SOLAR COLLECTORS FOR NORTHERN COUNTRIES

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ABSTRACT

Traditionally the solar energy has used in southern countries, but it has used also in northern ones. Most popular kind of use of the solar energy in Latvia is solar collector for water heating. Traditionally flat-plate solar collectors are used because of simplicity of manufacturing. However, some peculiarities in use of solar energy in northern countries must be taken into account. In northern countries there is lower irradiance, but longer day and longer path of the sun during summer. Therefore, traditional flat-plate solar collectors are not appropriate enough in northern countries and new forms have to be developed.

There are two forms of solar collectors - cylindrical and semi-spherical – proposed in this work. Such collectors can be made for both water and air heating.

Theoretical calculations and measurements of energy gain from those two collectors were carried out.

Results show that daily energy sum received by the semi-spherical collector from the sun at the middle of summer is 1.43 times more than that of the flat one, but for the cylindrical collector it is 1.74 times more than that of the flat one, or equal to that of the tracking the sun flat-plate collector. Resulting difference in energy gain from collector will be not so large because of the difference in heat loses. Heat loses can be decreased by switching off the water circulation pump when the sun is covered by clouds. For these purpose circulation pump powered by solar batteries can be used instead of complicated and expensive automatics. Even more important than overall energy gain is the fact that semi-spherical and cylindrical collectors work all the day (17 hours in the middle of summer at 57 northern latitude), while flat-plate collector only about 11 hours. Yearly energy sum received by the collector from the sun is 1.5 and 1.9 times larger for the semi-spherical and cylindrical collector respectively as for the flat one.

The cylindrical solar collector is easier to manufacture, but semi-spherical one is more aesthetical and durable against impact of the wind. Although solar collectors for water and air heating are studied in this article, main ideas are applicable also for solar batteries.

NOMENCLATURE

c	[J kg^{-1} K^{-1}]	Specific heat
D	[-]	Lucidity of atmosphere
E	[MJ]	Energy
i	[-]	Number of degrees of freedom
m	[kg]	mass
M	[-]	Atmosphere mass
P	[W]	Power
p	[Pa]	Atmospheric pressure
R	[J K^{-1}]	Universal gas constant
S	[W m^{-2}]	Solar constant
T	[K]	Temperature
t	[s]	Time
V	[m^3]	Volume
Special characters		
μ	[kg]	Molecular mass
Δ	[-]	Difference
β	[rad]	Incidence angle

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 is paid to renewable sources of energy, including the solar energy. The solar energy is used not only in Southern countries, but also in Northern ones.

Also in Latvia the solar energy is used, mostly in solar collectors for hot water production [1, 2]. Another possibility of the use of solar energy in Latvia is for draying of agricultural production. For this purpose, mainly air heating solar collectors are used.

However, in Latvia and other northern countries 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-th Northern latitude. Therefore there is rather small height of the sun (maximum 56 degrees) and thereby small intensity of the solar radiation, but at summer long day (reaches 17 h 15 min at solstice) and long path of sun (43º to 317º). Additionally there is often big cloudiness. Therefore, traditional flat-plate solar collectors are not appropriate for use in Northern countries and new kinds of collectors must be developed.

There are two ways to improve solar collectors. One is seeking for new materials and technologies for better using of received solar energy. There are rather many investigations in this direction [5-7]. However, there is also another way – to improve the shape and positioning of the collector in order to receive more solar energy. Such works mainly deal with tracking the sun and concentrating of solar radiation [8], and only few authors [9, 10] offer new forms of solar collectors.

Two new constructions of solar collectors – semi-spherical and cylindrical – are proposed in this work. The main advantage of both these constructions is ability to receive solar energy from all sides, what means receive also the diffused radiation and from clouds reflected one, and also better in comparison with the flat-plate collector receive energy at morning and evening. Similar constructions of air-heating cylindrical solar collector for drying of agricultural production already have been investigated by other authors [11, 12]. However, in these investigations the cylindrical solar collector was placed vertically, and was not investigated energy output and effectiveness of collector, only measured temperatures.

In our work the cylindrical solar collector has been mounted on axis pointed to the Polar star for perpendicular incidence of solar beams. In this study cylindrical collector was intended for air heating, but semi-spherical collector for water heating. However, both forms can be used for heating of water as well as of air, and even in photovoltaics. Continuous measurements of temperature of the flowing out air or water respectively allow to determine daily course of temperature and its dependence on meteorological conditions, and to calculate energy output and effectiveness of the collector, as defined in our previous works, *eg*. [13].

MATERIALS AND METHODS

Cylindrical solar collector for air heating is shown at **Figure 1.**

Figure 1. Cylindrical solar collector

It consists of two cylinders: inner one is black-painted metal (galvanized 0.5 mm thick steel sheet, coated with black mat silicon colour), and outer one is transparent 1 mm thick polyethylene terephthalate (PET) material, coated with UV-protective film. Diameter of the inner cylinder is 0.59 m, of the outer 0.67 m, the length of both cylinders is 1.3 m. Both cylinders are mounted on one axis which has been pointed to the Polar star to ensure perpendicular striking of solar beams to the collector surface all day. Ends of cylinders are closed with metal discs, from inside covered with 3 cm thick Rockwool heat insulation. There are openings in the discs for inflow of cold air and outflow of heated air. These openings are positioned so that inflow is from the bottom of the lower end of the cylinder and outflow is at the top of the upper end of the cylinder. Such positions allow convection-provided flow of the air without fan. There are two openings in every end allowing using heated air both from inner cylinder and from space between the metallic cylinder and the transparent one, either together or separately.

Temperatures were registered using HOBO logger. This logger is capable to measure air temperature and relative humidity and two external temperatures using sensors connected with cables. We used two such loggers to measure ambient air temperature and relative humidity, inflow air temperature, outflow air temperature and relative humidity and temperature inside the cylinder and in space between cylinder and outer transparent cover. Temperatures were measured after every 5 min with accuracy ±0.7°C, air humidity ±1%.

Air flow was measured using Lutron YK-2001TM vane type anemometer with accuracy ±0.5 m/s.

Measuring was carried out with and without forced flow. Without forced flow it is convectional flow. For full autonomy of the drying process the forced flow was ensured with fan powered by solar cell. The fan with 12 V direct current electrical engine was used. This voltage was ensured using 97W flexible PV module.

Semi-spherical solar collector for water heating is shown at **Figure 2.**

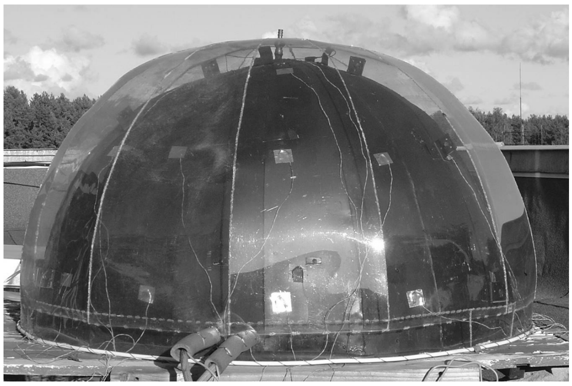

Figure 2. Semi-spherical solar collector

Absorber of the collector is made from copper sheet (thickness 1 mm) shaped as dome and painted black. The collector is covered with transparent PET dome. Radius of the collector is 0.56 m, what corresponds to 1 m^2 base area. Inside the absorber is 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 pump with productivity 30±2 l/h. Water temperature was measured after every 5 min with Pico TC-08 logger, ensuring accuracy ±0.5°C.

Solar energy was measured using pyranometer CMP 6 from „Kipp&Zonen“, corresponding to 1-sth class of ISO. Global solar energy was registered after every 5 minutes.

Power of the solar collector has been calculated for both cylindrical and semi-spherical collectors by equation (1):

$$P = c \cdot \frac{m}{t} \cdot \Delta T, \qquad (1)$$

where ΔT is the difference between inflow and outflow air or water temperatures. With the cylindrical collector air was heated. The specific heat of air is calculated from equation (2)

$$c = \frac{i+2}{2} \cdot \frac{R}{\mu} \qquad (2)$$

Values obtained from this formula were compared with those from thermodynamic tables and found to be the same.

The mass of heated air by equation (3) can be calculated

$$m = \frac{pV\mu}{RT} \qquad (3)$$

Volume of heated air can be obtained by multiplying velocity of the air flow with cross-sectional area of inflow (or outflow) tube of the collector.

Calculating in similar way of the energy amount received by water vapor at such little relative humidity of air gives approximately 100 times smaller value than that of the air and therefore can be neglected.

With semi-spherical collector water was heated. Mass of heated water in time unit is equal to water pump productivity.

The daily energy gain can be calculated using formula (4).

$$E = \sum P \cdot \Delta t \cdot 10^{-6} \qquad (4)$$

Theoretical calculations have been done using method explained in [14]. At first height and azimuth of sun are calculated. If height of sun is known, the air mass m can be calculated [15]. Transparency of atmosphere P has been considered as constant [16]. From orientation of receiving surface and coordinates of sun the incidence angle β can be calculated. Then energy received by surface can be calculated using formula (5).

$$I = S_0 \cdot P^M \cdot cos\beta, \qquad (5)$$

where S_0 is solar constant (1365 W/m^2).

Obtained data are compared with theoretical calculations using methods explained in our previous work [14].

RESULTS AND DISCUSSION

As it was expected, both semi-spherical and cylindrical solar collectors received the solar energy longer during day as the flat one. Theoretically calculated day course of power of cylindrical (a), semi-spherical (b) and flat (c) solar collectors is shown in **Figure 3.** Largest amount of energy was received by cylindrical collector during all day. Semispherical collector at midday receives the same amount of energy as the flat one (with equal area), but at morning and at evening the semi-spherical collector receives more energy than the flat one, and it starts to receive earlier in the morning and ends later in the evening. Such situation has been observed also experimentally.

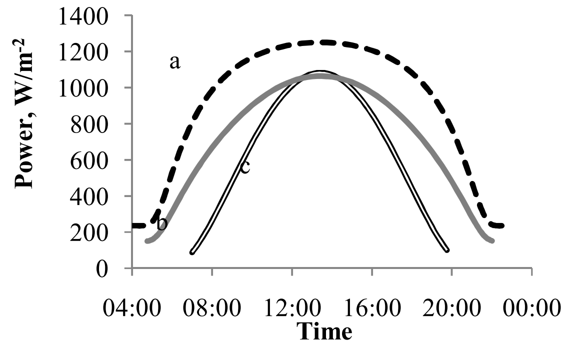

Figure 3. Theoretically calculated day course of power of cylindrical (a), semi-spherical (b) and flat (c) solar collectors.

Figure 4 shows day course of temperature of the air flowing out from the cylindrical solar collector (a) in comparison with course of the global solar energy (b), at almost sunny day of July 5.

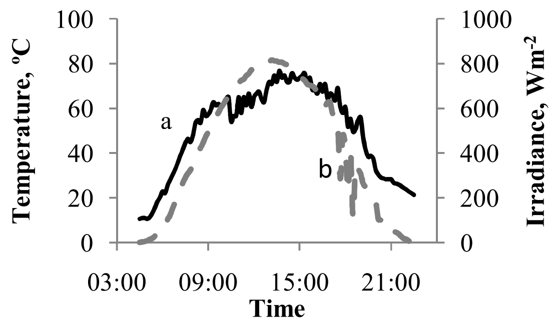

Figure 4. Day course of temperature of the air outflow from the cylindrical solar collector (a) and global solar energy (b).

Other interesting fact is that the cylindrical solar collector works rather good also at partly cloudy day, as shown in **Figure 5.**

From this picture can be seen, that at afternoon global solar energy (curve b) significantly reduces from time to time what indicates of the presence of clouds, but temperature of the collector decrease only slightly.

Another interesting fact from this picture (Fig. 5) is that when clouds appear, solar energy among the clouds is higher than that of the clear day. It means that we receive not only direct radiation, but also reflected from clouds, which, in general, is in other direction as the direct one. Therefore the cylindrical solar collector, which receives energy from all sides, has additional advantages in comparison with the flat one.

It might seem that the ability to receive radiation from all sides, when really radiation comes only from one side at the time, results with large temperature difference between the sun side and the dark side, but infrared pictures show that it is not so. Investigations show that at temperature of outgoing air 80ºC temperature difference of several places of collector surface does not exceed 10ºC, such difference is too small to show in grayscale pictures.

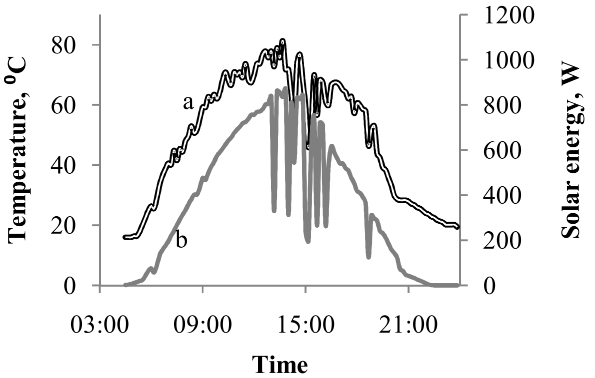

Figure 5. Day course of temperature of air heated with the cylindrical solar collector (a) and global solar energy (b).

Surface temperature of the semi-spherical collector without water flow had been measured. Daily course of temperature of four sides of the collector is shown in **Figure 6.** Each value has been averaged from 10 days.

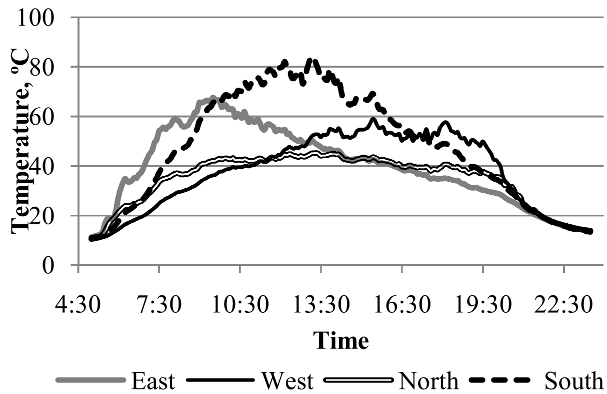

Figure 6. Day course of surface temperatures of semi-spherical solar collector.

As it was expected, the eastern side receives more heat at morning and the western side at evening, and the south side reaches the highest temperature, but it is important, that also northern side gets enough solar energy to warm up to 45ºC almost all day, and there is no point on the surface of the collector, which does not receive solar energy. Therefore use of the entire surface gives the best results.

Of course, differences in day course of received energy leads to similar differences also in year course. **Figure 7.** shows calculated daily sums of received solar energy for cylindrical, semi-spherical and flat solar collectors from March 1 till October 31, what is approximately the season of use of the solar energy in Latvia.

Effectiveness of the solar collector is defined [13] as ratio of energy output from the collector to global solar energy on horizontal surface of the same area as the collector has. It is not efficiency as usually used for characterizing of solar collectors. Efficiency is ratio of energy output to solar energy received by the collector. It does not depend on positioning of the collector, but effectiveness does. Furthermore, solar energy received of the collector is hard to evaluate.

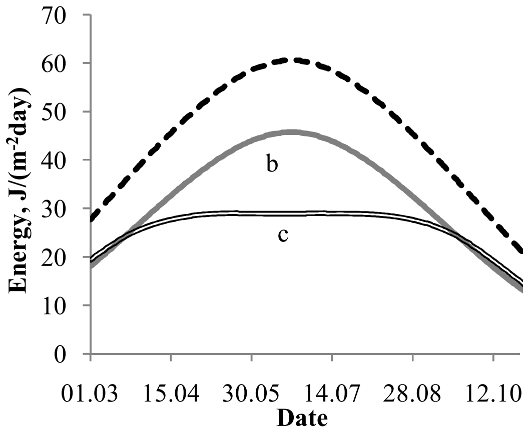

Figure 7. Calculated daily sums of energy received by cylindrical (a), semispherical (b) and flat (c) solar collectors

Global solar energy on the horizontal surface can be directly measured by pyranometer, but for calculation of energy received by slope surface solar coordinates must be known as well as separately beam and diffused radiation. Effectiveness unlike efficiency can be greater than one.

Simplest way to evaluate the effectiveness of the solar collector is to plot daily sums of energy output of the collector via those of global solar energy, then to draw linear trendline taking into account that the intercept must be zero, because when solar energy is zero then also energy output from the collector is zero. Slope of this trendline is the effectiveness of the collector.

For calculating of energy outcome of the cylindrical solar collector air flow was measured. Without fan (convection flow) it was 1±0.7 m/s. With photovoltaic powered fan flow was 3.9±0.5 m/s. Then calculations shows power of the collector 100 – 200 W at medium cloudy day without fan and 600 – 1100 W with the fan. It means that convectional flow without fan is not strong enough for effective use of such solar collector, but with the fan the power of the cylindrical solar collector is sufficient for the drying of the agricultural production.

Similarly was evaluated also the ability of water heating of semi-spherical solar collector.

Then if we draw the best-fit line of it dependence so that intercept is zero, the slope of the line characterizes the energy gain, which we can predict if the global solar radiation is known. This coefficient can be used instead of the effectiveness of solar collector. Traditionally the effectiveness is ratio between the energy gain from the collector end solar energy received by the collector, but the energy received of the collector is hard to measure, because in most cases only global solar radiation has been measured [17], but not the beam radiation and the diffused one separately. Furthermore, the effectiveness characterizes only materials and technologies used in construction of the collector, or how to better use energy received by the collector, but not shape and positioning of the collector in order to receive more energy. The slope of line described here characterizes all factors influencing the energy gain from the collector: materials, technologies, shape and positioning.

The plot of the daily sums of energy output from both cylindrical and semi-spherical solar collectors via those of the global solar energy on horizontal area is shown in **Figure 8.**

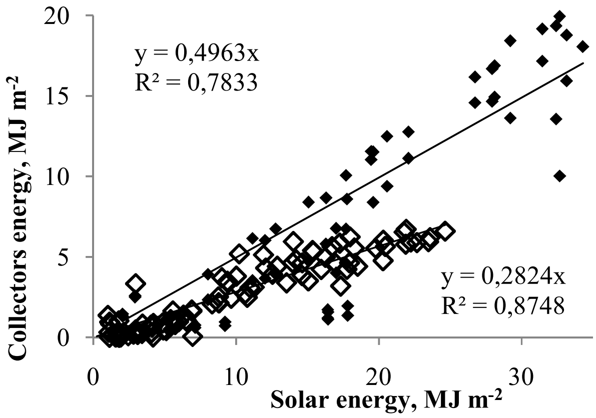

Figure 8. Dependence of daily energy gain from cylindrical (black rhombs) and semi-spherical (white rhombs) solar collectors on daily energy sums of solar energy density on horizontal surface

This plot gives trendline slope (or effectiveness) 0.50 with determination factor R^2=0.78 for cylindrical collector and trendline slope (or effectiveness) 0.28 with determination factor R^2=0.87 for semi-spherical collector. Such rather small effectiveness of both cylindrical and semi-spherical collectors can be explained with use of of very simple, "homemade" materials and technologies.

CONCLUSIONS

1. Other forms, than flat, of solar collectors are more appropriate for use of solar energy in Northern countries, where intensity of solar radiation is rather small, but the length of day reaches 17 hours.
2. The power of the cylindrical solar collector with diameter 0.6 m and length 1.3 m is approximately 600 W at medium cloudy day and up to 1100 W at clear day, using solar energy (photovoltaic) powered fan.
3. The power of the semi-spherical solar collector with radius 0.56 m (base area 1 m^2) is approximately 200 W at medium cloudy day and up to 500 W at clear day.

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