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AN OVERVIEW ON THE FLAT-PLATE SOLAR COLLECTORS AND THEIR THERMAL EFFICIENCY

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Abstract: Flat-plate collectors are stationary collectors that use solar radiation in order to heat water used especially in domestic household. Their thermal efficiency depends on several factors as: working fluid type, transmittance of the transparent covering, absorbance and emissivity of the absorber plate, the type of the flow tubes, thermal insulation, etc. So, the paper provides an overview, using information from the literature, on the technical solutions developed by the researchers, in order to increase the thermal efficiency of the flat-plate solar collectors.

Keywords: solar energy, flat-plate solar collector, thermal efficiency

1. INTRODUCTION

The sun is a free and inexhaustible source of energy that can be converted, depending on needs, into electrical energy using photovoltaic solar cells or in thermal energy using solar collectors [1]. One of the most important advantages of using solar energy is that is clean compared to other forms of energy generally used (natural gas, coal, oil), so does not pollute the environment [2].

Solar collectors can be classified as stationary (non-concentrating) and concentrating [2]. Flat-plate solar collectors are stationary collectors used generally to heat water for domestic uses, to heat swimming pools or in industrial application.

Since this type of collectors are the most widespread, was often put the issue of increasing their thermal efficiency.

So, over the years researchers have investigated how to enhance solar collector thermal efficiency, e.g. in order to improve the heat exchange between the absorber plate and the working fluid a solution was to replace the fluid (usually water) with other fluids or nanofluids with higher thermal conductivity, or to develop new highly selective coatings for the absorbing plate. Also they try to reduce thermal losses by assuring a good thermal insulation, or by using transparent covers with high transmittance and low emissivity.

The aim of this paper is to give an insight into the technical solutions developed by the researchers, in order to increase the thermal efficiency of the flat-plate solar collectors.

2. FLAT-PLATE COLLECTORS OPERATING PRINCIPLE

Flat-plate solar collectors were discovered in the 1950s by Hottel and Whillier. They are stationary collectors whose interception area is equal with the absorbing area [1,3]. The main components of the flat plate solar collectors are: glazing, flow tubes, absorber plate, thermal insulation and the casing (figure 1).

When solar radiation passes through the glazing and reaches the absorber plate which has a selective surface, about 80% [4] of this energy is absorbed, and then transformed into heat which is transferred to the working fluid that passes through the absorber flow tubes [2]. Usually the fluid, circulating in a closed circuit, heat up the water from a tank.

The glazing is a transparent cover that has two important functions: first is to reduce the convection losses from the absorber plate and the second is to reduce the radiation losses from the collector because the glass allows the passage of sort wave radiation from the sun, but does not allow long-wave thermal radiation emitted from the absorber plate to pass outside the collector glazing [2]. The sun energy is absorbed (α), reflected (ρ) and transmitted (τ) by the transparent cover, so in order to choose a good glazing material first we need to check its transmittance. The higher, the more it will allow the passage of a larger amount of energy to the absorber. Several gazing materials used at flat-plate solar collectors construction, and their transmittance are: crystal glass (0.91), window glass (0.85), polyvinyl fluoride (0.93), fluorinated ethylene propylene (0.96), etc. [3]. Also, the glazing must have low emissivity, in order to reduce the radiative heat loss [5].

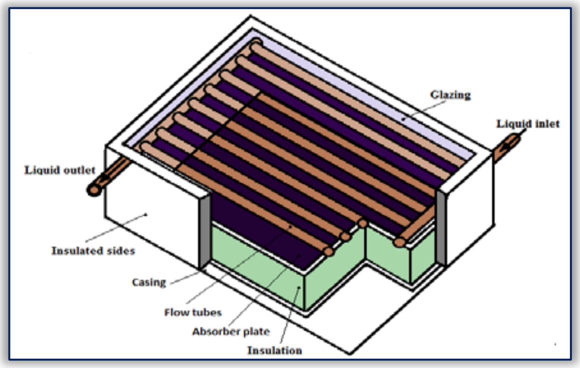

Figure 1. The components of a flat-plate solar collector [reproduction from ref 4]

A very important component of the collector is the absorber plate with selective finish. The material used for the plate must assure a high conductivity and the selective finish must have a high absorptance [6], in order to transfer more heat to the working fluid that passes through the pipes of the absorber plate. Also to reduce the heat losses, the back and sides of the collector is isolated generally with glass-wool.

3. THE THERMAL EFFICIENCY OF FLAT-PLATE SOLAR COLLECTORS

The flat-plate solar collector's efficiency η is expressed as the ratio between the useful energy and the incident solar energy for a period of time [4]:

$$\eta = \frac{\int Q_u dt}{A \int I dt} \tag{1}$$

So, the instantaneous thermal efficiency of a collector is [4,7,8,9]:

$$\eta = \frac{Q_u}{A \cdot I} \tag{2}$$

where: Q_u is the useful energy gain; I is the incident solar radiation on the solar collector, W/m², and A is the collector area, m².

The relation used to determine the useful energy gain is known as *Hottel-Whillier-Bliss* equation [4,6,10]:

$$Q_u = F_R A\left[I\tau\alpha - U_L\left(T_i - T_a\right)\right] \tag{3}$$

Replacing equation (3) in (2) results [4,6]:

$$\eta = F_R \tau\alpha - F_R U_L\left(\frac{T_i - T_a}{I}\right) \tag{4}$$

where: F_R is the collector heat removal factor; τ is the transmission coefficient of glazing; α is the absorption coefficient of plate; U_L is the collector overall heat loss coefficient, W/m²; T_i is the fluid temperature at the collector inlet, °C and T_a is the ambient air temperature, °C.

4. TECHNICAL SOLUTIONS TO IMPROVE THE THERMAL EFFICIENCY OF FLAT-PLATE SOLAR COLLECTORS

Since flat-plate solar collectors are used all over the word, especially because of the low cost, simple design and cheap maintenance [11,12] the researchers from this domain have tried to find solutions to enhance their thermal efficiency. So far, according to the studied literature, have been proposed changes to the working fluid, to the materials used (e.g. glazing, insulation, flow tubes, plate absorber) and to the geometry of flow tubes. The most important factors that can influence the thermal efficiency of flat-plate thermal collectors are:

⧉ Working fluid

First, must be mentioned that the conventional working fluids for flat-plate solar collectors are water, ethylene glycol and oil [11]. Beside water, in order to improve the thermal efficiency there were introduced other working fluids. For example Ranjith P.V. et al. [7] used as a working fluid propylene glycol/water mixture. The experiments were done at different propylene glycol volume concentration (0%, 25%, 50% and 75%) and at various mass flow rate (0.008, 0.0167 and 0.024kg/s). By analyzing the experimental results the authors concluded that the efficiency of the solar system is improved when the propylene glycol concentration is 50% and the fluid mass flow rate is of 0.0167 kg/s. They also observed that, to increase the efficiency of the solar system for a certain flow rate is needed a specific concentration of propylene glycol.

An intensively studied method to enhance the thermal performance of flat-plat thermal collectors is the use of nanofluids as working fluid. The suspension is obtained by introduction nano-sized metallic or nonmetallic particles in a base fluid as water. These nanoparticles that are dispersed in the fluid play an important role as substantially increase the thermal properties of a fluid [13]. In order to obtain a uniform distribution of the particles in the liquid, a surfactant is introduced [13,14] and a stirring method [8,14,15,16] is usually used. In some cases by assuring a proper pH is preserved the stability of the nanofluids [8,14]. Nanomaterials used generally are: Graphene nanoplatelets, Al_2O_3, Silver, Copper, SiO_2, CuO, TiO_2, Multiwalled carbon nanotubes – MWCNTs, etc.

Graphene, a recent discovered material has a very good thermal conductivity so Ahmadi A. et al. [8] investigated if the thermal efficiency of a flat-plate solar collector can be improve by adding Graphene nanoplatelets (*Gnps*) to the base fluid (deionized water). First, they establish that the pH of the working fluid should be of 11.6 in order to ensure a stable dispersion of the nanomaterial in the base fluid. The experiments were done at different mass fraction of *Gnps* (0, 0.01 and 0.02 wt%) and at a flow rate of $2.7x10^{-6}$ m^3/s. They concluded that the thermal efficiency increases with 12.19% for 0.01wt% $Gnps/H_2O$ and with 18.87% for 0.02 wt% $Gnps/H_2O$ compared to the case when they used deionized water as working fluid, when the heat lost parameter approached to zero.

Yousefi T. et al. [9] prepared the nanofluid by introducing the Al_2O_3 nanoparticles in double distilled water as the base fluid. Also, in order to obtain a uniform distribution of the particles in the liquid they used a natural surfactant (Triton X-100). The results showed an increase of the solar collector efficiency with 28.3% by using 0.2wt% Al_2O_3 nanofluid in comparison with water as a working fluid.

He Q. et al. [14] used as nanofluid Cu/H_2O mixture with nanoparticles size of 25nm and mass fraction of 0.1 and 0.2 wt%. In order to obtain a good dispersion of nanoparticle in the deionized water they added some dispersion agents (SDBS), and adjusted the pH to 8. The experimental results showed that the thermal efficiency of the collector increases with 23.83% for a mass fraction of 0.1%wt Cu/H_2O, compared to water. Moghadam et al. [15] also examined the effect of Cu/H_2O nanofluids on the efficiency of flat-plate collectors. They showed that for the optimal mass flow rate (1 kg/min for the nanofluid and 2 kg/min for water) the efficiency increases with 16.7% when is used nanofluid as working fluid compared to water.

SiO_2/water nanofluid was used by Noghrehabadi et al. [16] in their experiments. They concluded that by using the nanofluid the efficiency of the square flat-plane solar collector increases compared with pure water. Also by increasing the flow rate the efficiency is increased.

Meibodi S. et al. [17] used as working medium SiO_2/EG and water nanofluid. The volume fraction of SiO_2 particles was between 0 and 1% and the base fluid is a mix of ethylene glycol (EG) and water (50:50 vol%). The tests showed an increase in thermal efficiency with approximatively between 4-8% for 1% volume concentration of SiO_2 compared to the base fluid (EG and water).

The flat-plate thermal collector proposed by Jouybari H.J. et al. [18] is design with rectangular flow channel filled with copper metal foam, and as working fluid is used SiO_2/water nanofluid. Their experiments was done for various volume fraction of nanoparticles (0.2%, 0.4% and 0.6%) and for different flow rate (0.5l/min, 1l/min and 1.5l/min). They concluded that the thermal efficiency is improved when is used a nanofluid as working fluid compared to water.

Table 1 presents the percentage increase of the collector thermal efficiency compared to water for different types of nanofluids, when the heat loss parameter limits to zero.

Roy S. et al. [13] used silver nanoparticles mixed with water as a working fluid in order to study the heat transfer performance and efficiency of a flat plate solar collector and comparing it with that of water. The experiments were done for different silver particle volume concentration (0.01%, 0.03% and 0.04%) at different mass flow rate and as a surfactant was used polyvinyl pyrolidine (PVP). The best efficiency of the solar collector was 68.7% obtained for a 0.04% volume concentration of silver particle at 6 l/min mass flow rate, compared with that of water 60.7%.

A recent investigation was made by S.K.Verma et al. [19] for a large variety of nanofluids. The solid nanoparticles (Al_2O_3, TiO_2, SiO_2, CuO, Graphene, Multiwalled carbon nanotubes - MWCNTs) were mixed with double distillated water and as surfactant was used Triton 100X. They studied the exergetic and energetic efficiency of the proposed nanofluids compared to water as the working fluid. The best improvement regarding both exergetic and energetic efficiency was obtained for MWCNTs nanofluid followed in this order by Graphene, CuO, Al_2O_3, TiO_2, SiO_2 nanofluids.

Table 1. Percentage increase of the collector efficiency compared to water when the heat loss parameter limits to zero

Type of nanofluid (Nanoparticle/Base fluid/Surfactant)	Nanoparticle size	Other parameters	Percentage increase of the collector efficiency compared to water	Reference
Graphene nanoplateles/H_2O	At least one dimension of each platelet is < 100nm	Mass fraction - 0.02wt% Flow rate - $2.7x10^{-6}$ m^3/s Working fluid pH -11.6	18.87%	[8]
Al_2O_3/H_2O/ Triton X-100	15 nm	Mass fraction - 0.2wt% Mass flow rate - 3 l/min	28.3%	[9]
Cu/ H_2O/SDBS	25nm	Mass fraction - 0.1wt% Mass flow rate – 140l/h Working fluid pH - 8	23.83%	[14]
Cu/ H_2O	40nm	Volume fraction – 0.4% Mass flow rate – 1 kg/min	16,7%	[15]
SiO_2/H_2O	12nm	Mass fraction – 1% Flow rate - 2.8 l/min	Approx. 14%	[16]
SiO_2/EG and H_2O	40nm	Volume fraction – 1% Mass flow rate – 0.018-0.045 kg/s	Between 4-8%	[17]
SiO_2/deionized H_2O	20-30nm	Volume fraction – 0.6% Flow rate – 1.5 l/min (Note: the collector is design with a rectangular flow channel filled with copper metal foam)	9,4%	[18]

Glazing

According to Giovannetti et al. [5] the ideal material for glazing at flat-plate solar collectors is glass, due to its high transmittance and low cost. They studied the effect of highly transmitting and spectrally selective glass coatings on the performance for uncovered, single-glazed and double-glazed designs. As coating was used tin-doped indium oxide and aluminum-doped zinc oxide. Following experiments was achieved an increase in the thermal efficiency for double-glazed collectors with highly selective absorber and for single-glazed solar collector with low or non-selective absorbers.

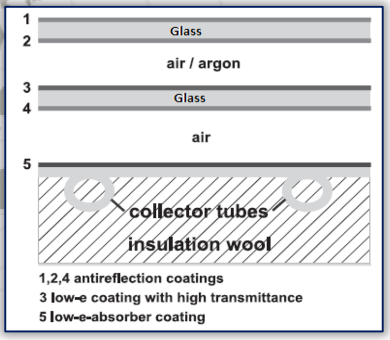

Figure 2. Double-glazed flat-plate solar collector cross section [20]

Ehrmann N. et al. [20] developed a new configuration for the transparent covering coating of the double-glazed flat-plate collector. They used low iron glass and each surface of the tow glasses was covered with antireflection (AR) coating or low-emitting coating with high transmittance; also the space between the two glasses was filled with air/argon (see figure 2). As low-e coating they developed a three layer system in which the middle one was aluminum-doped zinc oxide (AZO) and the other two were AR coatings. The results showed an improvement in the thermal efficiency of the flat-plate solar collector at high temperatures (above 100°C) or with low solar irradiation compared to a flat-plate collector without low-e coating.

Also in other work [21] they analyzed the influence of the process parameters of the AZO deposition and application of antireflection coating on the efficiency of the double-glazed collector. They concluded that the most important parameter is the target-doping concentration and that the application of the AR coating is essential. Their simulation showed that for temperature difference of 100°C the collector efficiency increases with approx. 45% for a double-glazed flat-plat collector compare with a single glazed collector. The double-glazed collector has the configuration from figure 2 with the AZO film sputtered from the target with 2wt% Al_2O_3, and the single glazed collector has AR-coating on both sides of glass.

Absorber plate coating

Föste S. et al. [22] in cooperation with partners from industry and research developed the thermochromic absorber coatings in order to reduce stagnation temperature of solar thermal collectors, while maintaining the collector efficiency. A surface with this type of absorber coating has low emissivity in the operating range of the collector and above a certain switching temperature the emissivity increases so the collector loses heat and the stagnation temperature is reduced. By comparing the efficiency of a standard collector with the prototype collector with thermocromic absorbing coating they concluded that below the switching temperature the efficiency is nearly identical. The main benefit in using this type of absorber coating are avoiding the formation of vapors in the solar circuit therefore the reduction of system costs. Given that flat-plate solar collectors are widespread all over the world, research has been carried out regarding their maintenance. So, because in time the absorber surface can loss the thermal efficiency, might be repaired by applying selective paints existing on the market. Moncada M.L. et al. [23] following investigations concluded that the epoxy coating is a suitable alternative in the maintenance of the collector heating system.

Type of the flow tubes

In order to improve the heat exchange between the flow tubes and the working fluid, so to improve the efficiency of the collectors, are used tube-side enhancement passive techniques. R. Herrero Martin et al. [24] used wire coil as an additional device to improve heat transfer and following experiments concluded that the efficiency optical factor is increased with 15 % as against a standard solar collectors. Jouybari H.J. et al. [25] studied the effect of using porous media on the thermal performance of a flat plate solar collector. The material used for the rectangular channel filled with open-cell porous structure was copper. They concluded that the copper metal foam enhance with 18.5% the absorbed energy parameter for flow rate of 0.5 l/min by comparison with the same type of collector without the porous medium. Marroquin-De J.A. et al. [26] in their research studied the performance of two types of absorber: one build of steel rectangular ducts and the other from copper pipes. Both absorbers were painted with fast dry black paint as selective absorber. The results showed that for the copper pipe type absorber the flow is more uniform in all ducts so it is a more efficient heating system.

Thermal insulation

Usually flat plate collectors are insulated at the rear side with glass wool and the recommended thickness is 10 cm [3]. Beikircherc T., et al. [27] developed a new insulation technique, more economical, that avoids the moisture problems that can appear at flat-plate solar collectors. Instead of mineral wool the thermal insulation was assured by an air gap, formed from two air chambers with specific dimension. The two air chambers are formed because between the absorber plate and the casing is placed a low-emission film (Al-foil) at a specific position. They discover that by using the film insulation instead of mineral wool the efficiency is the same but the thickness of the collector is reduced so the material cost are smaller and does not store moisture.

Other external factors

One of the external factors that can influence the energy collected by the collector is the angle of tilt. Thus in order to maximizing the energy collection, it is necessary to adjust the tilt angle from time to time [11]. To calculate the optimum angle of tilt for different geographical locations, Stanciu C. et.al. found that can be use the next simple relation [28]:

$$\beta_{opt} = \varphi - \delta \qquad (5)$$

where: φ is the latitude, and declination $\delta = 23.45 \sin\left(360 \frac{n+284}{365}\right)$

where: n is the number of day in a year.

A different new method to improve the thermal efficiency, designed by Bhowmik H. et al. [29], is by using the rectangular solar reflector in order to concentrate the radiation from the sun to the collector. They successfully have constructed a prototype collector and after tests concluded that the efficiency is improved with approx. 10 % compared with the case when the collector is made without reflector.

5. CONCLUSIONS

By analyzing the information from the literature can be concluded:

- Lately, the most intensively studied method by which can be increased the thermal efficiency of flat-plate solar collectors is by replacing the conventional working fluid with nanofluids. The nanoparticles generally used are: Al_2O_3, Silver, Copper, SiO_2, CuO, TiO_2, MWCNTs and Graphene nanoplatelets. In all cases the results show an increase in the thermal efficiency compare to water.
- Was noticed that increasing the nanoparticle mass fraction in the working fluid does not necessary improve the thermal efficiency, however must be find an optimum relation between the size of the nanoparticles, the mass fraction and the flow rate of the working fluid.

» Other factors that can influence the thermal efficiency are: the configuration and optical properties of the transparent cover, the selective coating of the absorber plate, the type of the flow tubes and the thermal insulation.

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