International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:8, No:11, 2014

The Optimization of Sun Collector Parameters

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***Abstract*—**In order to efficiently solve the problems created by the deepening energy crisis affecting Europe and the world, governments cannot neglect the opportunities of using the energy produced by sun collectors. In many of the EU countries there are sun collectors producing heat energy, e.g. in 2011 in the area of EU27 (countries which belong to European Union) + Switzerland altogether 37519126 m2 were operated, which are capable of producing 26.3 GWh heat energy. The energy produced by these sun collectors is utilized at the place of production. In the near future governments will have to focus more on spreading and using sun collectors. Among the complex problems of operating sun collectors, this article deals with determining the optimal tilt angle, directions of sun collectors. We evaluate the contamination of glass surface of sun collector to the produced energy. Our theoretically results are confirmed by laboratory measurements. The purpose of our work is to help users and engineers in determination of optimal operation parameters of sun collectors.

***Keywords*—**Heat energy, tilt angle, direction of sun collector, contamination of surface.

I. Introduction

IN order that the surface of the sun collectors should be able to convert as much as possible from the energy transported by the arriving sun rays we must be familiar with the Sun-Earth movements [1]. When determining the geometry of the Sun-Earth movement we tried to use the simplest formulas possible that engineers and enterprises designing the sun collectors may be able to work with. Fig. 1 shows the geometric relationships of sun collectors placed on the Earth's surface.

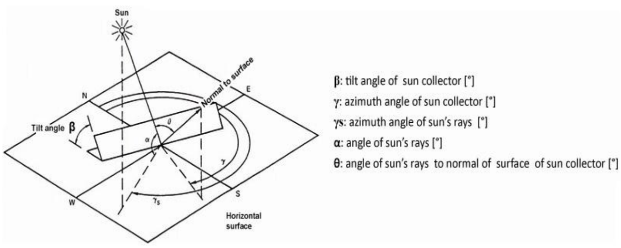

Fig. 1 Relationships of the incident beam radiation and a tilted surface [2]

The amount and intensity of the radiation arriving at the surface of the sun collector also depend on the relative position and movement of the Earth-Sun [3]. Fig. 2 depicts the movement of the Sun and Earth in relation to each other, the so-called sun paths at 48° north longitude [4].

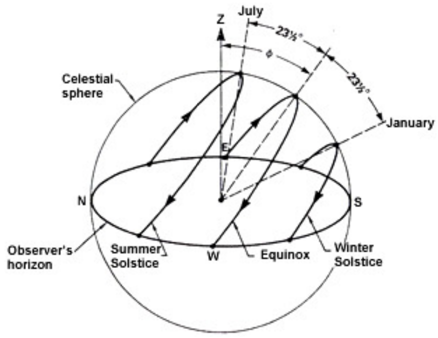

Fig. 2 Visualization of the sun paths across the sky [1]

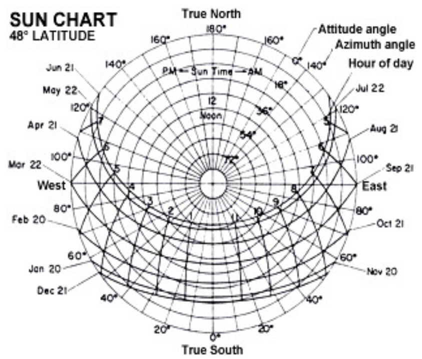

Fig. 3 Sun charts [1]

At 48° latitude of the northern hemisphere the figure shows the sun's movement at the time of the winter and summer solstice and the equinox. If we prepare the top-view picture of this figure, we get the sun chart of this northern latitude (Fig. 3) [4]. According to the sun charts [5] the sun gets the closest to the sun collector placed in the centre of the figure i.e. the observation point, at the time of the summer solstice, i.e. at 12.00 June 21st. It is obvious from this figure that if the sun collector is directed in the true south direction, it gets the largest possible radiation energy. During the day the angle of the sun to the normal of the sun collector (θ) changes according to the passage of time [7]. If we want the sun to reach the surface of the sun collector at the most optimal angle during the day, continuous east-west sun collector adjustment must be provided. In our work with change tilt angle β to the horizontal surface and we determine those tilt angles (β) at which, during the year, the collector will be capable of

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transforming the largest energy deriving from the sun. This means that the tilt angle of the (β) should be modified according to the movement of the sun each day of the year.

This is technically unimaginable and impracticable; therefore in this section of our article we determine the most optimal tilt angle values at the tested geographical location (N 47.5°):

- for the whole year (the tilt angle of the collector (β_{year}) is not modified during the year),
- seasonally (the tilt angle of the collector is modified according to the four seasons. Therefore four tilt angles will be defined (β_{summer}, β_{winter}, β_{autumn}, β_{spring})).

The Earth orbits the Sun in an elliptical orbit with an eccentricity of 3%. The Earth makes a full circle in a year. The Earth does not only go around the Sun but it also rotates around its own axis at a speed of one rotation per day. Its own axis is tilted at δ=23.5° from the axis of the orbit around the Sun. In this way during its orbit around the Sun, the northern hemisphere gets closer to the Sun in the summer than the southern hemisphere, and this is changed in winter. In spring and autumn the tilting of the Earth's axis (δ) is such that the distance of the northern hemisphere and the southern hemisphere relative to the Sun is the same. This is shown in Fig. 4.

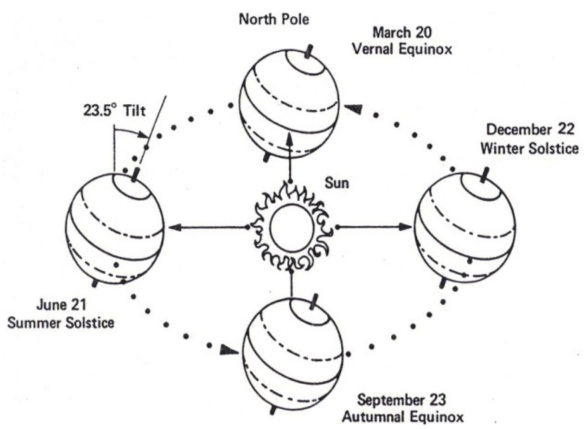

Fig. 4 Diagram of the Earth's orbit around the Sun

On the basis of our theoretical [6] considerations and experience we have accepted that – globally, regarding a whole year – the tilt angle of the sun collector equals the value of the northern latitude, i.e.:

$$\beta_{year} = \Phi$$

so at the test site, in Budapest, (47.5° N):

$$\beta_{year} = 47.5°$$

According to [1] $\beta_{year} = \Phi$ should be modified in the following way:

$$\beta_{year} = \Phi + (10°÷20°)$$

We disregard this assumption, proposal during our tests. The – theoretical – values of seasonal tilt angles are the following according to Fig. 6.

$$\beta_{summer} = \Phi - \delta$$
$$\beta_{winter} = \Phi + \delta$$
$$\beta_{autumn} = \Phi$$
$$\beta_{spring} = \Phi$$

The tilt angles of the sun collectors at the test site, in Budapest, (47.5°N):

$$\beta_{summer} = 24°$$
$$\beta_{winter} = 71°$$
$$\beta_{autumn} = 47.5°$$
$$\beta_{spring} = 47.5°$$

We made some measurements in order to verify the correctness of the values.

II. Material and Methods

A. Laboratory Measurements

We made a series of measurements with glass covered flat collectors in order to determine the ideal collector tilt angles (β) in the area of Budapest (47.5°N). The main point of the measurement is to determine the optimal tilt angles (β) as a result of comparative series of measurements. We measured the thermal characteristics of two sun collectors parallel, at the same time. We had set the tilt angle of one collector to a value – which we defined – relating to the whole year (β_{year}) and we did not change that during the series of measurements. This collector was marked collector B. The tilt angle of the other collector marked A was modified according to the seasonal values defined by us (β_{summer}, β_{winter}, β_{autumn}, β_{spring}) during the measurements. Fig. 5 depicts the collectors.

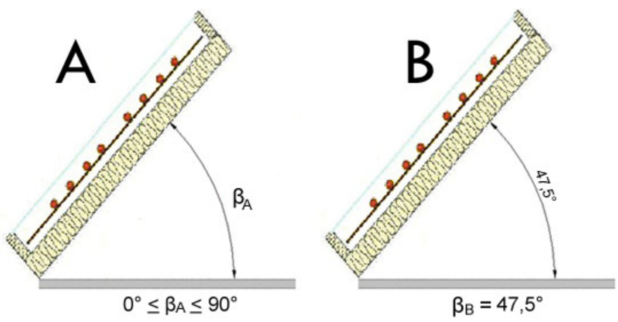

Fig. 5 Tilt angles of collectors

During the measurements the thermal characteristics of both collectors were measured and we made our conclusions by comparing these. The measurements were made in the summer, autumn and winter of 2011. In our opinion the autumn and spring measurements – relative to each other – must produce the same result, so we did not make any measurements in spring. This conclusion is supported by Fig. 6 as well.

B. Description of the Measuring Equipment

In order to confirm and support by experiments the sun collector tilt angles (β) determined theoretically in the previous sections, a special measurement station was created at Óbuda University (Budapest, Hungary) and installed on the roof of the building. With the measurement equipment – which is fully automated and controlled by a computer – we were able to continuously measure the thermal characteristics of the sun collector in summer, autumn and winter. The conceptual layout of the measuring equipment is shown in Fig. 6. The equipment incorporates two (2.0 m^2) glass covered flat collectors (marked A and B) witch were developed by us. The system has two loops. The primary loop which consists of the sun collector and the liquid heat exchanger placed in the solar tank is filled up with antifreeze liquid medium. The secondary loop utilizes the heat content of the water in the solar tank. Measurement points were established in the measuring equipment to measure the water and liquid material temperature, and the mass flow of water and liquids. In order to increase the safety and reliability of the measurements, we measured the amounts by MBUS and PLC systems. The measurements were processed by a monitoring computer and presented them on the screen by VISION system. During the measurements great care was taken to make sure the temperatures and mass flows of the medium entering the collectors – in the case of both collectors – should be equal. This was ensured by keeping the secondary loops and the tank temperatures at a constant value. The characteristics of the external atmosphere were measured by a meteorological station located on the roof and equipment measuring solar radiation, and the results were entered into the monitoring computer. Special care had to be taken of the winter measurements. The system had to be protected against freezing in a way that by the beginning of the – daily – measurement the temperature of the solar tank should not be higher than 2÷3°C. The conceptual layout of the measuring equipment is shown in Fig. 6.

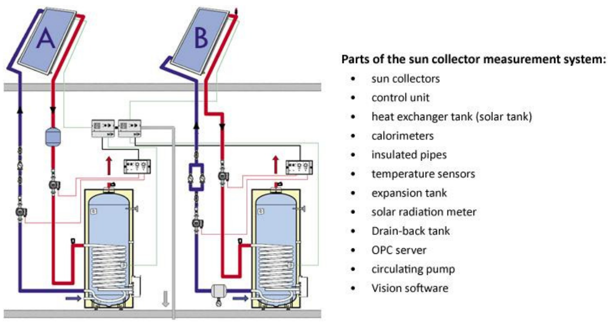

Fig. 6 Sun collector measurement system

C. Measurements of Optimal Tilt Angel(β)

We set the tilt angle of collector B to β_{year}=47.5° and kept it at the same angle during the measurements. We set the tilt angle of collector A to three values in each season. These values are the seasonal values which we determined, i.e.:

$$\beta_{summer} = 24°$$
$$\beta_{winter} = 71°$$
$$\beta_{autumn} = 47.5°$$

During the measurements we measured the temperature and the mass flow of the liquids entering and leaving the sun collectors, the temperature of the solar tank, the amounts of heat carried off the solar tank as well as the data of the external atmosphere and solar radiation. During the measurements it was ensured that the temperatures and mass flows of the medium entering the collectors should be equal.

According to the previous chapters the value of entry temperatures of both sun collectors and the value of mass flows of the medium flowing through the collectors were the same during the measurements. In such cases if we want to compare the power of the collectors (P_A, P_B).

The power relation ($R_{PA}/_{PB}$) of the two tested collectors should – approximately – equal the relations of the exit temperatures of the collectors, which were determined in our earlier paper.

The determined power relations, tilt angle β_A of collector A (with modified tilt angle) and the deviation of the calculated power relations – according to the seasons – were given in Tables I-III.

TABLE I
SUMMER, β_B= 47.5°

β_A [°]	$R_{PA/PB}$ [%]	Deviation
24	141	7.23
47.5	100	2.59
71	86	2.46

TABLE II
AUTUMN, β_B= 47.5°

β_A [°]	$R_{PA/PB}$ [%]	Deviation
24	80	1.55
47.5	100	1.83
71	81	3.37

TABLE III
WINTER, β_B= 47.5°

β_A [°]	$R_{PA/PB}$ [%]	Deviation
24	80	5.54
47.5	102	4.12
71	110	5.49

These diagrams shows – approximately – the $R_{PA}/_{PB}$ change of the power relation of collectors A and B at angles β_A and β_B =47.5°=constant value per season.

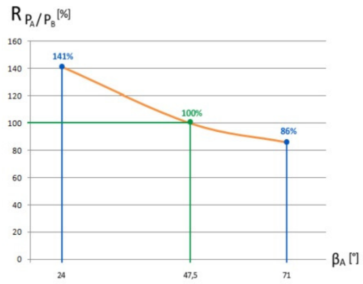

Fig. 7 Power relations of collectors in summer, $\beta_B = 47.5°$

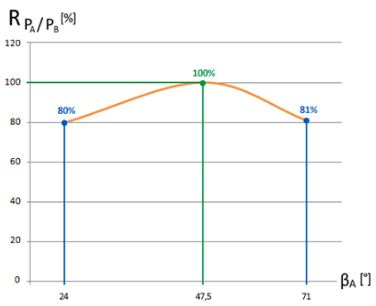

Fig. 8 Power relations of collectors in autumn, $\beta_B = 47.5°$

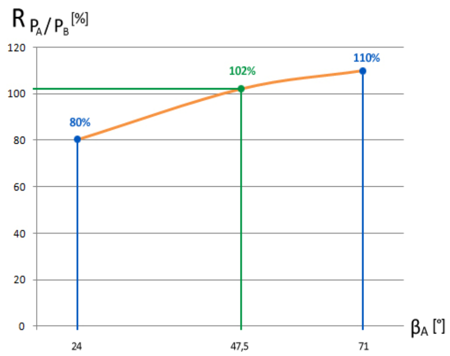

Fig. 9 Power relations of collectors in winter, β_B= 47.5°

D. Measurements of Infect of Surface Contamination

During operation, the surface of solar collectors gets contaminated. Depositing and airborne aerosols deposit on glass surfaces and therefore reduce glass transparency, which results in reduced solar collector power. No literature has been found on the relation between surface contamination of solar collectors and power drop. It is important though to carry out experiments to explain the relation between surface contamination of solar collectors and power drop. By changing surface contamination of solar collector B the different efficiency curves at different contamination rates were determined:

$$\eta = f\left(\frac{t_s - t_a}{I}\right)$$

where t_s is the solar collector average surface temperature, t_a is ambient temperature, and I is irradiance. To model surface contamination, carbon black was spread on the surface. In the course of measurements solar collector efficiency curves were taken at 4 different degrees of contamination: 0 g/m^2, 75 g/m^2, 150 g/m^2, and 225 g/m^2. Fig. 10 shows the characteristic curves determined by measurements.

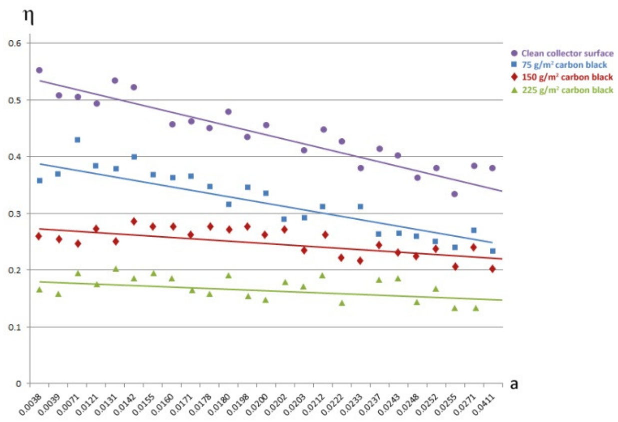

Fig. 10 Relation between surface contamination and collector efficiency

According to Fig. 10 it can be established that the more the surface of solar collector is contaminated the further efficiency curves are drifted toward lower efficiency value ranges. Experimental values are summarized in Table IV.

TABLE IV
SURFACE CONTAMINATIONS AND EFFICIENCY CURVE DATA

No.	Contamination [g/m^2]	Deviation R^2 [-]	Regression line
1	0	0.4215	η = -0.0079a + 0.5147
2	75	0.1828	η = -0.0057a + 0.3917
3	150	0.1901	η = -0.0021a + 0.2749
4	225	0.0847	η = -0.0013a + 0.1808

where:

$$a = \frac{t_s - t_a}{I}$$

E. Theoretical Approach to the Orientation of Sun Collectors

Orientation is of great importance in terms of solar collector performance. In the literature papers studying orientation have assumed solar collectors are faced to the true north in the South Hemisphere or the true south in the North Hemisphere. Fig. 1 shows that the angle between the vertical projection of sunlight on the ground and the true north (γ_s) is called the azimuth of sun, while the angle between the vertical projection of the normal of collector surface and the true north (γ) is called the azimuth of collector. β is tilt angle of solar panel, and θ is the incidence angle of sunlight.

If the observer is located at or near the Equator, then the orientation of solar panels needs not to face the right direction [8]. Fig. 1 clearly suggests that solar collectors work at optimum performance if $\gamma = \gamma_s$ and θ values minimum, that is $\theta = \theta_{min}$.

Sun path and collector tilt angle (β) also affect θ. Theoretical considerations and findings in the literature suggest that solar collector power will decrease if panels are not oriented to the true south (γ=180˚) in the Northern Hemisphere. According to our experiments, power at a given tilt angle (β) may drop by 20-60%, depending to the rate of deviation from the true south. Considering that solar collector surface is exposed not only to direct radiation (I_{dir}) but also diffused radiation (I_{diff}), the total irradiation of surface is $I_{total} = I_{dir} + I_{diff}$ [9]. Taking Sun constant (1353 W/m^2) and atmospheric losses (57%) into account, the value of direct radiation is I_{dirmax} = 582 W/m^2. Based on experimental values, diffuse radiation (I_{diff}) is $I_{diff} = I_{dirmax}$ *(0.4-0.8). It means that with γ=180˚ and at $\beta = \beta_{opt}$. The irradiation solar collector surfaces are exposed to be:

$$I = I_{dir} + I_{dirmax}(0.4 - 0.8)$$

At γ = 90º or γ = 270º, or at orientation to the west or east, respectively, the irradiation solar collector surfaces are exposed to is:

$I = 0 + I_{dirmax}$ (0.4 - 0.8), which results in a power drop by 20-60%. This expected drop in performance is seen in Fig. 11, where ΔP is the change in solar collector power caused by deviation in orientation. $\Delta P = P_{not\ south}/P_{south}$, where $P_{not\ south}$ is the power of sun collector when it's direction deviates from south, P_{south} is the power of sun collector when it's direction is south.

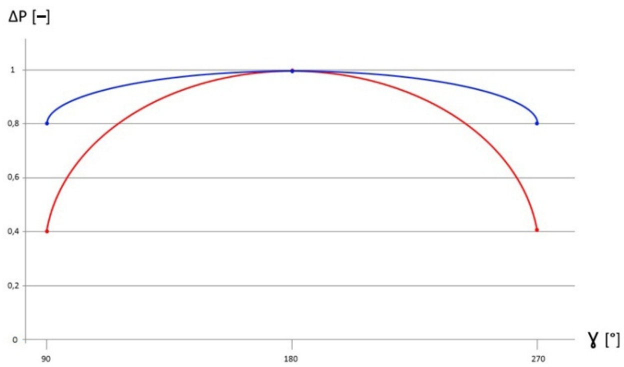

Fig. 11 The power drop of solar collector power in function to azimuth angle (γ)

III. Conclusion

Considering the efficient operation of sun collectors Óbuda University established a special measurement station capable of measuring the thermal characteristics of several sun collectors at the same time. Based on the laws of the Sun – Earth relative movement published in the specialist literature we determined the optimal tilt angle of the sun collectors at which the energy producing capability of the collector is optimal. In this way we determined a set-up angle for a whole year and the collector tilt angles for the four seasons (autumn, winter, spring, summer). Through laboratory measurements we confirmed our conclusions made theoretically. Our measurements made it clear that if the sun collector is not set at the right angle, the power of collector falls by up to 10-20%. Figs. 7-9 graphically depict this decrease in power due to improper tilt angles. If the tilt angle of the sun collector is not modified during the year, the power of the collector in summer – when the possibility of energy transformation is the best – is up to 20-30% less than the optimal value. In spring and autumn the operation and energy producing capability of the sun collector is optimal at this tilt angle ($\beta = \phi$ = 47.5°).

For the measurements we used a special sun collector developed by we, whose construction cost is lower compared to the commercial sun collectors available in Hungary. In the future we find it necessary to repeat our measurements under more precise circumstances, with more tilt angles and at least four collectors in parallel. We hope that those results will give us more accurate information how to modify the tilt angles of sun collectors. The effect of contamination of solar collector surface on collector performance and collector efficiency characteristic curve were determined. Based on theoretical considerations the expected drop in solar collector power was determined with collectors not facing the true south (in the northern hemisphere).

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