THE PUBLISHING HOUSE
OF THE ROMANIAN ACADEMY

PROCEEDINGS OF THE ROMANIAN ACADEMY, Series A,
Volume 25, Number 3/2024, pp. 193–199
DOI: 10.59277/PRA-SER.A.25.3.05

WEAKNESSES OF STEADY STATE ANALYSIS WHEN USED FOR SELECTING SOLAR AIR HEATERS

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Abstract. The paper highlights the constrains faced by the user when choosing the most appropriate solar collector from a set of collectors belonging to the same category. Two basic kinds of one porous and one non-porous with single flow/pass flat solar air heaters were tested. The collectors have the same size but different internal shapes and absorber materials. The two collectors were tested and a shading procedure was implemented in order to emphasize several aspects related to the thermal inertia of the collectors. Comparison has been made between the efficiency values obtained experimentally. The shade test shows a faster decrease of the outlet air temperature for V-porous absorber collector in comparison with the U-corrugated absorber collector *i.e.* 6 °C and –3.5 °C respectively in a time interval of 74 s. Exposing the collectors on a fresh heating cycle under a low stability radiative regime (450–750 W/m^2) one observe that 60% of the first 180 s the corrugated collector outperforms the porous collector; after that interval of time the porous collector becomes more effective. The low thermal inertia of the solar air collectors yields high variation of the thermal efficiency in days with low stability of the radiative regime. In such days, using measured series of solar irradiance data with long sampling period between two successive measurements does not allow a proper choice of the most appropriate solar collector type.

***Keywords**:* solar air heater, steady-state analysis, cloudy days.

1. INTRODUCTION

Solar air heaters (SAHs) can be classified under two basic categories [1, 2]: SAHs with non porous absorber plate [3] (*e.g.* conventional air heaters, air heaters with fins, Vee-corrugated air heaters, double exposure heaters, double flow solar air heaters, two pass solar air heaters) – and SAHs with porous absorber plate [4] (*e.g.* packed bed solar air heaters, overlapped glass plate air heaters, matrix air heaters, honeycomb porous bed air heaters, all plastic solar air heaters). In the recent years, the research on SAHs was focused on enhancing the overall thermal efficiency -by increasing the absorbance of the absorber plate, maximizing the solar heat transfer area, optimising the collector geometry, stabilising the heat transfer process – and, on reducing manufacturing and operating costs. A considerable amount of literature exists on using new materials, innovative geometries and more effective heat transfer procedures. Due to the large volume of information, many review papers have been published [5–14].

Presently, the data provided by the manufacturers for the performance of SAHs refer to standard steady-state operation. But SAHs operation is highly sensitive to the short-time variations of the incoming solar energy flux, due to the low thermal inertia of the working fluid and to the poor heat convection transfer from the absorber plate to the air stream. Therefore, SAHs performance evaluation by experiments under steady-state conditions or under slow time-dependent conditions is not fully relevant. Indeed, steady-state operation is the special rather than the common case since the radiative regime is usually variable [15–17].

Therefore, the available manufacturer information concerning the SAHs steady-state operation should be considered with care, when the users are choosing among different types of SAHs.

The paper shortly outlines several difficulties related with the SAH selection. A controlled shading procedure was implemented in order to quantify the SAHs thermal inertia. The procedure is exemplified by showing experiments performed for two basic SAH types.

2. TESTING OF SAHS

Two basic flat SAHs, single flow/pass, were considered. They have the same size but different internal shapes and absorber materials. The first SAH has a porous absorber plate while the second SAH has a non porous absorber plate. The porous SAH (V-porous absorber collector) has a double layer of steel fine mesh [18–22]. The non porous SAH (U-corrugated absorber collector) has an aluminium corrugated sheet and three straight baffles [23–28]. The two SAHs have been experimentally analized under the same meteorological conditions.

2.1. Experimental setup

The SAHs used for experiments were placed at Polytechnic University of Bucharest, (44° 26' North, 26° 6' East and 63 m altitude above mean sea level). The experimental studies were conducted during September and October 2014. The collectors slope was adjusted to 55°, which is considered adequate for geographical location of Bucharest (Fig. 1). The SAHs have one single glass cover. The SAH module consists of the absorber, glazing, insulation, back and front plenum and a wood collector frame to assemble these components. The casings were made of wood. The back and edges of the both SAHs were insulated in order to avoid heat dissipation. The insulation is made of polystyrene. Table 1 shows design details for the V-porous absorber collector and U-corrugated absorber collector.

a) b) c)

Fig. 1 – U-corrugated absorber collector (UCAC) and V-porous absorber collector (VPAC [29]):
a) the collectors structure: 1. air fan; 2. humidity transducers; 3. pressure transducers; 4. air inlet; 5. porous absorber; 6. fins; 7. thermal transducers; 8. pyranometer; 9. air outlet; 10. U-corrugated absorber); b) experimental setup;
c) absorber plates of the U-corrugated absorber collector (left) and V-porous absorber collector (right).

Identical air fans were mounted at the outlet section of the collectors in similar positions and the air velocity throughout the collectors was settled down at 1 m/s. On the bottom side of SAHs boxes an identical grid of thirty-two thermal sensors was mounted in order to measure the air flow temperature near the absorber surface. Humidity, static pressure and air velocity control sensors were installed, in the same positions, inside the collector. All the measured parameters, including wind velocity and solar irradiance were sampled simultaneous for both SAHs at time intervals of 10 s.

Table 1

Parameters of solar air collectors used in this study [29]

Parameters	VPAC	UCAC	Units
Collector absorber area	1.25	1.25	m^2
Height of the collector	0.085	0.085	m
Number of transparent covers	1	1	–
Transparent cover absorbance	0.2	0.2	–
Absorber metal	soft steel	Aluminium	
Absorber emissivity	0.8	0.1	–
Absorber area	3.15	3.4	m^2
Absorber thickness	0.0007	0.0007	m
Absorber density	7820	2700	kg/m^3
Absorber layer	2	1	–
Specific Heat of the soft steel	502.4	904	J/kg K

2.2. Procedure used to process experimental data

Measurements were performed in order to obtain the dynamic thermal characteristics for each collector. The useful heat flux transferred to the air is obtained by using the air temperature variation across the collector, according to the following equation [30]:

$$Q_u = \dot{m}_a C_{p,a}\left(T_{a,\text{out}} - T_{a,\text{in}}\right), \tag{1}$$

where $T_{a,\text{in}}$ and $T_{a,\text{out}}$ is the inlet and outlet air temperature, respectively, while $\dot{m}_a$ is the air mass flow rate given by:

$$\dot{m}_a = \rho_a \dot{V}_a = \rho_a v_a \frac{\pi d^2}{4}. \tag{2}$$

Here $\dot{V}_a$ is the volume of the air leaving the collector by the duct with diameter d; v_a is the air speed and ρ_a is the density of air. The specific heat of air is assumed to vary linearly with temperature (°C) by [31]:

$$C_{p,a} = 1.0057 + 0.000066\left(T_{a,m} - 27\right), \tag{3}$$

where: $T_{a,m} = (T_{a,\text{out}} - T_{a,\text{in}})/2$ is the average air temperature inside the collector.

The thermal efficiency of the collector, η, is given by: [32]:

$$\eta = \frac{Q_u}{A_c G_T}, \tag{4}$$

where A_c is collector surface area and G_T is the solar global irradiance incident on the collector surface.

2.3. Experimental results

A large number of experiments were accomplished during days with clear sky, simultaneously for both SAHs, in two scenarios.

In the first scenario, the performance of the SAHs has been evaluated under direct exposition to solar radiation. During experiments the incident solar irradiance ranged between 900 and 950 W/m^2, which is typical for a clear sky autumn day around the noon. Figure 2 shows sample results. The thermal efficiency of the V-porous absorber collector is close to 58% while for the U-corrugated absorber collector it reaches only 42%. Therefore, the experimental data show that in the first scenario the V-porous absorber collector is more effective than U-corrugated absorber collector.

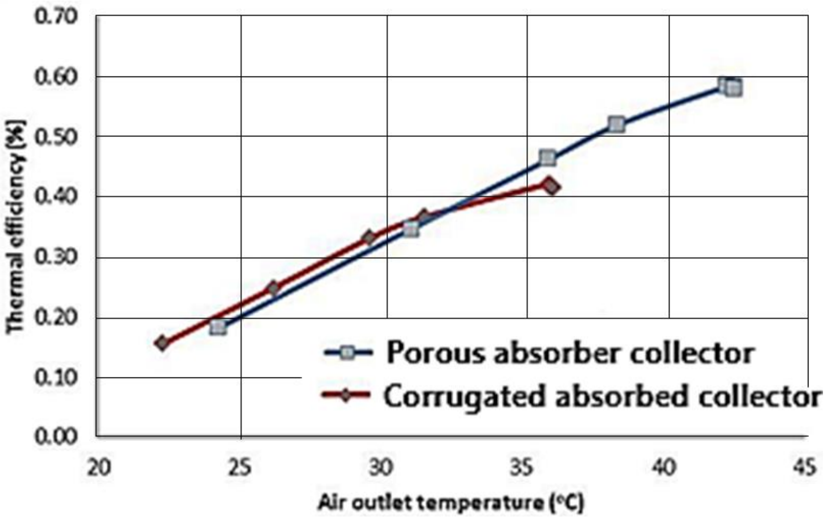

Fig. 2 – Sample experimental results showing the efficiency of the collectors as a function of outlet air temperature during clear sky days.

However, the results of the first scenario are not totally relevant for long term SAHs operation. Indeed, in some temperate climates cloudy sky days are much more frequent than clear sky days. During a cloudy day the solar irradiance incident on the collector changes in time and this determines a change of several thermal parameters of the collector, including its thermal efficiency. The speed of change of these parameters is a measure of the thermal inertia of the collector. Therefore, in the second scenario shading tests have been performed. A simple shading simulator has been built for this purpose. It consists of a cover being placed in front of both SAHs (see Fig. 3).

Fig. 3 – Simple shading test setting.

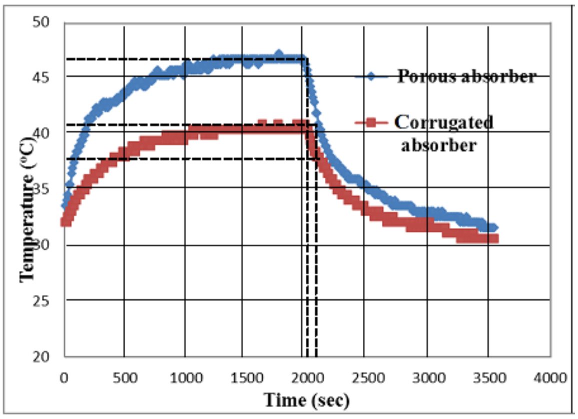

Fig. 4 – Sample experimental results of the simple shading test -time variation during a clear day of the outlet air temperature UCAC and VPAC.

The simple shading test was performed for a time interval considered long enough (*i.e.* 3 600 s) until equalizing the outlet temperature of both SAHs to the outdoor temperature *i.e.* 31°C. Figure 4 shows sample results concerning the variation of the outlet air temperature during the time interval before the time when the cover is placed over the collectors and after that time. During the time interval of direct exposure to sun radiation, both collectors had a similar behavior, *i.e.* the outlet air temperatures of the collectors increase. The outlet air temperature of the V-porous absorber collector decreases quickly during the time interval with the cover placed over the collectors. The slope of the decreasing temperature of the V-porous absorber collector is steeper than that of the U-corrugated absorber collector. One observes that after 74 s from starting the shade test the outlet air temperature decreased with 6 °C for the V-porous absorber collector (from 47 °C to 41 ºC) and became equal with the initial outlet air temperature of the U-corrugated absorber collector. For the case of U-corrugated absorber collector, in the same interval of time the temperature decreased from 41 ºC to 37.5 ºC – this means a temperature variation of –3.5 ºC.

Taking into account the rapid decrease in output temperature for the porous collector when compared to the corrugated collector, one chose to investigate the behavior of both collectors when exposed to solar radiation in a fresh heating cycle but under a low stability radiative regime. Figure 5 depicts sample experimental results for the variation in outflow air temperature after exposing the SAHs. During this interval the incident solar irradiance ranged between 450 and 750 W/m^2 as presented in Table 2.

For the first 105 seconds the sun irradiance is unstable and the corrugated collector is more efficient. For the next 65 seconds the radiative regime is more stable and the output temperature of the porous collector increases slightly faster than the corrugated collector.

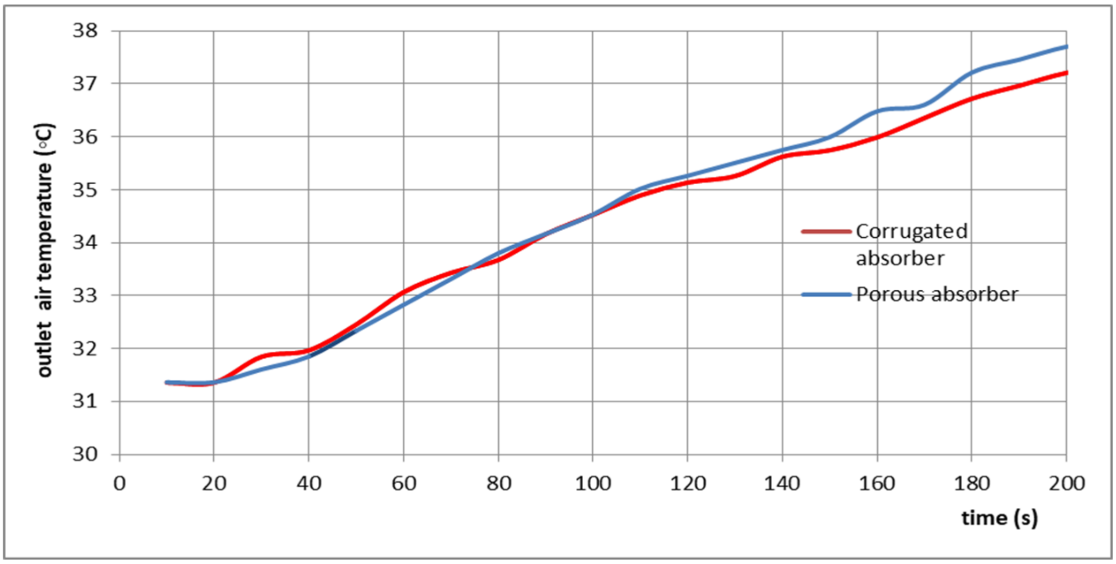

Fig. 5 – Sample experimental results – time variation for unstable solar radiative regime of the outlet air temperature corrugated collector UCAC and porous collector VPAC.

Table 2

Variation of solar irradiation during heating up process

Time (s)	0–20	21–40	41–50	51–105	106–170	171–200
Solar irradiance (W/m^2)	560	575	450	620	750	800

Finally, after 180 seconds, the radiative regime is totally steady, and hence the porous collector has a greater output temperature than the corrugated collector, as shown in Fig, 4. The shading test for this case scenario demonstrates that over a 3 minutes heating operation, the corrugated collector outperforms the porous collector around 60% of the time. As a result, if a series of solar irradiance data is obtained with large sample durations between two successive measurements (for example, more than 170 seconds in the case study), the results do not allow for a realistic selection of the best solar collector type.

If long intervals for data sampling are available, the thermal system could be identified by considering the shadow tests as a step response of the solar heaters. This can indicate a first-order system might be an appropriate model for SAH. But the model may be improved because the cooling down process is faster than the warming up one. Therefore the system is not a simple first order one. Still the transfer function could be useful for an effective approximate model i.e. typical utilization for the time domain.

3. CONCLUSIONS

Solar air heaters (SAHs) are highly sensitive to variations of the solar irradiative regime due to the poor heat convection from absorber plate to the internal air stream. The objective of this paper is to highlight the weaknesses of the steady state analysis, when used for selecting SAHs operating in climates with cloudy skies.

Two SAHs were selected in order to cover the main types of such devices: one porous and one non-porous with single pass/flow – with the same geometrical dimensions. The two SAHs were tested during clear sky operation to obtaining their basic characteristics and thermal efficiency. A shading test was also accomplished.

The best thermal efficiency of the two collectors considered here was 58% for V-porous absorber collector and 42% for U-corrugated absorber collector respectively – for a global solar irradiance of 935 W/m^2. Generally, the V-porous collector is 2–10% more efficient than the “U”-corrugated plate collector.

The shade test shows a faster decrease of the outlet air temperature for V-porous absorber collector in comparison with the U-corrugated absorber collector. The decrease of mean air temperature at the collector outlet for the V-porous absorber collector and for the U-corrugated absorber collector were registered, in a time interval of 74 s, –6 ºC and –3.5 ºC respectively. The shade test was completed by exposing both collectors to solar irradiation in a fresh heating cycle under a low stability radiative regime – between 450 and 750 W/m^2. During the heating up process of 3 min, in 60% of the time the corrugated collector outperforms the porous collector. After 3 minutes the porous collector becomes more efficient. These results shows the risk that by using large sampling periods especially at low stability radiative regimes errors when computing the collectors thermal efficiency occur.

A major conclusion of this study is that the heating and relaxation time of SAHs must be provided by the manufacturer in order to identify the maximum accepted time interval for outlet temperature. It was revealed that as the frequency of solar irradiation measurements lowers higher errors occur, hence contradictory conclusion when selecting most appropriate air solar collector.

ACKNOWLEDGMENTS

The author Qahtan A. Abed thanks the Ministry of Higher Education in Iraq.

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Received February 4, 2024