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SEMI-SPHERICAL COLLECTOR FOR WATER HEATING

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Abstract

Latvia is the country located on the 57th north latitude having rather low average solar radiation. Therefore stationary placed ordinary flat plate solar collectors are not effective enough for the use in Latvia. Solar collectors of special constructions like tracking the sun, concentrating the radiation and others are more complicated by their construction and are therefore quite expensive. More perspective in the meteorological conditions of Latvia and other northern countries could be solar collectors with absorber of semi-spherical form. Such collectors are able to absorb the solar radiation from its entire surface and do not contain moving parts. The results of our calculations have shown that at clear and sunny summer day the semi-spherical collector with base area of 1 m^2 receives 1.3 times more heat energy than a flat plate collector, positioned at optimal (approx. 40^o) inclination, and 1.5 times more heat energy than flat plate horizontally placed solar collector.

Key words: *semi-spherical solar collector, solar radiation, effective area, efficiency*

1. INTRODUCTION

More and more attention has been paid to renewable and inexhaustible energy resources all over the globe. Next to other inexhaustible energy resources the solar energy is widely used in many countries not only in the south, but in north latitudes as well. Solar thermal for water heating is a proven technology, which is one of the most cost-effective ways of reduction of fossil fuel use and is reliable and efficient. In Latvia, as in many other countries, the solar energy is mostly used for hot water production, converting the solar radiation into the thermal energy by means of flat plate solar collectors (Ziemelis, Iljins & Navickas 2004; Kancevičа et al. 2006). Latvia is situated on the 57˚ north latitude and has rather small maximal height of the sun and therefore small intensity of the solar radiation. Latvia has long summer days and therefore long path of the sun; unfortunately even in summer days there is a high level of nebulosity. More than 50% out of all days can be considered as overcast, and only approximately 10% days are clear. Presence of clouds decreases the intensity of the direct solar radiation and slightly increases the intensity of the diffuse one. For solar collectors it is important to collect the solar energy from all sides including diffuse radiation as well. The ordinary constructions of solar collectors are not effective enough in Latvian weather conditions. Therefore, in order to heighten the efficiency of solar collectors in the meteorological conditions of Latvia and other northern countries, the special construction of a solar collector, so called semi-spherical solar collector was developed (Pelece 2011). The collector has been made and its experimental investigation on the received heat energy carried out. The semi-spherical collector has several advantages in comparison with traditional fixed flat plate solar collectors. It effectively receives both direct and diffuse solar radiation during all the day from all sides. It is nice looking and durable against destructive impact of wind. Theoretical calculations and experimental investigation on the amount of heat energy produced by the collector has been carried out. Theoretical calculations have been based on the visible position of the sun at the sky at every moment of time, and on the data about cloudiness and lucidity of the atmosphere as well.

2. MATERIALS AND METHODS

In general, the solar radiation can consist of direct and diffused radiation. At the first approximation the diffused radiation and the lucidity of the atmosphere can be considered as constant and independent on orientation of the radiation receiving surface.

The direct radiation received by some surface can be calculated knowing the inclination of the surface and azimuth of the sun. Solar energy at the upper border of the atmosphere is considered constant and equal to the solar constant S_o = 1367±7 W m^{-2}. At the ground level the direct solar radiation, received on the perpendicular to the sun rays surface, depends on the lucidity of the atmosphere and air mass, which in its turn depends only on the elevation of the sun, and can be calculated as

$$I_o = S_o \cdot P^m, \tag{1}$$

where I_o – direct solar radiation at the ground level, W m^2;

P – lucidity of the atmosphere, relative units;

m – atmosphere mass, relative units.

The lucidity of the atmosphere can be expressed by formula (1) and calculated using our measurements of the intensity of solar radiation as following

$$P = \left(\frac{I_o}{S_o}\right)^{\frac{1}{m}}. \tag{2}$$

The lucidity of the atmosphere characterizes the decrease of the intensity of the solar radiation due to dispersion, absorption and other processes when going through the atmosphere mass unite. The lucidity would be equal to 1, if the atmosphere is not influenced by through going radiation. The lucidity of the atmosphere in Latvia usually is within the limits of 0.75-0.85, but sometimes 0.5-0.95. The atmosphere mass depends on the zenith angle of the sun and can be figured (Young 1994) as

$$m = \frac{1.002432\cos^2\theta + 0.148386\cos\theta + 0.0096467}{\cos^3\theta + 0.149864\cos^2\theta + 0.0102963\cos\theta + 0.000303978}, \tag{3}$$

where θ – zenith angle of the sun, rad.

The direct solar radiation received on the flat surface oriented at any angle, can be calculated by formula

$$I_{dir} = I_o \cdot \cos\alpha, \tag{4}$$

where α - angle, at which the solar rays are falling on the surface.

For calculation of the received solar energy by any (curved) surface, a method of effective area is offered. Effective area L is the area of the receiving surface visible from the direction of the sun. The radiation energy received by the effective surface is

$$E = I_o \cdot L\,, \tag{5}$$

where the direct solar radiation I_o from formula (1) can be calculated, and does not depend on the radiation receiving surface. The value of the energy received by a particular surface (formula 3) can be characterized as the effective area L. For a flat surface with area S the effective area is calculated as

$$L = S \cdot \cos\alpha\,. \tag{6}$$

The intensity of the diffused radiation is possible to calculate by subtracting the intensity of the direct radiation from the global radiation

$$I_{dif} = I_{gl} - I_o \sin\delta\,, \tag{7}$$

where I_{dif} – intensity of diffused radiation, W m-2;

I_{gl} – intensity of global radiation, W m-2;

I_o – intensity of direct radiation on the surface perpendicular to the sun beams, W m^{-2};

δ – height angle of the sun above the horizon, rad.

For Latvian meteorological conditions collector with absorbing surface like a semi-sphere would be better than traditional flat plate collector (Iljins et al. 2007). The heat absorber of such a collector is made of 6 one mm thick welded together copper sheets of a certain shape. The heat carrier circulation tubes were fixed to the absorber from the inside (Fig.1), which later was covered by a layer of heat insulation. From the outside the absorber was painted in black for better heat absorption (Fig.2), and covered by a plastic cover to protect the absorber from heat losses by the convection (Fig.3). 29 thermocouples in different absorber's places were fixed for measuring surface temperature (Fig.4).



Fig.1. Copper sheet absorber with tube-type heat exchanger inside

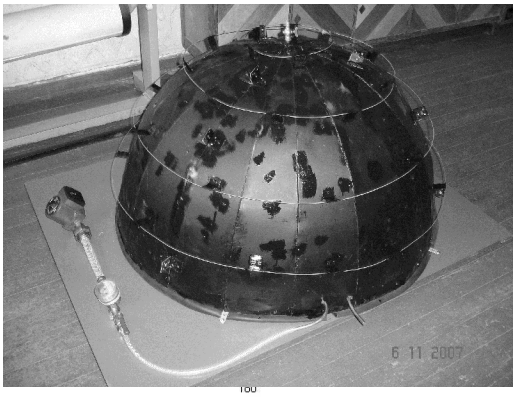


Fig.2. Absorber painted in black, fluid meter and circulation pump



Fig.3. Collector ready for experimental investigation

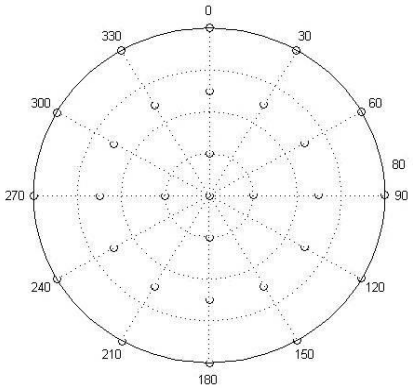


Fig.4. Thermocouples on the surface of the semi-spherical collector

Additional thermo-sensors were used for measuring the surrounding air temperature as well as flowing in and out of the collector heat carrier temperatures. All the measurements were made in every 5 minutes and recorded into a computer using 4 Pico TC08 devices (Fig.5). The experimental investigation was carried out using the transparent cover and without it, using the heat carrier and not using it in order to state the maximum possible temperature on the absorber's surface.



Fig.5. Temperature metering devises Pico TCO8.

For metering the intensity of global radiation received by horizontal surface from 2π stereo-radian angle the ISO 1st class pyranometer CMP 6 produced by „Kipp&Zonen" with the range of receiving from 310 to 2800 nm was used. The global radiation additionally was metered by the device MMD-4 (Putans et al. 2010). For metering the direct solar radiation pyrheliometer CNP 1 (Kipp&Zonen) with the special range of metering from 200 to 4000 nm and system for tracking the sun was used. The measurements were made and recorded at automatic regime in every 5 min from June 2008 till December 2010.

3. RESULTS AND DISCUSSION

3.1. Theoretical and experimental assessment

The theoretically calculated heat energy received by the flat surface was compared with the measured one, carried out from March 1st to October 31st 2006. The heat energy received by two surfaces was measured: one fixed so that would be perpendicular to solar rays at noon, and other tracking the sun (always perpendicular to the sun beams). It has been found that at meteorological conditions of Latvia depending on the season the atmosphere lucidity is about 0.78 and the intensity of diffuse radiation is about 150 W m^{-2}. Using the solar coordinates, calculation method given in our work (Pelece et al. 2007) and the method for the atmosphere mass calculation given by Kasten and Young (Kasten & Young 2000), a good coherence between the calculated and measured values of a daily energy are obtained (Fig. 6).

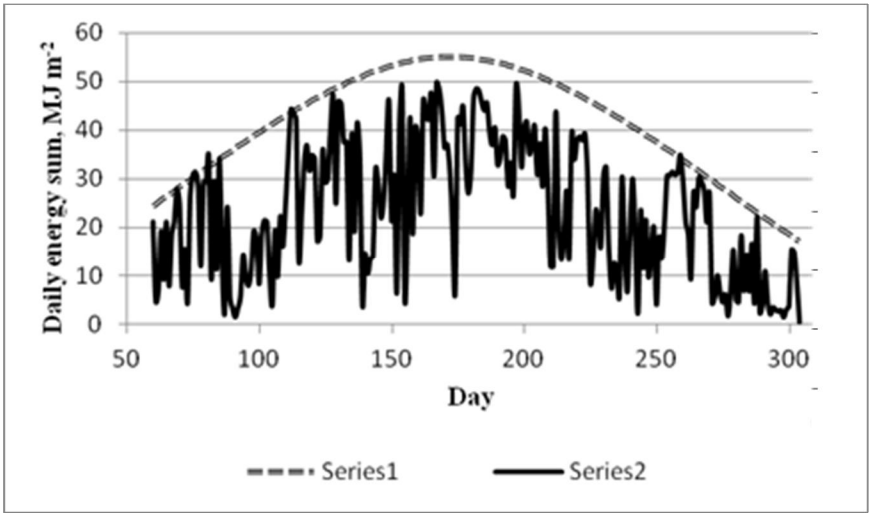


Fig. 6. Calculated (series 1) and measured (series 2) daily sums of the heat energy received by tracking the sun receiver in 2006.

Effective area of spherical surface was calculated as following. A normal vector $\vec{h}$ of the surface at any point (Fig.7.) can be represented in polar coordinates

$$\vec{h} = \sin\theta \cdot \cos\varphi \cdot \vec{i} + \sin\theta \cdot \sin\varphi \cdot \vec{j} + \cos\theta \cdot \vec{k} \quad (8)$$

Direction of solar rays can be represented with vector $\vec{l}$. As y axis can be chosen vertically up, but x axis in the vertical plane, which coincides with the sun beam plane. In such a coordinate system the unit vector of the sun rays $\vec{l}$ can be expressed in more simple way

$$\vec{l} = \cos\delta \cdot \vec{i} + \sin\delta \cdot \vec{j}, \quad (9)$$

where δ is the solar angle, expressing the elevation of the sun. The multiplier $\cos\nu$ in formula (3) becomes equivalent to the normal vector's (formula (8)) and the sun beams' direction vector (formula (9)) product, that is

$$\cos\nu = \vec{h} \cdot \vec{l} = \cos\partial \sin\theta \cos\varphi + \sin\partial \sin\theta \sin\varphi. \quad (10)$$

Taking before brackets multiplier $\sin\theta$ we obtain

$$\cos\nu = \sin\theta(\cos\partial\cos\varphi + \sin\partial\sin\varphi). \quad (11)$$

The expression in brackets in formula (11) is the difference between cosines of angles ∂ and φ

$$\cos\nu = \vec{h} \cdot \vec{l} = \sin\theta \cdot \cos(\delta - \varphi). \quad (12)$$

Energy received by surface area element

$$dE = I_o \cdot R^2 \cdot \sin^2\theta \cdot \cos(\delta - \varphi) d\theta d\varphi. \quad (13)$$

For the calculation of all energy received by the surface of radius R this expression must be integrated along the all irradiated surface, i.e., θ from 0 to π and φ from 0 to $\pi/2-\delta$ (Fig.7):

$$E = I_o \cdot R^2 \cdot \int_0^{\pi} d\theta \int_0^{\pi/2+\delta} \sin^2\theta \cos(\delta-\varphi) d\varphi . \quad (14)$$

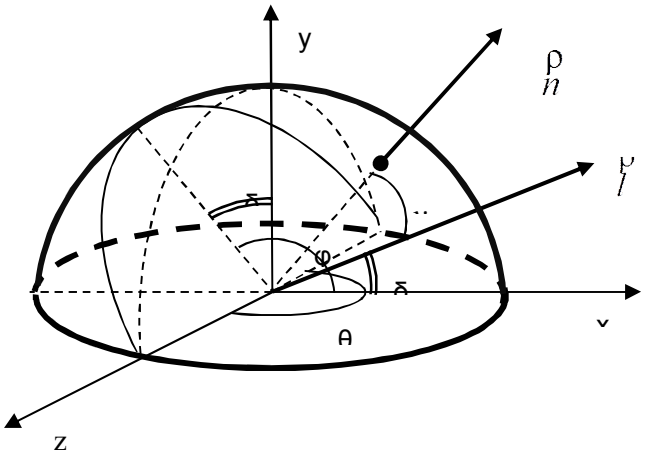


Fig. 7. Calculations of energy received by the spherical surface.

After integrating we obtain:

$$E = I_o \cdot R^2 \cdot \frac{\pi}{2}(1+\sin\delta). \quad (15)$$

Effective area of spherical surface:

$$L = \frac{\pi}{2} R^2 (1+\sin\delta). \quad (16)$$

Comparison of diurnal changes of the effective area of the flat 1 m^2 large surface, positioned at optimal 40° declivity (Pelece et al. 2007), with that of the spherical surface with base area 1 m^2 (Fig. 8) gives that only at the very noon the effective area of the flat surface is larger, but at the rest of the day the effective area of the spherical surface is considerably greater than that of the flat one.

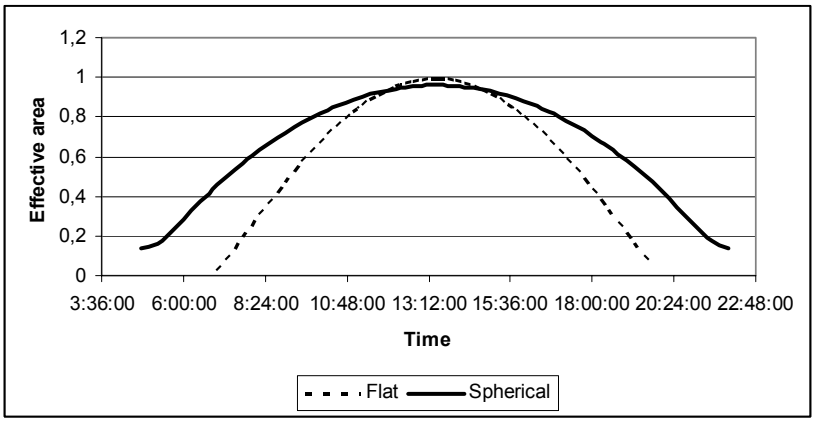


Fig. 8. Calculated effective areas of the flat under 40° declined and spherical surfaces on June 22, 2010.

Figure 9 shows that at the completely clear sky conditions the spherical surface with base area 1 m^2 will produce 9.9 GJ, what is 1.3 times more than that of the flat 1 m^2 large surface positioned at optimal 40° angle (7.4 GJ), and 1.6 times greater than that of the flat horizontal 1 m^2 large surface (6.2 GJ). Calculations of the received energy were made for all season from March 1st to October 31st, 2010 (Pelece 2011).

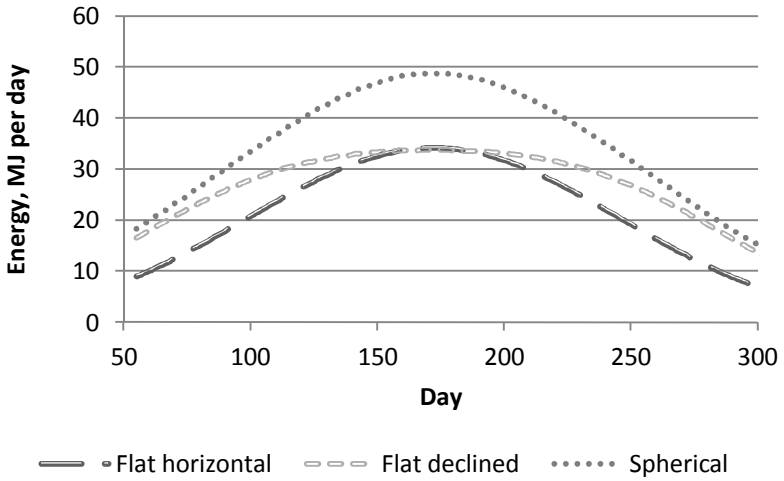


Fig. 9. Calculated daily obtained heat energy sums of flat horizontal, under 40° declined and spherical surfaces with base area 1 m^2 at clear sky conditions.

3.2. Economical assessment

For the evaluation of the production costs of the semi–spherical collector three different size collectors were compared:

1) with the radius R=0.56 m, which was experimentally tested;

2) with the radius R=0.63 m, which would have the least amount of cut off, producing the absorber from two 1 m x 2 m copper sheets;

3) with the radius R=1.27 m, which would have the least amount of cut off, producing the absorber from eight 1 m x 2 m copper sheets.

The amount of warm water consumption of a mean household according to the Latvia Central Statistical data is about 1200 to 2000 kWh per year, so the share of a solar collector would account 700 to 1200 kWh per season. Such amount of energy would ensure semi-spherical collector with radius R=1.27 m. The calculations show that it is possible to gain from such collector about 1300 kWh heat energy per season. It is not rationally to make a very big collector, if only there is no idea about roof replacement with solar collector. If there is a need to produce more heat energy, it is preferable to use a number of jointly connected solar collectors.

The prime cost of the produced heat energy by a solar collector can be expressed as

$$P = \frac{\sum C}{Q}, \tag{17}$$

where P – prime cost of the produced heat energy, € kWh^{-1};

C – total expenses per year, €;

Q – heat energy produced by the collector per year, kWh.

The production and operation costs per year are calculated by the following formula

$$\sum C = \left[\frac{C_{mc}}{T_{et}} + \frac{C_l}{T_{et}}\right] \cdot 1.1 + C_{ee}, \tag{18}$$

where C_{mc} – costs of materials and components, €;

T_{et} – employment time of the collector, 15 years;

C_l – labour cost of the production of a collector, €;

C_{ee} – exploitation expenses per year, €.

Multiplier 1.1 incorporates manufacturing tools and equipment amortization. The common employment time of similar collectors is given in the literature (Ziemelis, I, Iljins, U & Putans, H 2002) and is estimated as 10 years (usually in practise the life time is longer), therefore in our calculations the employment time of the collector is taken as 15 years.

Table 1. The necessary materials and components for the collectors' production.

Materials	Size	Price, €, without VAT	Radius R of the collector, m					
			0.56		0.63		1.27	
			Quantity	Sum	Quantity	Sum	Quantity	Sum
Copper tinplate (1 mm thick)	sheet 1×2 m	176.00	2	352.00	2	352.00	8	1408.00
Tube (diameter 10 mm)	m	3.24	21	68.04	25	81.00	50	162.00
PET (300 µm)	m^2	4.23	6	25.38	8	34.56	15	63.45
Pump, 40 W	piece	59.15	1	59.15	1	59.15	1	59.15
Antifreeze	l	3.20	5	16.00	6	19.20	11	35.20
Colour	kg	5.32	0.5	2.66	1	5.32	2	10.64
Tubes PP PN20 (25×4.2 mm) 3 m	piece	4.51	5	22.56	5	22.56	5	22.56
Tube insulation materials (2 m)	piece	0.73	2	1.46	2	1.46	2	1.46
Screws, fastenings, joints	compl.	10.31	1	10.31	1	10.31	2	20.62
Water tank Junkers	l	*model*	SO160-1		SO200-1		SK300-3Z	
		price	160 l	311.34	200 l	351.07	300 l	730.00
Total, €				868.90		936.63		2513.08
Total with VAT 22%, €				1060.06		1142.69		3065.96

Naturally, for the production of a semi-spherical solar collector with R=1.27 m the necessary amount of materials will be the biggest. Taking into account the value added tax (VAT), the prime price of such a collector is 3095.96 € (Table 1). About 75% of these costs are spent on collector's material and components, but 25% of the cost goes for the purchase of the hot water basin and water drainage tubes.

Consumed labour costs are summarized in Table 2. Collector manufacturing costs are the following: absorber production, heat removal tube inflexion, fixation and transparent cover production, hot water system development and placement in the space. Labour costs include employee's taxes, compulsory social security contributions (CSSC) and Personal Income Tax (PIT).

Table 2. Labour costs of the collectors production and operation.

Work type	Pricing, €/h	Radius of the collector					
		0.56		0.63		1.27	
		Time, h	Sum, €	Time, h	Sum, €	Time, h	Sum, €
Production of copper absorber	14.08	24	337.92	24	337.92	28	337.92
Tube inflexion and fixation	14.08	15	211.20	16	225.28	18	253.44
Production of transparent cover	12.27	15	184.05	16	225.28	18	220.86
Hot water system development and placement	12.27	10	122.70	10	122.70	10	122.70
Labour costs of the collectors		62	855.87	66	882.22	74	991.24
Collectors operating costs per year	12.27	12 h	147.24	12 h	147.24	15 h	184.05
Costs during exploitation		15 years	2028.17	15 years	2028.17	15 years	2535.21
Total, €			2884.04		2910.39		3526.45

It should be taken into account that for collector maintenance and operation there is a need for a regular monitoring (on the average 1-1.3 h per month) and electric energy for the operation of the circulation pump. It is sufficiently enough to use the pump with working power of 40 W. Running the pump for about 8 hours per day and assuming that the season is from March 1st till October 31st, what makes 244 days, the total amount of consumed electric energy would be 78 kWh per year, what according to the current electric energy price in Latvia it would make 9.07 € per year. The share of the production cost per year for the collector with radius R = 0.56 m using formula (16) is

$$\sum I_s = \left[\frac{1060.06}{15} + \frac{2884.04}{15}\right] \cdot 1.1 + 9.07 = 298.30 \text{ €}. \quad (19)$$

According to our calculations and experimental investigation, such a collector with R = 0.56 m during one season of its exploitation is able to produce on the average about 260 kWh of heat energy. Then the prime cost of 1 kWh produced by the collector heat energy according to formula (1) is

$$P = \frac{298.30}{260} = 1.147 \text{ € kWh}^{-1}. \quad (20)$$

The results of economical calculations for different size of the semi-spherical collectors in the Table 3 are given

Table 3. The prime cost of the produced heat energy by the semi-spherical collectors.

Radius of the collector, m	0.56	0.63	1.27
Gained energy, kWh year^{-1}	260	330	1340
Prime cost, € kWh^{-1}	1.147	0.923	0.365

The results of the economical assessment show that the prime cost of the gained heat energy decreases if the size of the collector increases, comparing collector with radius R = 0.56 m and the collector with radius R = 1.27 m. The prime cost of the biggest collector is 3 times less than for the smallest one, but optimal collector size is dependent on the consumer's needs. It should be noted, that collector operation costs are dependent on the consumed warm water amount. At higher consumed warm water amount the heat losses will be smaller, which in our calculation is not considered. In average these losses account 5% of the produced heat energy. Taking into account these losses, the production costs of heat energy would increase for 0.02 to 0.06 €.

In our research the efficiency of different types of solar collectors were compared. In this paper the semi-spherical collector (R=1.27 m) with the vacuum tube solar collector Vitosol 200 SD is compared (Table 4).

Table 4. Comparison of the prime cost of heat energy obtained from 1 m^2 of solar collectors' area.

The type of the collector	Area m^2	Equipment price, €		Prime cost of the produced heat energy € kWh^{-1}
		Total	1 m^2 price	
Vacuum tube collector Vitosol 200 SD	3.80	6901	1816	0.25
Semi-spherical collector (R = 1.27 m)	5.16	6592	1277	0.365

The prime cost of 1 kWh heat energy produced by 1 m^2 area of the semi – spherical collector, as it is seen from Table 4, is by 32% higher than the prime cost of 1 kWh m^{-1} heat energy obtained from a vacuum tube solar collector produced by industry.

4. CONCLUSIONS

1. The calculated amount of the obtained heat energy from a semi – spherical collector with base area 1 m^2 is 1.3 times larger than that of an optimal angle inclined flat plate solar collector of 1 m^2 area, and 1.6 times larger than that of horizontally placed flat plate solar collector of the same size.

2. The prime cost of the semi – spherical collector with R=1.27 m is about 3 times less than for the smallest one (R=0.56 m), but optimal collector size is dependent on the consumer's needs.

3. The prime cost of the produced heat energy by 1 m^2 of the semi – spherical collector is by 32% higher as the prime cost of produced by the vacuum tube solar collector Vitosol 200 SD of the same size.

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