CALCULATION OF ENERGY PRODUCED BY SOLAR COLLECTORS

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Abstract. Only a part of solar radiation striking the solar collector is converted into heat energy. The value and the intensity of solar insolation over a year, strongly depend on the latitude and weather conditions of the place. The heat energy produced by a solar collector depends on the type and design of the collector. Several types of solar collectors both theoretically and experimentally have been investigated and formulae for the calculation of their efficiency and heat energy produced by the collector have been developed. By the use of the computer program MS Excel the amount of the produced heat energy for a flat plate solar collector with one glass cover, two glass covers and selective tracking the sun solar collector has been calculated and the results presented.

Keywords: solar collector, heat energy, efficiency, calculation.

Introduction

The sun is a nuclear reactor that has been working reliably for many years. Inside the sun, atomic nuclei of hydrogen are fused under immense pressure to atomic nuclei of helium. Due to this process a large amount of energy fluxes are released at very high temperature. The surface temperature of the sun is about 5900 ˚C.

The radiation power of the sun arriving at the top of the earth atmosphere is about 1360 W m^{-2}, and is called the solar constant. The earth atmosphere absorbs a part of the radiation, so that reaching the earth surface has the maximum value of approximately 1000 W m^{-2}. This solar radiation flux (called insolation) [1] is reduced by clouds, water drops, dust and other particles in the air. The resulting or global radiation is composed of both diffuse and direct components. Both components can be utilized in solar technology. Solar energy annually radiating onto the earth surface has immense potential. It exceeds the annual energy demand of the world population ten thousand fold. The solar resource is far larger than all available fossil and nuclear energy reserves.

The solar energy availability is geographically unequally spread and subject to seasonal variations. In regions near the Equator the annual radiation flux may total 2300 kWh m^{-2}.

The absolute value and the intensity of solar radiation over a year, depend strongly on latitude. In regions near the Equator, the average monthly insolation is evenly distributed through the year, but at higher latitudes it is greater in summer. The weather and slope, and orientation of the collecting surface greatly affect the intensity of solar radiation.

We have examined several types of solar collectors both theoretically and experimentally in order to specify the data about the ratio of solar energy received by statically placed collector and collector tracking the sun, as well as distribution of the obtained heat energy during a day, month and year. A specific device MD-4 has been developed and used [2]. The device was envisaged for measuring and automatic registration of the surrounding air temperature, its relative humidity and intensity of solar insolation striking both constantly located and tracking the sun surface.

Matherials and methods

The experimental examination of solar insolation in Ulbroka (Riga region) during three years (2005, 2006, and 2007) has been carried out and large amount of theoretical and experimental data obtained. In this paper some of them are presented and analyzed. The experimental data acquisition during summer time of these years from 1 March till 1 November in every 12 minutes had been performed and the results fixed in a data storage device, and after processed and analyzed by the use of the computer program MS Excel.

The objective of the research is to develop the methodology for calculation amount of heat energy produced by a flat plate solar collector depending on parameters influencing the heat yield, and to compare the theoretical results with the experimentally obtained data.

The calculation of energy produced by solar collectors of several types, their efficiency for a month and day takes a lot of time. In order to decrease the calculation time, using certain mathematical expressions from the literature, the computer program for MS Excel has been developed.

By the use of these formulae the produced amount of heat energy for three types of solar collectors during 8 months has been calculated. As the advantage of this system can be noticed that inserting into the computer program MS Excel formulas and numerical value of coefficients and other parameters, the computer figures out the value of the produced energy for each of the variants. By changing the ingoing data new results are obtained.

1. Theoretical calculations

As it was noticed, only a part of solar insolation on the surface of a collector is transferred into heat. The amount of this energy depends on the type of the solar collector and meteorological conditions of the place, where the collector is working. The average amount of heat energy produced by a flat plate solar collector during a day has been calculated by formula [3]

$$q_c = E_c \eta \left(1 - aK + bK^2\right), \tag{1}$$

where q_c – average amount of heat energy, produced by a solar collector during a day, kWh m^{-2};
E_c – average amount of heat energy, received by 1 m^2 of a solar collector during a day, kWh m^{-2};
η – efficiency of the collector (Table 1);
a, b – experimentally determined coefficients (Table 1);
K – parameter, ˚C.

Table 1

Value of coefficients for flat plate solar collectors

Type of collector	η	*A* 10^3	*b* 10^6
Flat plate with 1 glass	0.78	10.7	29.3
Flat plate with 2 glasses	0.73	6.9	12.7
Flat plate selective	0.70	5.6	8.7

The parameter *K* can be calculated by formula [3]

$$K = \frac{T_{in} - T_o}{L}, \tag{2}$$

where T_{in} – heat carrier inlet temperature into collector, ˚C;
T_o – surrounding air temperature ˚C;
L – average monthly value of atmosphere lucidity.

$$L = \frac{E}{E_{out}}, \tag{3}$$

where *E* – average daily amount of global solar energy received during a month by 1 m^2 of horizontal surface area, kWh m^{-2};
E_{out} – average daily amount of global solar energy received during a month by 1 m^2 of horizontal surface outside the atmosphere, kWh m^{-2}.

Amount of global solar energy, received by 1 m^2 of solar collector surface during a sunny day, depends on the length of the day and power of maximum solar insolation [3]:

$$E = \frac{2N}{\pi} P_{max}, \tag{4}$$

where *N* – duration of the day, h;
P_{max} – maximal power of solar insolation on the collector surface during the day, kW m^{-2}.

Duration of the day

$$N \approx \frac{2\varpi}{15} \approx \frac{2}{15}\arccos\left(- tg\varphi \cdot tg\delta\right) \cdot \tag{5}$$

The maximal power of solar insolation on the collector

$$P_{max} = C_s\ (\cos\delta{*}\cos\varphi{*}\cos\omega + \sin\delta{*}\sin\varphi), \qquad (6)$$

where C_s – solar constant (C_s = 1355 W m^{-2}.);
φ – latitude angle of the place (for Latvia φ = 57˚);
ω – angle of solar hours (in the middle of a day ω = 0);
δ – declination angle of the sun, degree.

The declination angle of the sun

$$\delta = 23.45[\sin(360\frac{284+n}{365})], \qquad (7)$$

where n – number of the year day counted from January 1.

2. Mathematical expressions for calculation of heat energy, produced by a solar collector using the computer program MS Excel

In order to perform calculations using the computer program MS Excel, formulae (6) and (7) are transformed in a form understandable to the computer program, and the following expressions obtained. Five of them are used for calculation of the parameter K, but one, amount of energy, produced by the collector.

The declination angle of the sun for i-day

$$\delta_i = \text{SIN}((280.11+0.9863\ n_i)\ \pi/180)\ 23.45; \qquad (7')$$

$$(\text{-TAN}\varphi\ \text{TAN}\ \delta_i) = \text{-1 TAN}(57\ \pi/180)\ \text{TAN}(\delta_i\ \pi/180). \qquad (5')$$

The duration of the i-day

$$N_i = \text{DEGREES(ACOS(-TAN}\varphi\ \text{TAN}\ \delta_i))\ 0.1333. \qquad (5'')$$

Global insulation energy outside the atmosphere

$$E_{out} = (\text{COS}(\delta_i\ \pi/180)\ \text{COS}(57\ \pi/180) + \text{SIN}(\delta_i\ \pi/180)\ \text{SIN}(57\ \pi/180))\ N_i\ 0.863. \qquad (4')$$

Parameter

$$K = (T_{in} - T_o)\ E_{out}/E. \qquad (2')$$

Energy produced by the collector during a unit of time

$$q = (1\text{-}a\ 10\text{\^{}-3}\ K{+}b\ 10\text{\^{}-6}\ K\text{\^{}2})\ E_c\ \eta. \qquad (1')$$

3. Data necessary for the calculation

It is envisaged to calculate the collector parameters by months. In order to perform the calculation we have to use the data about global insulation (at average duration of a day during the month) E and the received amount of heat energy by the collector during a unit of time (a month) E_c.

In order to solve the task, data about the global insolation from the literature are taken [4], but about the energy produced by the solar collector data from our experimental investigation are used. Summarizing the experimental data the average yearly values for each of the three years (2005-2007) are obtained (Table 2): T_{ov} – average daily temperature, E_{cst} – amount of solar insolation energy daily received by static in south direction oriented surface, and E_{ctr} – amount of solar insolation energy daily received by tracking the sun to sun beams normaly oriented surface.

At calculation of the technical parameters of the collector it was envisaged to simulate two regimes of the collector operation. For this reason we have to state two values of the parameter K: K' – at the constant heat carrier inflow temperature (T_{in} = 50 ˚C) into the collector, and K'' – at constant temperature difference ($\Delta T = T_{in} - T_o$ = 50 ˚C). According to the values of these parameters it was envisaged to calculate the possible amount of energy produced by solar collectors and its efficiency.

Table 2

Average values of meteriological parameters obtained by device MD-4 in comparision with the global insolation [5] in Ulbroka 2005-2007

Month	Number of the middle day of the month, n	T_{ov}, ˚C	E_{cst}, kWh m^{-2}	E_{ctr}, kWh m^{-2}	E kWh m^{-2}
March	75	2.6	111	139	79
April	105	8.1	136	185	120
May	135	14.3	159	231	170
June	162	18.6	180	272	206
July	198	21.1	176	267	192
August	228	19.7	146	204	146
September	258	15.5	120	158	87
October	288	9.5	69	81	43
T_{ov}, ΣE		13.7	1096	1538	1043

Results and discussion

An example of the course of calculation of the parameter *K'* by the computer program MS Excel is shown in Table 3. Analogically the parameter *K''* is calculated, the amount of energy produced by a solar collector and its efficiency forecasted, when the collector has one glass cover, two glass cover and the absorber with selective coating. For the collector with selective coating the forecasted amount of the produced heat energy when working in tracking the sun regime also is figured out. All the above mentioned indexes are calculated at two collectors working regimes, that is, at permanent for all looked at months heat carrier inflow into the collector temperature T_{in} = 50 ˚C, and at constant temperature difference 50 ˚C between the heat carrier inflow temperature into the collector and ambient air temperature ($\Delta T = T_{in} – T_o$ = 50 ˚C).

Table 3

Calculation of the parameter *K'*

Month	Nr. of a day	π 180^{-1}	δ, deg	-tanφ *tanδ	Number of hours in a day, N	E_{out}, kWh m^{-2}	E, kWh m^{-2}	T_{ov}, ˚C	K'
March	75	0.017453	-2.42	0.07	11.50	5.05	2.55	2.55	94.02
April	105	0.017453	9.42	-0.26	13.97	8.13	4.00	8.07	85.24
May	135	0.017453	18.79	-0.52	16.21	10.99	5.48	14.33	71.49
June	162	0.017453	23.09	-0.66	17.47	12.51	6.87	18.63	57.14
July	198	0.017453	21.18	-0.60	16.88	11.81	6.19	21.10	55.12
August	228	0.017453	13.45	-0.37	14.88	9.31	4.71	19.73	59.81
September	258	0.017453	2.22	-0.06	12.45	6.20	2.90	15.47	73.80
October	288	0.017453	-9.60	0.26	9.98	3.42	1.39	9.53	99.84

The calculated values (forecasted) of heat energy produced by solar collectors during summer months (March-October) for collectors with one glass cover, two glass cover and for a collector with selective coating working in static and in tracking the sun regime have been obtained. The calculation has been completed at the conditions $\Delta T = T_{in} – T_o$ = 50 ˚C (Fig. 1) and at T_{in} = 50 ˚C (Fig. 2). As it is seen from Fig. 1 and 2, the amount of energy produced by collectors covered with one and two glasses are rather similar, but considerably smaller than at the operation regime $\Delta T = T_{in} - T_o$ = 50 ˚C. This working regime is characteristic for classical individual solar collector systems. For example, during summer time at the outside air temperature 25 ˚C such regime will be set when the water temperature in the hot water tank is about 75 ˚C. In the absorber of a collector the heat carrier temperature rises up. Therefore the average temperature of the absorber will be by several degrees higher then at the inflow into the absorber. As a result between the absorber temperature and the surrounding air temperature some difference of 55 ˚C is established.

This temperature difference provokes heat loss, the value of which depends on the design factors of the collector. In our case the greatest heat losses are from the collector with one glass cover. For example, in July (Fig. 1) the collector is able to produce approximately two times (34/67) less heat energy than the selective collector, and considerably less (34/59) than the collector with two glass cover. The collector with one glass cover is able to produce relatively more less heat energy at the beginning and at the end of the season, March and October.

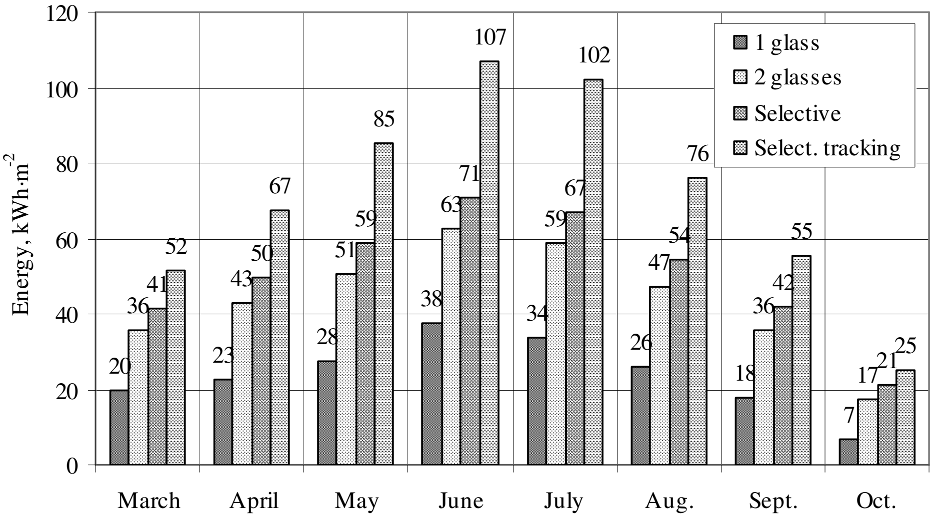

Fig. 1. **Calculated amount of heat energy produced by solar collectors at $\Delta T = T_{in} - T_o = 50$ ˚C**

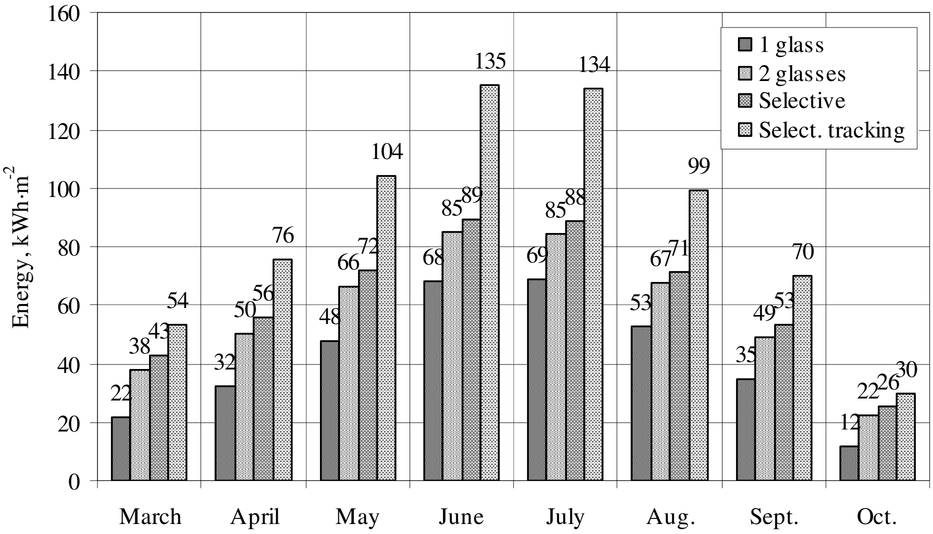

Fig. 2. **Calculated amount of heat energy produced by solar collectors at T_{in} = 50 ˚C**

Another simulated working regime of a collector at the condition T_{in} = 50 ˚C (Fig. 2) is characteristic by the condition that during the operation of the collector the inflowing heat carrier temperature is restricted (stabilized), for example, at 50 ˚C by the use of an additional heat tank-accumulator, water disturbing valve and so on. As it is seen from Fig. 2, at this working regime the amount of the produced heat energy by all types of the collectors increases especially in the middle of the season. The greater increase in the produced heat energy has the collector with one glass cover, for example, in July almost two times (68/38). Less increase in the produced energy has the selective collector, in July (88/67) approximately 1.31 time. In the sense of the produced heat energy the selective tracking the sun solar collector, which in the middle of the summer (Fig. 2, 2 July) has produced 1.52 times (135/89) more energy than the stationary placed collector is more productive.

In Fig. 3 and 4 the efficiency of solar collectors for both simulated working regimes are shown. In Fig. 3 it is for the collector with one glass cover and in Fig. 4, for the selective collector.

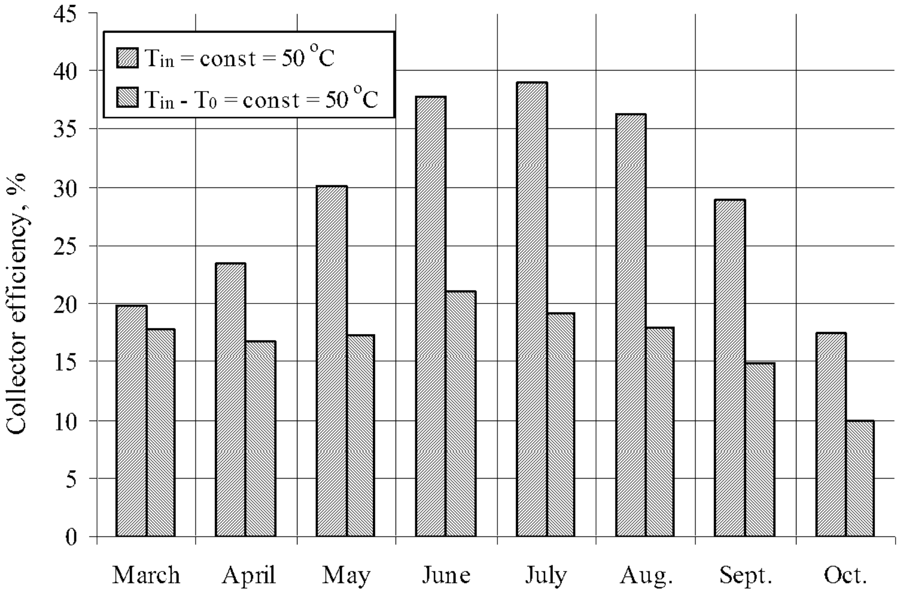

Fig. 3. **Calculated values of the efficiency of solar collector with one glass cover**

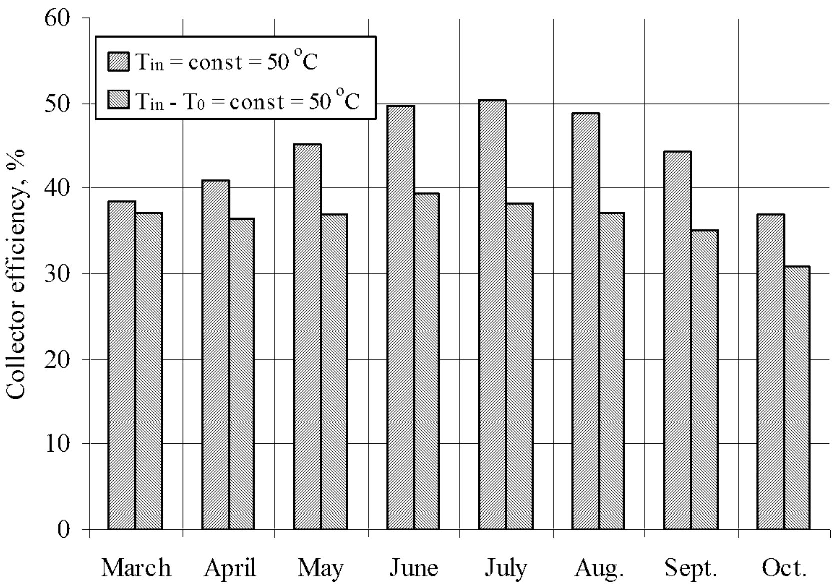

Fig. 4. **Calculated values of the efficiency of solar collector with selective coating**

The efficiency of the collector with one glass cover is considerably dependent on the working regime. In the middle of summer, at T_{in} = 50 ˚C, it is approximately two times higher than at $\Delta T = T_{in} - T_o$ = 50 ˚C. The efficiency of a selective collector has rather small dependence on the working regime. In the middle of summer, at the regime of T_{in} = 50 ˚C, it has been only 1.3 times higher than at the regime of $\Delta T = T_{in} - T_o$ = 50 ˚C.

Conclusions

1. By the use of the computer program MS Excel and developed mathematical expressions it is possible rather simply with small labor and time consumption to simulate the necessary working regime of the collector and to calculate the corresponding technical parameters of the collector.
2. The efficiency of a selective solar collector and produced by it amount of heat energy are less dependent on the difference between the absorber and surrounding air temperature, as it is in the

case of a simple flat plate solar collector with one glass cover. Therefore, in comparison of collectors operation regimes at the conditions T_{in} = const = 50 ˚C and T_{in} - T_o= const = 50 ˚C it is seen that in the middle of summer for the selective collector at the condition T_{in} - T_o = 50 ˚C the decrease of efficiency is 22 %, but for the collector with one glass cover it is 47 %.

3. The selective and tracking the sun solar collector in the middle of summer can produce 1.5 times more heat energy as the stationary placed selective solar collector of the same working surface.

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