Surface temperature distribution and energy gain from semi-spherical solar collector

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Abstract: Usual constructions of solar energy receivers are not efficient enough in Latvia and others northern countries, and new constructions are required, that would be able to collect energy from all sides as well as to use the diffused radiation more efficiently.
The aim of the paper is to elaborate method for calculation of energy received by solar collector, usable for developing of new constructions of solar collectors, and to develop a new construction of solar collector using this method.
Such new construction can be a semi-spherical solar collector. Such collector has been made, and measurements of water heating have been carried out.
Method of calculations of received energy has been elaborated. Theoretical calculations of the energy gain from semi-spherical solar collector have been performed and verified by comparison of calculated daily energy sums with measured ones, and good coincidence has been obtained.
Method of calculations allows calculating not only integral received energy, but also distribution of the received energy along the surface. The measured distribution of surface temperature of the semi-spherical solar collector corresponds to the calculated one. There are no spot on the semi-spherical surface which would never get warm.
Such semi-spherical solar collector could be appropriate for use of solar energy in Latvia and other countries with similar geographical and climatic conditions.

Keywords: *Solar collector, Semi-spherical, Distribution of surface temperature, Energy gain*

Nomenclature

E_W	*daily energy gain from solar collector* ..... *J*	I	*intensity of the solar radiation* .... *W m*$^{-2}$
E	*daily energy sum at cloudy conditions*...... *J*	I_D	*intensity of the diffused radiation*...... *W m*$^{-2}$
E_C	*daily energy sum at clear sky conditions*.. *J*	z	*zenith angle of the sun*........................... *rad*
c	*specific heat of water*...................*J kg*$^{-1}$ *K*$^{-1}$	δ	*altitude of the sun* .... *rad*
K	*productivity of the water pump*.......... *kg h*$^{-1}$	Φ	*azimuth of the sun*................................. *rad*
t_1	*temperature of inlet water* .... °*C*	S	*solar constant*.................................... *W m*$^{-2}$
t_2	*temperature of outlet water* .... °*C*	P	*lucidity of the atmosphere* .... *r.u.*
Δt	*time between two measurements*................*s*	m	*air mass* .... *r.u.*
β	*angle of incidence of solar rays* ....*rad*	M	*nebulosity* ....*grades*

1. Introduction

Align with decrease of 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 [1,2]. However in Latvia because of its geographical and climatic conditions there are some features in comparison with traditional solar energy using countries [3, 4]. Latvia is located at 57° northern latitude and 24° eastern longitude near the Baltic Sea. In Latvia at summer the length of day excides twelve and maximally reaches seventeen hours, accordingly is also long path of sun, but rather small altitude of sun (maximally 56 degrees above horizon) and therefore also small intensity of solar radiation. There is also frequently considerable nebulosity.

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

Because of mentioned above features traditional flat plate collector without tracking to 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. To these requirements a collector with a semi-spherical absorber considered in this article could correspond [5]. Energy gain from such collector is similar to that from flat plate collector tracking to sun, but tracking device is complicated, expensive and hard to exploit, while semi-spherical collector is rather simple, with good appearance, durable against wind.

For a better elaboration and evaluation of new constructions of solar collectors, also new, more precise, complete and convenient methods for calculation and forecasting of the received energy are required, capable to calculate received solar energy of surface of any shape and orientation, taking into account also the nebulosity. Such method is proposed in this article. Calculations consist from three steps. At first, solar coordinates at every moment must be calculated. These calculations are based on astronomical considerations [6]. Second step is calculations of the energy received by some surface, depending on its shape and orientation. Third step is evaluation of impact of clouds. There is a new improved model of taking into account impact of the nebulosity used in these calculations.

The method has been verified by comparison of results of calculations with experimentally measured values. A collector with the semi-spherical absorber has been used in these measurements.
Method of calculations allows calculating not only integral received energy, but also distribution of the received energy along the surface. The measured distribution of surface temperature of the semi-spherical solar collector corresponds to the calculated one. There are no spot on the semi-spherical surface which would never get warm.

2. Methodology

Calculations and measurements of the solar radiation as well as the received energy of the solar collector have been performed in this article.

2.1. Measurements

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) accordingly the World Meteorology Organization methodology after every 3 hours.
Measurements of the received energy of the solar collector have been performed using a new construction – solar collector with a semi-spherical absorber, shown in Fig. 1.

The collector is made from a copper sheet shaped as semi-sphere and coloured black. Inside the dome is a copper tube shaped close to dome. Diameter of the tube is 10 mm, length 21 m. In this tube flows heat remover – water, transporting heat to the reservoir. The collector is covered with transparent polyethylene terephthalate (PET) dome. Radius of the collector is

1.12 m, what corresponds to 1 m^2 base area. In order to determine the received energy of collector temperatures of incoming and outgoing water have been measured after every 5 min. Water flow ensured a pump, which productivity was 30 l/h. Measurements with the semi-spherical solar collector have been carried out at 2009 from 1 August to 31 October and at 2010 from 1 Jun to 30 August.

Energy gain from solar collector has been calculated from Eq. (1)

$$E = \sum c \cdot K(t_2 - t_1) \cdot \Delta t \cdot 10^{-6} \qquad (1)$$

where E is daily energy gain from solar collector (J), C is specific heat of water (4190 J kg^{-1} K^{-1}), K is productivity of the water pump (kg/h), t_1 and t_2 are inlet and outlet water temperatures respectively (°C) and Δt is time between two measurements. All positive E values must be summed.

Fig. 1. Semi-spherical solar collector.

The distribution of the surface temperature of semi-spherical solar collector also has been investigated. For this investigation there are 30 thermocouples mounted onto surface of the semi-spherical solar collector at even distances from each other. Measurements of temperatures have been carried out using termologgers Pico TC08. Surface temperature investigations have been carried out with and without water flow in tubes.

2.2. Theoretical calculations

For the theoretical calculation of the received energy of some surface [7] at first solar coordinates (declination and azimuth) must be calculated at every moment (we used interval 15 min). From solar coordinates and the orientation of the surface (normal of the surface) the angle of incidence of solar rays β can be calculated. Then the intensity of the radiation received of a surface element can be calculated from Eq. (2).

$$I = SP^m \cos\beta + I_D \quad (2)$$

where S is solar constant (equal to 1367 W m^{-2}), P is lucidity of the atmosphere, r.u., m is air mass, r.u., and I_D is intensity of the diffused radiation, assumed to be constant and equal to 75 W m^{-2}.

The air mass *m* accordingly to literature [8] can be calculated from empirical expression Eq. (3).

$$m = \frac{1.002432\cos^2 z + 0.148386\cos z + 0.0096467}{\cos^3 z + 0.149864\cos^2 z + 0.0102963\cos z + 0.000303978} \quad (3)$$

where z is zenith angle of the sun.
In order to determine the daily energy sum received by some surface the intensity calculated from Eq. (1) have to be integrated (summed up) in time from sunrise to sunset as well as over all irradiated surface.

Calculation of the clear sky energy according to Eq. (2) and (3) has been explained in our previous works [3,4,7] and therefore is not considered here.
Impact of clouds has been taken into account using a new empirical model Eq. (4) with experimentally evaluated numerical coefficients A, B and C.

$$E = E_C\left(A - B\exp(CM)\right) \quad (4)$$

where E is daily energy sum at cloudy conditions (J), E_C is the same at clear sky conditions, and M is nebulosity (grades).

Comparison of calculated and measured values has been done using graphical method. The model can be evaluated from the scatter plot of calculated daily energy sums via measured ones. About correspondence of calculated values to measured ones indicate slope (must be close to one) and intercept (must be near to zero) of best-fit line, as well as coefficient of determination R^2 (must be close to one).

3. Results

3.1. Impact of clouds

Impact of clouds has been taken into account via Eq. (4). Coefficients A, B and C has been evaluated from comparison of calculated daily energy sums with those measured with pyranometer, then the model for calculating of daily energy sum at cloudy conditions is Eq. (5)

$$E = E_C\left(1.01 - 0.0425\exp(0.295M)\right) \quad (5)$$

Such model gives good coincidence of calculated daily energy sums with measured ones, shown in Fig. 2.

The slope of the best-fit line in this case is 1.005, i ntercept 1.13, and coefficient of determination R^2= 0.88.

3.2. Surface temperature distribution of semi-spherical solar collector

Energy received by semi-spherical solar collector surface element, which is determined with spherical coordinates θ and φ, can be calculated from Eq. (2), where β is angle of incidence of solar rays and can be expressed as scalar product of two vectors: surface normal $\vec{n}$ and solar rays direction $\vec{l}$, Eq. (6).

$$\cos\beta = \vec{n}\cdot\vec{l}_1 = \sin\theta\cos\varphi\cos\delta\cos\Phi + \sin\theta\sin\varphi\cos\delta\sin a + \cos\theta\sin\delta = \\ = \sin\theta\cos\delta\left(\cos\varphi\cos\Phi + \sin\varphi\sin\Phi\right) + \cos\theta\sin\delta \qquad (6)$$

where δ is the altitude of the sun and Φ is the azimuth of the sun.

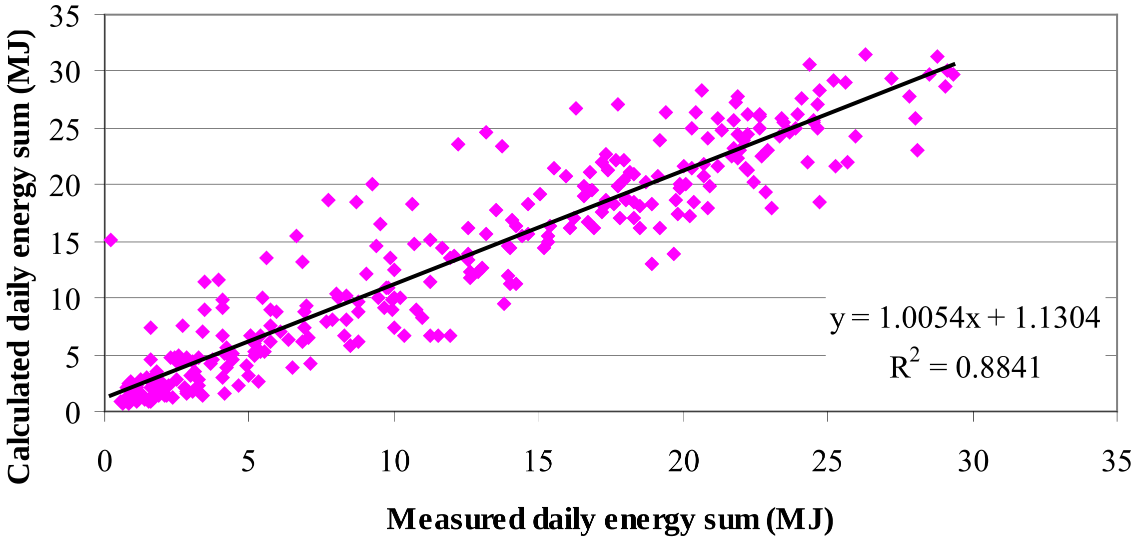
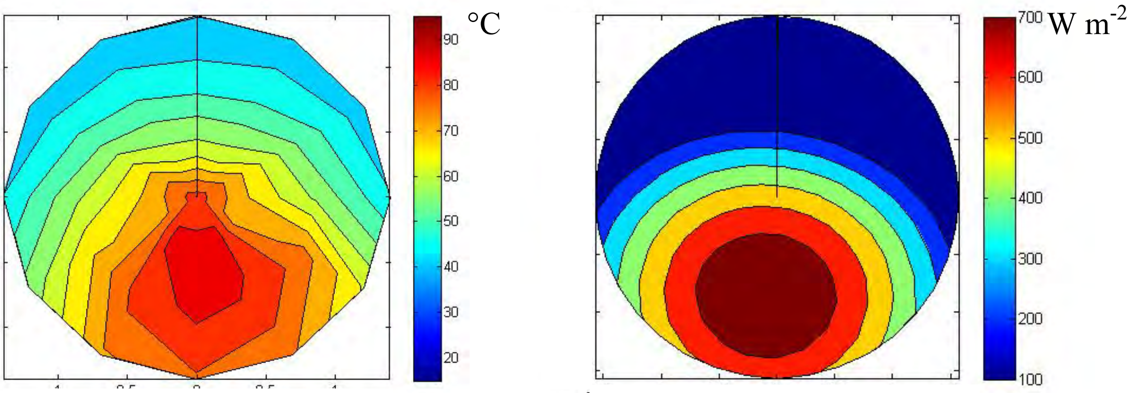


Fig. 2. Comparison of daily energy sums of solar energy, calculated from Eq. (5) with those measured with pyranometer from 1 January 2009 to 31 October 2009.

Results of these calculations in Fig. 3 b ha s been shown in comparison with measured distribution of surface temperature of semi-spherical solar collector Fig. 3 a.



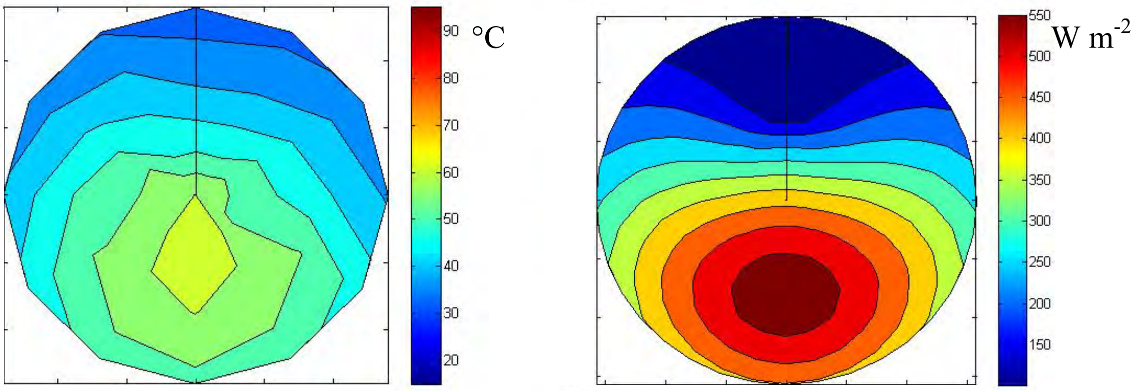
a b

Fig. 3. Distribution of: (a) measured surface temperature and (b) calculated received energy of semi-spherical solar collector at 11 April 2010 at 13:00

Picture shows good correspondence between calculated and measured distributions. Measured distribution is more even because of heat conduction and convection in collector.

Fig. 4 shows daily mean distribution of measured surface temperature (a) and calculated received energy (b). Also good correspondence has been obtained.

Fig. 5 shows daily course of mean temperature at eastern and western sides (arithmetical mean from measurements of 6 thermocouples mounted at corresponding side) of semi-spherical solar collector, but Fig. 6 of northern and southern sides. Of course, eastern side receives more energy at morning, but western side at evening. It is not explained yet why maximal temperature at eastern side is higher than that at western side. Temperature of southern side is certainly higher than that of northern side, with the exception early at morning at late at evening in the middle of summer, when sun rises at northeast and sets at northwest.



a b

Fig. 4. Distribution of daily mean values of: (a) measured surface temperature and (b) calculated received energy of semi-spherical solar collector at 11 April 2010

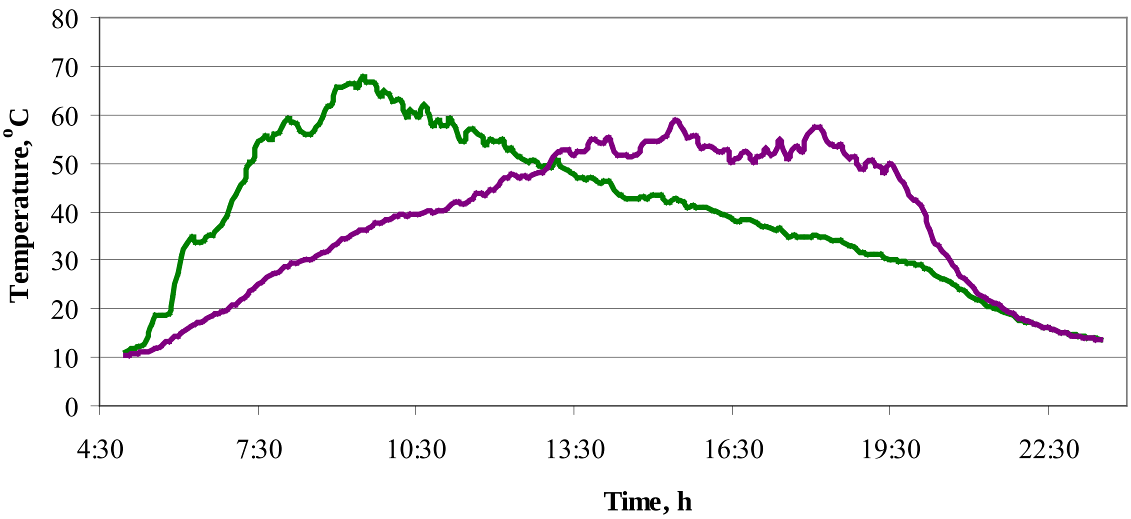


Fig. 5. Daily course of mean temperature at eastern (——) and western (——) sides of semi-spherical solar collector

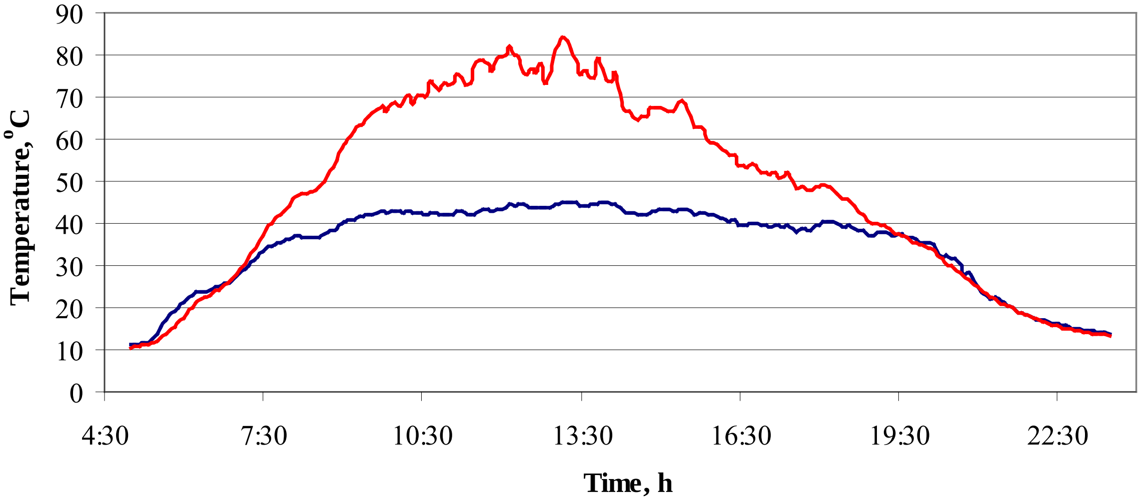


Fig. 6. Daily course of mean temperatures at northern (———) and southern (———) sides of semi-spherical solar collector

But at middle of day, when temperature of southern side reaches 80 ºC , temperature of northern side reaches 40 ºC. There is no s pot on the surface of the semi-spherical solar collector, which never gets warm.

3.3. Energy gain from semi-spherical solar collector

Daily energy gain from semi-spherical solar collector has been calculated from Eq. (1). Results are shown in Fig. 7. There is daily energy gain from semi-spherical solar collector compared with daily sum of solar energy, measured with pyranometer. A linear coherence can be observed, with coefficient of determination R^2= 0.87.

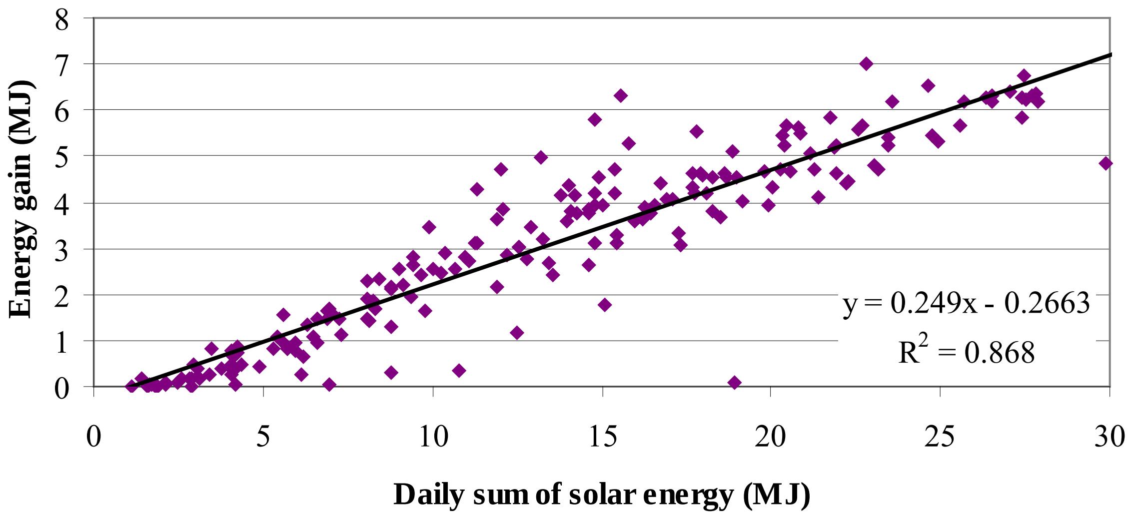


Fig. 7. Daily energy gain from semi-spherical solar collector via daily sum of solar energy, measured with pyranometer from 1 August to 31 October 2009 and from 1 Jun to 30 August 2010.

The slope of the best-fit line (0.25) in this case characterises efficiency of collector. It can be increased using up-to-date materials in the construction of the collector.

4. Discussion and conclusions

Obtained results suggest that semi-spherical solar collector can be appropriate for use of solar energy in Latvia and other countries with similar geographic and climatic conditions. Daily course of surface temperature suggests that semi-spherical solar collector better than common flat plate collector collects solar energy at morning and at evening.

The strong linear coherence between daily energy gain from solar collector and daily sum of solar energy can suggest on independence of work of semispherical solar collector on other circumstances. It can also be because the semi-spherical solar collector uses solar energy evenly all day. However this question needs to be studied additionally, as well as difference between maximal temperatures at eastern and western sides of semi-spherical solar collector.

Other result of this work is method of calculation of received energy of some surface, including impact of clouds. This method is rather simple, precise and not need many input data. This method is usable not only for solar collectors, but also for solar cells, also possible at several forms for better receiving of solar energy. Further study would be interesting on impact of several forms of clouds.

References

[1] L. Kancevica, J. Navickas, E. Ziemelis, I. Ziemelis, Increase of the Efficiency of Solar Collectors, Proceedings of the Second International Scientific Conference “Biometrics and Information Technologies in Agriculture: Research and Development”, Lithuanian University of Agriculture, 2006, pp. 89-92.

[2] I. Ziemelis, U. Iljins, J. Navickas, 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”, Lithuanian University of Agriculture, 2004, pp. 23 – 25.

[3] I.Pelece, Influence of nebulosity on use of solar energy in Latvia, Proceedings of the International Scientific Conference “Engineering for rural development”, 2008, Latvia University of Agriculture, pp. 28-33.

[4] I. Pelece, U. Iljins, I. Ziemelis, Theoretical calculation of energy received by semi-spherical solar collector, Proceedings of the International Scientific Conference “Engineering of Agricultural Technologies”, Lithuanian University of Agriculture, 2008, Vol. 6. pp. 263-269.

[5] U. Iljins, I. Ziemelis, I. Pelece, E.Ziemelis. Spherical solar collector. (In Latvian: Saules enerģijas kolektoriekārta ar sfērisko enerģijas kolektoru un tās pielietojumi) *Patent LV 13550 B* Riga: Patenti un precu zimes 5/2007 p.637

[6] J. Zagars, I. Vilks. Astronomy for high schools. (In Latvian: Astronomija augstskolām) Riga: LU 2005.

[7] I. Pelece, U. Iljins, I. Ziemelis, Forecast of energy received by solar collectors, Proceedings of the International Scientific Conference „Applied Information and Communication Technologies”. - Jelgava: LLU, 2008. - lpp. 62-67.

[8] A. T. Young, Air mass and refraction, Applied Optics, 1994, Vol. 33, pp. 1108–1110.

[9] S. Younes, T. Muneer, Improvements in solar radiation models based on cloud data, Building Serv. Eng. Res. Technol., 2006 Vol. 27, pp. 41-54.