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THE INFLUENCE OF THE INCLINATION ANGLE ON THE EFFICIENCY OF A FLAT PLATE SOLAR COLLECTOR

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Abstract: The paper presents the influence of the inclination angle of a flat plate collector on the efficiency of a solar thermal system. The analytical form for the efficiency is presented, and the results of experimental measurements, on a laboratory installation, are discussed. At the end the theoretical and the experimental values are compared concluding on the necessity of using tracking systems for solar collectors to enhance the degree of use of the solar radiation. In this way the experimental efficiency of the system can be increased up to 11%.

1. Introduction and analytical modelling of the efficiency

In the last years, due to the problems caused by the global warming as well as the problem of the limited amount of conventional energy sources, the politicians and engineers turned their interest to find and to promote non-conventional sources for energy. The sun is the main renewable source, either direct, as solar energy, or indirect as wind energy, biomass, tides etc. The solar energy is collected by different types of devices, depending on the type of the output energy. The solar collectors are used to transform the solar energy into heat.

The paper presents a study on the performance of a solar thermal system with flat plate solar collectors, using liquid heat carrier, when the inclination angle of the panel is varied.
Usually, the flat plate collectors are installed in fixed positions, at an inclination angle depending on the latitude. This results in a variable degree of use of the solar radiation, with a maximum at noon, when the radiation is straight on the collector's surface.

The tracking systems attached to a flat plate collector insure the straight angle (0^o), between radiation and panel surface, during the full insolation period. The motion follows the daily motion of the Earth.

The efficiency is expressed as a ratio between the effective power, P_N, from the heat transfer liquid and the irradiance from the sun, P_S, and.

$$\eta = \frac{P_N}{P_S} \cdot 100 \ [\%]; \tag{1}$$

The useful power P_N, is evaluated by measuring the feed and return temperatures difference (T_2-T_1), and the mass flow rate of the liquid heat carrier, $\dot{m}$, with the specific heat capacity, c_p:

$$P_N = \dot{m} c_p (T_2 - T_1); \tag{2}$$

In equation (2) it is needed to know the mass flow, $\dot{m}$, which can be calculated with:

$$\dot{m} = Q \cdot \rho; \tag{3}$$

where Q is the volumetric flow, and ρ is the density of the liquid from the solar circuit.
The notation is made:

$$T_2 - T_1 = \Delta T \,; \tag{4}$$

The useful power becomes:

$$P_N = Q \cdot \rho \cdot c_p \cdot \Delta T \,; \tag{5}$$

The irradiance P_S, is calculated by multiplying the collector area, A_c, and the radiation density, E:

$$P_S = A_c \cdot E \,; \tag{6}$$

Replacing equation (1) with (2), (3), (4) and (5), the efficiency can be calculated as follows:

$$\eta = \frac{Q \cdot \rho \cdot c_p \cdot \Delta T}{A_c \cdot E} \cdot 100 \ [\%] \,; \tag{7}$$

The equation is given for a normal incidence of the radiation on the collector's surface. For an angle, α, between the collector and the sun rays, the incident radiation becomes $E\cos\alpha$. Consequently, the efficiency will be calculated for $\alpha \neq 0^0$:

$$P_S = A_c \cdot E\cos\alpha \,; \tag{8}$$

$$\eta = \frac{Q \cdot \rho \cdot c_p \cdot \Delta T}{A_c \cdot E\cos\alpha} \cdot 100 \ [\%] \,; \tag{9}$$

Based on the analytical model, the efficiency for a real case can be easily calculated. The measurements using an experimental stand are made and compared with the theoretical calculations.

2. The experimental installation and the testing program

For the tests, an experimental laboratory rig is used (s. Fig.1).

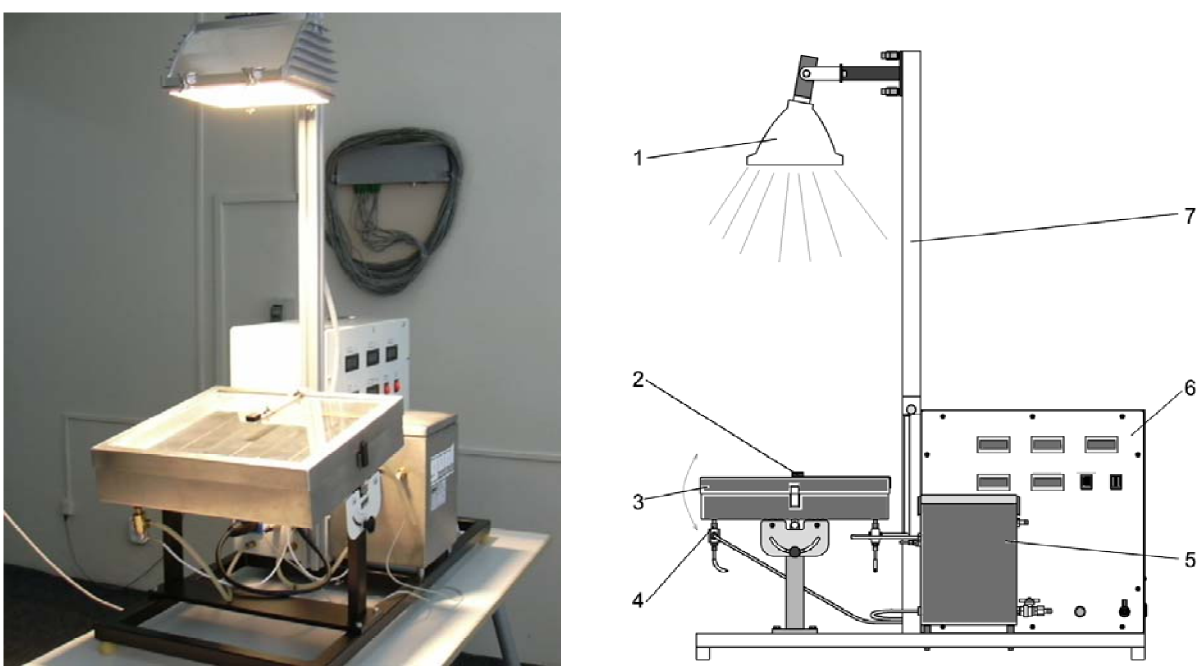

Figure 1: The experimental stand with solar collector

In Figure 1 there are presented the image and the scheme of the rig, where: 1 trolley, 2 lamp tripod, 3 flat collector, 4 luxmeter, 5 halogen lamp at adjustable height, 6 flow meter (not visible), 7 hot water tank, 8 hot water tank overflow connection, 9 filler/drain valve for hot water, 10 circulating pump (not visible), 11 filler valve in primary circuit, 12 regulator valve for setting the volumetric flow rate, 13 control cabinet, 14 digital displays for sensor measured values, 15 master switch for lamp and circulating pump, 16 temperature sensors, 17 air bleed valve, 18 computer interface.

The test rig is a functional system for heating domestic hot water. The sun radiation is replaced with a halogen lamp (1000W) which has adjustable intensity that can be positioned at adjustable height. The radiation is absorbed by a flat absorber and the heat is transferred to a liquid heat carrier (water). The liquid is circulated in the solar circuit with a circulating pump. The heated liquid is crossing a hot water tank and releases the heat by an integrated heat exchanger. The system is equipped with sensors for temperatures, light intensity, volumetric flow and a data acquisition card for data storage. The measured values are displayed on a PC monitor or on the digital displays on the unit. The solar collector can be adjusted at different angles, between $0^0 – 50^o$.

The system diagram is shown in Figure 2. The heat carrier which flows through the collector is water. In order to measure the temperatures, sensors are provided: feed in (3a) and return (3b). The inclination of the collector can be adjusted. The intensity of light from the halogen lamp is measured with a luxmeter (4). The hot water runs out from the collector into a water tank (7) and releases the heat through a heat exchanger (7b). A sensor for measuring the temperature (7a) in the tank is placed inside. An additional domestic water circuit (secondary circuit) that can be connected by a hose fitting (9) is used to release the surplus heat. For the primary circuit is used a circulating pump (10).

In order to adjust the flow rate in the primary circuit a regulator valve (12) is used and recorded with a sensor (6a) at the flow meter (6). For the primary circuit a pump (3a) for circulation is used.

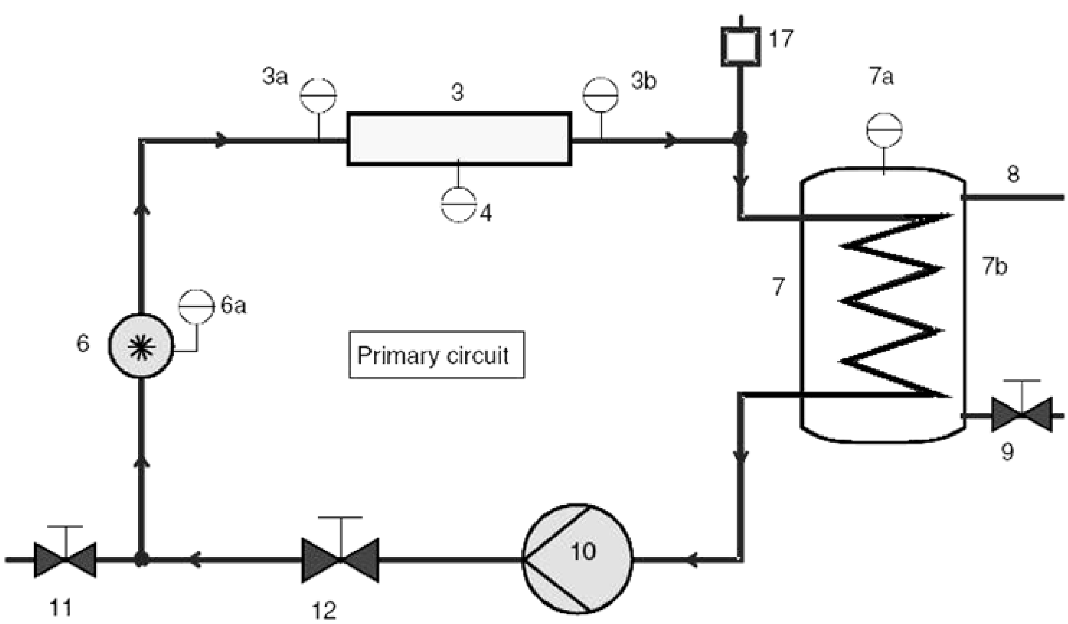

Figure 2: The system diagram

3. Experimental determination

For the experimental measurements, the water tank is filled with water, and the solar circuit is filled with the liquid heat carrier (water). The lamp is fixed at constant intensity and constant height from the solar collector. The collector is inclined at different angles.

There have been made measurements, in the same conditions, in order to start from the same water temperature. The system is turned on and the measurements are made for an inclination angle of the collector of 0^0, 10^0, 20^0, 30^0, 40^0 and 50^0 at every 15 minutes after the angle adjustment. The intensity of the radiation is different for all these cases. The results are recorded. For the three measurements, for the same angle the same lamp position is maintained.

The registered data are shown in Table 1.

Table 1: Measurements results

Incidence Angle	T_1 [^{0}C]	T_2 [^{0}C]	ΔT [K]	Q [l/h]	$E^{\cdot}\cos\alpha$ [kW/m^2]	P_N [W]	η [%]
$\alpha = 0^0$	20.1	41.2	21.1	2.2	1.52	50	32
$\alpha = 10^0$	19.5	40.7	21.2	2.2	1.49	33	30
$\alpha = 20^0$	20.1	40.1	20.0	2.1	1.44	27	27
$\alpha = 30^0$	20.5	39.4	18.9	2.0	1.18	16	24
$\alpha = 40^0$	21.2	37.0	15.8	2.1	0.88	56	27
$\alpha = 50^0$	21.9	33.9	12.0	2.0	0.61	34	21

4. Results

The theoretical values are calculated, considering the same panel's inclination. In each case, the irradiance P_S is calculated using eq. (8), the useful power P_N with eq. (5) and the efficiency with eq. (1). The results are listed in Table 2.

Table 2: The calculated values

Incidence Angle	Irradiance P_S [W]	Calculated useful power P_N [W]	Calculated efficiency η [%]
$\alpha = 0^0$	165.376	54.027	32.66
$\alpha = 10^0$	162.863	52.283	32.10
$\alpha = 20^0$	155.402	48.883	31.45
$\alpha = 30^0$	143.219	43.995	30.71
$\alpha = 40^0$	126.685	38.617	30.48
$\alpha = 50^0$	106.301	27.933	26.27

In the calculations made there are used the fixed values for the specific heat $C_p = 4.19 kJ/kgK$, and for the collector's area $A_c = 320x340mm$. Table 3 shows the theoretical efficiency values and the measured ones.

Table 3: The values for efficiency

Inclination angle	Theoretical efficiency [%]	Measured efficiency [%]	Efficiency increasing with the tracked system [%]
$\alpha = 0^0$	32.66	32	11
$\alpha = 10^0$	32.10	30	9
$\alpha = 20^0$	31.45	27	6
$\alpha = 30^0$	30.71	24	3
$\alpha = 40^0$	30.48	27	6
$\alpha = 50^0$	26.27	21	0

5. Results discussions and conclusions

The results presented in Table 1, show that, in the tracked position (permanent angle of 0^o) there can be registered an efficiency increase up to 11%. So, tracking, even in a limited angle domain, can strongly improve the solar-thermal conversion efficiency.

Comparing the experimental results with calculated efficiency it can be concluded that, at full irradiation (0^o) there can be used the proposed formula without any modifications (error: 2%). If the inclination angle is higher, the calculated values exceed strongly the experimental data: for 50^o, the difference is of 20%. The cause may be related to the fact that several aspects are not considered in the theoretical formula: light reflection on the glass surfaces (which is stronger by increasing the inclination angle, various flow rate of the liquid in the panel, etc.) In Figure 3 there is illustrated the variation chart for both efficiencies, calculated and measured.

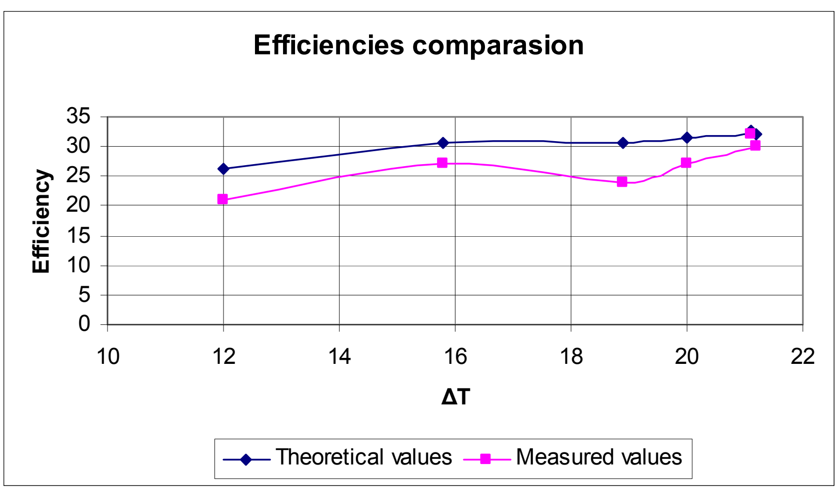

Figure 3: The efficiency variation chart

In order to enhance the conversion efficiency, it is necessary to collect the maximum possible amount of radiation, as it's shown in the chart above. Therefore, tracking systems for solar collectors are recommended, to get normal incidence of radiation on collector's surface.

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