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Solar chillers for air conditioning systems

T. Baydyk, E. Kussul and N. Bruce

Department of Information Technology
Centro de Ciencias Aplicadas y Desarrollo Tecnológico, Universidad Nacional Autónoma de México
Circuito Exterior S/N, Ciudad Universitaria, AP 70-186, CP 04510, México D. F. (México)
Tel.:+52 55 56228602,
e-mail: tbaidyk@unam.mx, ekussul@unam.mx, neil.bruce@ccadet.unam.mx

Abstract. Air conditioning systems can use heat energy to reduce electrical energy consumption. For this purpose absorption-type chillers are used. In these chillers only 10% of the energy is supplied as electrical energy and the rest is supplied as heat energy. At present, many chillers of this type are manufactured with solar heating devices. As a rule, flat panel solar heaters are used for this purpose. Unfortunately, the highest temperature of the heaters is slightly lower that is necessary for efficient work of absorption-type chillers. For this reason sometimes evacuated tube solar heaters are used to obtain sufficiently high temperature. Trough solar collectors have also been proposed for this purpose. This increases the cost of solar heaters. At present, this cost equals approximately 100 USD per square meter. We have developed a low-cost flat facet solar concentrator that can have a cost of 20-30 USD in mass production and provides a temperature of about 200ºC that is sufficient practically for all types of absorption type chillers. In this paper we shortly describe the design of the flat facet solar concentrator and its possible applications in air conditioning systems.

Key words

Flat facet solar concentrator, chiller, air conditioning system, thermal energy storage.

1. Introduction

At present many companies produce solar chillers for air conditioning systems [1], [2], [3]. As a rule, they use flat panel solar collectors to supply heat energy for these chillers. The main disadvantage of the systems is the low temperature that can be obtained in flat panel solar collectors. Low temperature decreases the total efficiency of solar chillers. To obtain higher temperature sometimes the companies use vacuum tube flat panels or trough solar concentrators. This increases the cost of solar collectors approximately up to 100 USD per square meter [4].

Recently, we developed a low cost flat facet solar concentrator that has the shape of a parabolic dish [5], [6]. Our estimation of the cost of these concentrators in mass production shows approximately 20-30 USD per square meter [7]. In this paper we propose to use these solar concentrators for residential and district cooling systems.

2. Flat Facet Solar Concentrator

A flat facet solar concentrator contains a large number of triangular flat mirrors supported by a special structure that permits us to approximate a parabolic dish shape (Fig.1).

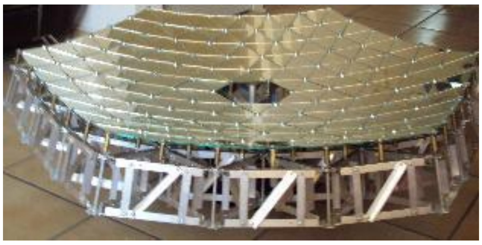

Fig.1 Prototype of flat facet solar concentrator

To adjust the parabolic shape we use a special parabolic gauge [8] that is installed into the central tube (Fig. 2) of the support structure and can be rotated over the special adjustment nuts.

Fig.2 Gauge for flat facet solar concentrator

When the gauge is placed over the nut, the nut position is changed up to contact with the gauge. This method gives the possibility of adjustment of the parabolic shape very fast and precisely [8].

This structure of flat facet solar concentrator makes it possible to organize low cost mass production of these devices. The disadvantage of the structure is the large number of bars and nodes that are used to implement the support structure (Fig. 3). This support structure contains 144 bars of different lengths.

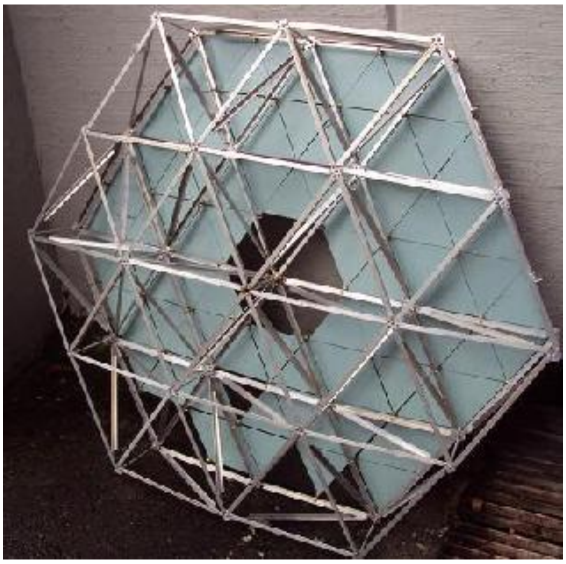

Fig.3 Structure of support frame

To avoid this disadvantage at present we develop a new support structure that contains only 18 bars with length $D/2$ and 18 bars with length $D/4$, where D is the diameter of the circumscribed circle of the support structure. In total this structure contains 36 bars in comparison with 144 bars of the previous version. In Fig.4 and Fig.5 we demonstrate the new structure of the solar concentrator.

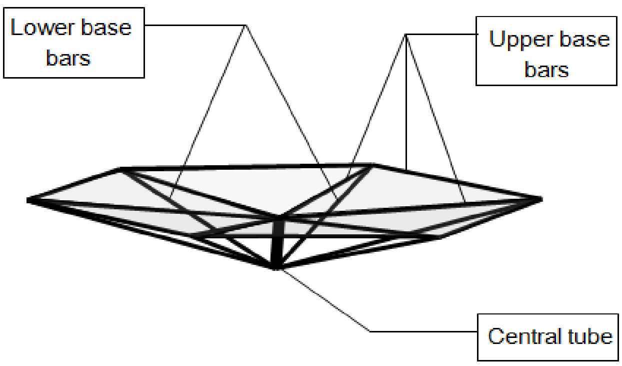

Fig.4. Base bars in the new structure of the support frame for the solar concentrator

Below we make a rough evaluation of the cost of the new solar concentrator. Let us consider the circumscribing circle of the support frame presented in Fig.4. We term the diameter of this circle as the concentrator diameter. We make our calculations for the concentrator of diameter D=3m. It contains lower base bars and upper base bars. The lower base bars are longer than the upper base bars. The average length of base bars for this concentrator is approximately 1.5 m, because they do not reach the central point of the concentrator. They are fixed to the special disks of the central tube subassembly.

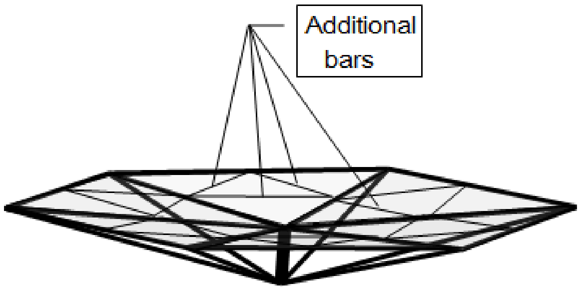

Fig.5 Additional bars in the new structure of the support frame of the solar concentrator

The number of base bars in the concentrator is 18 (Fig.4), so the total length L_{bb} of all base bars is L_{bb}=18*1.5m=27m. We suppose that each base bar is made from steel angle of 25*1.5mm^2. The area of the square section S_{bb} of the angle is approximately equal to S_{bb}=75 mm^2=75x10^{-6} m^2. So the volume of the material needed for all base bars is:

$$V_{bb} = L_{bb} * S_{bb} = 27 * 75 * 10^{-6} = 2025 * 10^{-6}\ \mathrm{m}^3. \qquad (1)$$

The density ρ_{st} of the steel is 7800kg/m^3. The total weight G_{bb} of base bars is:

$$G_{bb} = \rho_{st} * V_{bb} = 7800 * 2025 * 10^{-6} = 15.795 \approx 15.8kg \ (2)$$

At present the cost c_{st} of steel angles is 0.8 USD per kilogram. So the material cost c_{bb} of the base bars is

$$c_{bb} = G_{bb} * c_{st} = 15.8 * 0.8 = 12.64\ .\mathrm{USD}. \qquad (3)$$

Now we analyse the material needed for additional bar manufacture. The number of additional bars (Fig.5) is 18 and the length of every additional bar is 0.75 m. So the total length L_{ab} of all additional bars is

$$L_{ab} = 18 * 0.75 = 13.5\ \mathrm{m}. \qquad (4)$$

Every additional bar is made from steel angle of 15x1.5 mm^2. The area of the square section S_{ab} of the angle is approximately equal to S_{ab} =45 mm^2=45x10^{-6} m^2. So the volume of the material needed for the additional bars is:

$$V_{ab} = L_{ab} * S_{abb} = 13.5 * 45 * 10^{-6} = 607.5 * 10^{-6} \approx 608 * 10^{-6}\ \mathrm{m}^3 \qquad (5)$$

The total weight G_{ab} of the additional bars is

$$G_{ab} = \rho_{st} * V_{ab} = 7800 * 608 * 10^{-6} \approx 4.7kg \qquad (6)$$

The cost of material c_{ab} of the additional bars is

$$c_{ab} = G_{ab} * c_{st} = 4.7 * 0.8 = 3.76\ \mathrm{USD} \qquad (7)$$

The solar concentrator contains adjustment devices (Fig.6) that support the mirrors and serve for parabolic surface adjustment. The adjustment device contains a distance screw, a distance nut and a mirror support nut. For our concentrator of diameter D=3m the sizes of the adjustment device is

$$\begin{matrix} D_1 = 20mm \\ D_2 = 12mm \\ D_3 = 7mm \\ D_4 = 6mm \end{matrix}, \quad \begin{matrix} H_1 = 3mm \\ H_2 = 90mm \\ H_3 = 100mm \end{matrix}. \tag{8}$$

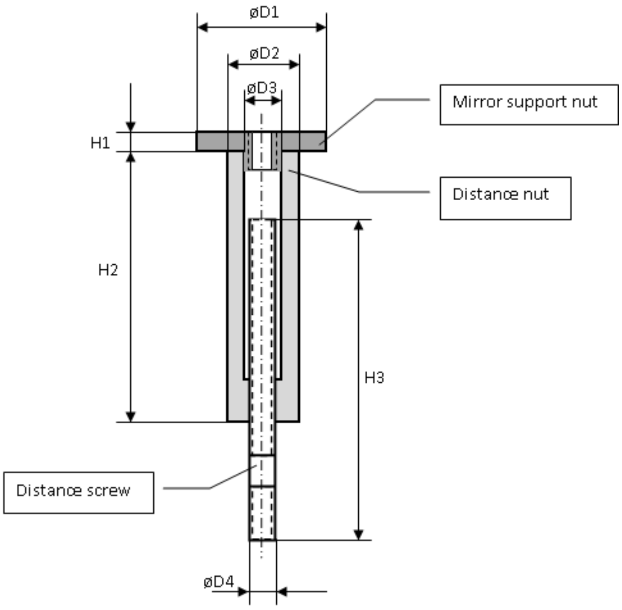

Fig.6. Adjustment device with distance screw and distance nut

The material of the adjustment device is carbon steel. It is easy to calculate that the weight of the adjustment device equals approximately 82 gr. The concentrator shown in Fig.5 contains 66 adjustment devices. So the total weight of the material for all adjustment devices is G_{ad} =5.4 kg. The cost of this material is:

$$c_{ad} = G_{ad} * c_{st} = 5.4 * 0.8 = 4.32 \text{ USD}. \tag{9}$$

Now we evaluate the cost of the flat mirrors c_{mr}. The wholesale cost of flat mirrors on the market is 3-4 USD per square meter. Let us calculate the total area of flat mirrors in our solar concentrator. The size a of a side of an equilateral triangle mirror is:

$$a = \frac{D}{2*Z} = \frac{3}{2*4} = 0.375 \text{ m} \tag{10}$$

where Z is the number of zones, in our case Z=4. The area of one triangle mirror is

$$A_1 = \frac{\sqrt{3}}{4} * a^2 = 0.069 m^2 \tag{11}$$

Our concentrator (Fig.3) contains 90 mirrors. So the total area of mirrors is

$$A_t = A_1 * 90 = 5.48 \text{ m}^2. \tag{12}$$

Taking into account 4USD per square meter of flat mirror we obtain the total cost of mirrors $c_{mr}=A_t*4=5.48*4=21.9$USD.
The total cost of materials for the solar concentrator is C_{bm}

$$C_{bm} = c_{bb} + c_{ab} + c_{ad} + c_{mr} = 12.64 + 3.76 + \\ + 4.32 + 21.9 = 42.62 \tag{13}$$

So the total cost of basic materials C_{bm} for our solar concentrator is approximately 43 USD. We assume that the cost of auxiliary materials (including all the fasteners) is 10% of the cost of basic materials. In this case the total cost of materials:

$$C_{am} = 0.1 * C_{bm} = 4.3 \text{ USD}. \tag{14}$$

The total cost of all materials is:

$$C = C_{bm} + C_{am} = 47 \text{ USD}. \tag{15}$$

All the components of the solar concentrator have very simple design, so in the mass production of the concentrators the manufacture and assembly processes can be made automatically. In this situation we assume that the cost of manufacture and assembly is approximately equal to the cost of materials. In this case the total cost of the concentrator $C_t=2*C=2*47=94$ USD.
If we include the company profit of 20% we have the final cost of solar concentrator $C_c=1.2*C_t=1.2*94=112.8$ USD.
We suppose that the sun tracking device will be cheaper than the solar concentrator and accept it as $0.3*C_c$. To take into account this device we add it to the cost of the solar concentrator; the cost of the sun tracking device is 33.84 USD.
The total cost of installation of the solar concentrator we estimate as 147 USD (112.8+33.84). Our concentrator has a mirror area 5.48 m^2 (equation 12). So the cost per square meter is C_{sm} =26.8 USD.

3. Residential solar cooling systems

The scheme of a residential solar cooling system is presented in Fig. 7.

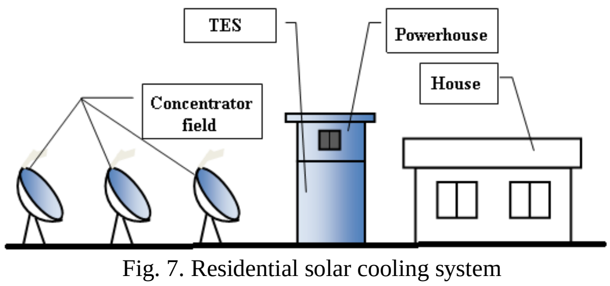

Fig. 7. Residential solar cooling system

The residential solar cooling system contains the field of concentrators that supply solar thermal energy to the absorption chillers located in the powerhouse. In this scheme the powerhouse is built near the house and permits us to use not only ($LiBr+H_2O$)-based chillers but also (NH_3+H_2O)-based chillers that can be used not only for air conditioning system but also for refrigeration purposes if needed. The powerhouse is placed over the thermal energy storage (TES).

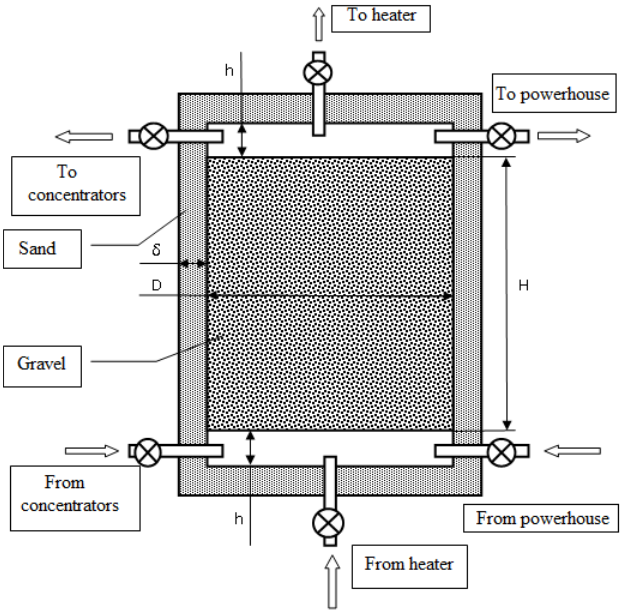

Fig. 8. 24 hours thermal energy storage

In this section we consider the thermal energy storage that can be used for an air conditioning system with 5 KW thermal energy. The TES permits us to store thermal energy during 24 hours. In this article we perform calculations similar to the calculations of a TES for 15 KW thermal energy storage of a power plant [9] that must store thermal energy during one week.

The scheme of TES is shown in Fig.8. The TES is designed as a cylindrical vessel with internal diameter D covered with thermal insulation of thickness δ. The vessel is filled with gravel that serves as thermal storage material. The thermal insulation is made as a dried sand layer. The gravel body has height H. Two free spaces (lower free space and upper free space) are left for hot air intake and outlet. The heat energy is introduced to the TES with hot air that flows from the concentrators to the lower free space, goes through the gravel and comes out through the upper free space. The user obtains heat energy from the upper free space with hot air and returns cold air to the lower free space. The heat energy enters the powerhouse hall where it is used for the chilling cycle. The TES has an additional inlet for heating of the gravel when solar energy from concentrators is absent.

In this project the TES has the following parameters: the maximal temperature of the gravel is $T_{\max} = 200°C,$ the minimal temperature of the gravel is $T_{\min} = 100°C,$ the external air temperature is $T_0 = 0°C,$ the gravel heat capacity is $C_g = 800 J/(kg \cdot K)$, the gravel density $\rho_g = 1500 kg/m^3$, the dried sand density is $\rho_s = 1500 kg/m^3$, the dried sand thermal conductivity is $\lambda = 0.2\, W/m \cdot K$. The efficiency of TES is $\eta = 0.7$ (it means that 0.7 of the total heat energy is obtained by the user, and 0.3 of the energy is lost through the thermal insulation).

The approximate calculations of TES dimensions show that the internal diameter D will be 2 m, the height of gravel layer H will be 1.64 m, the height of free spaces h will be 0.2 m, and the thickness of insulation δ will be 0.4 m. With these dimensions the TES will have $G^{(g)} =$ 7.7 tones of gravel and $G^{(s)} =$ 16.5 tones of dried sand.

At present the cost of gravel can be estimated as $C^{(g)}$ =12$/tone, the cost of dried sand $C^{(s)}$ =10$/tone. In this case the cost of the base materials will be:

$$C^{(bm)} = G^{(g)} \cdot C^{(g)} + G^{(s)} \cdot C^{(s)} = \\ 7.7 \cdot 12 + 16.5 \cdot 10 = 257\$ \tag{16}$$

With auxiliary materials it will cost about 370$. Adding labor costs and unexpected expenses we evaluate the total cost of the TES as 850$.

To calculate the number of solar concentrators for each air conditioning system in Mexico we use the following equations. The average incident solar energy for Mexico W_m is:

$$W_m = 200 W/m^2 \tag{17}$$

We suppose that the efficiency of the concentrator is $\eta = 0.7$.

For this efficiency the mean useful energy W_m^1 is:

$$W_m^1 = W_m * \eta = 200 * 0.7 = 140W \tag{18}$$

We accept that the thermal energy consumption for an air conditioning system is W_{dc} =5000W. In this case the total area of the solar concentrators S_c can be calculated as:

$$S_c = \frac{W_{dc}}{W_m^1} = \frac{5000}{140} \approx 35.7 m^2 \tag{19}$$

The area of the mirrors of one solar concentrator A_t is 5.48 square meters. So to obtain the required amount of energy we need the number of solar concentrators n_c:

$$n_c = \frac{S_c}{A_t} = \frac{35.7}{5.48} = 6.5 \tag{20}$$

The nearest integer number is 7, so we accept the number of concentrators n_c =7.

The total area of mirrors for 7 concentrators is:

$$S_c^* = n_c * A_c = 7 * 5.48 = 38.4 m^2 \quad (21)$$

The cost of square meter is

$$C_{sm} = 26.8 \text{ USD.} \quad (22)$$

The cost of the whole field of concentrators is:

$$C_{cf} = C_{sm} * S_c^* = 26.8 * 38.4 \approx 1030 USD \quad (23)$$

If we include the cost of the TES the total cost of the system is approximately 1900 USD.

4. District solar cooling system

The main difference in a district solar cooling system from the residential one is the larger size of the concentrator field, the TES design, and the size of powerhouse. The TES for a district solar cooling system should be made as the hot pyramid TES described in [9]. This TES can be used as seasonal storage system that permits the usage of thermal energy obtained in the winter for cooling the district in the summer.

5. Conclusion

Absorption chillers give the possibility to replace the major part of electrical energy with heat energy. The heat energy can be obtained from solar heaters. The concentrating solar heaters have the advantage of high temperature heating that increase the chiller efficiency. This mode permits higher coefficient of performance (COP) of the chillers. New flat facet solar concentrators described in this paper permit us to obtain low cost (approximately 27 USD per square meter). The possible structure of a residential solar cooling system was presented.

Acknowledgement

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