WATER HEATING EFFECTIVENESS OF SEMI-SPHERICAL SOLAR COLLECTOR

Ilze Pelece, Imants Ziemelis
Latvia University of Agriculture
ilze.pelece@llu.lv; Imants.Ziemelis@llu.lv

Abstract
Energy gain from a solar collector depends not only on materials and technologies used in its construction, commonly characterized with efficiency of the collector, but also on the geometry of the absorber of solar collector. These factors together determine the effectiveness of the collector. While new materials and technologies are widely studied in the world, there are not enough investigations on the absorber geometry yet. The geometry of the solar collector is most important in Latvia and other northern countries because of their geographical and climatic conditions: the path of the sun is long in summer, and nebulosity is frequently considerable. For developing of new constructions of solar collectors, methods of calculations of energy received by several surfaces are necessary. Such method has been proposed in this work. Using this method of calculation it has been found that effectiveness of solar collector with semi-spherical absorber is 1.37 times greater than that of flat plate solar collector, using the same materials and technologies. Such semi-spherical solar collector has been manufactured and measurements of water heating have been carried out.
Key words: efficiency, effectiveness, semi-spherical, solar collector, water heating.

Introduction

Align with decrease in reserves of fossil fuel, as well as impact of use of fossil fuel on climate, in the world more attention has been paid to renewable sources of energy, including solar energy.

Also in Latvia the solar energy has been used, mostly in solar collectors for hot water production (Ziemelis et al. 2004; Kancevica et al. 2006). However, in Latvia, because of its geographical and climatic conditions there are some peculiarities in comparison with traditional solar energy using countries (Pelece 2008; Pelece et al 2008). In Latvia in summer, the length of day exceeds twelve and maximally reaches seventeen hours, accordingly also the path of the sun is long, but altitude of the sun is rather small (maximally 56 degrees above horizon), therefore also intensity of solar radiation is low. There is also frequently considerable nebulosity.

In winter the altitude of sun is very small (10^{o}) and the length of day is 7 h, therefore use of solar energy in winter in Latvia is not possible.

Because of mentioned above features traditional flat plate collector without tracking the sun is not appropriate enough for use in Latvia, but new collector constructions are required, that would be able to collect the energy from all sides as well as to use the diffused radiation more efficiently.

Ability of the solar collector to use solar energy has been frequently characterised with efficiency, which has been defined as ratio between energy gain from solar collector and solar energy incident to the absorber. However, this efficiency depends only on materials and methods used in construction of the solar collector, but not on shape and orientation of the collector as well as other factors influencing energy incident to absorber.

In this article we propose to use term “effectiveness”, taking into account also geometry of the absorber, instead of “efficiency”. Such approach allows evaluating energy gain from solar collectors with absorber of other shape, not only flat, for example, semi-spherical absorber.

It has been found that effectiveness of a solar collector with semi-spherical absorber is 1.37 times greater than that of a flat plate solar collector, using the same materials and technologies. Such semi-spherical solar collector has been manufactured and measurements of water heating have been carried out. Good coincidence between the calculated and the measured results has been obtained.

Materials and methods

Measurements have been carried out at Ulbroka, where solar collector and measuring devices are situated on the roof of Institute of Agricultural Machines (5 storey building).

Measurements of the global solar radiation have been performed using an ISO 1. class pyranometer from “Kipp&Zonen”. Measurements have been performed automatically, taking intensity of radiation after every 5 minutes and accumulating data in a logger. Thereafter from these data the daily energy density has been calculated. Measurements have been carried out from April 2008 till November 2010.

Data on the nebulosity from “Latvian Environment, Geology and Meteorology Centre” have been obtained. The nebulosity is evaluated visually in grades from 0 (clear sky) to 10 (entirely overcast) according to the World Meteorology Organization methodology after every 3 hours.

Measurements of the received energy of the solar collector have been performed using a new

Source: made by the authors

Figure 1. **Semi-spherical solar collector**

construction – solar collector with a semi-spherical absorber, shown in Fig. 1.

The absorber of the collector is made from copper sheet (thickness 1 mm) shaped as a dome and coloured black. The collector is covered with a transparent polyethylene terephthalate (PET) dome. Radius of the collector is 0.56 m, which corresponds to a 1 m^2 base area. Inside the absorber is a copper tube shaped close to the absorber, in which the heat remover (water) flows. Diameter of the tube is 10 mm, but length - 21 m. Water flow ensures the pump with productivity of approximately 30 l h^{-1}.

Measurements with semi-spherical solar collector have been carried out from 1 August till 31 October 2009, almost every day from 8:00 till 19:00.

In order to measure energy gain from the semi-spherical solar collector, water flow was measured as well as temperature of incoming and outgoing water. Measurements of temperatures have been done using thermocouples and "Pico" TC-8 termologer, ensuring measurements automatically after every 5 minutes. Then a power of the collector can be calculated from formula (1):

$$N = C \cdot K \cdot (t_2 - t_1), \quad (1)$$

where

- N – power of collector, W;
- C – specific heat of water, J kg^{-1} K^{-1};
- K – water pump productivity, l s^{-1};
- t_1 – cold water (input) temperature, ºC;
- t_2 – hot water (output) temperature, ºC.

In order to calculate the daily energy gain from solar collector, from the values of power must be selected the positive ones. Then daily energy gain can be calculated using formula (2):

$$E = \sum N \cdot \Delta t \cdot 10^{-6}, \quad (2)$$

where

- E – daily energy sum, MJ;
- Δt – interval between measures, s.

The summing in formula (2) must include all positive (output water temperature higher than input temperature) values of the day.

A new convenient method for calculating the received solar energy of several shape and orientation surfaces – a method of effective area – has been proposed in this article. The effective area of some surface at some moment is equal to the area of projection of this surface at the plane perpendicular to solar beems.

Then power of the direct solar radiation received by the surface at the moment is:

$$J = I_0 \cdot L_{ef} \quad (3)$$

where

- J – power received by surface, W;
- I_0 – intensity of beem radiation on surface perpendicular to solar rays, W m^{-2};
- L_{ef} – effective area of the receiving surface, m^2.

The effective area characterises the power of solar energy received by the collector. For calculation of the energy received at some period this equation must be integrated via time.

On the other hand, efficiency usually used for characterizing the solar collectors describes their ability to use the received energy:

$$e = \frac{Q}{E_k} \quad (4)$$

where

e – efficiency of collector;
Q – energy gain from collector, J;
E_k – energy received by collector, J.

Efficiency of the collector depends only on materials and technologies used in its construction, but not on its shape, orientation, or tracking to the sun. For example, efficiency of a stationary mounted flat plate collector and the same tracking the sun, both constructed using identical materials and technologies, will be equivalent.

For complete characterization of the solar collector, these values, efficiency and effective area, must be used together. Therefore we offer characterize the solar collector with effectiveness, which is product of the efficiency and ratio of effective area to the area of the solar collector.

$$\eta = e \cdot \frac{L_{ef}}{L} \quad (5)$$

where

η – effectiveness of the collector;
L_{ef} – effective area of the collector, m^2;
L – area of the collector, m^2.

Energy received by solar collector E_k in formula (4) is equal to the product of effective area of the collector and the solar beam energy on surface perpendicular to sun rays:

$$E_k = L_{ef} \cdot E_M \quad (6)$$

where

E_M – solar beam energy on surface perpendicular to solar rays, Jm^{-2}.

Therefore effectiveness of the collector can be calculated:

$$\eta = e \cdot \frac{L_{ef}}{L} = \frac{Q}{L_{ef} \cdot E_M} \cdot \frac{L_{ef}}{L} = \frac{Q}{L \cdot E_M} \quad (7)$$

Solar beam energy on the surface perpendicular to sun rays E_M is the energy received by a flat plate collector with ideal tracking to the sun, or maximal possible received energy. So, effectiveness of the solar collector is the ratio between energy gain from the collector and maximal possible solar energy received by solar collector.

It must be taken into account that all these values are changing with the height and azimuth of the sun.

Results and discussion

The effective area and the calculated energy gain from several solar collectors on a clear day of June 22 are shown in table 1. Flat plate solar collectors at several tilt angles, semi-spherical, spherical and cylindrical solar collectors there are considered.

It can be seen from the table that the largest effective area and therefore greatest energy gain (with equal efficiency, or materials and technologies used in construction) characterizes the spherical and cylindrical collectors, next is semi-spherical collector.

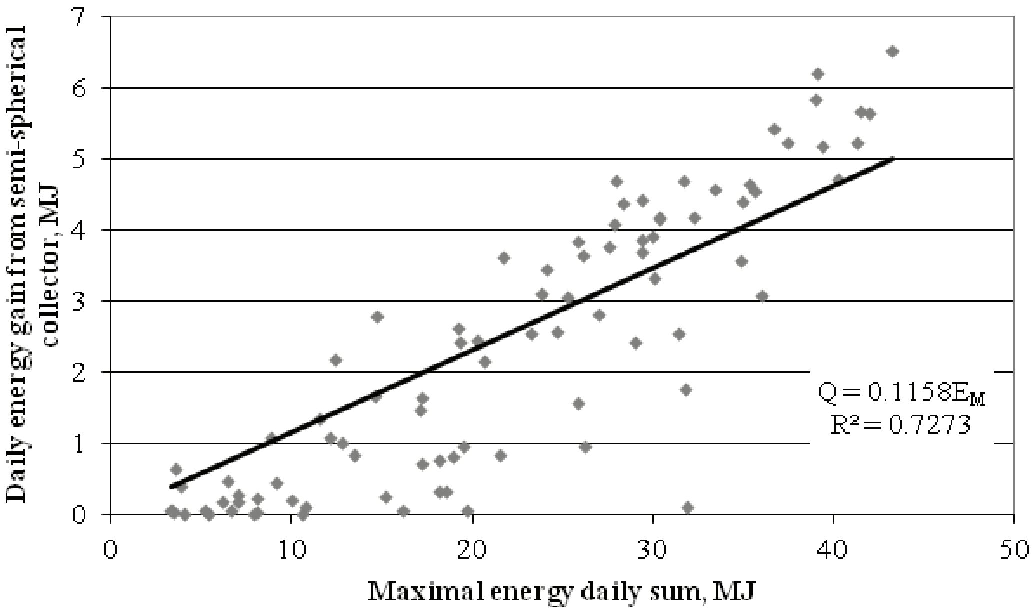
Energy gain from the stationary mounted flat plate collector is considerably smaller, and the smallest it is for the collector mounted at traditionally used 56° tilt angle. The effective area, of course, is not the only criteria for evaluation of the collector. Important is also the full surface area of the collector because of the heat loss from the whole area. For example, both spherical and cylindrical collectors have the effective area of 1 m^2 (if axis of the cylinder is perpendicular to solar rays) and therefore equal amount of received energy, but the cylindrical collector has smallest full surface area and therefore lowest heat loss. Taking into account both summary energy gain and mean effective area, expressed in percentage from all surface area, the best of all the considered forms of collectors is semi-spherical solar collector.

Table 1

Effective area and calculated received energy of several receiving surfaces

	Semi-spherical	Spherical	Cylindrical	Flat 34º	Flat 40º	Flat 56º
Radius, m	0.564	0.564	0.5			
Surface area, m^2	2.00	4.00	3.14	1	1	1
Mean effective area, m^2	0.74	1	1	0.48	0.47	0.41
Maximal effective area, m^2	0.9	1	1	1	0.99	0.92
Mean effective area, %	37	25	32	48	47	41
Energy, MJ	36	45	45	28.8	28	24.6

Source: made by the authors



Source: made by the authors

Figure 2. **Dependence of daily energy gain from the semi-spherical solar collector on the daily sum of maximal possible solar beam energy, 29 July to 31 October 2009 and 1 June to 30 September 2010**

Table 2

Calculated seasonal energy gain from several solar collectors

Modification of collector	E, MJ	E, kWh	E, % from tracking to the sun collector	Effectiveness
Tracking to the sun	1155	321	100	0.18
Semi-spherical	1058	294	92	0.17
Flat 40º tilted	805	224	70	0.13
Flat 56º tilted	771	214	67	0.12
Flat horizontal	685	190	59	0.11

Source: made by the authors

The effectiveness of the solar collector for all seasons can be evaluated using graphical method. Plotting the daily energy gain from solar collector via daily sum of maximal possible solar beam energy, the slope of this graph is effectiveness of the collector (Fig. 2).

Intercept of the graph equation must be zero, because if solar energy is zero, then also energy gain from solar collector is zero.

Thus it is obtained, that seasonal mean daily effectiveness of the semi-spherical solar collector is 0.12. It should be taken into account that semi-spherical solar collector used in these experiments was made from simple materials, without modern technologies such as selective coatings and others, therefore its efficiency is experimentally evaluated as 0.18. Increasing the efficiency by using up-to-date materials and technologies will proportionally increase also effectiveness.

The seasonal energy gain and effectiveness for several solar collectors is given in table 2. For better comparison, collectors of all kinds are taken with equal efficiency of 0.18 and with equal base area of 1 m^2.

Energy of solar radiation for these calculations has been evaluated using the method explained in our previous works (Pelece 2010). Real nebulosity data averaged over 5 years for each day have been used in these calculations.

The effectiveness of the semi-spherical collector in table 2 differs from that illustrated in Fig. 2 because the former shows the calculated long-time values but the latter – the real measurements taken in rather short time.

Table 2 shows that energy gain from semi-spherical solar collector makes 92% of the energy from tracking the sun flat plate collector. It is a very good ratio taking into account that tracking system is expensive and hard to exploit, while semi-spherical solar collector is simple, durable against wind and visually attractive.

On the other hand, semi-spherical solar collector produces 1.37 times more energy than the stationary (at traditional 56° tilt angle) flat plate solar collector.

The semi-spherical solar collector used in the present experiments is only a prototype. For practical use a larger collector would be better. Calculations show that semi-spherical solar collector with the radius of 1.25 m (and with the same efficiency as of that used in the experiments) produces 1300 kWh heat energy in a season, which exceeds the statistically mean hot water use of a household.

Conclusions

Energy gain from a solar collector can be characterized with effectiveness which includes both technological aspects described with efficiency and geometrical ones described with effective area.

A semi-spherical solar collector produces 1.37 times more energy than a stationary flat plate solar collector.

Energy gain from a semi-spherical solar collector with the radius of 1.25 m is sufficient for a statistically mean household in a summer season.

References

1. Kancevica L., Navickas J., Ziemelis E., Ziemelis I. (2006). Increase of the Efficiency of Solar Collectors. Proceedings of the Second International Scientific Conference “Biometrics and Information Technologies in Agriculture: Research and Development”, pp. 89-92, Lithuanian University of Agriculture.
2. Pelece I. (2008). Influence of nebulosity on use of solar energy in Latvia. Proceedings of the International Scientific Conference “Engineering for rural development 2008”, pp. 28-33, Latvia University of Agriculture.
3. Pelece I., Iljins U., Ziemelis I. (2008). Theoretical calculation of energy received by semi-spherical solar collector. Proceedings of the International Scientific Conference “Engineering of Agricultural Technologies 2008”, Vol. 6. pp. 263-269, Lithuanian University of Agriculture.
4. Pelēce I. (2010) Modelling of new constructions of solar collectors. Proceedings of the International Scientific Conference “Applied information and communication technologies”, April 22-23, 2010, Jelgava, Latvia. Latvia University of Agriculture. Faculty of Information Technologies. Jelgava: Latvia University of Agriculture, p. 200-207.
5. Ziemelis I., Iljins U., Navickas J. (2004). Economical Comparison of Some Parameters of Flat-Plate Solar Collectors. Proceedings of the International Research Conference “The Role of Chemistry and Physics in the Development of Agricultural Technologies”, pp. 23 – 25, Lithuanian University of Agriculture.