of the incidence angular modifier $K(\theta)$ is most often approximated by the simple function:

$$K(\theta) = 1 - b\left(\frac{1}{cos(\theta)} - 1\right) \qquad (3)$$

where b is a constant from the range $0.1 < b < 0.2$ dependent on the collector construction.

For evacuated tube collectors the incidence angle dependence can be much more complicated and the incidence angle modifier is not dependent on one single incidence angle only. Instead, the incident radiation beam must be split into two components: longitudinal and transverse to the collector tube. For each beam radiation component the incidence angle can be defined as it is shown in Fig. 2 – transverse θ_T and longitudinal θ_L incidence angles. The transmissivity of the glass tube is a function of these angles and each point of the flat absorber inside tube has a different energy gain along the x direction (across the tube), Fig. 2 and 3. The transmissivity of tubular

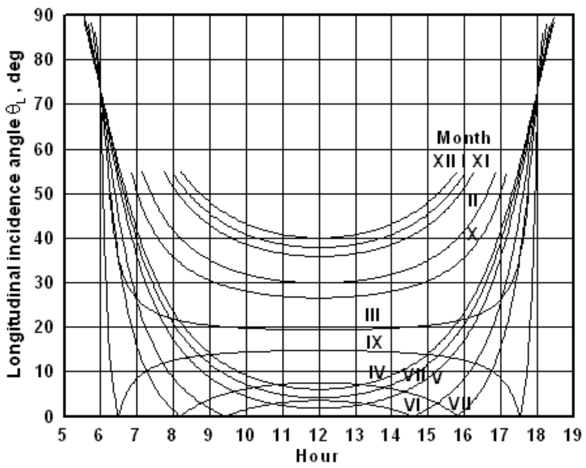

Figure 4: . Longitudinal incidence angles θ_L for a south facing plane sloped at 35° to the horizontal

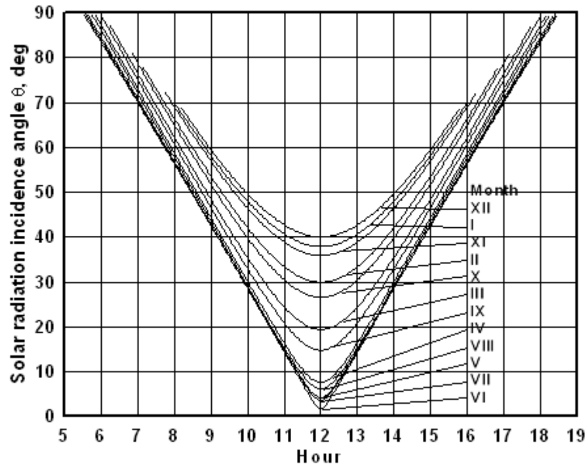

Figure 5: Normal incidence angles θ for a south facing plane sloped at 35° in respect to the horizontal level

shell of types A and B can be related to these angles and finally the transmissivity-absorptivity product, according to Theunissen [9], can be expressed as

$$(\tau\alpha)_\theta = K_T(\theta_T) \cdot K_L(\theta_L) \cdot (\tau\alpha)_{\theta_T=0,\theta_L=0} \qquad (4)$$

where $K_T(\theta_T)$ and $K_L(\theta_L)$ are the transverse and longitudinal angle modifiers. Fig. 3 presents exemplary transmissivity of A and B types of tubular glass collectors dependent on angles θ_T and θ_L. $K_T(\theta_T)$ and $K_L(\theta_L)$ can be approximated using the same cos function as (3) with b coefficients. The same figure shows typical transmissivity incident angle dependence for a flat plate collector. Dewar type collectors C and D have a more complex relation for angle modifiers, as they are a function of three variables [3].

Relations (3) and (4) are valid for beam radiation only. For diffuse radiation having no specified direction Theunissen [9] recommends constant equivalent transmittance equal to that for beam radiation reaching collector surface with angles $\theta_T = 37°$ and $\theta_L = 57°$.

Interestingly, tubular collector transmissivity-absorptivity products for normal radiation incidence angles $\theta_T = 0$ and $\theta_L = 0$ are significantly lower than those for flat plate collectors. Without the booster reflector placed under the tube bottoms their values fall into the 0.5–0.75 range compared to 0.75–0.82 for flat plate collectors. Therefore, efforts have been made to design a flat glass vacuum collector in which the angular relationship of transmittance is one-dimensional [10]. Moreover, it is clear from Fig. 4 that the temporary energy amount collected by the vacuum collector is comparable to that for the flat plate only when both radiation incidence angles θ_L and θ_T are close to null (the radiation beam is perpendicular to the collector plane).

4. Operating conditions for flat plate and evacuated tube solar collectors

The angle of incidence of solar radiation on the collector plane changes constantly, depending as it does on the track of the sun across the sky. It also depends on the location of the collector (site latitude, collector inclination to the horizontal and orientation to the south). The graphs and calculation results presented below are valid for Warsaw, Poland (latitude 52° North).

In Polish conditions the collector tilt angles that maximize energy gain fall within the limits 25–60°, depending on the anticipated period of operation [7]. Fig. 5 shows the monthly average angles of incidence as a function of hours of the day (true solar time) for a flat plate collector facing south, tilted at an angle of 35° (optimal angle for the key operating period of early spring to late autumn). The values of θ presented in this figure can be used to determine the average monthly rates of transmissivity-absorptivity products $(\tau\alpha)$ for flat plate collectors. For evacuated

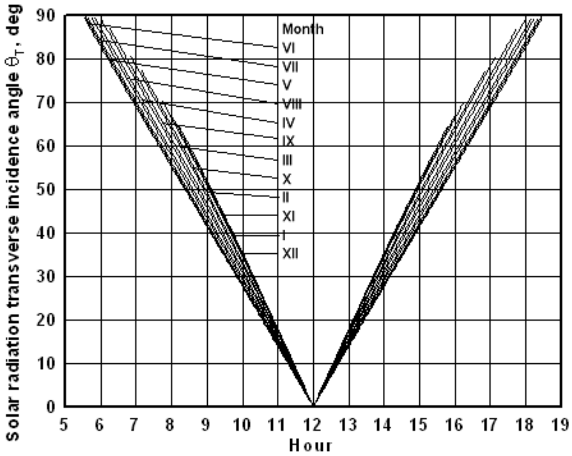

Figure 6: Transverse incidence angles θ_T for a south faced plane sloped at 35° to the horizontal

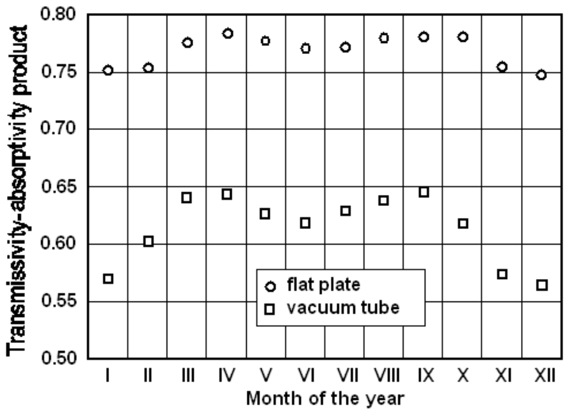

Figure 7: Monthly averaged transmissivity-absorptivity products for the two collectors under consideration. The maximal values $(\tau\alpha)_{max}$ = 0.82 for flat plate collector and $(\tau\alpha)_{max}$ = 0.72 for evacuated tube one were assumed

tube collectors the same relations for longitudinal incidence angles are shown in Fig. 4, and for transverse ones in Fig. 6.

Longitudinal incidence angle θ_L is a weak function of the hour around the solar noon and the main variation of θ_L is related to the month. Greater changes as an hour function occur near sunrise or sunset, but at that time the solar radiation flux density is very low.

On the other hand the transverse incidence angles θ_T are almost the same for consecutive months and a strong dependence is seen along the day hours only, Fig. 6.

Application of the incidence angles presented in Figs. 5–6 to the transmissivity functions from Fig. 3 allows one to determine averaged monthly transmissivity-absorptivity products for chosen solar collectors using the procedures presented in [7, 8].

Two kinds of solar collectors have been selected for comparison – a typical flat plate single glazed vs. evacuated tube of A or B type. Fig. 7 presents monthly averaged transmissivity-absorptivity products of that collector for consecutive months in a year. The points shown in Fig. 7 were obtained on the assumption that maximum transmissivity-absorptivity products for radiation falling normal to the collector plane were $(\tau\alpha)_{max}$ = 0.82 for the flat plate collector and $(\tau\alpha)_{max}$ = 0.72 for the evacuated tube.

5. Energy gain of Solar Domestic Hot Water Units depending on type of solar collectors used

Energy yields given by the solar collector depend strongly on the type of equipment, the required temperature at the output of collector and the climatic conditions. In particular, the following are key climatic parameters: solar flux density, its diffuse radiation ratio and outdoor temperature. In order to assess the expected gains of energy derived from the use of equipment with related types of collectors, the calculations were performed using the F-Chart method [7, 8]. The calculations were made for average climatic conditions in the region of Mazowsze, which may be considered broadly representative of Poland [7]. Two solar DHW units were compared. These units were assumed to have the same size but with different types of solar collectors.

The following additional assumptions were made:

- The solar equipment is to work throughout the year;
- each DHW unit is equipped with collectors with an effective absorbing surface area of 6 m^2 and a storage tank with capacity of 300 dm^3;
- the collector loop is connected to a heat exchanger located in the storage tank;
- the collectors face south and are tilted at an angle of 35° to the horizontal;

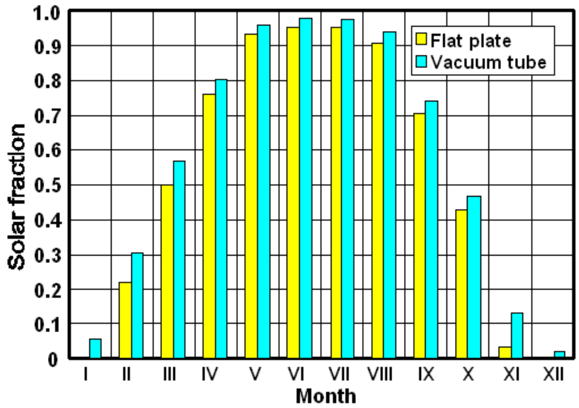

Figure 8: Comparison of an average monthly solar fraction for two analysed DHW units

- daily hot water consumption is 200 dm^3 and assumed water temperature is 55°C;
- time-averaged transmissivity-absorptivity product $(\tau\alpha)$ was adopted in accordance with Fig. 7 and the mean coefficients of heat losses from the collector to the surroundings were assumed U_L = 4 $W/m^2/K$ for the flat plate collector and U_L = 1.8 $W/m^2/K$ for the evacuated tubes.

The results of these calculations are presented in Table 1 below, while Fig. 8 shows a comparison of the solar fractions in preparing DHW for the two considered types of equipment.

An analysis of the results of the calculations shows that in Polish climatic conditions both collectors have approximately the same energy yields in the summer months. The vacuum collectors demonstrate a pronounced advantage only in the winter months - from November to February, although in those months the angles of incidence of solar radiation give smaller values of the coefficients $(\tau\alpha)$, Fig. 7.

In contrast, in these months the amount of solar radiation reaching the collector surface is negligible and consequently the evacuated collector gathers throughout the year about 9% more energy than the flat plate collector.

The annual energy yields of 1 m^2 of aperture of the collector are 1160 $MJ/m^2/a$ for the flat plate and 1246 $MJ/m^2/a$ for the vacuum collector respectively. While the annual solar irradiation of the horizontal plane at the considered location is 3398.7 $MJ/m^2/a$, the average annual DHW units efficiency are 34.1% for flat plate collectors and 36.7% for the evacuated tubes.

6. Summary and conclusions

The analysis presented in this paper leads to the following conclusions:

- In most solar collector materials provided by their producers the coefficients $(\tau\alpha)$ for solar collectors are usually given for solar radiation incident normal to the plane of the collector, which correspond to the maximum value of $(\tau\alpha)_{max}$. While for flat-plate collectors the change of $(\tau\alpha)$ in a large range of angles of radiation incidence θ is weak, in the case of tube collectors it is very strong. Forecasting the performance of evacuated tube collectors based on knowledge of only the maximum values $(\tau\alpha)_{max}$ may lead to a significant overestimation of collector energy gain.
- In view of the anticipated operation of the solar hot water system only during the summer months, in our climatic conditions there is no clear advantage over vacuum flat plate collectors. It should also be taken into account that vacuum tube solar collectors are on average twice the price of flat plate collectors. In addition they usually occupy a much larger area (gross collector surface of a flat plate collector is a few percent greater than the absorber surface, while for the vacuum collectors the respective differences attain 50%). The weight of a vacuum tube collector is often greater than flat ones of the same collecting area and sometimes the construction of special platforms to ensure rigidity of the collector structure is required.
- Vacuum tube solar collectors are much more sensitive than flat plate collectors in terms of optimal inclination angle. As is seen in Fig. 3 increasing the θ_L incidence angle rapidly reduces the transmissivity of the glass tube, so the solar energy yield is smaller. Therefore, for the projected year-round operation of the vacuum tube collector, optimal tilt angles should be selected

Table 1: Results of calculations

Month	Climatic data				Flat collector		Evacuated tubes collector	
	$\overline{T}_a$	φ	H_h	H_{35}	F	E_{sol}	F	E_{sol}
-	°C	%	MJ/m^2/day	MJ/m^2/day	-	MJ/month	-	MJ/month
I	-3.1	73.6	2.00	3.09	0.0	0.0	0.059	68.7
II	-2.2	65.2	4.29	6.02	0.217	229.1	0.301	317.8
III	1.6	58.0	7.59	9.31	0.500	571.3	0.567	647.2
IV	7.6	52.6	12.25	13.06	0.761	822.2	0.804	868.2
V	13.8	47.8	16.86	16.32	0.933	1017.1	0.963	1050.2
VI	17.3	49.5	17.80	16.45	0.952	980.4	0.980	1009.5
VII	19.1	51.0	17.00	16.00	0.954	1014.9	0.976	1039.3
VIII	18.2	48.3	14.64	15.04	0.910	968.1	0.940	1000.5
IX	13.8	53.2	9.68	11.34	0.706	744.6	0.742	781.4
X	7.8	56.3	5.46	7.73	0.427	476.8	0.470	524.0
XI	2.5	69.4	2.42	3.74	0.035	38.2	0.129	142.1
XII	-1.1	77.2	1.42	2.21	0.0	0.0	0.020	28.1
Annual totals:			3398.7	3667.2	-	6862.6	-	7477.0
			MJ/m^2/a	MJ/m^2/a		MJ/a		MJ/a

for the winter months. However snow falls disturb the transmission of radiation through the tube glass shield. The excellent vacuum insulation of the absorber hinders snow melt and finally limits the operating time of the collector.

- For solar domestic hot water systems where the required temperature of warm water is not too high, there is no clear superiority of vacuum solar collectors over the much cheaper flat plate collectors. Some evacuated tube collectors having $(\tau\alpha)_{\max} < 0.6$ (most equipment with C type collectors from Fig. 1) may even work worse than conventional flat plate collectors. This is the effect of additional heat resistances imposed by the collector construction (the inner glass tube absorbs solar radiation and the heat generated is transferred to the energy carrier fluid not directly, but through additional metal elements in the tube).

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