OPTIMIZATION OF SOLAR AIR COLLECTOR

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by

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Aalborg, 2010

ABSTRACT

The key case in this report is to investigate the solar air collector and to perform possible optimizations of it. Whole research is done on a model of solar air collector produced by Danish company SunEcoAir.

Firstly measurements concerning collector like air flow, temperature of air in the collector and pressure loss are performed. Additionally parameters describing weather like wind speed, solar radiation and outdoor temperature are checked. Simultaneously the power produced by solar cell is also measured. Secondly in order to check the performance of the collector the heat balance and efficiency is determined.

In order to optimize the performance several changes are made on the collector e.g. changing size of inlets.

Than on the basis of measurements and DRY file yearly performance of the collector was obtained. Additionally results from the measurements are compared with simulations.

Next solar air system is implemented into BSim in two different cases: firstly in summer house which is used normally at the weekends, and secondly in a normal family house for three people family.

Master Thesis, 10th semester
Indoor Environmental Engineering
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Contents

1 INTRODUCTION

1.1 Background

Indoor climate in buildings

Indoor climate in a building depends on following parameters:

- Air quality (air changes)
- Humidity
- Temperature
- Light (windows)

First three of them can create a risk of health damages if the parameters will not be on the right level (not enough air changes, too high humidity, too low temperature). It is important to focus on these risks as they can cause asthma or other allergy types which are very dangerous for people's health. They can also have bad influence on the buildings, because of damp, moulds, dust mites.

That is the reason why recently there is a growing interest not only in ventilation but also in proper indoor environment. It can help to minimize risk of sick building syndrome, moulds or others. One solution to improve the conditions in the building can be solar air system.

Solar air system

Solar air system is a type of system which collects solar energy and transforms it into heat. The general idea is that the air is flowing through solar collector and heat from sun naturally raises the temperature of the air. In other words cold, outside air is heated and delivered to the room. The collector has on outer layer of glazing/polycarbonate which is exposed to sun. Circulation of the air in the building can be by natural driving forces (buoyancy effect) or by fan which is more certain. Optionally the fan can be powered by solar cell mounted on collector.

Preheating of air supplied to buildings has gained much interest during recent years. The advantage of this technology is that it is cheap and simple. It is especially efficient for summer houses as it can work without anyone's attendance. It can help to get rid of mould and bad smells as well as increase the temperature inside without need of additional heating. In this way the indoor environment in such houses is maintained on a good level after winter.

This type of air collector is similar to typical conventional water collector, but instead of water there is air in pipes.

This collector may be:

- Façade or roof-integrated panel which can be used for:
  - Space heating
- Double window with an internal adjustable blind which can be used for:
  - Heating of ventilation air
- Transparent double façade which can be used for:
  - Heating of ventilation air
  - Space heating
- Glazed space like atrium, attic, sun space which can be used for:
  - Preheating of ventilation air
  - Solar chimneys (assist of natural ventilation),

Solar air system can perform many functions what constitute this system more economical.

1.1.1 Advantages and disadvantages of solar air system

Advantages:

- Better absorbance of solar energy without restriction of direct solar gains in comparison to typical solar passive technologies,
- Better timing of solar heat with usage of thermal wall, when there is no sunshine heat is released from the wall,
- They reduce costs of energy consumption for the building,
- In comparison with water collectors no chemicals for antifreeze are needed and in case of damage they do not cause any loss for the building,
- They can cooperate with HVAC systems, for example for preheating air,
- They can be utilized for very low energy residence and commercial, institutional buildings.

Limitations:

- Very small heat capacity in comparison with water (air=0,0003 kWh/m^3K; water=1,16 kWh/m^3K),
- A lot of air should be supplied to a building to obtain a higher temperature inside.

1.1.2 Variations of solar air collectors

- **Type 1 (ambient → collector → room)**

  Outside air is circulated through the collector directly to the space which should be ventilated and heated. This collector has got a very high efficiency because the outside air is supplied directly to the collector.

  This type of solar air collector can be used for vacation cottages and spaces which are normally closed and used only temporarily to minimize damp and mould.

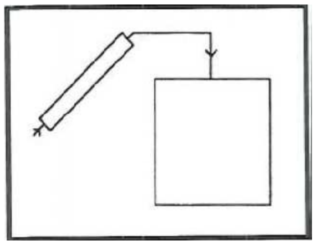

Figure 1.1.2.1 Type 1 solar air collector

- **Type 2 (collector →room → collector)**

  This system was created by Bara Constantini and that is the origin of the name of this system. Air is circulated from the bottom part of the room by collector (where the air is heated) into upper part of the room which constitute storage ceiling. All is driven by natural convection without any fan support. The thermal mass ceiling releases the heat into the room after sunset. In summer the air in the collector can be released to the outside and replaced by fresh cold air from northern part of the room.

  This type of system can be utilized for apartment buildings.

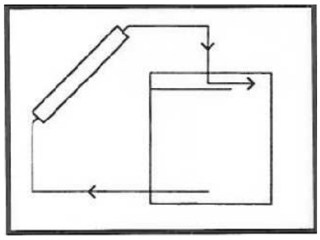

Figure 1.1.2.2 Type 2 solar air collector

- **Type 3 (collector → shell → collector)**

  Warm air is circulated between the collector and open space – buffer which is situated between outer insulated wall and inner wall. This type of system minimizes heat losses from the building what reduces energy consumption for the building. This collector can be inexpensive and very weak solar radiation causes this investment cost-effective.

  This system is utilized in poorly insulated existing buildings or new apartment buildings.

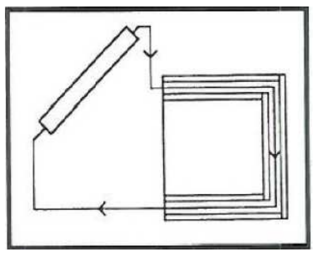

Figure 1.1.2.3 Type 3 solar air collector

- **Type 4 (collector → storage → collector)**

  This is a popular type of solar heating system. Air is circulated in close circuit from thermal mass wall or floor to collector. Heat is released through the convection to maximum 4-6 hours after sunset. Advantage of this system

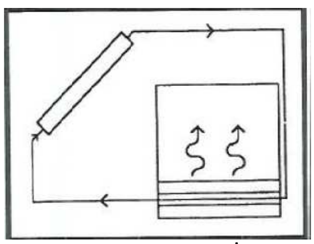

Figure 1.1.2.4 Type 4 solar air collector

is a huge radiating surface (whole floor). Cooperation with fan increases the efficiency of this system.
This system has got practical usage in buildings with large floor area.

- **Type 5 (collector → storage → collector plus room → storage → room)**

  This type of solar air collector is almost the same like type 4 but in this case heat can be stored for longer time and released when it is needed. Till now in only few buildings this system was applied because of the costs of having two independent systems of air channels.

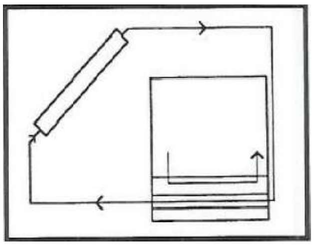

Figure 1.1.2.5 Type 5 solar air collector

- **Type 6 (collector → heat exchanger → collector plus heat exchanger → load → heat exchanger)**

  This type combines hot air and water with use of heat exchanger. Hot air which flows in collector diaphragm heats up water for heating in building that supplies conventional heaters or radiant floor or wall. Additionally domestic hot water can be heated. This system can be applied in existing buildings with traditional heating systems with radiators or radiant floors.

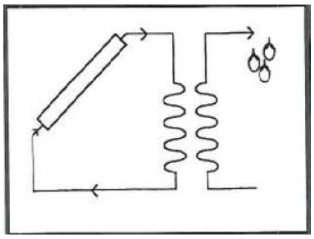

Figure 1.1.2.6 Type 6 solar air collector

1.2 SunEcoAir Solar Collector

This project will be focused on 1st type of solar air collector (ambient → collector→ room) made by Danish Company SunEcoAir.

Main ideas of this system:

- Free heating system
- Free ventilation in a building
- Free dry buildings by hot air obtained from sun energy

1.2.1 Solar air collector – operating principle

To understand usage of solar air collector there are factors that have influence on the performance.

Mounting angle of a collector

Sun's height on the sky is changing almost every week of the year. The highest is in summer when is the best time for collector and the lowest in winter. In order to obtain best efficiency of the collector the sunshine should be fully used through the whole year. In Denmark sun's angles are between 57^{o} in June and 10^{o} in December. For a collector operating through the whole year the best effect would be obtained when the panel was set with angle 37,5^{o}.

Winter – sun at its lowest, minimum 10^{o}

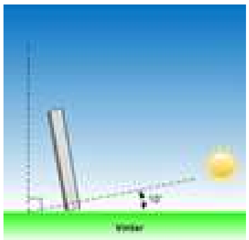

Figure 1.2.1.1 Sun angle for winter

Summer – sun at its highest, maximum 57^{o}

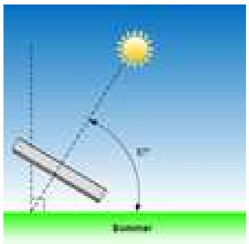

Figure 1.2.1.2 Sun angle for summer

Average set for the solar air collector – 37,5^{o}

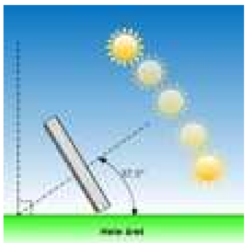

Figure 1.2.1.3 Average sun angle

Heating power from the collector

This system has got a unique principle for air heating. Air is transported from two inlets, which are situated on the bottom of each corner on the back side of collector. Next air is transported through the channels and then air streams will meet in the middle part of collector. Hotter air is flowing towards the outlet where small support fan is situated. This collector was basically tested on account of

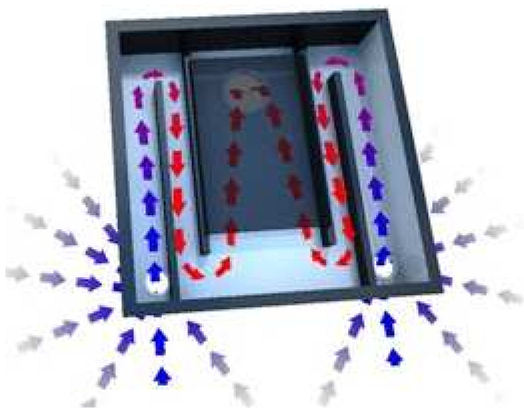

Figure 1.2.1.4 Air transfer in collector

temperature difference between inlet and outlet. The results were that air was heated maximally 26-44^{o}C depending on the size of the collector.

Solar cell

This element converts energy from sunlight directly into electricity. The more intensive is the sunlight the more electricity the solar cell produces. This electricity is later used to run the fan without other sources of energy.

In the figure 1.2.1.5 a sun cell is shown, that was used for collector. It was mounted on the roof so that no object would cast any shadow on it. Normally it is situated inside the collector. Its disadvantage is that even small shadow causes big decrease of efficiency. Normally efficiency of solar cells is very low and equals around 14%-17%.

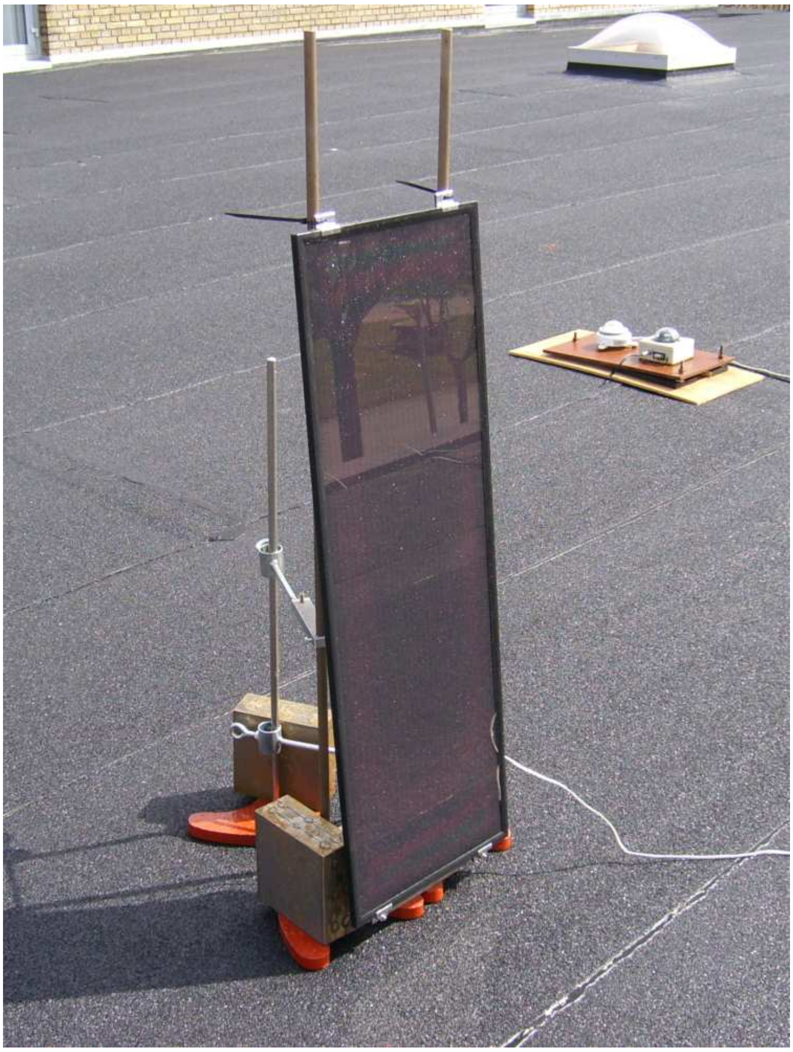

Figure 1.2.1.5 Solar cell

1.2.2 Solar air collector – usage possibilities

It is the best solution for:

- Weekend Cottage house,
- Summer house,
- Garden house,
- Container for people,
- Commercial buildings,
- Caravans,
- Garages,
- Warehouses,
- Basements,
- Other buildings which have got problem with ventilation and heating in autumn-winter season

Solar air collector provides fresh and hot air into a building for whole year. They are mostly used to keep buildings dry without humidity and mould especially in winter when buildings are not used. The system may in some cases prevent buildings from freezing, i.e. it will keep temperature above zero inside a building. In hot climates collectors are used to dehumidify dwellings. Capacity of this collector ranges from 70 m^3/h to 250 m^3/h depending on floor area. Dump, humid and contaminated air is exchanged by fresh hot air. More intense sunshine provides more effectiveness of the fan (which takes power from solar cell) and ventilation. If the hotter air is needed, then less air flows through the collector and by flowing longer through it, obtains higher temperature. Fan is controlled by an automatic regulator which is powered by collector.

Installation of solar air collector

The solar air collector can be installed vertically or horizontally on southern part of the building on the roof, outer wall or on frame near the building. The last solution is chosen if there is a lot of trees or other buildings close to the building that can cast shadow on a collector. Diffuser in building is connected with collector by isolated flex pipe.

- On the roof

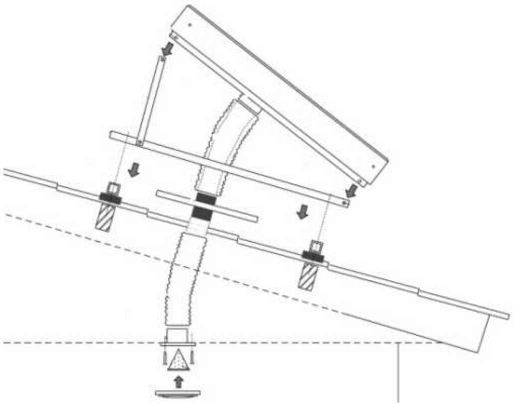

Figure 1.2.2.1 Installation of the collector on the roof

- On the outer wall

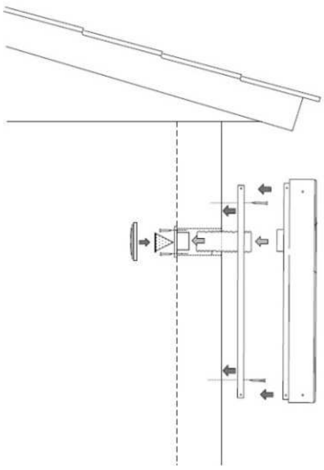

Figure 1.2.2.2 Installation collector of the wall

Advantages of usage of solar air collector (SunEcoAir):

- Hot and fresh air through whole year in non-occupied buildings,
- Air is heated up automatically and provided directly to the room,
- It reduces risk of humidity and mould,
- It is independent from power network,
- It reduces risk from allergy, therefore it is healthy for people.

1.3 Similar technologies to SunEcoAir

1.3.1 Similar technologies

Three similar solar air collectors were found.

- **Solarventi air collector**

Collector principle:

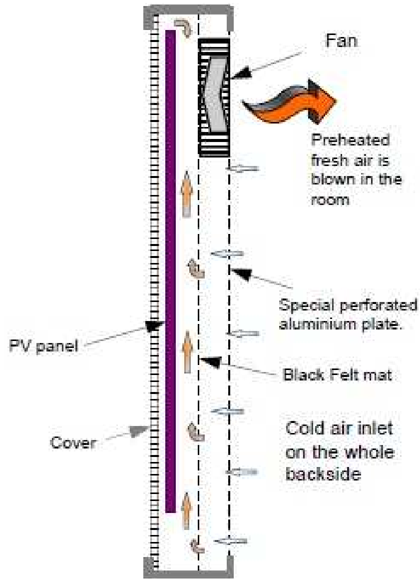

Figure 1.3.1.1 SolarVenti air collector

Special patented collector construction to blow fresh and hot air through whole year. Isolated back side constitutes aluminum cover with a lot of small holes which operate as a filter for fresh air through the fan. Power energy for fan and thermostat is delivered from photovoltaic module which is built in collector. Capacity of this collector ranges from 15 m^3/h to 150 m^3/h, maximum air temperature increase 40^{o}C (between inlet and outlet).

Practical application:

- Summer houses,
- Cottage houses,
- Small temporarily used buildings.

- **Twin and Top Solar air collector (Grammer solar company)**

TwinSolar and TopSolar collectors are the best solution for houses which want to have fresh and hot air through the whole year. They prevent from creating mould and moisture on inner walls of buildings. They are characterized by high effectiveness and need short time to heat the air.
These collectors are very good for places with low level of insolation. Maximum increase of temperature is up to 40^{o}C with intensity 700 W/m^2. Theoretical efficiency equals to more than 80%.

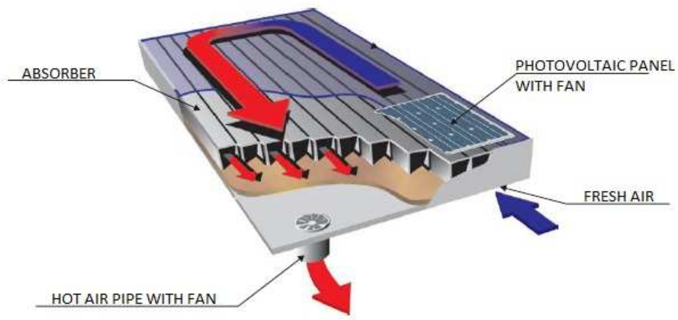

Figure 1.3.1.2 Twin and Top Solar air collector

Practical applications:

- Dwellings,
- Sacred buildings,
- Summer houses,
- Mountain shelters.

- **JumboSolar air collector (Grammer solar company)**

This type of collector consists of few standard GLK type collectors with total area of 20 m^2. One module has got an area of 2,5 m^2. It can be connected to many modules to build a system that is necessary. System has got many possibilities of regulation, installation. Additionally there is a possibility to make a close circuit ventilation – air for summer time. Principle of work is the same like for a Top Solar system, difference is only about the size of collector. JumboSolar collector is designed for a buildings with huge floor area where collectors can be connected to create a bigger set. System is connected with fan and with power which is needed for system.

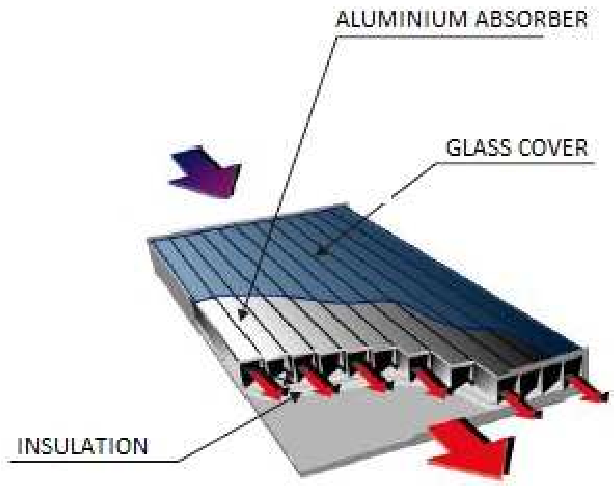

Figure 1.3.1.3 JumboSolar air collector

Practical applications:
- Multifamily houses,
- Sacred buildings,
- Factories,
- A covered market,
- Sports hall,
- Swimming pools,
- Hotels,
- Restaurants.

1.4 Literature review

1.4.1 Jensen S. Ø. "Test of the Summer House Package from Aidt Miljø"

This report had an aim to determine the efficiency of the Summer House Package from air flow. This package consists of an air solar collector and a small fan driven by a solar cell panel.
During measurements the Summer House Package was exposed to an artificial sun with a constant radiation. The radiation was set to be perpendicular to the area of the collector and cell panel. Additionally air was blown along the collector with speed of 3 m/s.

In order to calculate the efficiency the following equation was used:

$$\eta = \frac{\upsilon \rho c_p \Delta T}{AI} \qquad (1.4.1)$$

where:

- v – flow rate through the collector [m^3/h]
- ρ – density of the air [kg/m^3]
- c_p – specific heat of the air [J/kgK]
- ΔT – temperature difference across the collector [K]
- A – transparent area of the collector [m^2]
- I – radiation from the artificial sun [W/m^2]

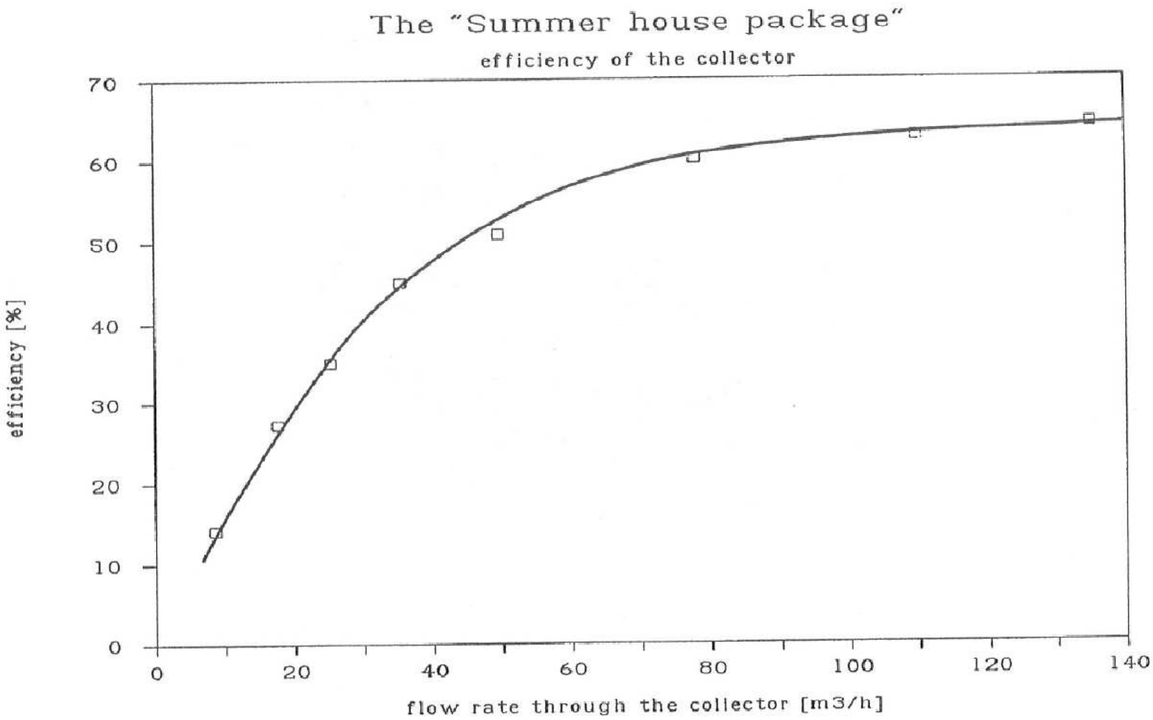

Figure 1.4.1.1 The efficiency of the air solar collector of the Summer House Package dependent on the air flow through the collector

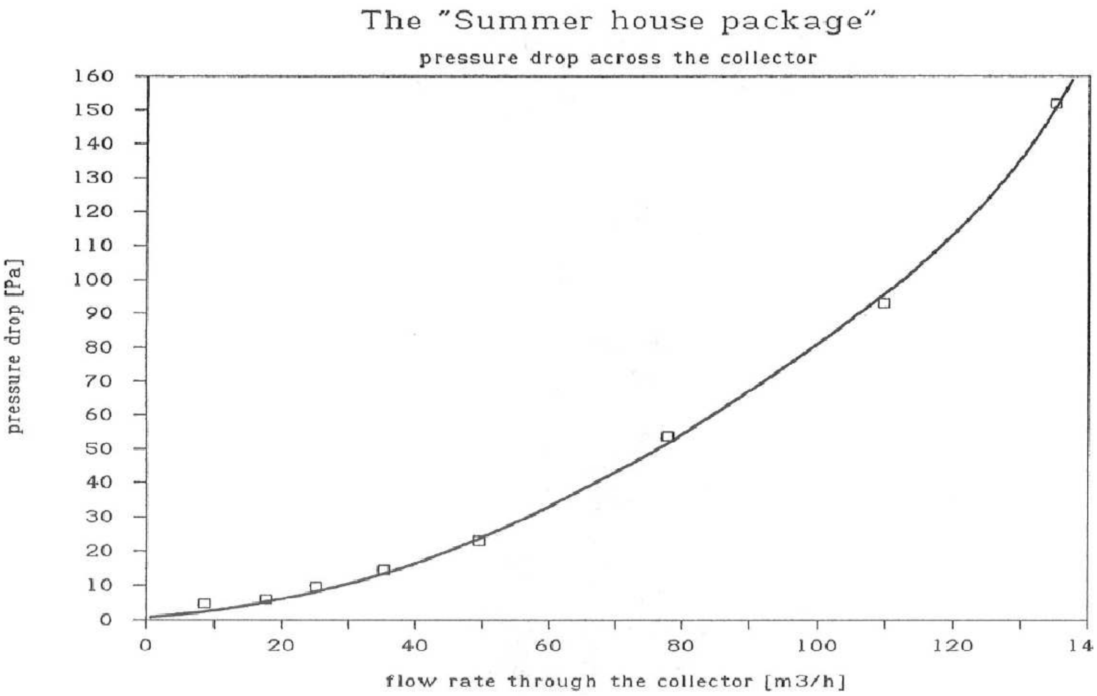

Figure 1.4.1.2 The pressure drop across the solar air collector of the Summer House Package (including 30 cm of flexible duct) dependent on the air flow through the collector

As the fan is driven by the solar cell panel, that is dependent on the solar radiation, the solar air collector and air flow is dependent on the solar radiance as well.

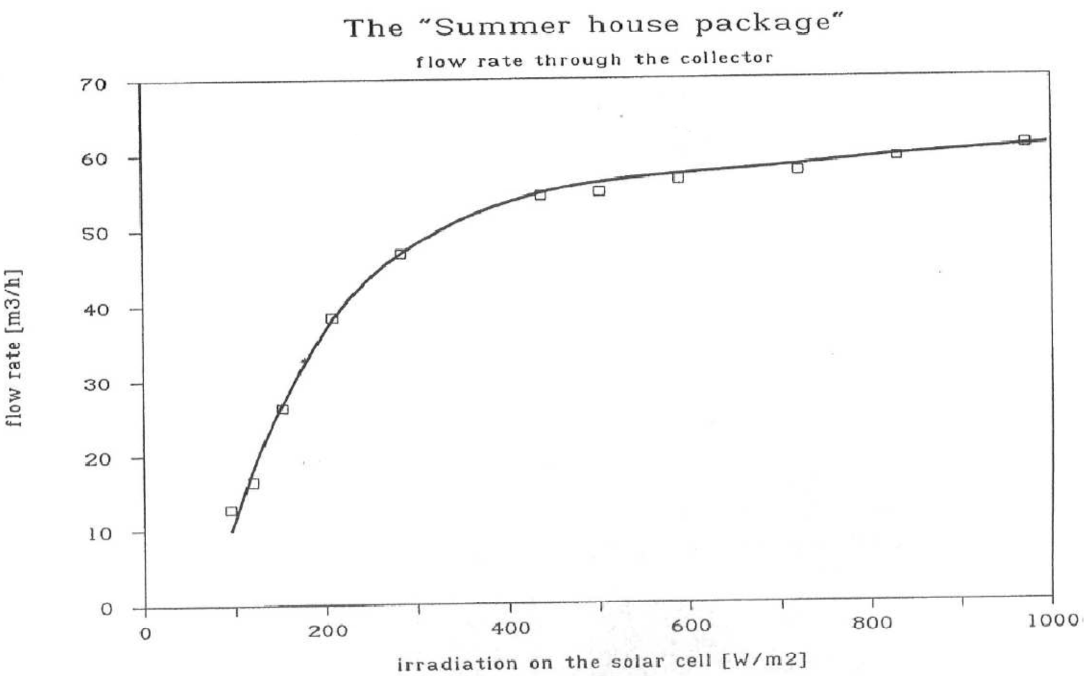

Figure 1.4.1.3 The flow rate through the air solar collector dependent on the radiation on the solar cell panel

When the radiation level is lower than 90 W/m^2 the fan starts working on lower speed that cannot assure the even distribution of the air flow through the collector. Below the radiation level of 15-55 W/m^2 the fan stops working.

Apart from above mentioned reasons the another parameter affecting the efficiency is the influence of the incidence angle of the solar radiation. On the basis of measurements performed in Thermal Insulation Laboratory an equation describing this influence was found:

$$k_a = 1 - \tan^a (V/2) \tag{1.4.2}$$

where:

a – was found to be 2,91,

V – incidence angle of the solar radiation [rad].

Therefore on the basis of that equation and measurements a graph was created:

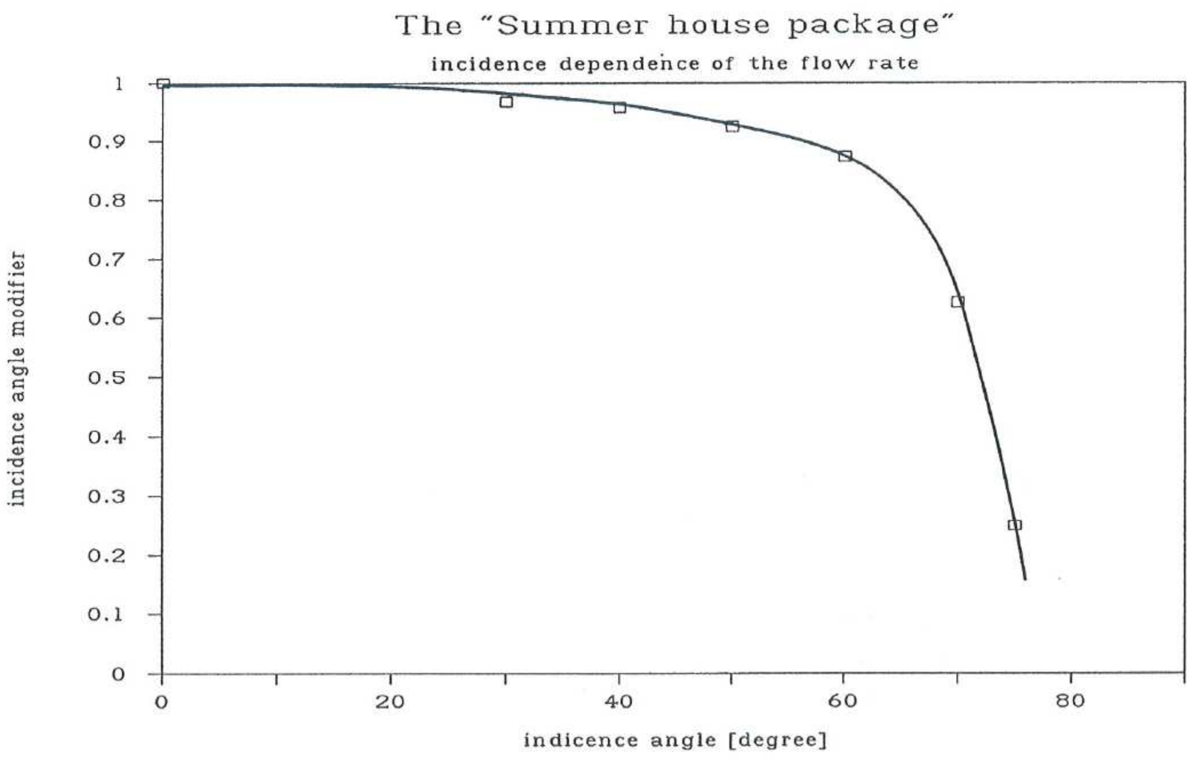

Figure 1.4.1.4 The influence of the incidence angle on the efficiency

Conclusions:

- The air flow through the collector has an influence on its efficiency,
- Solar radiation affects indirectly through the solar cell panel on the air flow,
- Efficiency of the solar air collector and solar cell panel depend on the incidence angle of the solar radiation.

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2 HEAT BALANCE

2.1 Energy balance of the collector.

In order to define the energy balance of the solar air collector the following equation shall be used:

$$Q_u = A_c F_R \left[S - U_L \left(T_{fm} - T_a \right) \right] \quad [W] \tag{2.1.1}$$

Where:

A_c – collector area [m^2],

F_R – heat removal factor [-],

S – absorbed solar radiation per unit area [W/m^2],

U_L – collector overall heat loss coefficient [W/(m^2·K)],

T_{fm} – mean fluid temperature [K],

T_a – ambient temperature [K].

2.1.1 Heat removal factor

Heat removal factor – relates the actual useful energy gain of a collector to the useful gain if the whole collector surface were at the fluid inlet temperature.

In order to calculate the heat removal factor some partial equations need to be solved.

Radiation heat transfer coefficient:

$$h_r = \frac{4 \cdot \sigma \cdot T_{fm}^3}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \quad [\frac{W}{m^2 \cdot K}] \tag{2.1.2}$$

σ – Stefan – Boltzmann constant [W/m^2·K^4],

T_{fm} – mean fluid temperature [K],

ε_1 – emittance of glass [-],

ε_2 – emittance of plate [-].

Reynolds number:

$$\mathrm{Re} = \frac{\dot{m} D_h}{A_f \mu} \quad [-] \tag{2.1.3}$$

$\dot{m}$ - flow rate [kg/s],

D_h – hydraulic diameter; for flat plates is twice the plate spacing [m],

A_f – fluid area (air channel depth times width) [m^2],

μ – dynamic viscosity [kg/(s·m)].

Nusselt number

$$Nu = 0{,}0158 \cdot \mathrm{Re}^{0{,}8} \quad [-] \tag{2.1.4}$$

Heat transfer coefficient

$$h = Nu \cdot \frac{k}{D_h} \quad [\frac{W}{m^2 \cdot K}] \tag{2.1.5}$$

k - thermal conductivity [W/m·K].

Heat removal factor:

$$F' = \left[1 + \frac{U_L}{h + (\frac{1}{h} + \frac{1}{h_r})^{-1}} \right]^{-1} \quad [-] \tag{2.1.6}$$

$$F'' = \frac{\dot{m} C_p}{A_c U_L F'} [1 - \exp(-\frac{A_c U_L F'}{\dot{m} C_p})] \quad [-] \tag{2.1.7}$$

$$F_R = F' \cdot F'' \quad [-] \tag{2.1.8}$$

Where:

$\dot{m}$ - flow rate [kg/s],

C_p – specific heat [kJ/kg·K]

2.1.2 Absorbed solar radiation

$$S = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d \left(\frac{1+\cos\beta}{2}\right) + \rho_g \left(I_b + I_d\right)(\tau\alpha)_g \left(\frac{1-\cos\beta}{2}\right) \quad [\frac{W}{m^2}] \tag{2.1.9}$$

Absorbed solar radiation consists of three different radiations. Index b means beam radiation (direct), index d – diffuse radiation, index g – ground-reflected radiation.

I – irradiation [W/m^2],

R_b – ratio of beam radiation on the tilted surface to that on horizontal surface [-],

τ – transmittance [-],

α – absorptance [-],

(1 + cosβ)/2 and (1 - cosβ)/2 – view factors from the collector to the sky and from the collector to the ground respectively,

ρ_g - ground reflectance [-].

For a vertical collector the above equation is transformed into:

$$S = I_b R_b (\tau\alpha)_b + \frac{1}{2} I_d (\tau\alpha)_d + \frac{1}{2} \rho_g \left(I_b + I_d\right)(\tau\alpha)_g \quad [\frac{W}{m^2}] \tag{2.1.10}$$

2.1.3 Collector overall heat loss coefficient

$$U_L = U_t + U_b + U_e \quad [\frac{W}{m^2 \cdot K}] \tag{2.1.11}$$

Where:

U_t – top loss coefficient [W/(m^2·K)],

U_b – the energy loss through the bottom of the collector [W/(m^2·K)],

U_e – edge losses [W/(m^2·K)].

2.1.4 Top loss coefficient

$$U_t = \left\{ \frac{N}{\frac{C}{T_{pm}}\left[\frac{(T_{pm} - T_a)}{(N+f)}\right]^e} + \frac{1}{h_w} \right\}^{-1} + \frac{\sigma (T_{pm} + T_a)(T_{pm}^2 + T_a^2)}{(\varepsilon_p + 0{,}00591 N h_w)^{-1} + \frac{2N + f - 1 + 0{,}133\varepsilon_p}{\varepsilon_g} - N} \quad (2.1.12)$$

U_t – top loss coefficient [W/(m^2·K)],

N – number of glass covers,

f = (1 + 0,089h_w – 0,1166$h_w \varepsilon_p$)(1 + 0,07866N),

C = 520(1 – 0,000051β^2) for 0˚ < β < 70˚

For 70˚ < β < 90˚use β = 70˚,

e = 0,430(1 - 100/T_{pm}),

β – collector tilt (degrees),

ε_g – emittance of glass [-],

ε_p – emittance of plate [-],

T_a – ambient temperature [K],

T_{pm} – mean plate temperature [K],

h_w – wind heat transfer coefficient [W/m^2·K],

σ – Stefan – Boltzmann constant [W/m^2·K^4].

Wind heat transfer coefficient:

$$h_w = \frac{8{,}6 \cdot V^{0{,}6}}{L^{0{,}4}} \quad [\frac{W}{m^2 \cdot K}] \quad (2.1.13)$$

Where:

V – wind speed [m/s]

L – cube root of the house volume [m]

2.1.5 Energy loss through the bottom of the collector

$$U_b = \frac{k}{L} \quad [\frac{W}{m^2 \cdot K}] \tag{2.1.14}$$

k – insulation thermal conductivity [W/m·K],

L – thickness of insulation [m].

2.1.6 Edge losses

$$U_e = \frac{(UA)_{edge}}{A_c} \quad [\frac{W}{m^2 \cdot K}] \tag{2.1.15}$$

$(UA)_{edge}$ – edge loss coefficient-area product

2.1.7 Outlet temperature

$$T_o = T_i + \frac{Q_u}{\dot{m}C_p} \quad [°C] \tag{2.1.16}$$

T_i – inlet air temperature [˚C].

2.1.8 Efficiency of the solar air collector

$$\eta = \frac{Q_u}{A_c G_T} \cdot 100\% \tag{2.1.17}$$

Bibliography

[1] John A. Duffie, William A. Beckman, “Solar engineering of thermal processes”, John Wiley and Sons, inc., 1991

3 MEASUREMENTS

3.1 Experimental setup

The solar air collector was mounted on the south – west laboratory wall. Collector investigated in a project is made by SunEcoAir company. Firstly no changes to the collector were made.

The height of the collector equals to 1800 mm, width 700 mm and the thickness is 100 mm, where 30 mm constitutes insulation on back wall, whereas side walls are insulated with 20 mm of polystyrene foam. Front of the collector constitutes one chamber polycarbonate. Absorber of the collector is made from aluminum painted matt black. Two inlets for cold air are situated in down parts of the collector and outlet is placed as a one hole in higher part in which the fan is mounted too.

The picture of the model is shown below.

Figure 3.1.1: Picture of the collector with thermocouples mounted inside

In order to get results, below mentioned measurements have to be performed:

- Temperature measurements,
- Air flow measurements,
- Solar radiation measurements,
- Pressure drop measurements,
- Wind measurements,
- Power supply from photovoltaic (PV).

Before the start of the measurements the sampling frequency and pressure drop on pipe and diffuser (components of the package which were delivered with collector) were made.

3.2 Sampling frequency for 1 – hour integration time

In order to obtain the most accurate results for an integration time of 1 hour the sampling frequency has to be measured. It indicates the sufficient time to obtain results that are closest to real values. In order to do that the average values of measured parameters with different sampling frequency have to be compared and then the longest sufficient time has to be chosen. Sampling times used to check the sampling frequency were: 10 sec, 20 sec, 30 sec, 1 min, 2 min, 5 min.

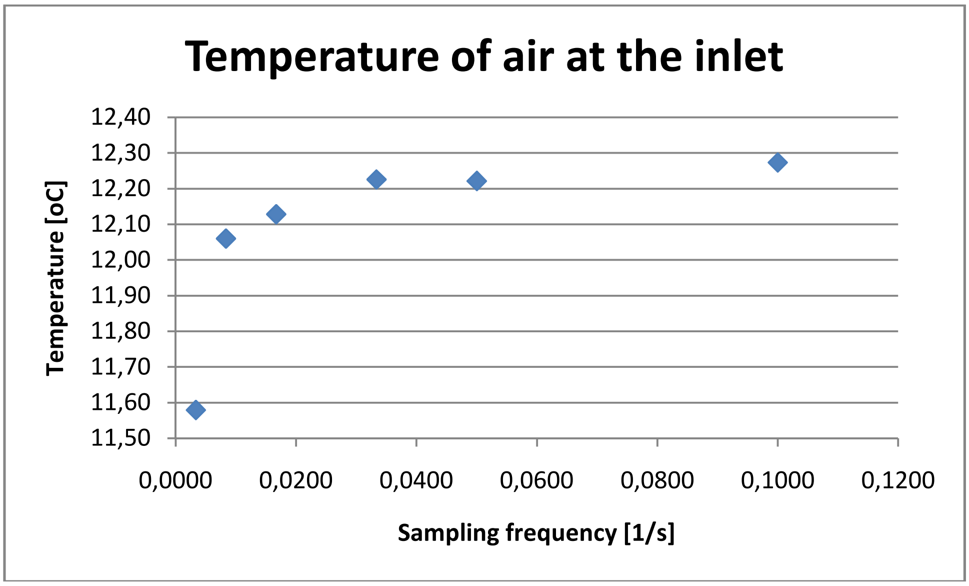

Figure 3.2.1: Average results for temperature of air at the inlet with different sampling frequency

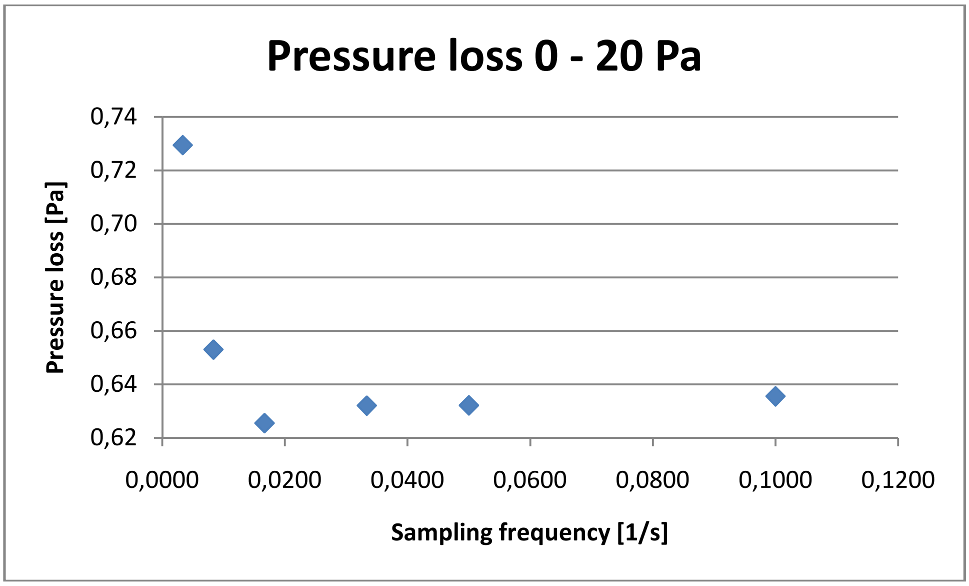

Figure 3.2.2: Average results for pressure loss with different sampling frequency

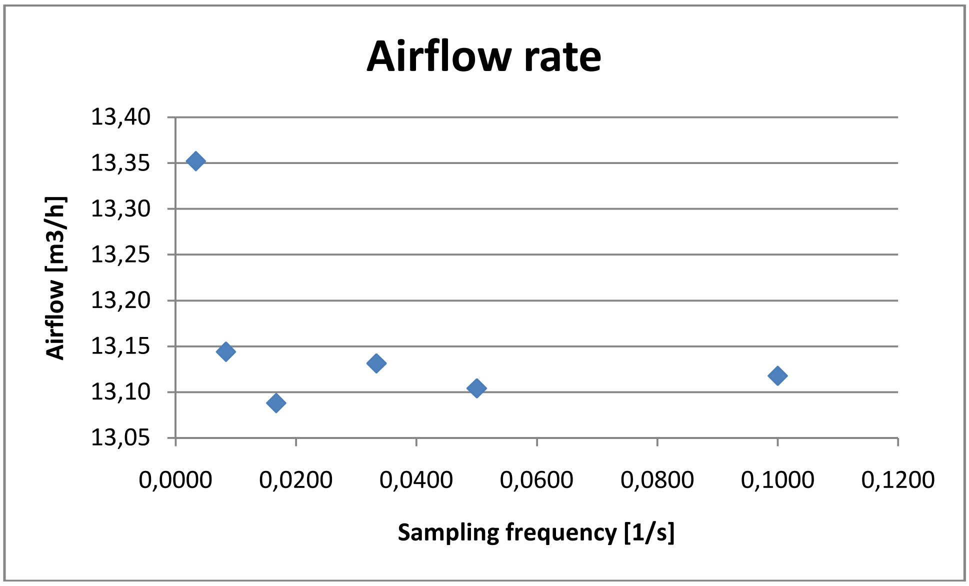

Figure 3.2.3: Average results for airflow rates with different sampling frequency

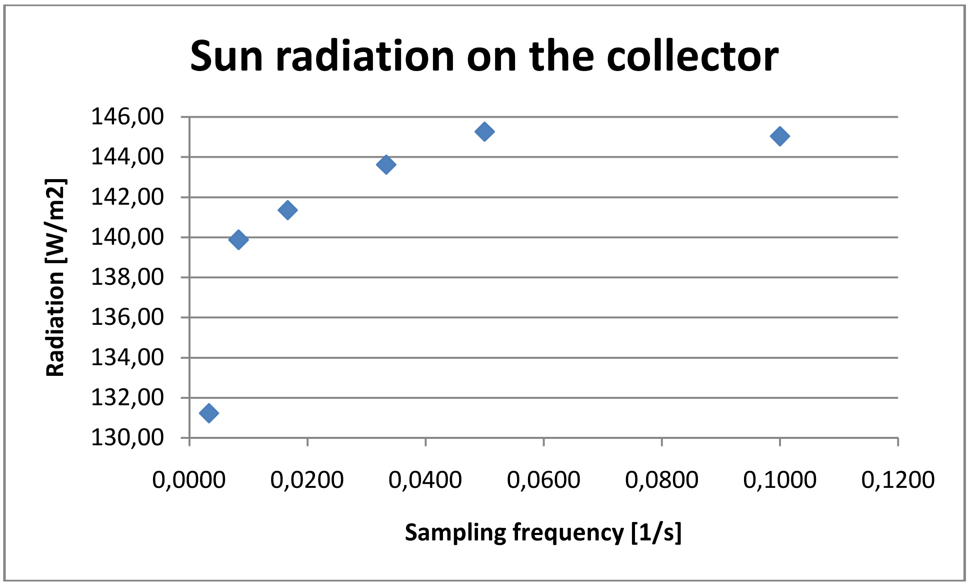

Figure 3.2.4: Average results for sun radiation on the collector with different sampling frequency

From the above presented charts it can be concluded that the sampling frequency is 0,05 1/s. This means that all the measurements in the project will be performed with 20 seconds step.

3.3 Pressure drop

3.3.1 Pressure drop on the flex pipe and diffuser

The air to the room is supplied by a flex pipe added to a set. In order to calculate the pressure loss on the collector, the pressure loss on the flex has to be known. Measurements are performed by means of a micromanometer, an orifice, a fan and an inverter to control the airflow. On the second micromanometer the pressure loss on the flex pipe could be read.

This measurements are performed because the pressure drop on the orifice connected to the measurements setup should be lower than the pressure drop on collector, flex and the diffuser. Otherwise the orifice can block the airflow.

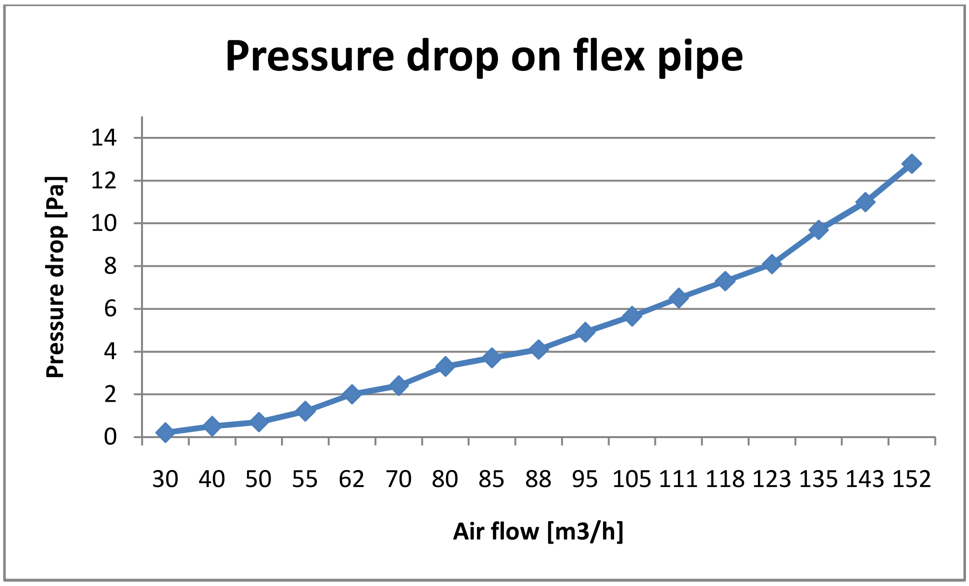

Figure 3.3.1.1: Pressure drop on the flex pipe.

Additionally to the flex pipe there is an adjustable diffuser. Therefore a pressure loss was also measured in three different positions of the opening: one when it was maximally closed, one when it was maximally opened and one just in the middle.

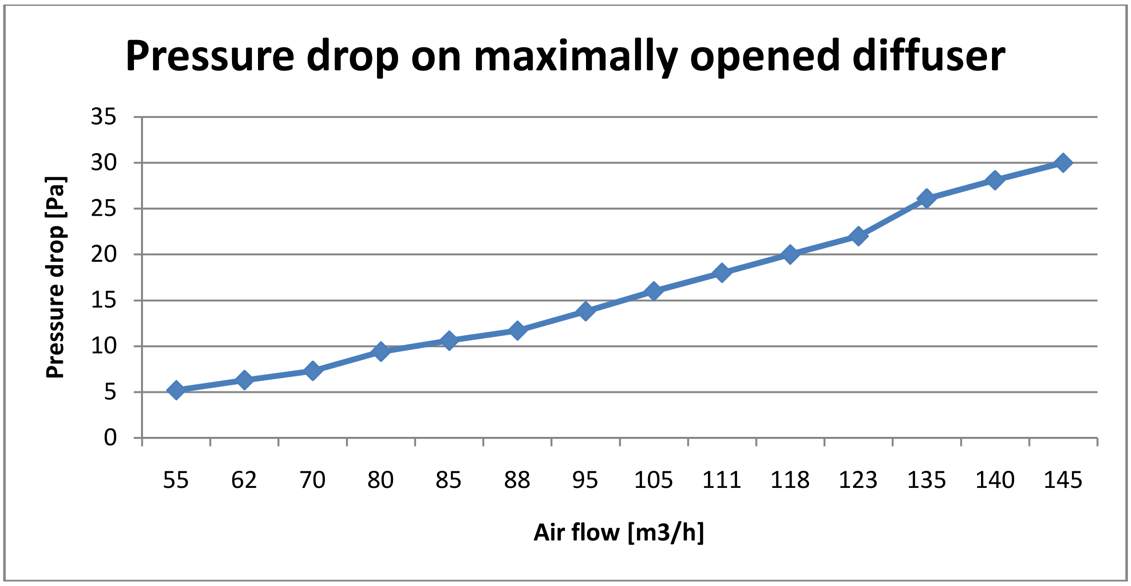

Figure 3.3.1.2: Pressure drop on flex pipe with maximally opened diffuser

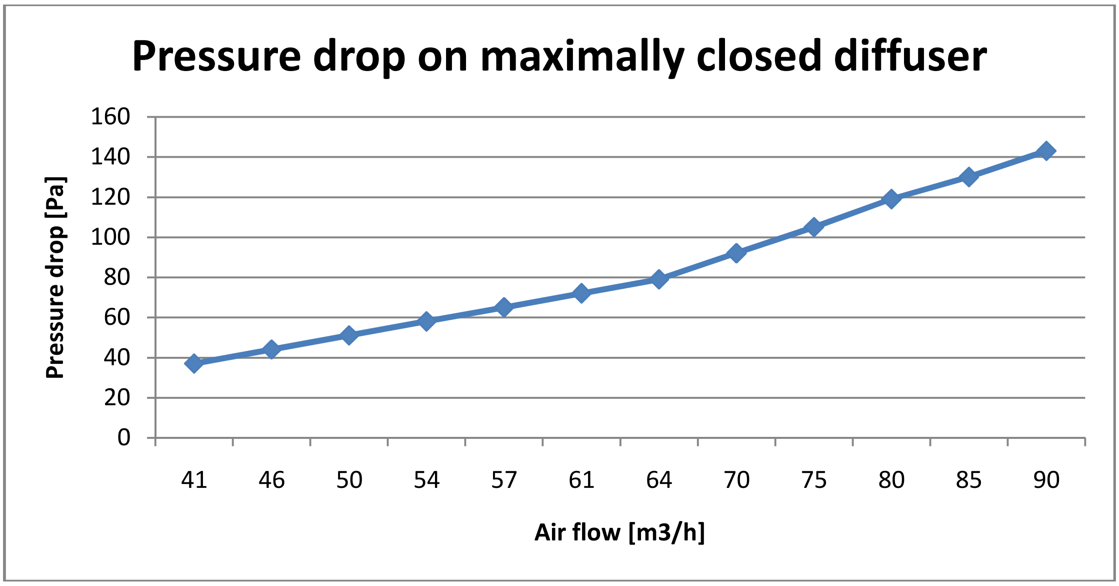

Figure 3.3.1.3: Pressure drop on flex pipe with maximally closed diffuser

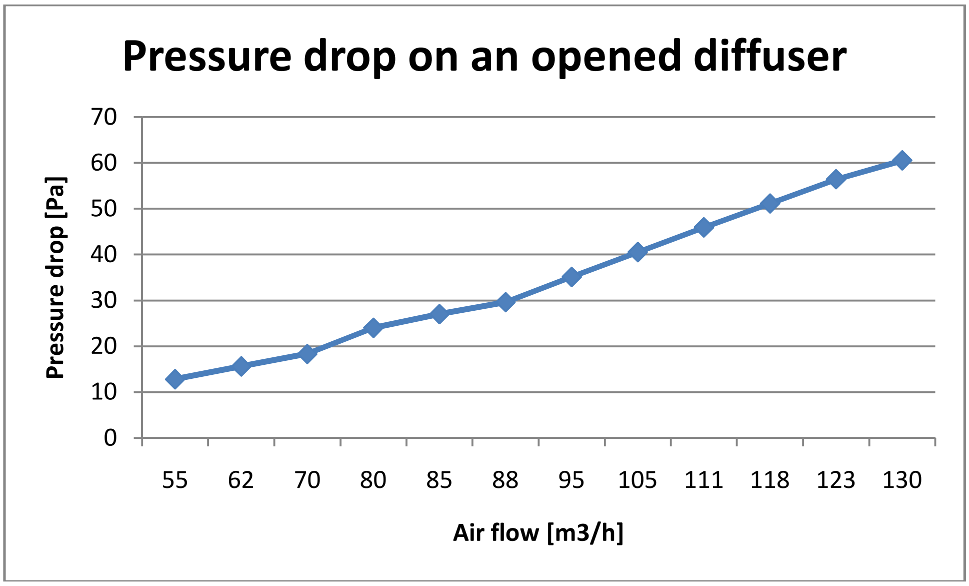

Figure 3.3.1.4: Pressure drop on flex pipe and diffuser in a middle position.

3.4 Temperature measurements

The temperature in the solar collector needs to be measured to obtain the temperature distribution. For this purpose the K-type thermocouples were used. Thermocouples were placed in different locations in the collector and outside of it. Some of them were situated directly on the heated surface - on the plate, some to measure the air temperature in the collector were mounted in small silver coated tubes (see Appendix 9.1 – Temperature measurements).

Points at which the temperature was measured:

- Temperature of the plate (in the collector),
- Temperature of air (in the collector),
- Indoor temperature (in the laboratory),
- Inlet temperature after fan,
- Outside temperature.

Below in Figure 3.4.1 position of all thermocouples on the collector is shown.

Figure 3.4.1: Position of the thermocouples

Thermocouples placed on the left side (1, 2, 3, 4) are measuring air temperature, and these on the right (5, 6, 7) are measuring plate temperature.

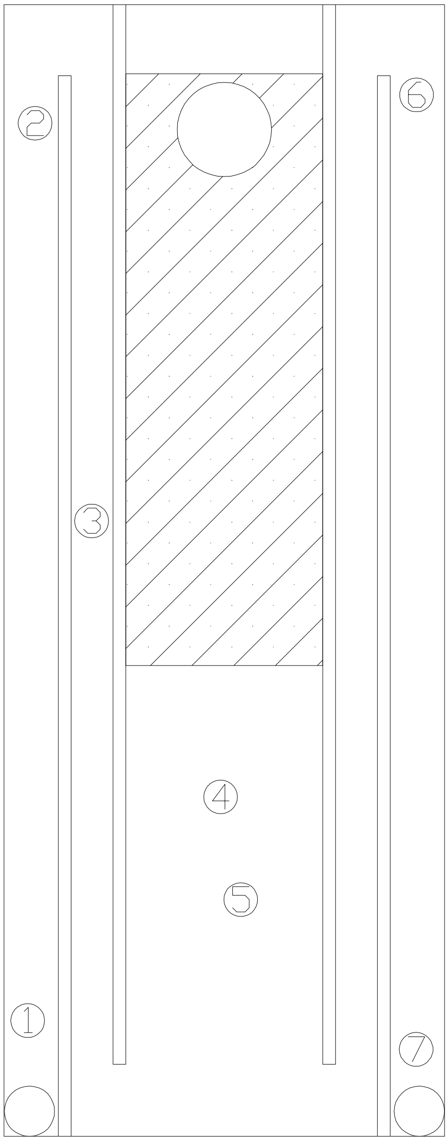

Figure 3.4.2: Position of the thermocouples on the collector

3.5 Airflow measurements

Airflow from collector is measured by pressure difference which is measured by an orifice that is connected to a differential pressure transducer. The airflow is then calculated from an equation given on the orifice. Two types of orifices were used depending from air flow through the collector.

3.6 Solar radiation measurements

The solar radiation is measured by several pyranometers. Two out of four pyranometers are placed on the roof. These are: BF3 which is measuring total and diffuse radiation and Wilh. Lambrecht Kg Pyrheliometer which is measuring total radiation. The other two will be measuring local conditions in the neighborhood of the collector. CM21 will be measuring total radiation on height of 2,5 meter from the ground and CM11 will measure ground reflected radiation and is situated on half height of the collector – 1,4 meter from the ground. (see Appendix 9.2 – Radiation measurements)

3.7 Pressure drop on the collector

In order to measure the pressure drop on the collector the differential pressure transducers were used. The pressure difference was measured in three points: pressure difference between inlet and in first case the outlet before fans and in second the outlet after fans. (see Appendix 9.3 – Pressure loss measurements).

3.8 Wind measurements

For a mathematical model there is a need to measure the velocity of the wind. It will be made in two places: one to measure global velocity at 10 meters height and second to measure local velocity near the collector. For measuring global velocity of wind a Wind Master was used. It can measure wind speed and the direction in 3D.

Figure 3.8.1: Wind Master

For the local velocity an anemometer was used. It can measure the wind speed and the direction of it in 2D.

Figure 3.8.2: Anemometer to measure local velocity.

Wind Master and 2D anemometer are connected to MCG Plus – the Universal Data Acquisition System. Next this instrument is connected to a PC where the results are shown.

3.9 Power supply from photovoltaic cell

Additionally power supply from PV was measured. Into the circuit of power from PV to fan the amperometer was connected. In this way the power supply from the PV can be calculated.

4 RESULTS

During measurements different parameters were measured. Those included three different types of measurements:

- When collector is working with high resistance created by a small orifice during different weather conditions – power for the fan is taken from solar cell,
- When fan in the collector is working on constant power taken from outside source – different cases were considered and measurements were performed during cloudy weather,
- When fan is controlled by the weather, so by power produced by solar cell – this use of bigger orifice means smaller resistance in comparison to the first case.

All measurements were conducted for couple of days. Each result is an average for one hour. In tables there are only some results presented to make them more readable.

The measurements were performed from beginning of April till May with partly cloudy weather and sunny weather. The fan was working usually between 11 and 19 hour when there was enough sun to run it.

4.1 Collector working with high resistance

High resistance created by a small orifice in this case causes smaller airflows and thus during sunshine higher temperature increase. During those measurements fan was supplied with power from solar cell.

Flow rate [m^3/h]	Temperature increase [˚C]	Heat balance [W]	Radiation [W/m^2]	Pressure drop [Pa]	Efficiency [%]
6,94	6,38	16,16	108,21	2,11	3,92
9,15	8,25	32,54	160,93	4,62	4,92
9,66	9,89	36,92	186,56	6,62	5,25
10,91	13,25	46,09	245,73	10,19	5,75
12,32	16,79	58,52	299,29	13,30	9,68
12,71	17,71	60,98	350,30	15,40	7,10
13,77	15,04	62,07	392,58	14,88	8,05
14,09	19,57	75,70	406,18	19,07	8,57
13,85	18,13	87,37	420,87	18,48	10,31
16,00	29,67	234,72	597,78	24,06	28,64
14,69	30,54	210,81	646,81	22,38	23,98
14,96	24,02	220,05	664,66	23,12	24,08
15,54	20,99	180,24	702,82	25,91	18,30
14,96	26,46	189,52	716,85	24,62	19,20

Figure 4.1.1: Results from measurements with collector working with high resistance

Low sun radiation is a probable reason for both low temperature increase and airflow in first few cases. The flow rate is small because the solar cell is not giving enough power for the fan, and because of lack of sun the temperature increase is small as well. Additional reason for the small flow rate is the high resistance produced by the orifice. Those conditions explain poor efficiency and low airflow explains low pressure drop on the collector. With increase of flow rate the temperature increase rises as well. The sun radiation runs the fan and better heats up the air. With bigger airflows the pressure drop and efficiency are increasing as well.

Interesting is the result of an airflow of 16,00 m^3/h. There the efficiency of the collector rises to almost 30%. This measurement was performed at the end of a sunny day. The collector was already well heated up. Therefore despite lower radiation (comparing to the airflow of 15,54) the final results are better.

These results are obtained by small airflows. Therefore the temperature increase rises in some cases to almost 30 degrees.

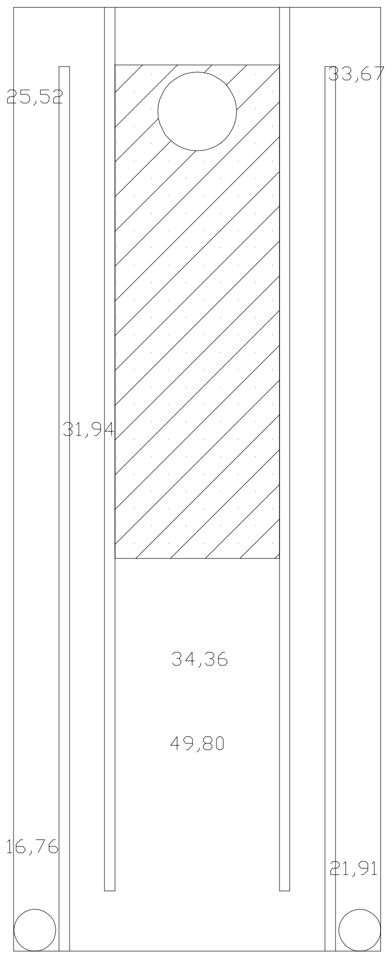

Figure 4.1.2: Collector with temperature distribution for an airflow equal to 16,0 m3/h

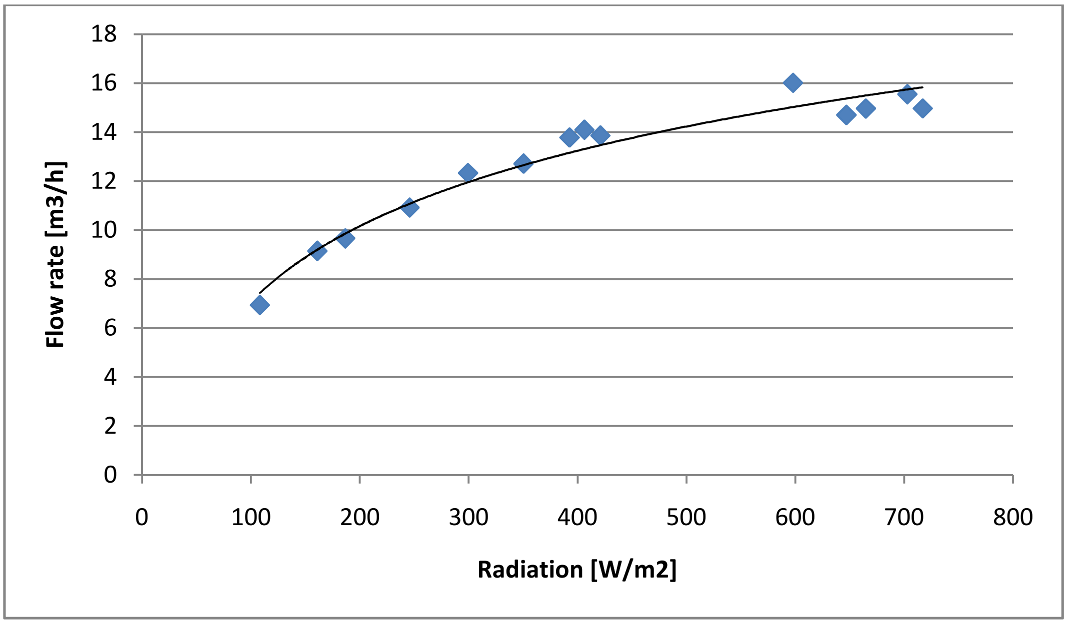

Figure 4.1.3: Dependence of the flow rate from the solar radiation

In the figure 4.1.3 it can be seen that with an increase of the solar radiation, the flow rate also increases. It is so because the fan is powered by a solar cell.

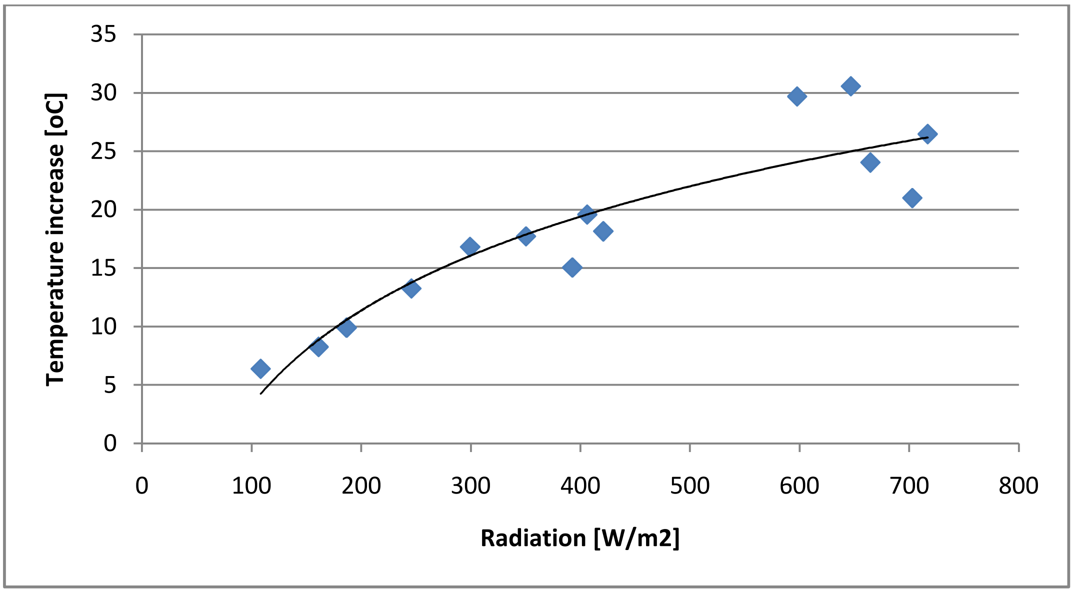

Figure 4.1.4: Dependence of the temperature increase from the solar radiation

With an increase of the radiation the temperature increase is bigger. By small airflows the air is heated up longer when it flows through the collector, so in this case big temperature increases can be obtained.

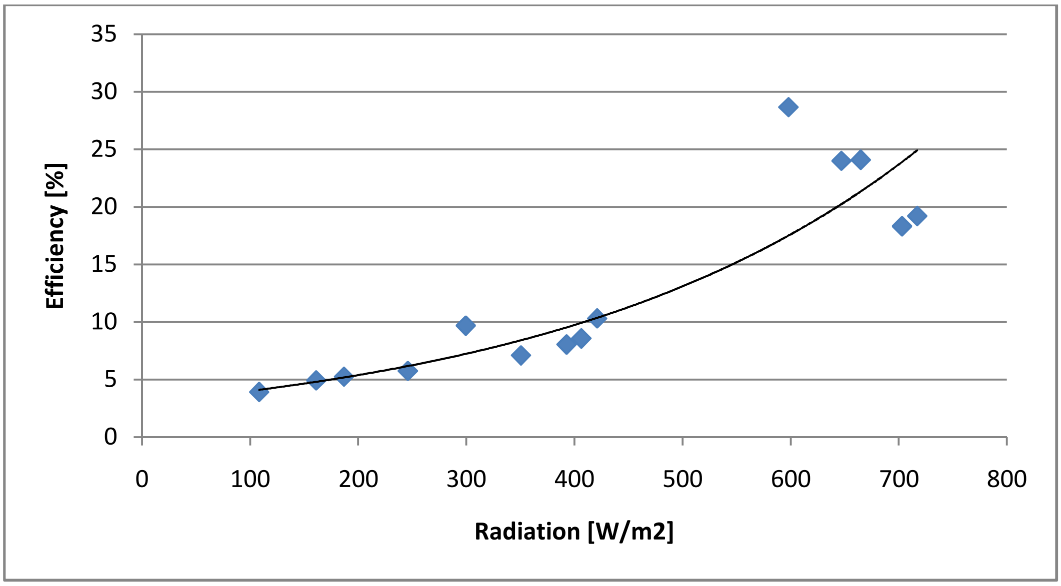

Figure 4.1.5: Dependence of the efficiency from the solar radiation

Because of the growing radiation the temperature increase and airflow are bigger, therefore with an increase of the radiation the efficiency is growing.

4.2 Fan working on a constant power

During these measurements fan is connected to a constant power supply. Series of measurements for different voltage were made. The voltage was changed every 1,5 V and the performance was checked. The sky was overcast at the day of the measurements, so it can explain small temperature increase.

During those measurements some problems occurred. The collector has two fans: one that is supplying air into the room and one that is exhausting warm air from inside to outside. When measurements with maximum power – around 12 volts were performed the first fan was working with full speed influencing the other fan to run as well in this same direction (they are arranged in series). This situation resulted in growth of the airflow and the pressure loss. However, in reality, because of the controller, the fan can work on 70% of the maximum power, so the second fan will probably create additional pressure loss.

Flow rate [m^3/h]	Temperature increase [˚C]	Heat balance [W]	Radiation [W/m^2]	Pressure drop [Pa]	Efficiency [%]
32,51	2,35	36,90	59,38	6,65	12,72
32,72	2,51	34,27	55,87	6,37	12,68
36,05	2,37	48,46	69,87	11,12	13,59
36,06	2,29	50,92	72,66	11,20	13,64
38,43	3,09	68,04	103,03	17,34	13,97
38,75	2,83	65,27	95,99	16,79	14,13
49,74	2,79	55,91	74,27	29,01	15,89
58,90	2,09	54,33	64,64	39,63	17,45
72,26	1,69	49,11	53,72	56,21	19,28
72,97	1,54	45,31	49,83	55,88	19,49

Figure 4.2.1: Results from measurements when fan was working on a constant power

In this case with an increase of the flow rate the temperature increase decreases. Such small temperature increases are caused by a small radiation. Additionally with increasing flow rate, pressure drop and efficiency increase too.

From the table it can be seen that the heat balance depends on the radiation. The pressure drop increases with an increase of the flow rate and so does the efficiency.

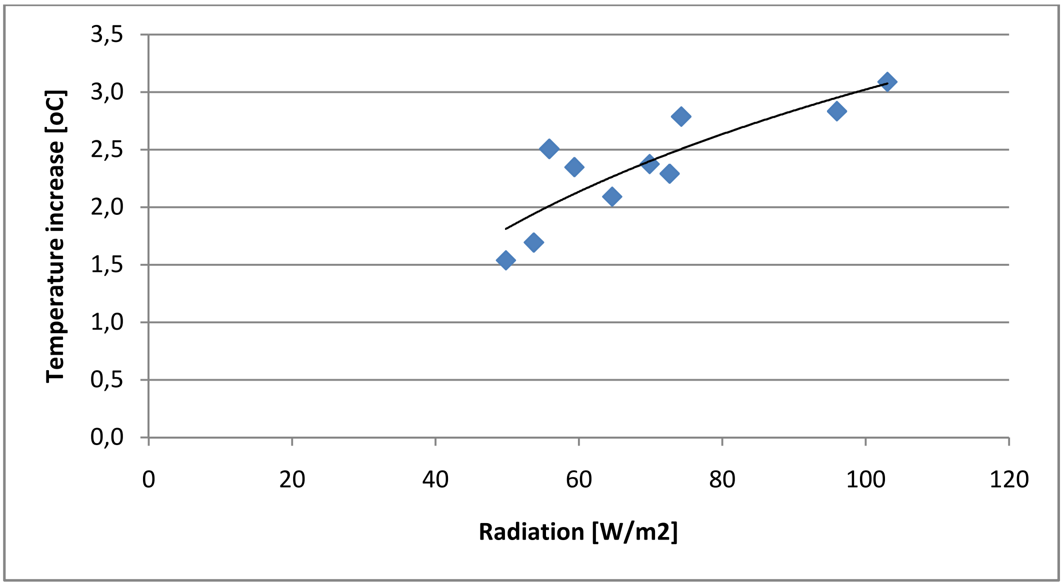

Figure 4.2.2: Dependence of the temperature increase from the solar radiation

As in the first case it is similarly in this one. The bigger the sun radiation is, the bigger the temperature increase.

In this case sun radiation does not have any influence on any other parameter.

4.3 *Fan working on maximal power*

In this case the collector is working on power taken entirely from the solar cell so the airflow depends on the solar radiation. The measurements are performed during a partly sunny weather. Here the maximal airflow is researched so the temperature increase is not as big as in the first case.

Flow rate [m^3/h]	Temperature increase [˚C]	Heat balance [W]	Radiation [W/m^2]	Pressure drop [Pa]	Efficiency [%]
26,13	7,61	54,15	168,68	4,16	13,67
28,9	6,27	64,90	186,12	5,58	11,83
27,36	7,73	67,06	204,30	5,33	15,84
32,53	12,51	94,62	253,33	9,48	18,90
22,5	12,14	42,17	302,10	1,58	8,67
28,45	11,24	91,35	397,33	10,13	11,46
40,15	14,19	193,70	429,63	16,55	26,30
28,40	13,71	97,58	436,40	11,77	11,56
30,43	14,66	143,07	441,59	8,50	15,77
28,91	15,91	112,07	442,53	12,05	13,17
31,22	17,02	153,61	505,17	10,44	16,20
30,62	16,28	141,63	535,54	13,31	15,06
35,46	13,23	220,89	570,93	12,22	22,16
38,94	13,45	262,72	614,03	14,93	25,25
49,8	16,06	240,37	633,32	24,38	25,78
54,4	16,78	455,02	713,32	26,51	46,08
53,3	15,27	396,95	764,07	25,93	36,72

Figure 4.3.1: Results from measurements with fan working on maximal power

With an increasing airflow, the temperature increase rises but not as much as in first case where by highest airflow the air was heated up by almost 30 degrees. In this case however much bigger flow rates are obtained. The pressure drop rises with bigger airflows. Efficiency equals to approximately 25% and higher. In cases with low temperature increase there was a low sun radiation. Different results are caused by measurements performed during different weather conditions.

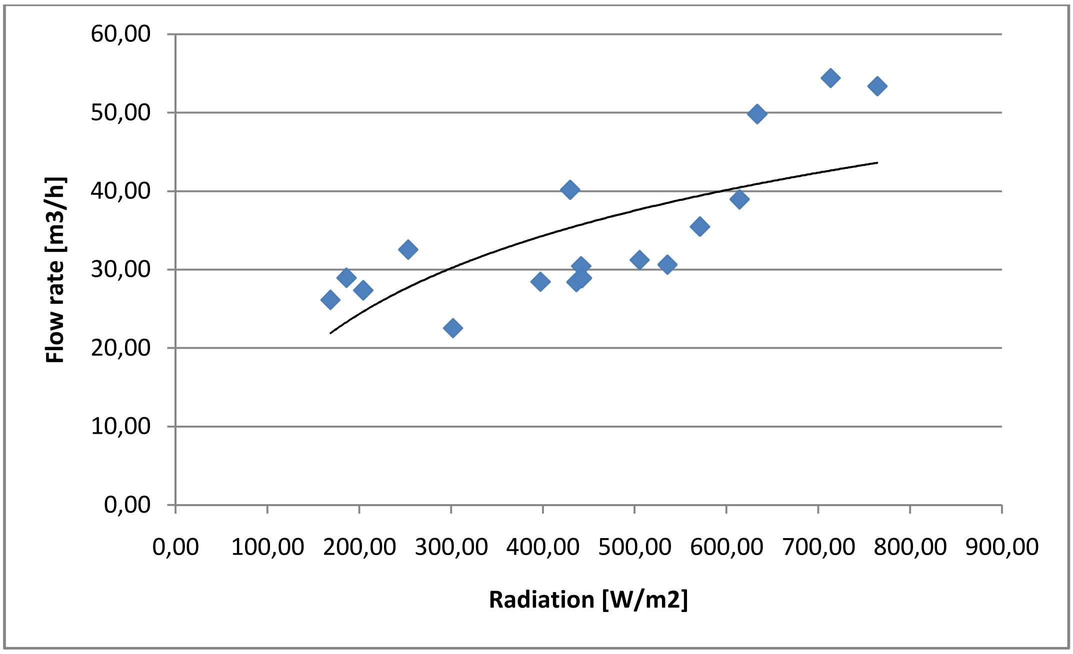

Figure 4.3.2: Dependence of the flow rate from the solar radiation

In this case the flow rate is much bigger than in the first case. It is so because of smaller resistance. The flow slightly rises with radiation because the fan acquires more energy from the solar cell.

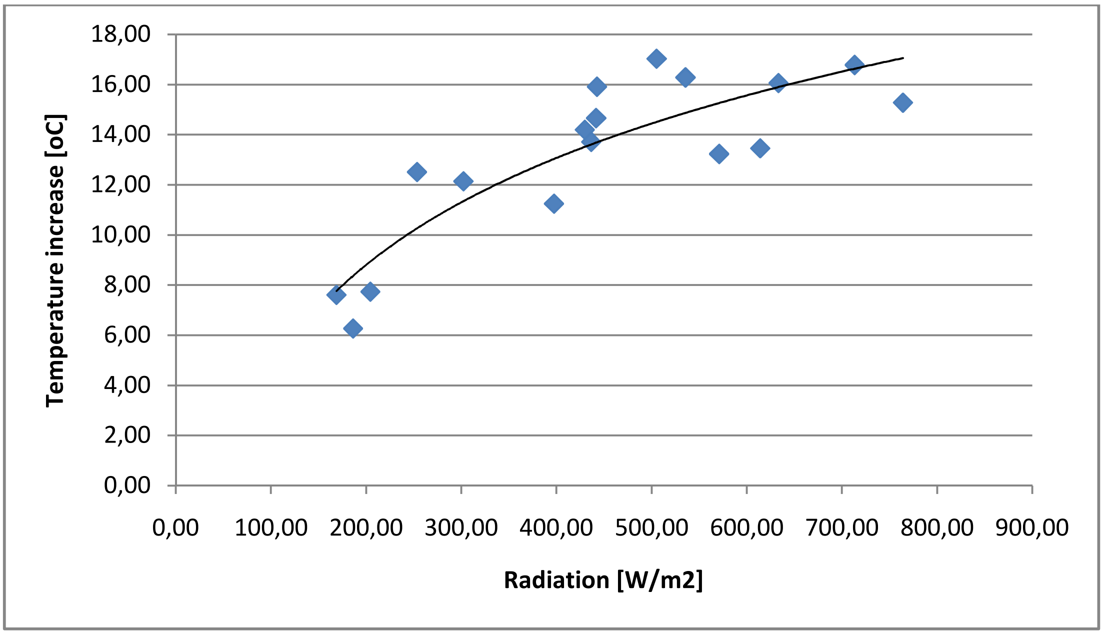

Figure 4.3.3: Dependence of the temperature increase from the solar radiation

As in previous cases the temperature increase rises with bigger radiation.

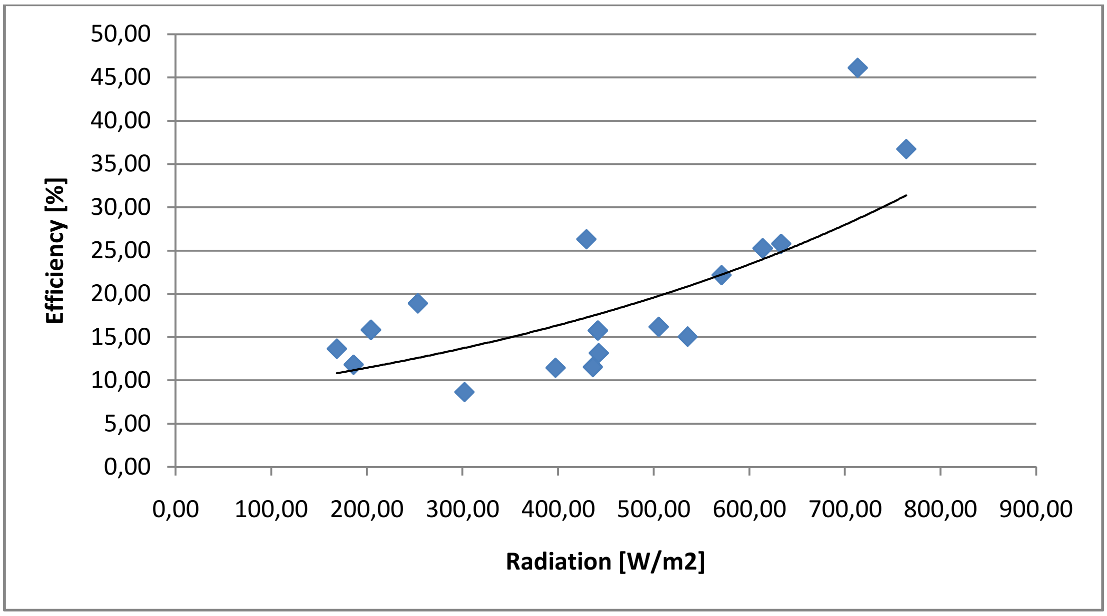

Figure 4.3.4: Dependence of the efficiency from the solar radiation

The efficiency increases with radiation so also with bigger airflows and higher temperature increase.

5 OPTIMIZATION

In order to perform a full research of the collector some changes in it can be made:

- Taking out one fan and inlet covers,
- Enlarging inlet holes.

5.1 Taking out one fan and inlet covers

First of all to decrease the pressure loss the second fan (that removes hot air from the room) and both inlet covers were taken out.

The measurements were performed during a partly cloudy day and a sunny day.

Flow rate [m^3/h]	Temperature increase [˚C]	Heat balance [W]	Radiation [W/m^2]	Pressure drop [Pa]	Efficiency [%]
24,0	6,13	28,84	106,05	3,01	8,21
23,79	5,43	24,69	117,67	1,88	7,69
26,5	6,39	48,09	124,26	4,98	11,49
27,6	7,67	48,98	136,93	5,88	12,56
27,56	6,88	46,72	138,98	7,21	11,16
28,73	6,46	60,56	145,67	8,52	11,81
27,8	7,51	54,40	164,74	6,57	10,01
26,33	7,19	32,67	165,15	3,02	8,11
27,09	7,66	48,62	176,83	5,24	9,15
29,3	9,23	58,45	180,60	8,33	10,85
31,9	10,79	72,85	190,45	12,56	13,73
29,91	8,15	60,85	197,46	6,75	11,47
32,1	8,08	90,46	228,61	12,96	14,81
33,1	10,79	80,98	240,48	13,54	12,77
34,6	9,98	93,09	240,93	15,58	13,82
33,1	12,48	111,15	297,24	12,16	19,12
36,3	13,69	135,11	315,59	18,31	27,00
37,31	16,29	112,25	344,34	13,44	15,99
37,93	16,00	188,06	399,42	13,38	30,49
39,4	13,65	138,71	400,25	21,34	18,17
39,1	14,70	181,24	470,58	20,41	23,15
45,6	16,55	129,40	495,91	28,75	16,25
44,97	19,26	159,51	546,02	20,46	15,61
47,5	22,96	205,05	630,63	30,88	18,85
47,11	14,79	325,48	637,90	22,56	35,28
47,59	17,10	260,34	662,71	24,10	25,73

Figure 5.1.1: Results from measurements of the collector with one fan and both inlets taken out

The results are relatively similar to those performed before introduced changes. Because of smaller maximum radiation (by almost 100 W/m^2) than in previous case the flow rate was smaller after changes. When we consider the fact that each result is an average for one hour then the difference in radiation is relatively significant. The temperature increase is rather similar in both cases. When the efficiency results are compared, the case before changes obtains higher values but within the same radiation range in the second case the efficiency was higher.

Below presented charts concern: a before changes collector, and a collector after first changes when one fan and both inlet covers were taken out.

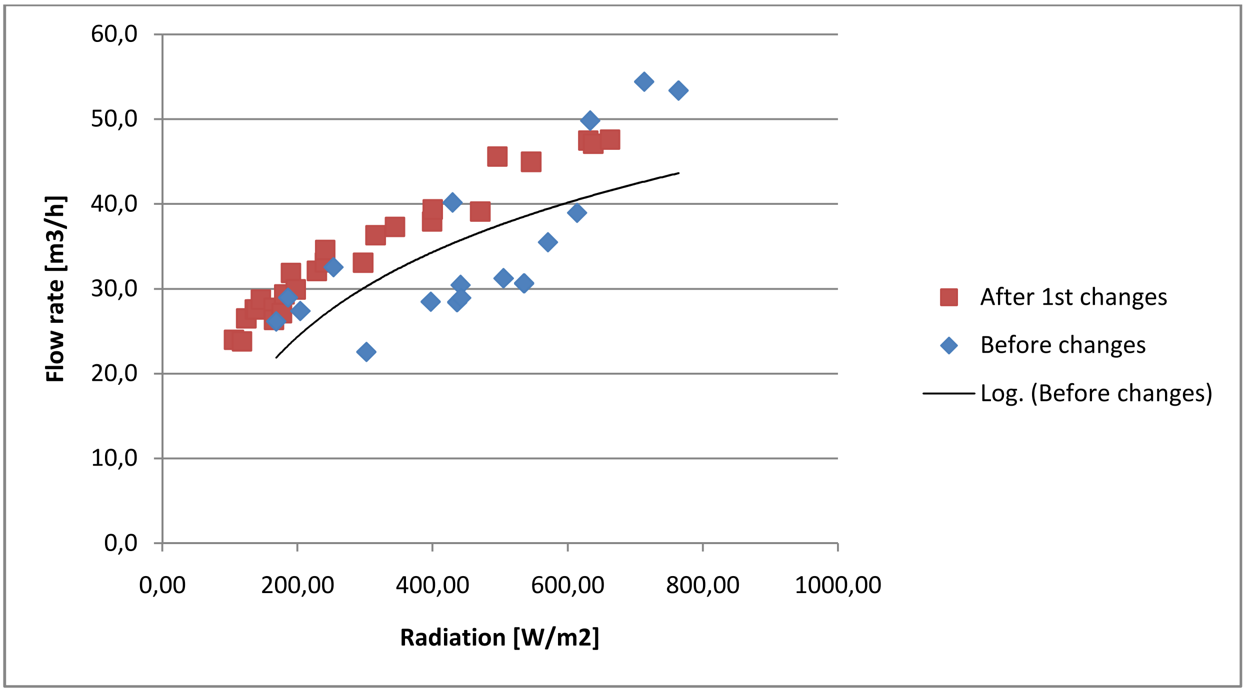

Figure 5.1.2: Flow rate dependent from radiation in two cases

In most cases the results obtained after changes are bigger from those before changes. By the same radiation higher values were obtained. The reason for that might be lower pressure losses (no fan and inlet covers).

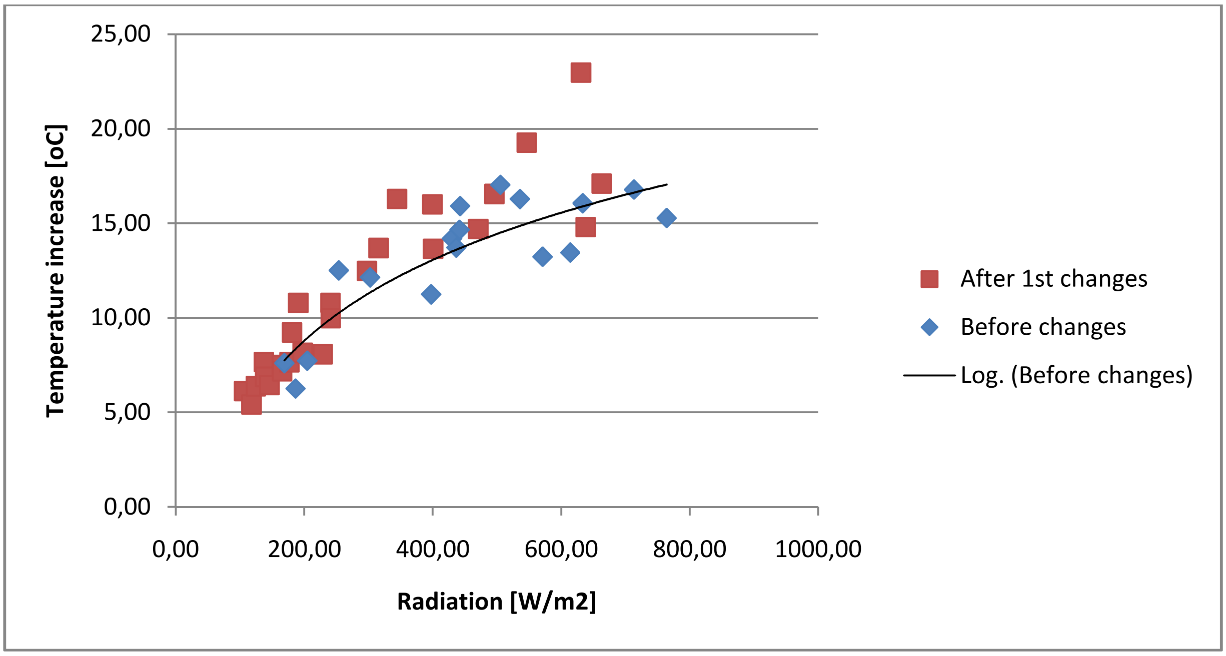

Figure 5.1.3: Temperature increase dependent from radiation in two cases

Both cases obtain similar values. On the basis of temperature increase it is difficult to assess in which case the performance of the collector was better.

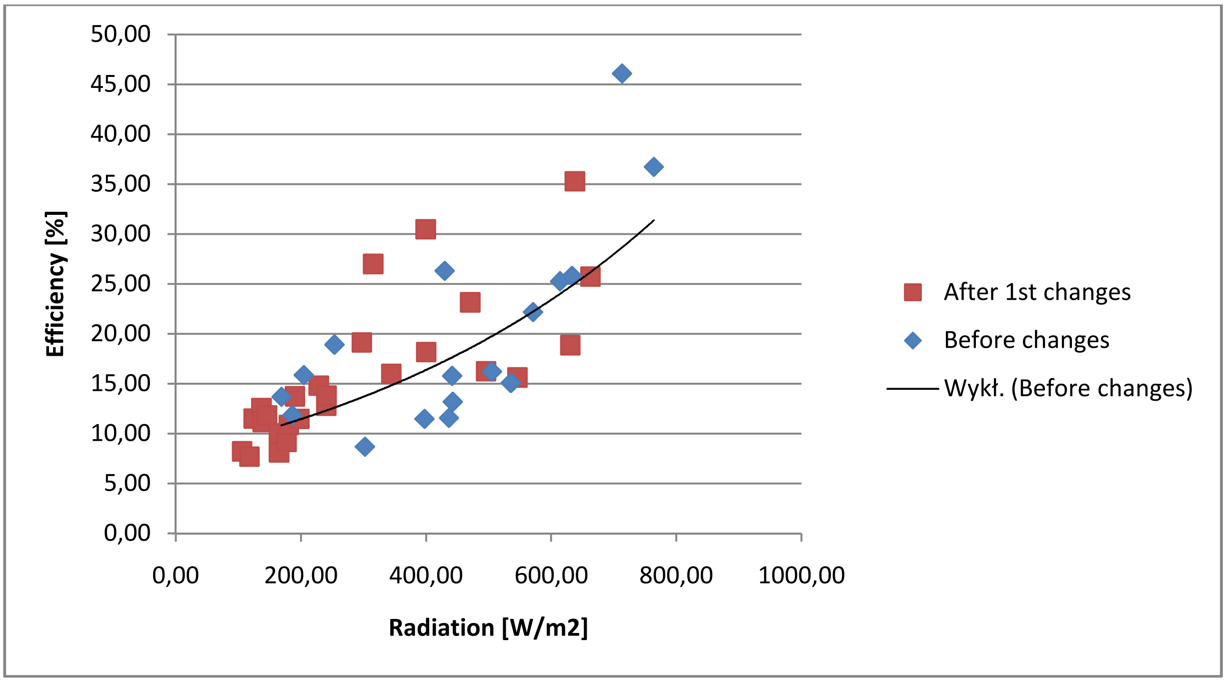

Figure 5.1.4: Temperature increase dependent from radiation in two cases

The efficiency in both cases is similar. The advantage of the system after first changes is that the pressure loss is lower. Consequently it can obtain higher airflows.

5.2 Making bigger inlets

As the inlets originally made were smaller than the outlet, the next change was to make them bigger. The area of them was enlarged to the area of the air channels in the collector. The measurements were performed on a sunny day.

Flow rate [m^3/h]	Temperature increase [˚C]	Heat balance [W]	Radiation [W/m^2]	Pressure drop [Pa]	Efficiency [%]
28,6	3,76	23,60	110,24	7,76	8,47
27,75	8,38	42,55	184,69	4,02	8,52
34,6	4,67	31,05	188,69	7,63	9,12
38,7	8,78	71,67	311,03	10,19	12,55
37,34	10,86	73,13	317,25	11,58	12,07
49,6	15,05	141,72	497,29	18,04	17,05
46,82	21,74	165,07	527,54	23,09	19,58
46,77	18,25	129,74	533,18	24,32	16,47
52,4	16,58	214,59	601,99	20,55	22,22
51,1	13,46	251,61	611,27	20,74	25,10
56,3	18,73	428,40	690,59	24,83	46,00
52,06	21,95	411,10	699,16	26,83	42,83
54,97	14,82	312,94	713,28	28,69	30,78
54,01	17,41	415,03	756,80	29,09	39,33
58,3	16,21	439,75	794,64	25,33	39,12

Figure 5.2.1: Results from measurements of the collector with bigger inlets

The airflow is bigger than in previous cases. If the fan was working on a constant power on 12 volts it would have obtained a maximal airflow of 80 m^3/h. In reality it is working on 70% of power and can obtain an airflow of 60 m^3/h.

In this case, on the other hand, the temperature increase is smaller. An explanation for that is that the bigger airflows are harder to be heated up. However if the efficiency is compared then by high sun radiation the values are higher than before changes and obtain approximately 40%.

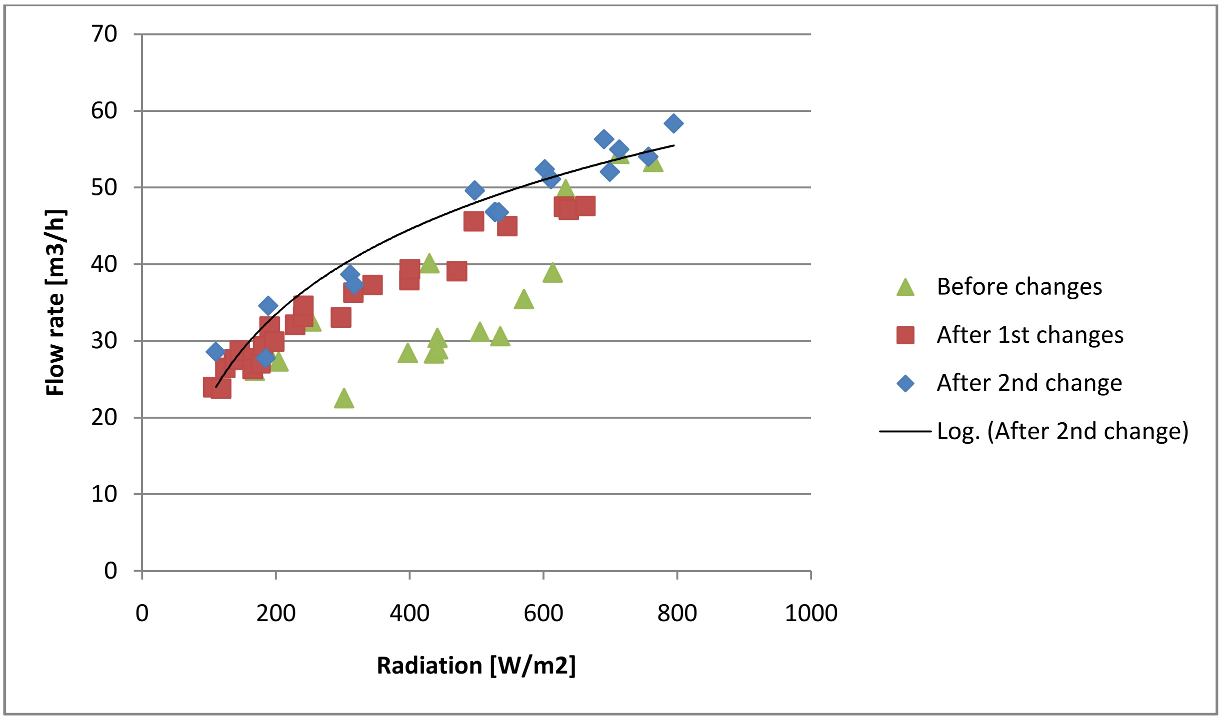

Figure 5.2.2: Flow rate dependent from radiation in three cases

In the figure above it can be seen that in the last case the flow rate is biggest. By the biggest radiation the airflow is approximately equal to 60 m^3/h. The collector after second change obtains higher airflows in comparison to one before changes.

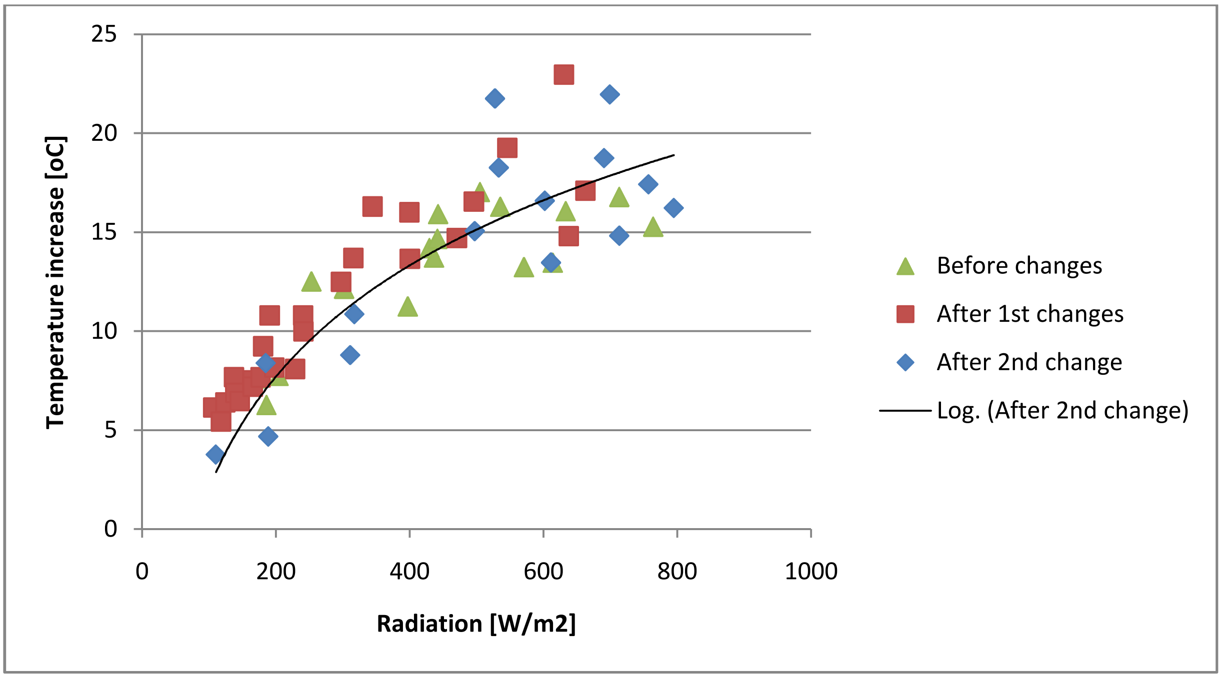

Figure 5.2.3: Temperature increase dependent from radiation in three cases

In most cases the temperature increase is smaller than after first changes but is still bigger that it was before any changes. Therefore there is still an improvement comparing to an original version of the collector.

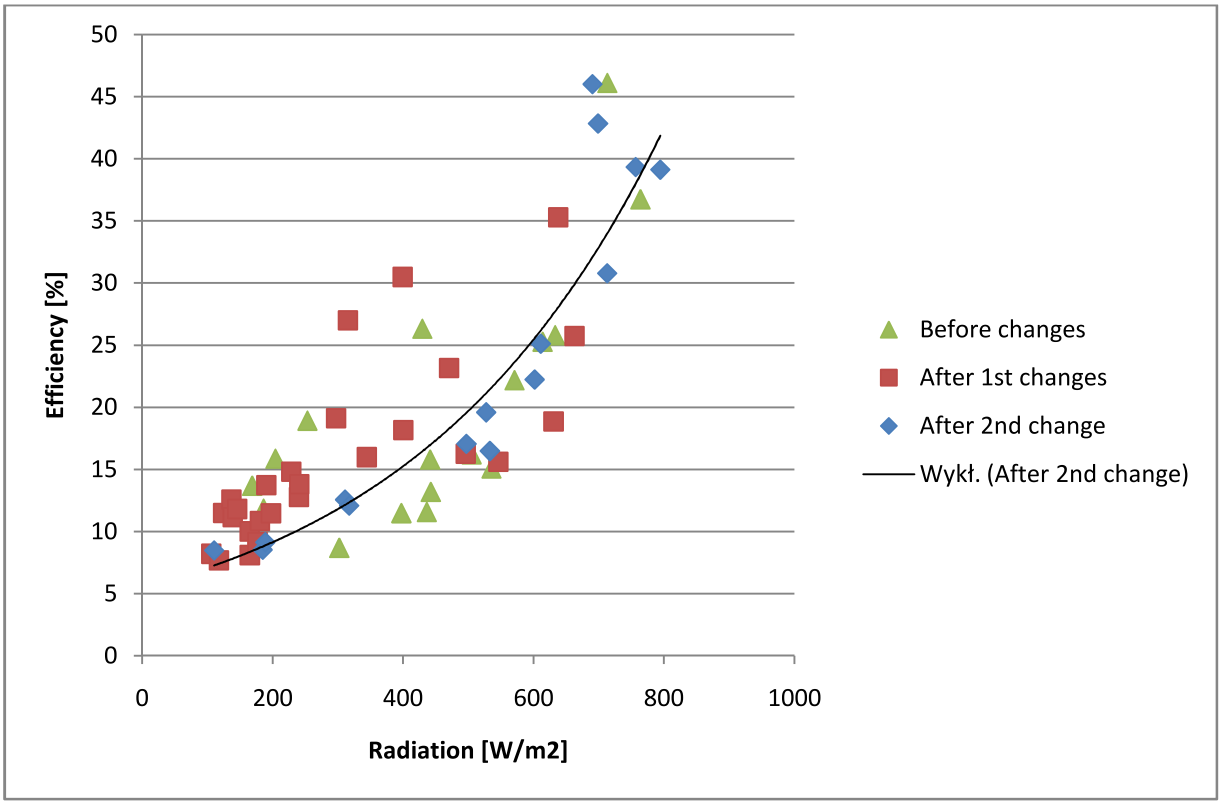

Figure 5.2.4: Efficiency dependent from radiation in three cases

The trend line was created for the collector after 2^{nd} change. Despite changes the efficiency has not improved much. By bigger sun radiation it obtains much better results. However this improvement cannot be seen by smaller values of radiation.

5.3 Fan working in reverse direction

Originally the collector had two fans and one of them was already checked. In this chapter there are measurements performed on the other one. The task of this fan is to exhaust warm air to the outside during summer time. The fan was powered by a solar cell. The measurements are performed on a sunny day.

Flow rate [m^3/h]	Radiation [W/m^2]	Pressure drop [Pa]
27,68	81,54	3,56
24,60	107,50	3,83
29,45	135,25	6,84
25,52	145,23	2,75
23,49	152,76	2,93
25,42	159,24	3,04
25,82	198,03	4,67
27,01	223,00	4,95
28,16	263,89	7,35
28,40	265,91	7,35
29,26	296,90	7,52
37,86	326,38	15,62
32,57	395,34	10,81
32,06	463,09	9,74
34,76	504,86	12,70
40,82	703,81	18,24
41,28	723,09	18,46

Figure 5.3.1: Results from measurements of the collector with reverse fan

Despite similar sun radiation the airflow is smaller than in case of the other fan. The reason for that may be buoyancy forces against which the fan is working. The pressure drop is smaller as well because of smaller airflow.

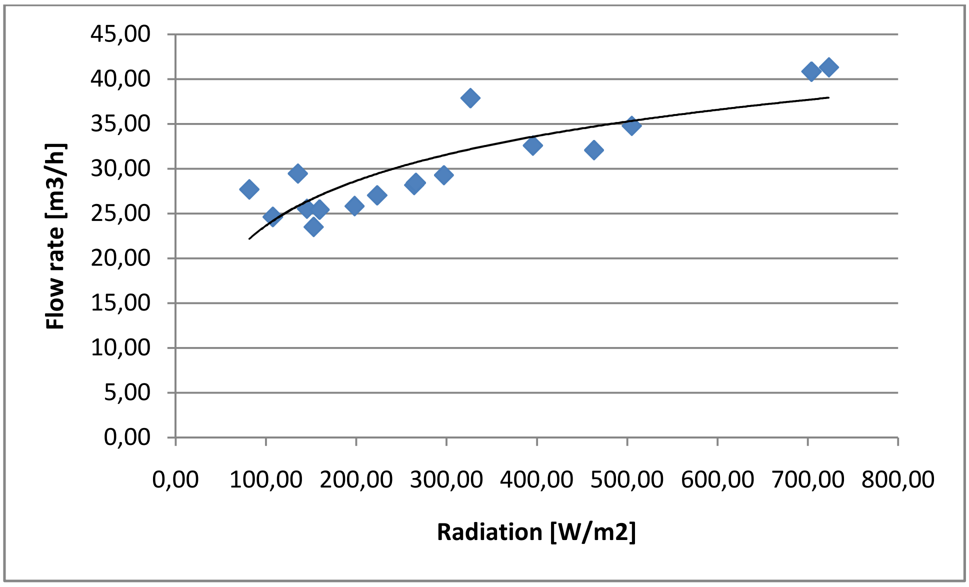

Figure 5.3.2: Flow rate dependent from radiation in case of reverse fan

Similarly to all other cases the flow rate increases with an increase of radiation.

6 Yearly Performance Of The Collector – DRY

The measurements on the collector were performed in April and May. On the basis of weather data from Danish Reference Year (DRY) and equations from Heat Balance (Chapter 2) the yearly performance of the collector can be estimated.

In order to simplify the calculations from the equation

$$Q_u - A_c F_R \left[S - U_L \left(T_{fm} - T_a\right)\right] = 0 \tag{6.1}$$

constant values of F_R and U_L were estimated. By using measurements, different values were compared and such values of F_R and U_L were chosen, that the equations would give the results as closest to 0 as it is possible. For further calculations they will equal:

$F_R = 0,3$

$U_L = 5,5\ W/m^2K$.

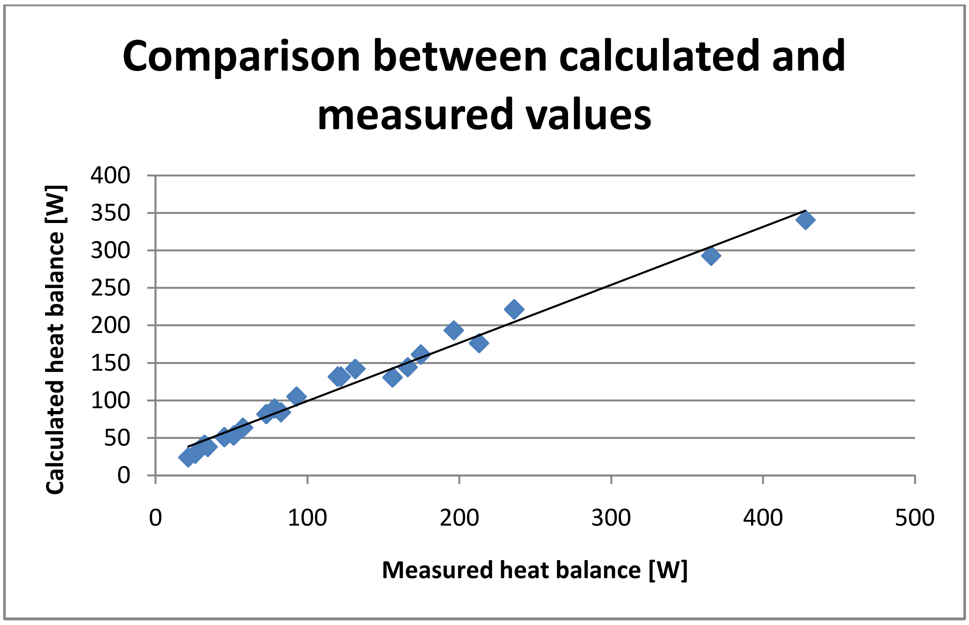

Figure 6.1: Comparison between calculated and measured values

From the figure 6.1 it can be seen that the approximation of F_R and U_L was relatively good.

6.1 Calculation of heat balance

$$Q_u = A_c F_R \left[S - U_L (\Delta T)\right] \tag{6.1.1}$$

F_R, U_L, A_C – are constant values,

S – calculated on the basis of radiation (total, direct, diffuse) taken from DRY file,

ΔT – is the temperature difference between mean air temperature and ambient temperature. This temperature difference will be calculated from equation created on the basis of trend line made on chart temperature difference – absorbed solar radiation (Figure 6.1.1). It is almost a linear correlation.

$$\Delta T = 0{,}015 \cdot S + 0{,}673 \tag{6.1.2}$$

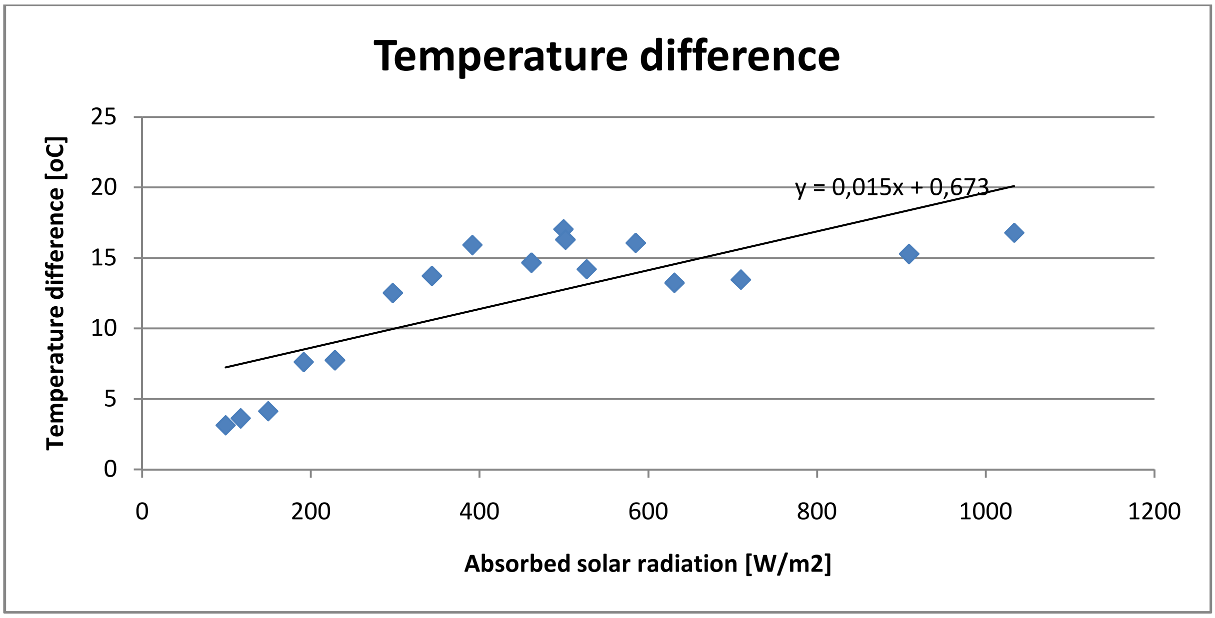

Figure 6.1.1: Equation for temperature difference

6.2 Calculation of outlet temperature

To calculate the outlet temperature the following equation shall be used:

$$T_o = T_a + \frac{Q_u}{m \cdot C_p} \tag{6.2.1}$$

Q_u – is taken from calculations in 6.1,

T_a – values taken from DRY file,

C_p – specific heat

m – airflow is dependent on solar radiation and temperature difference between mean air temperature and ambient temperature. In order to develop an equation for the airflow the coefficients $a_1 - a_9$ in the below presented equation must be found.

$$m = a_1 + a_2 \cdot S + a_3 \cdot \Delta T + a_4 \cdot S \cdot \Delta T + a_5 \cdot S^2 + a_6 \cdot \Delta T^2 + a_7 \cdot S \cdot \Delta T^2 + a_8 \cdot S^2 \cdot \Delta T + a_9 \cdot S^2 \cdot \Delta T^2 \tag{6.2.2}$$

On this basis of nine measurements, the unknowns were calculated by using linear equations in Jordan – Gauss elimination method and an equation for airflow was developed:

$$\begin{aligned} m &= 513{,}6311 + 4{,}1861 \cdot S - 618{,}3858 \cdot \Delta T + 7{,}9483 \cdot S \cdot \Delta T - 0{,}1037 \cdot S^2 - 21{,}8783 \cdot \Delta T^2 - \\ &+ 0{,}8434 \cdot S \cdot \Delta T^2 + 0{,}01246 \cdot S^2 \cdot \Delta T + 5{,}6850 \cdot 10^{-6} \cdot S^2 \cdot \Delta T^2 \end{aligned} \tag{6.2.3}$$

6.3 Efficiency of the solar air collector

$$\eta = \frac{Q_u}{A_C \cdot G_T} \cdot 100\% \tag{6.3.1}$$

$G_T = I_b + I_d$

6.4 Temperature increase

$$\Delta T_{inc} = T_o - T_a \tag{6.4.1}$$

6.5 *Yearly performance of the collector*

Only those hourly values were taken into consideration when the sun radiation exceeded 100 W/m^2 (because the fan starts working at minimum sun radiation of 100 W/m^2). Then the average value was calculated from those values and presented on the chart.

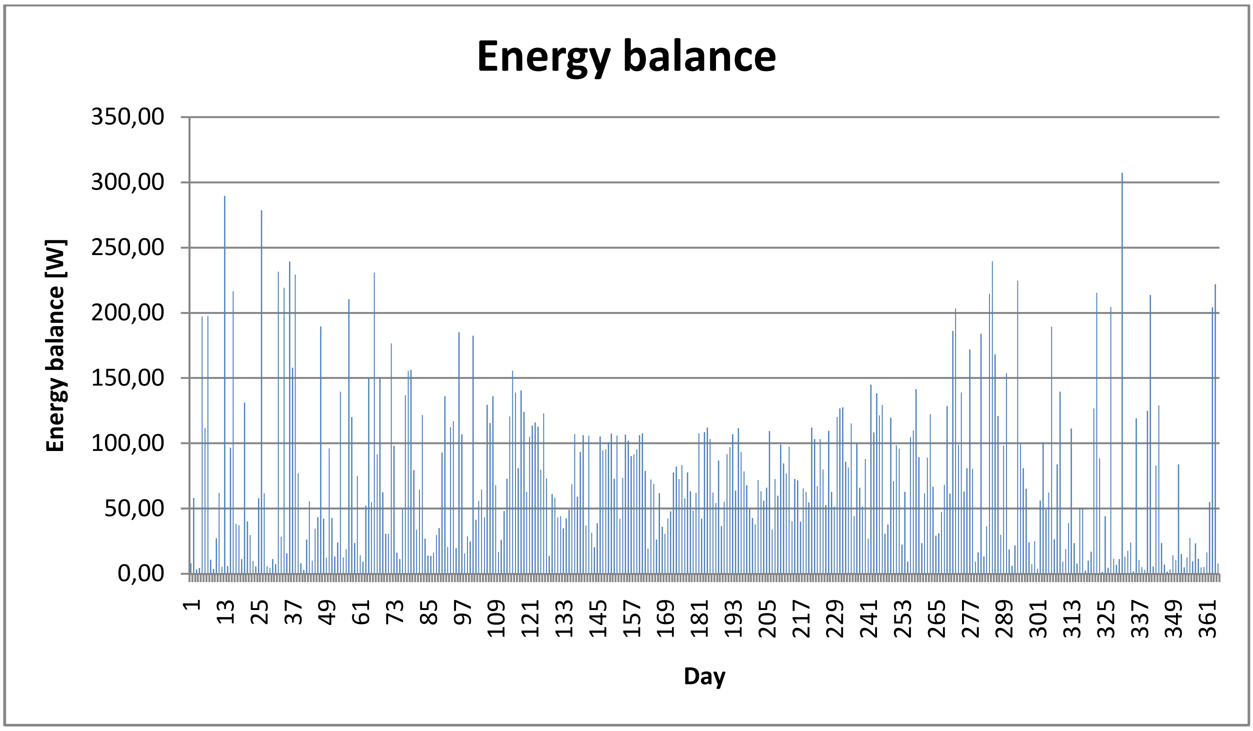

Figure 6.5.1: Yearly performance of the collector – energy balance

During winter if there is enough sunshine to run the fan there are relatively high values of energy balance as the sun is low on the sky and can shine directly on the collector. The solar cell is in such position that it gains as much sunshine in the winter as it can. Values on the chart show how much energy is delivered to the airflow to heat it up. However during winter there are many days when the collector is not working because of low sunshine. During summer they are smaller, but at the same time the energy balance is quite stable and the collector works every day.

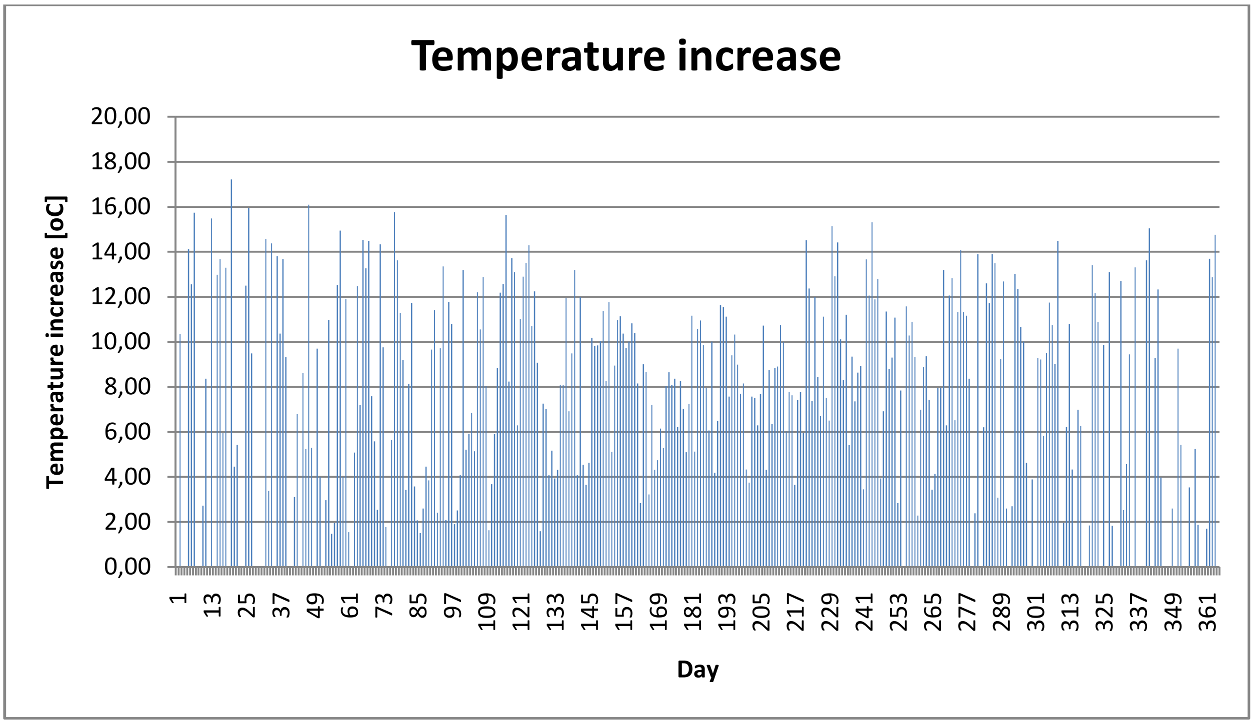

Figure 6.5.2: Yearly performance of the collector – temperature increase

The biggest temperature increases are in winter. When there is enough sunshine to run the fan the cold outside air can be heated up considerably in the collector. On the other hand there are some days when it is not heated at all because of lack of sunshine. However the sun cell was mounted in such way to gain maximum sun during winter. In summer the temperature increases are lower but more stable. The collector works every day. Hot air is heated up by only few degrees. The temperature is controlled by the controller all the time.

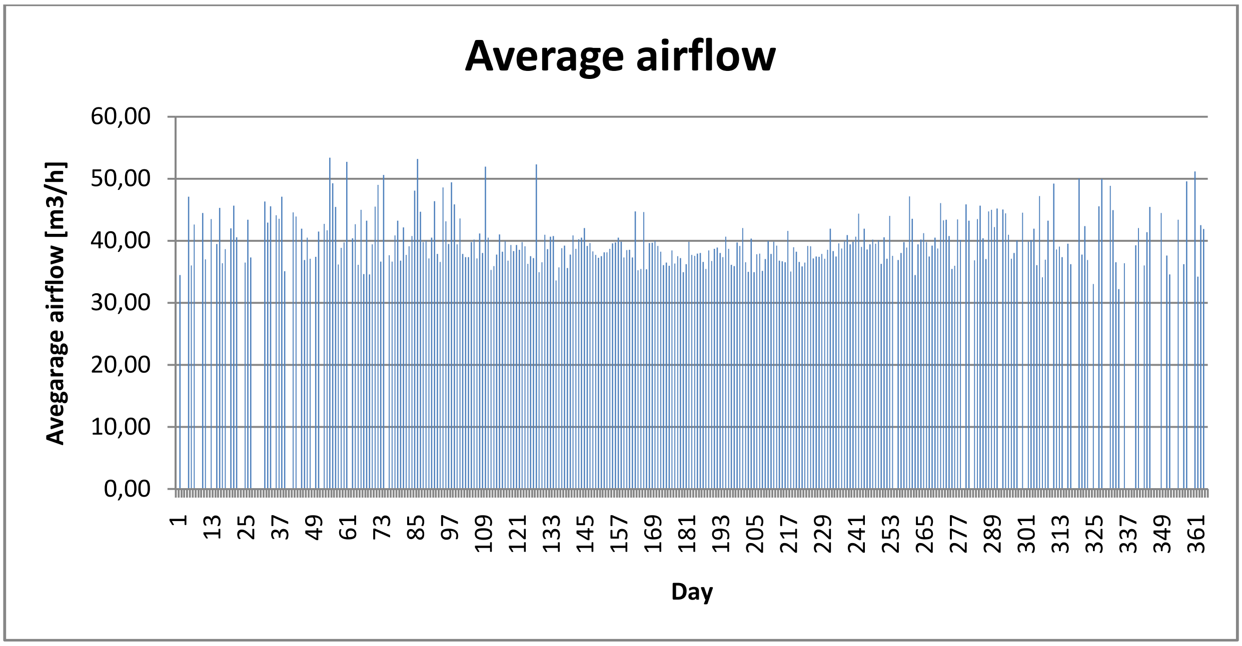

Figure 6.5.3: Yearly performance of the collector – airflow

In the table an average airflow is presented so the values can be higher in some moments. The maximum values can reach up to 60 m^3/h. During the whole year collector is working more less on the same amount of air but at different time of a day because of height of the sun. Higher values are obtained during sunny winter and spring days.

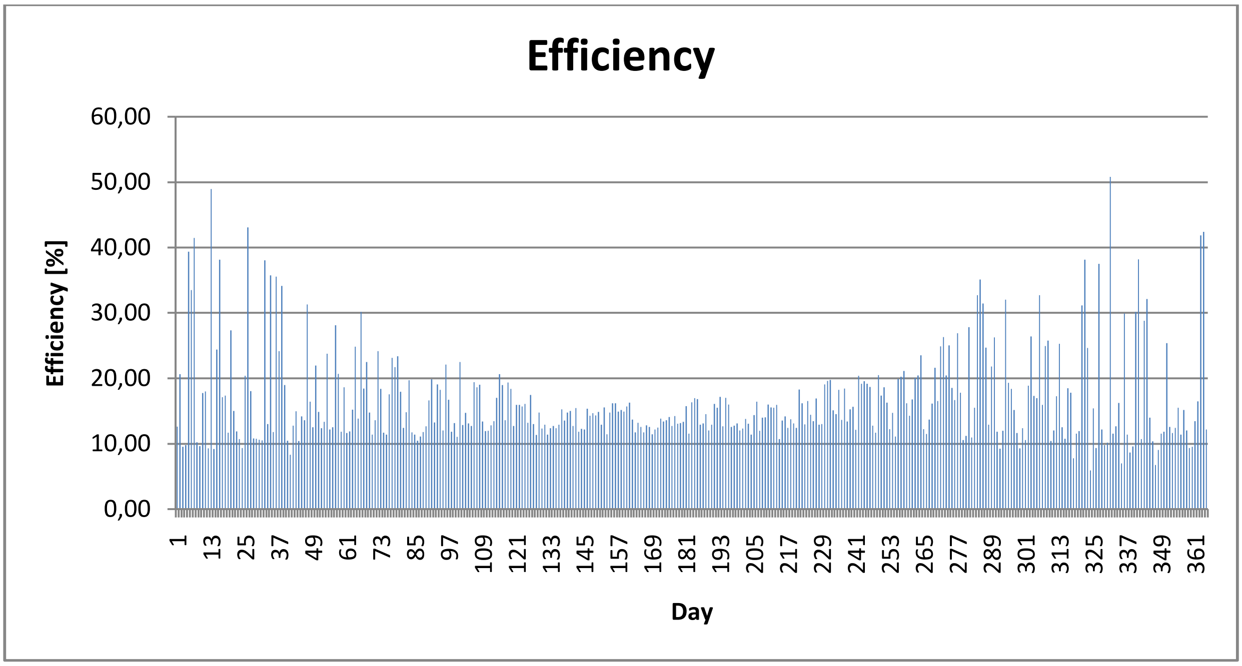

Figure 6.5.4: Yearly performance of the collector – efficiency

The efficiency of the collector is biggest during winter. This is caused by high gains of energy from sun. For calculations of efficiency the heat balance is used. In order to calculate the heat balance the absorbed solar radiation needs to be calculated. In the equation for that there is a ratio of beam radiation on the tilted surface to that on horizontal surface. During winter it is very high as the sun is low on the sky. It can cause high results during wintertime. The energy transferred to the airflow is bigger as the air is at low temperature and gains much heat from the sun. During summer the sun radiation is more stable (not changing much in comparison to winter) so the efficiency is similar at this time of year.

Partial monthly results of above presented parameters are placed in Appendix – chapter 10 – Detailed results of yearly performance.

6.6 Comparison of results from DRY and measurements

After measurements and simulations based on DRY file it was decided to compare these two parts. Both of them were carried out on the basis of absorbed solar radiation which was calculated on every hour from one day measurements: direct solar radiation, total solar radiation and diffuse solar radiation. It means that both for calculations for measurements and for simplified equations for simulations the same values of solar radiation were used. This same was done with outdoor temperature.

Results of this comparisons will be presented on three different charts:

- Heat balance - absorbed solar radiation
- Efficiency – absorbed solar radiation
- Temperature increase – absorbed solar radiation

All of this calculations were performed basing on the measurements without any changes in the collector.

On the chart below the correlation between heat balance and absorbed solar radiation is presented. The results are very similar. The values from DRY are more stable. It is like that because of the simplifications made for example: constant value of heat losses (U_L) and heat removal factor (Fr) which have got influence on heat balance calculations.

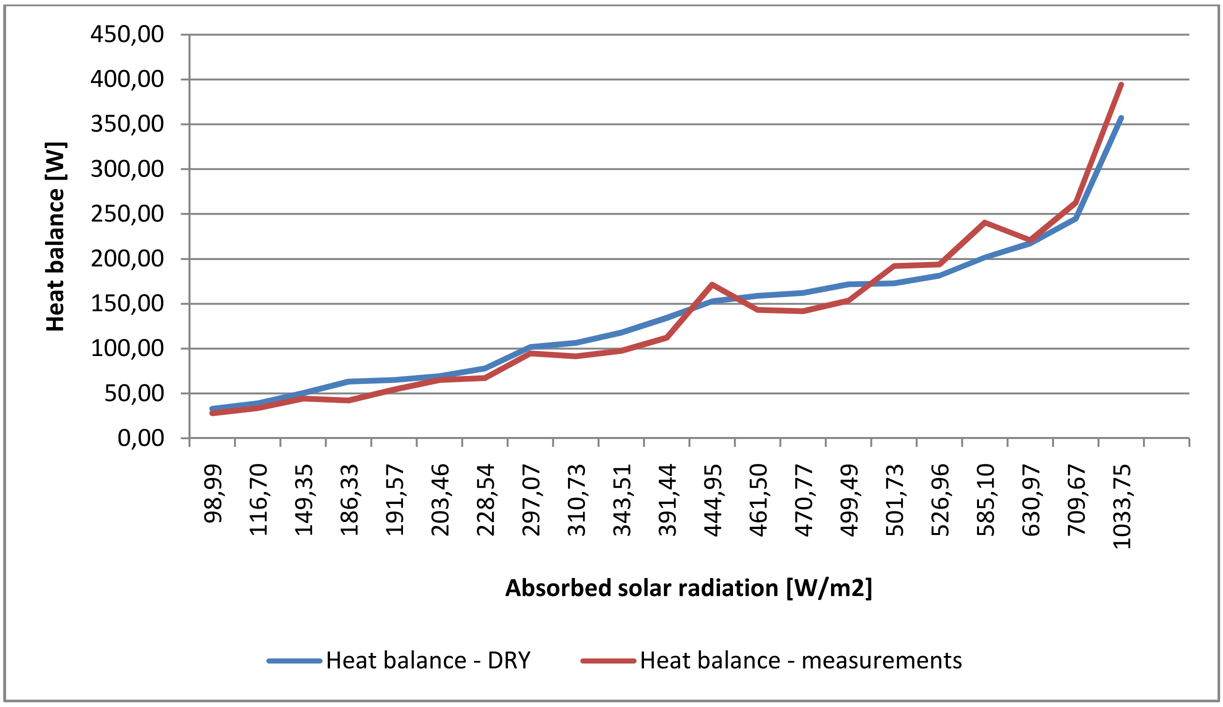

Figure 6.6.1: Comparison of heat balance from DRY file and measurements in reference to absorbed solar radiation

In the table presented below there are one day average values of heat balance. They are almost the same, difference equals to 1,2%, which is very small. It can allow to assume that whole year heat balance gives very realistic results.

Heat balance – DRY [W/m^2]	Heat balance – measurements [W/m^2]
137,04	135,40

Figure 6.6.2: Daily average heat balance

On the next step the comparison based on efficiency was taken into consideration. The values look similarly. In the calculations only values with radiation more than 100 W/m^2 were used, because with smaller radiation airflow is driven only by buoyancy forces.

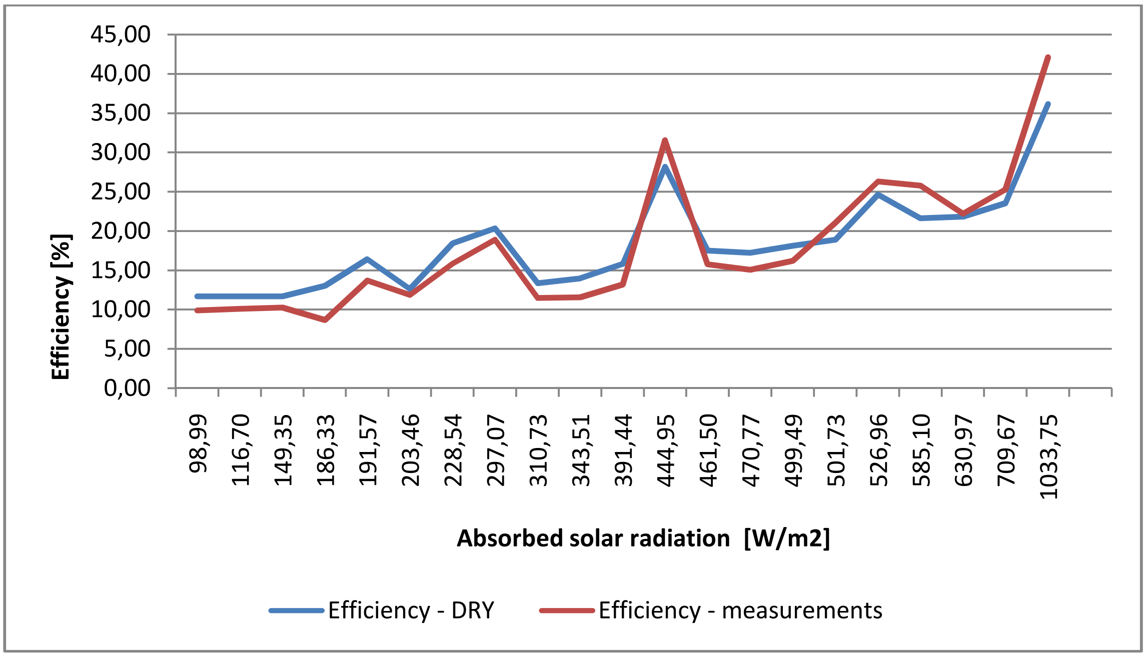

Figure 6.6.3: Comparison of efficiency from DRY file and measurements in reference to absorbed solar radiation

For daily averages efficiency values look to be very close to each other. Difference between them equals to 2,5% which is on acceptable level.

Efficiency – DRY [%]	Efficiency – measurements [%]
18,40	17,93

Figure 6.6.4: Daily average efficiency

The last comparison was carried out for temperature difference between outlet temperature and ambient temperature. On the chart below it can be seen that the results are not so similar as in the above presented cases.

The values from DRY are very stable. It is so because of constant values used in heat balance equation, on the basis of which the outlet temperature is calculated. In case of measurements the outlet temperature is measured.

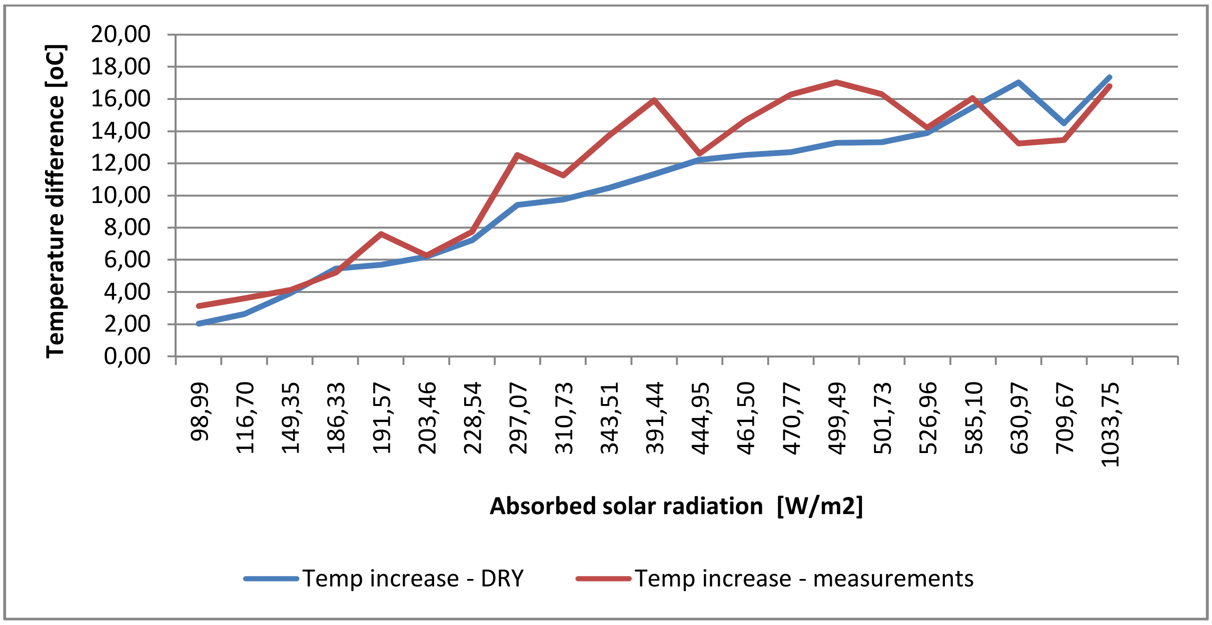

Figure 6.6.5: Comparison of temperature difference from: DRY file and measurements in reference to absorbed solar radiation

The daily average temperature difference looks quite similarly. Difference between this values equal to 1,2 °C what in case of solar collector is on good level.

Temperature difference – DRY [℃]	Temperature difference – measurements [℃]
10,30	11,50

Figure 6.6.6: Daily average temperature difference

To sum up comparisons between measured and calculated values can confirm that the simulations made with a usage of DRY file are reliable and they can show an estimated performance of the collector for whole year.

7 SIMULATIONS IN BSIM

In order to obtain more detailed simulations of energy balance and also to evaluate additional values such as temperature increase and humidity simulations in BSim are also conducted. They were performed for two cases:

- For summer house with area around 35m^2
- For typical family house with area around 70m^2

To carry out the simulation, the following systems have to be applied in BSim in both cases:

System	Summer house	Family house
Infiltration	X	X
Lighting	X	X
People load	X	X
Heating	-	X
Equipment	X	X

Figure 7.1: Systems installed in both cases

Because of lack of possibilities to put a collector on the wall in BSim, it was created by means of two systems: ventilation system and additional windows on south wall of house with size of collector. Fresh air supplied by collector will be simulated by means of ventilation system and heat gains by additional window.

7.1 Model of the building

Separate models are made for summer house and for family house. The geometry is much simplified to make the simulations easier to conduct. There is no division into rooms, the area is a big space.

Figure below presents model of summer house used in BSim

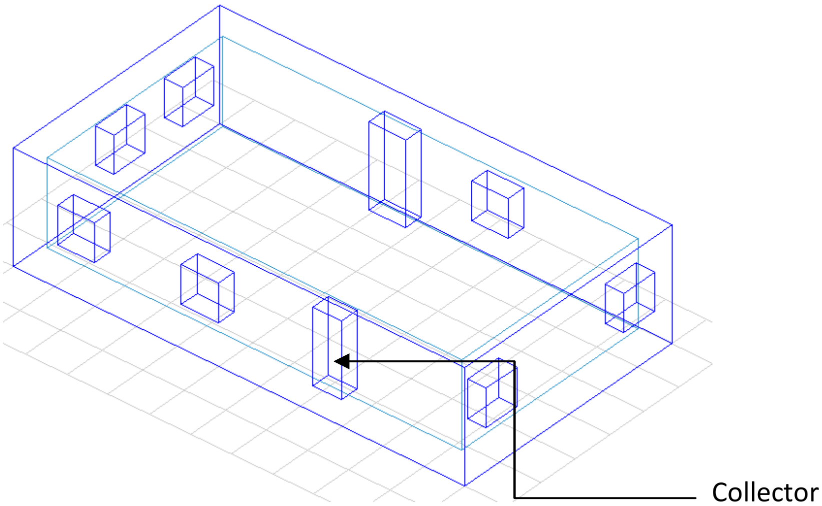

Figure 7.1.1 Model of summer house in BSim

Figure below presents model of family house used in BSim.

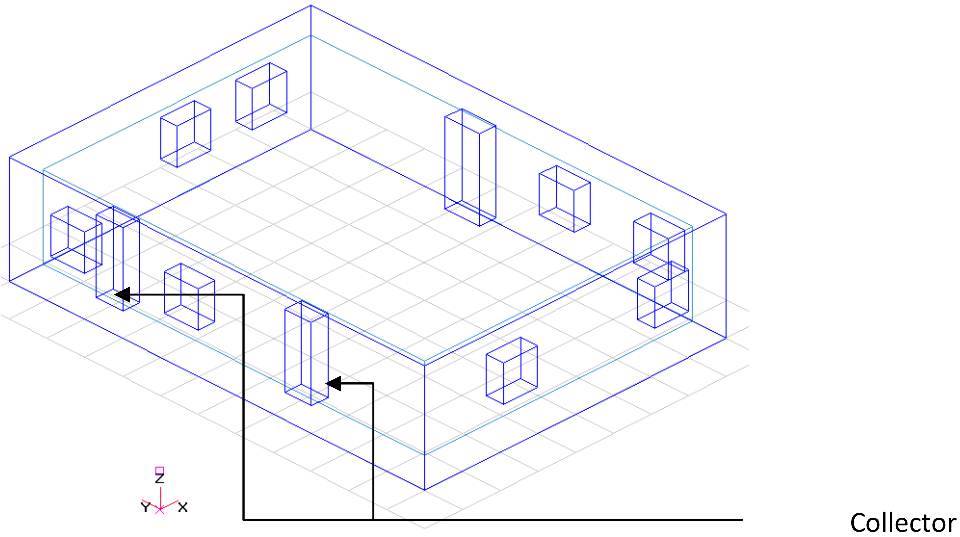

Figure 7.1.2 Model of family house in BSim

The weather data for both cases was taken from DRY.

7.2 Construction

BSim contains a material database for different components. All of envelope elements have been chosen as typical for this type of houses. Additional window (which simulates collector) is different than other windows. It has got very small g-value=0,25 but U-value equals to U-value of wall.

7.3 Systems

Various systems which can represent infiltration, lighting etc. are used in calculations for BSim.

People load

This system describes heat load and moisture release from the occupants in the thermal zone. Variations can be described by use of the schedule. Level of activity can be also defined to specify how much heat is transmitted.

Heating

This model simulates heating by use of convectors or radiators that are controlled by thermostats. Maximum power of the system can be set, as well as part of heat released by means of convection. Use of heating is controlled by set point – radiator works when indoor temperature drops below it. It is also regulated accordingly to outdoor temperature.

This system is installed only in family house.

Infiltration

Infiltration is an uncontrolled leakage of air through building envelope. Calculation of amount of infiltration air is based on two terms: one is based on temperature difference between indoor and outdoor and the second on wind pressure difference.

Lightning

This system consists of general ceiling lightning. Working hours of the lightning are defined by the schedule. Lux level can be set and in our case it equals 200 lux. If the lighting level is below 200 lux then the artificial light is switched on.

Equipment

This system describes heat emissions in the current thermal zone from machines, appliances, equipment, etc. Variation over the day, week and year can be defined in the schedule. Also part to air value can be set, which defines proportions of heat emission that is supplied to the room by means of convection.

7.3.1 Description of installed systems

Summer house

Summer house is used from March to October only at the weekends.

<table>
<tr><td>System</td><td colspan="3">Values</td><td>Control</td><td>Schedule</td></tr>
<tr><td rowspan="2">Equipment</td><td>Part to air</td><td>[-]</td><td>0,5</td><td rowspan="2">-</td><td rowspan="2">-100% during weekends 8-21
-50% during weekends – 22-7</td></tr>
<tr><td>Heat load</td><td>[kW]</td><td>0,6</td></tr>
<tr><td rowspan="6">Lightning</td><td>Task lightning</td><td>[kW]</td><td>0,05</td><td rowspan="6">- Light control:
Factor: 1
Lower limit (kW) : 0,1
Temp. Max: 28°C</td><td rowspan="6">- During weekends
7-8, 17-21</td></tr>
<tr><td>General lightning</td><td>[kW]</td><td>0,2</td></tr>
<tr><td>Lightning level</td><td>[lux]</td><td>200</td></tr>
<tr><td>Lightning type</td><td>[-]</td><td>Incadesc.</td></tr>
<tr><td>Solar limit</td><td>[kW]</td><td>0,2</td></tr>
<tr><td>Exhaust part</td><td>[-]</td><td>0</td></tr>
<tr><td rowspan="3">People load</td><td>Number of people</td><td>[-]</td><td>3</td><td rowspan="3">-</td><td rowspan="3">-100% during weekends 8-21
-80% during weekends – 22-7</td></tr>
<tr><td>Heat generated</td><td>[kW]</td><td>0,07</td></tr>
<tr><td>Moisture generated</td><td>[kg/h]</td><td>0,06</td></tr>
<tr><td rowspan="4">Infiltration</td><td>Basic air change</td><td>[1/h]</td><td>0,173</td><td rowspan="4">-</td><td rowspan="4">100% - 1-24 during weekends
69% - 1-24 during rest of the week</td></tr>
<tr><td>Temperature factor</td><td>[1/h K]</td><td>0</td></tr>
<tr><td>Temperature power</td><td>[-]</td><td>0</td></tr>
<tr><td>Wind factor</td><td>[-]</td><td>0</td></tr>
</table>

Figure 7.3.1.1: Values used for systems in summer house

For simulations of the collector additional ventilation systems were installed in summer house.

<table>
<tr><td>System</td><td colspan="3">Values</td><td>Control</td><td>Schedule</td></tr>
<tr><td rowspan="6">Venting (Natural ventilation)</td><td colspan="3">Input:</td><td rowspan="6">-Venting control:
SetPoint: -20°C
SetP CO_2: 0 PPM
Factor: 1[-]</td><td rowspan="6">April – August, whole week 10-19
September – March, whole week 11-16</td></tr>
<tr><td>Basic AirChange</td><td>[1/h]</td><td>0,42</td></tr>
<tr><td>TmpFactor</td><td>[-]</td><td>0</td></tr>
<tr><td>ToTmpPower</td><td>[-]</td><td>0</td></tr>
<tr><td>WindFactor</td><td>[s/m/h]</td><td>0</td></tr>
<tr><td>Max AirChange</td><td>[1/h]</td><td>2</td></tr>
</table>

Figure 7.3.1.2: Values used for ventilation system in summer house

Family house

Family house is used whole year. In this case all air is supplied by means of infiltration. Through additional windows placed on south wall the heat will be transferred into the house.

System	Values			Control	Schedule
Equipment	Part to air	[-]	0,5	-	-50% 22-16 -90% 17-22
	Heat load	[kW]	0,6		
Lightning	Task lightning	[kW]	0,05	- Light control: Factor: 1 Lower limit (kW) : 0,1 Temp. Max: 28°C	-April – August 19-24 - September – March 7-9, 18-24
	General lightning	[kW]	0,2		
	Lightning level	[lux]	200		
	Lightning type	[-]	Incadesc.		
	Solar limit	[kW]	0,2		
	Exhaust part	[-]	0		
People load	Number of people	[-]	3	-	-100% 14-22 - 80% 23-13
	Heat generated	[kW]	0,07		
	Moisture generated	[kg/h]	0,06		
Infiltration	Basic air change	[1/h]	0,5	-	-100% 1-24
	Temperature factor	[1/h K]	0		
	Temperature power	[-]	0		
	Wind factor	[-]	0		
Heating	Max power	[W/m^2]	50	-Heat control 1: Set point: 22°C Design temp: -12°C Min power: 5 [W/m^2] Te min: 15°C	-During heating season – September - April
	Part to air	[-]	0,6		

Figure 7.3.1.3: Values used for systems in family house

7.4 Simplifications

For BSim simulations few simplifications were implemented:

- Both summer house/family house were built like one big zone without rooms,
- For simulating air flow through the collector in summer house venting system was used with stable value of air flow – 40 m^3/h,
- Heat gains through the collector were made by additional window with heat transmittance – 25%,
- Summer house is occupied only at weekends,
- Infiltration was designed on level 0,18 1/h for summer house and 0,5 1/h in family house,

- Collector is situated on south wall.

7.5 Results

7.5.1 Summer house

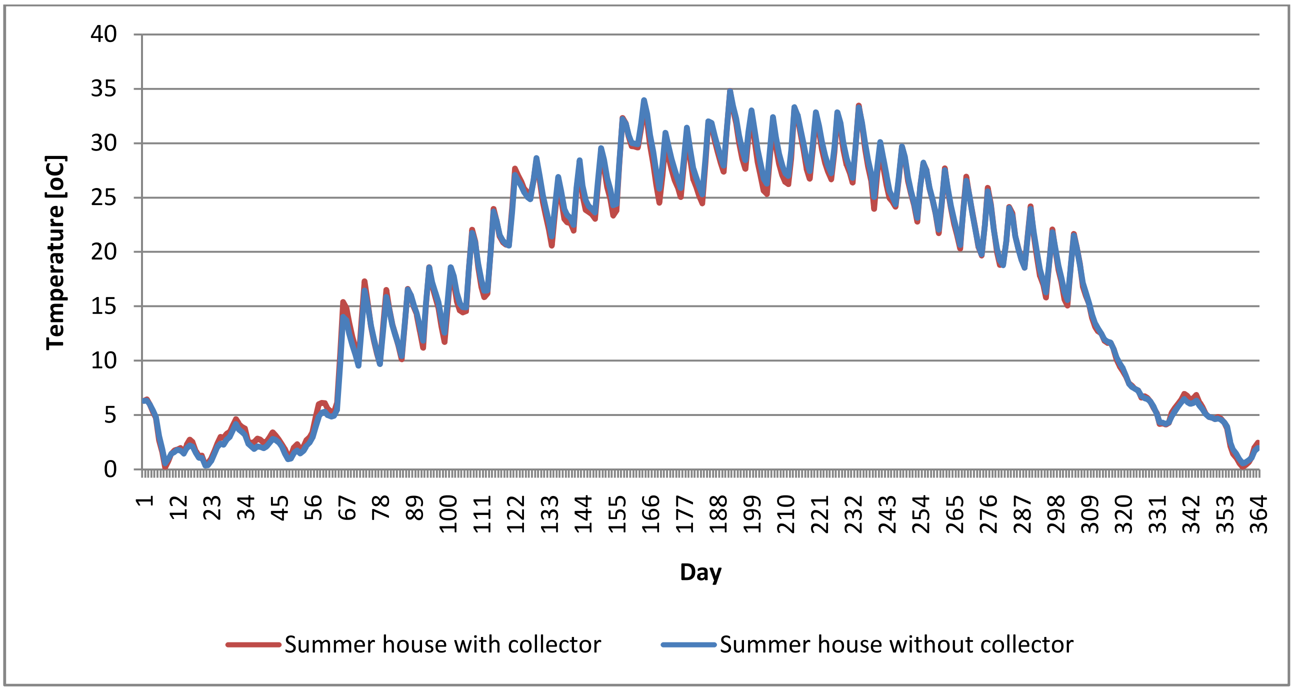

Figure 7.5.1.1: Results for comparison of inside temperatures in summer house

In the Figure 7.5.1.1 the temperature is presented in two cases: one without solar air collector and one with it. The values were calculated as an average daily values when the collector is working (winter 11-16, summer 10-19). The influence of the collector on the temperature is relatively small. On the chart it can be seen that in winter the collector slightly increases the temperature and in summer it decreases it. On the average it changes the temperature for about 1-2˚C.

As for the temperature increase it is relatively small probably because of two reasons. First it was impossible to create a collector in the programme. Therefore the simulations can be inaccurate (see 7.4 Simplifications). In reality the indoor temperature can be higher. Secondly in reality the airflow is controlled by a controller.

Additionally in reality during summertime the second fan is exhausting hot air from the inside so the temperature at that time would be smaller than in simulations.

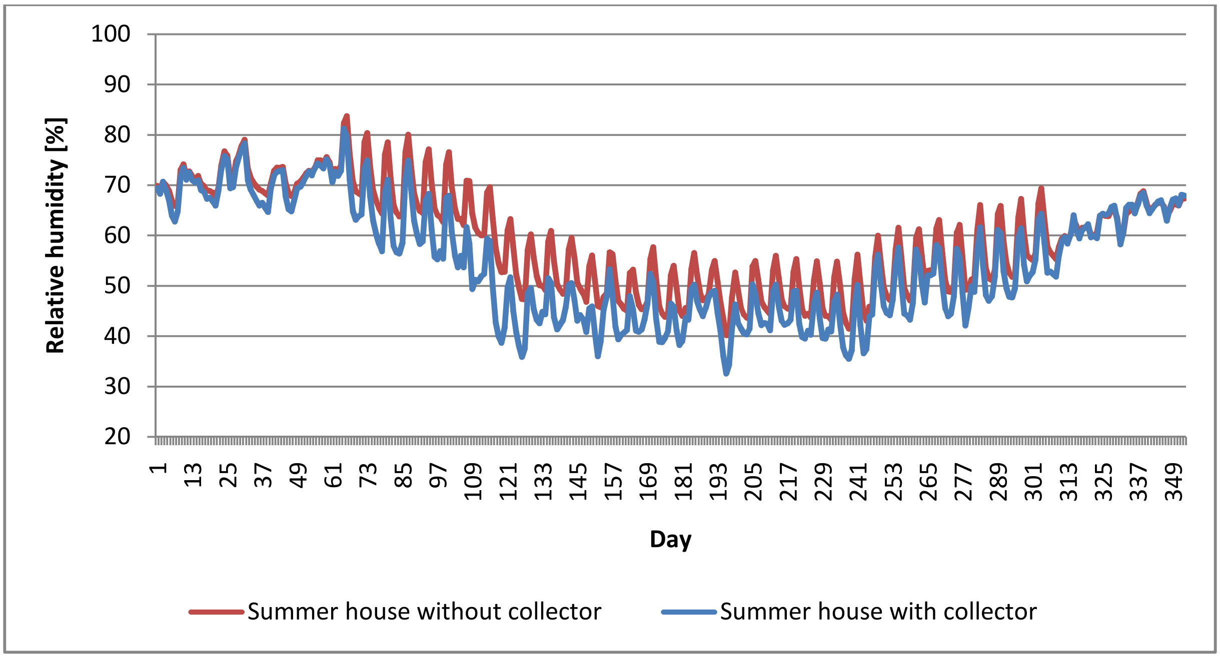

Figure 7.5.1.2: Results for comparison of relative humidities in summer house

Moulds and fungi form when the relative humidity exceed 70-75%. From the figure 7.5.1.2 it can be seen that the humidity inside the house does not decrease significantly after installing the collector. The difference equals to 1-10%. In winter critical value of humidity for moulds is reached and the collector does not decrease it to a safe level. In summer almost all the time humidity is low enough to prevent from forming moulds and fungi. In this time of the year there are more hours of sun the collector works longer. Therefore the amount of supplied air is bigger and this can be the reason of higher decrease of humidity during summer time.

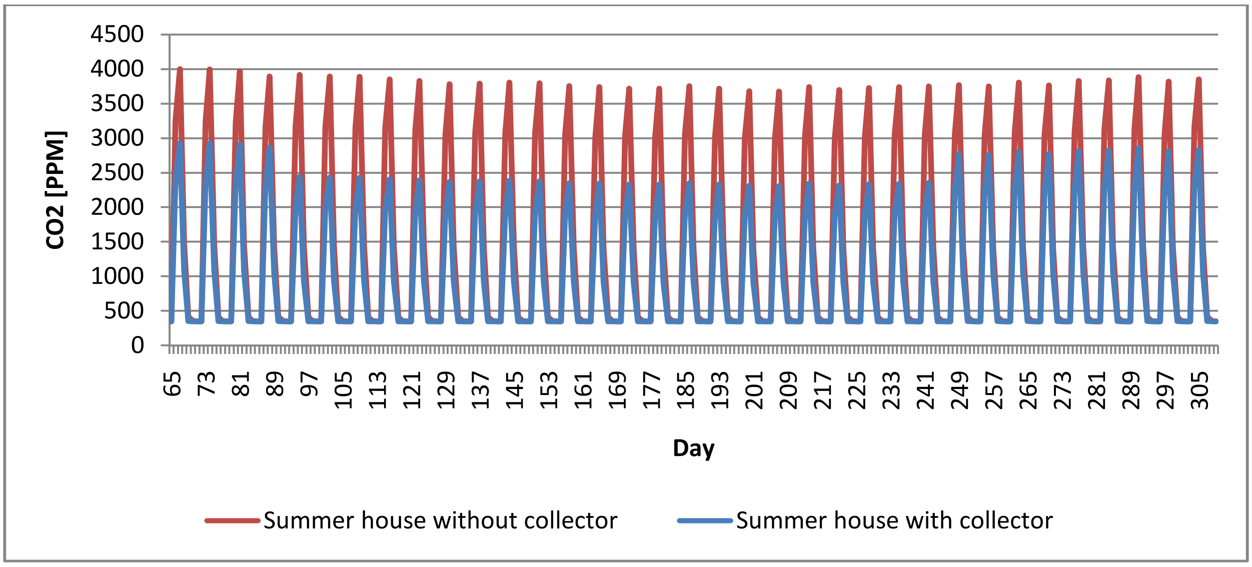

Figure 7.5.1.3: Results for comparison of CO_2 levels in summer house

In the figure the CO_2 level is presented only for the time when the summer house is used (March – October). During wintertime there is nobody in the house so this level stays low.

On the chart it can be seen that CO_2 level during the time when collector is working and when summer house is occupied decreases by around 25%. However, the concentration of CO_2 is still relatively big. It is so because on the small area of 35 m^2 at the weekends there are three people what increases significantly the CO_2 level.

7.5.2 Single family house

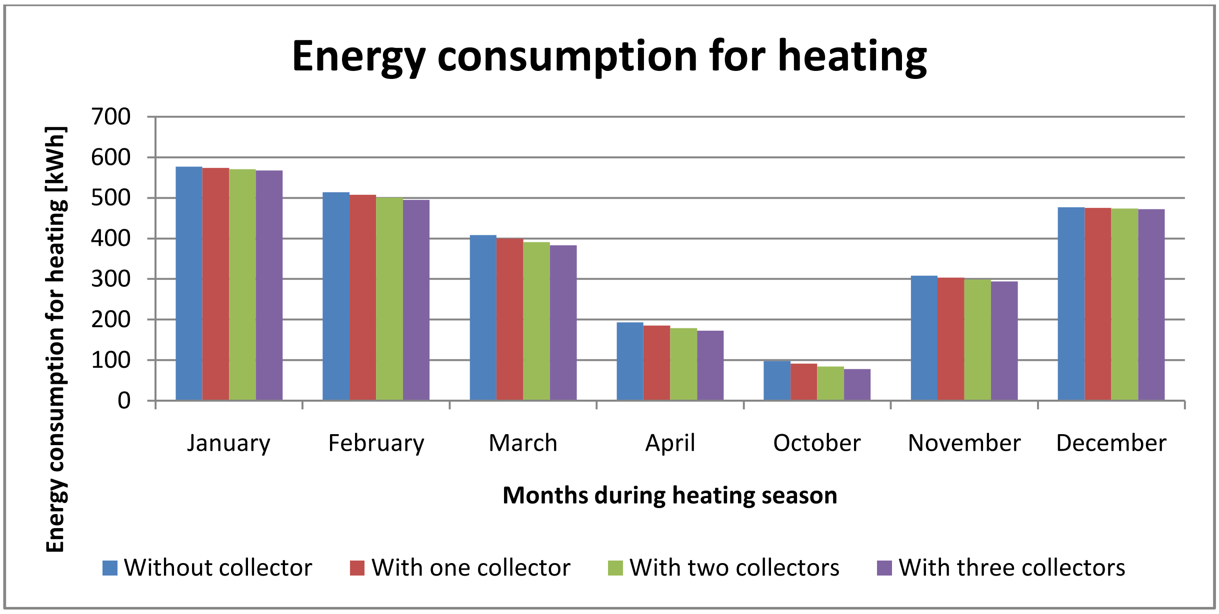

Figure 7.5.2.1: Results for energy consumption for heating in family house

Without collector	With one collector	With two collectors	With three collectors
[kWh]	[kWh]	[kWh]	[kWh]
2575	2536	2498	2462

Figure 7.5.2.2: Results for energy consumption for heating in family house

On the charts it can be seen that the usage of the collector in such a family house. The usage of three collectors has decreased the energy consumption by approximately 100 kWh per year. It is so small because the collector works only during the day and usually in wintertime (when the house is heated) only for a few hours. Another disadvantage of this system is that it works only during sunny or partly sunny days. However during winter there are many cloudy days so it does not work every day.

On the basis of detailed results the heat gains through one collector (see Figures: 7.5.2.3 and 7.5.2.4) are relatively high because during winter one collector can produce almost 200 Watts and in summer around 110 Watts (what is similar to the measurements). On the other hand in winter the sun is low in the sky and only for a few hours.

On the charts below there is sun radiation transmitted through one window (of size of a collector).

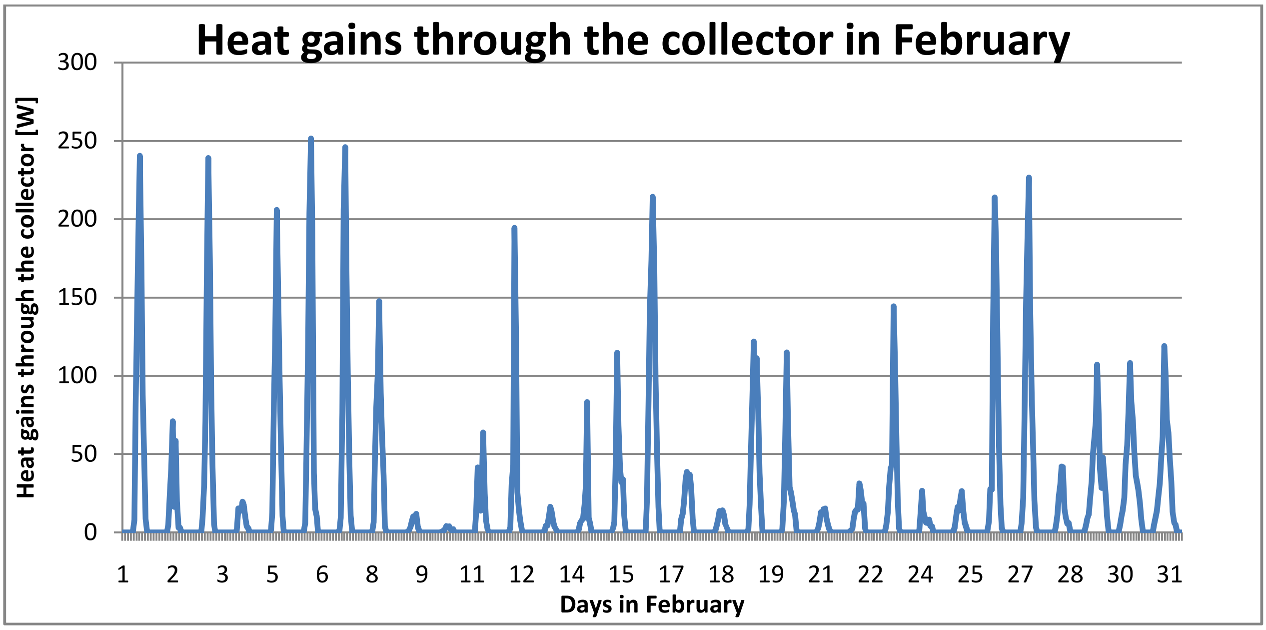

Figure 7.5.2.3: Results for heat gains through the collector in February

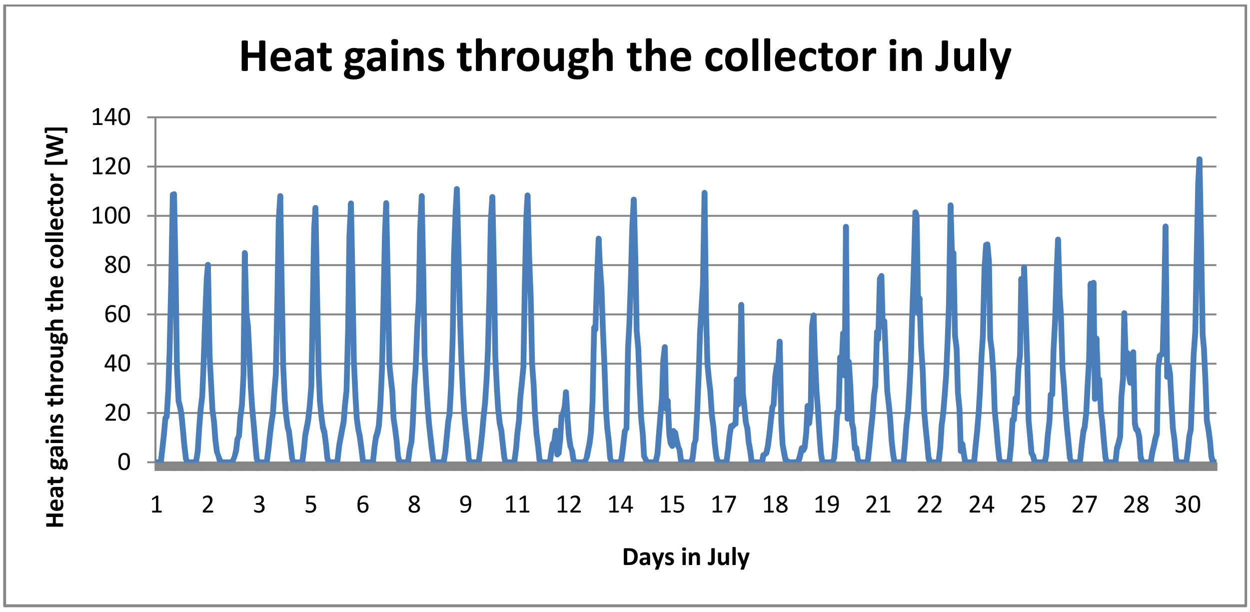

Figure 7.5.2.4: Results for heat gains through the collector in July

8 CONCLUSIONS

At the end of the project, after all measurements, calculations and simulations (DRY and BSim) some conclusions and recommendations were made. They are divided in few categories based on previous work.

8.1 Measurements

- Collector inlets can be made bigger to have the same area as air channel. One of them has got 38 cm^2, but size of the channel equals to 56cm^2. In this way more air could be supplied to the room, but with smaller temperature increase.
- Different inlet covers should be used because they block the airflow. It is caused by their shape which looks like small grate and takes up approximately 30% of the inlet area.
- The best orientation for the collector is south, because the sun is operating for the longest time in comparison with other directions.
- Changes made to the collector in Optimization (Chapter 5) have increased the maximal possible airflow from 50 m^3/h to 60 m^3/h what has influence on increase of efficiency.
- Measurements of power supply from solar cell has shown that PV can produce power equaled to 5-11 Watts.
- With smaller airflows (high resistance made by small orifice) and high sun radiation the temperature increase can be up to 30 degrees. On the other hand with bigger airflows (smaller resistance and bigger orifice) the temperature increase was smaller and equals to maximum 20 degrees.
- On the basis of measurements it can be noticed that with bigger airflows there is bigger pressure drop on the collector. This values can be seen in all tables.
- Maximal calculated heat balance based on measurements obtained during sunny day and big airflows was 450 W.
- The efficiency of the collector was exceeding in some cases 45%. In comparison to other models of solar air collectors on market it was relatively high.
- When the fan was working in reverse direction (exhausting air from the inside) the maximal airflow after introduced changes was around 40 m^3/h. This value is so small because of opposite buoyancy driving forces.
- When considering 0,5 1/h what is a required value, one collector is sufficient for a house of 35-40 m^2 area.

8.2 Yearly performance calculations and simulations

- On the basis of yearly performance of the collector the average energy balance is small – around 100 Watts in summer. It is higher in winter and equals to 300 Watts.

- The airflow for whole year is stable and before introduced changes it equals to 40 m^3/h. In winter and autumn season the collector is not working every day because of lack of sun.
- On the basis of chart depicting yearly performance it can be seen the efficiency in summer time equals to 15%, but in winter time is higher and reaches to 40% but is working on fewer days than in summer.

8.3 BSim simulations of usage of collector in summer house and family house

- The collector does not help much for summer houses which are occupied only at the weekends and do not have any heating inside. It does not decrease much the possibility of moulds, fungi etc. and prevent from stale air. It decreases the humidity only around 1 - 10%. The temperature is changing on a small extent.
- In case of family houses which are two times bigger than summer houses one collector does not change indoor conditions significantly. For size of houses about 70m^2 there should be at least two or even three collectors to improve the indoor air quality (minimum requirements of 0,5 1/h).
- The usage of three collectors in family house has decreased the energy consumption by approximately 100 kWh per year. It is so small because the collector works only during the day and usually in wintertime (when the house is heated) only for a few hours.

8.4 Recommendation

- Solar cell can be divided into smaller pieces then if on one part of solar cell there is shadow the other part can still power the fan.
- Solar cell can be provided separately from the collector to put it on the roof in order not to have any shadow on it.
- Instead of two fans, one fan working in two directions can be a better solution (that type of fan has 100% power working one way, when reverse it is 70%).

9 APPENDIX - EQUIPMENT

9.1 Temperature measurements

9.1.1 Equipment

Thermocouples are one of the most widely used temperature sensors and one of the easiest to use as well. Thermocouples are pairs of dissimilar metal wires, which are joined at least at one end. When the junction of two metals is heated or cooled a voltage is produced that can be correlated back to temperature.

There are many types of thermocouples. Different kind means different combination of metals. However only four, identified by letters K, J, T, E are mostly used.

In our measurements only thermocouples type K (Chrome (+) – Alumel(-)) were used. This type of thermocouple is most commonly used for general purposes as it is inexpensive and available in a range of -200°C to 1350°C.

Figure 9.1.1.1: K-type thermocouple

Direct solar radiation can strongly affect the temperature results when measuring the air temperature. As silver has a really good reflectivity of visible light rays silver coated thermocouples were used. Additionally they were placed in a silver coated shielding tube ventilated by a fan to obtain most accurate results.

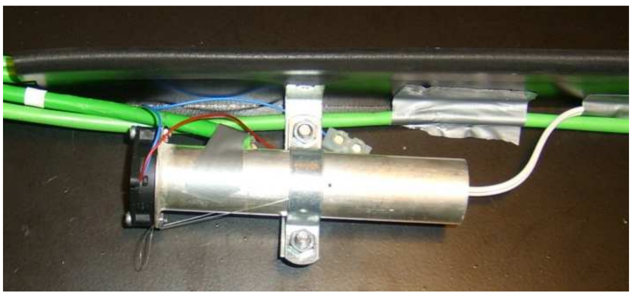

Figure 9.1.1.2: Thermocouples in silver coated shielding tube

Fluke Helios Plus 2287A Data Logger

All thermocouples except one are measuring temperature in collector or air temperature and are connected to Compensation Box. The Compensation Box is then connected with Fluke Helios Plus 2287A from where all data could be transferred into a PC. One left thermocouple is connected to both Compensation Box and Ice Point Thermocouple Reference to measure the temperature of the Compensation Box.

Figure 9.1.1.3: Fluke Helios Plus 2287A Data Logger with Ice Point Thermocouple Reference

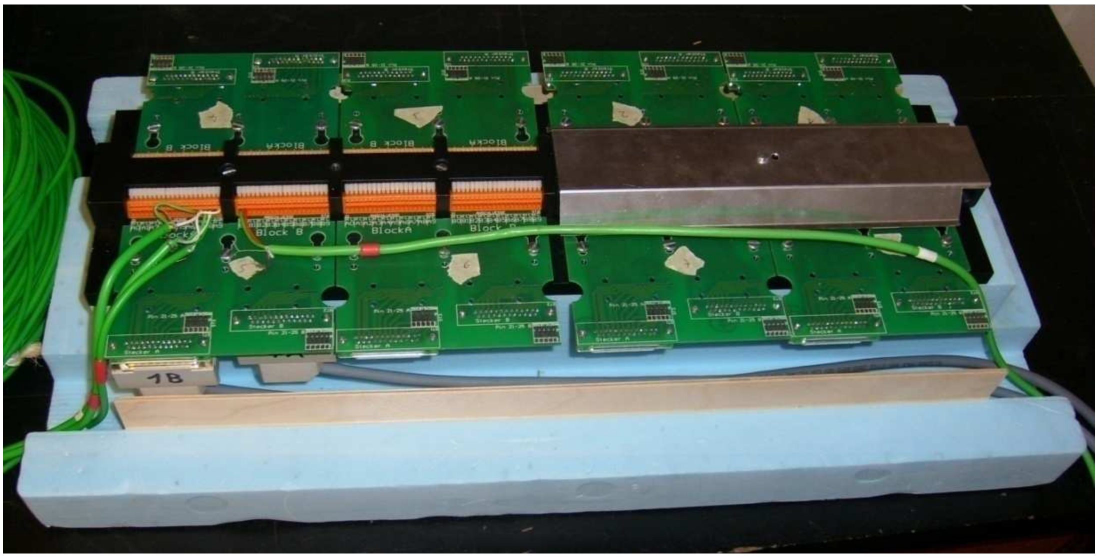

Figure 9.1.1.4: Compensation Box

In the experiment temperature is measured by 10 thermocouples.

9.1.2 Calibration

Thermocouples were calibrated by means of ISOCAL 6 VENUS2140B+ and Precision Thermometer F200.

Calibration was made for temperatures: 10°C, 30°C, 50°C, 70°C, 90°C and 110°C. It consists in comparing the temperature shown by the precision thermometer and this measured in ISOCAL 6, which is measured by Fluke Helios Plus 2287A.

Figure 9.1.2.1: ISOCAL 6 VENUS2140B+

Figure 9.1.2.2: Precision Thermometer F200

9.2 Radiation measurements

9.2.1 Equipment

For radiation measurements four different types of pyranometers were used. As they are endangered by weather and wind therefore all of them are protected by a ball-shaped protective glass.

- Kipp&Zonen CM11 and CM 21 (which is also a reference pyranometer) are used for measuring total radiation (sum of direct and diffuse radiation) or reflected radiation,

Figure 9.2.1.1: Pyranometer CM11

Figure 9.2.1.2: Pyranometer CM21

- Delta – T Devices BF 3 is used for measuring both total and diffuse radiation,

Figure 9.2.1.3: Pyranometer BF3

- Wilh. Lambrecht Kg Pyrheliometer number 1550 which is measuring total radiation.

Figure 9.2.1.4: Pyranometer Wilh. Lambrecht Kg

All of them are connected with Fluke Helios Plus 2287A data logger, the same as thermocouples. Then the data are transferred to PC.

9.2.2 Calibration

Pyranometers CM11, BF3, 1550 were calibrated by means of reference pyranometer (CM21). During a sunny day all 4 pyranometers were placed in a wooden box painted black (to prevent reflectance of sun rays). All obtained results were compared with those from the reference pyranometer and new values of sensitivity were calculated.

Figure 9.2.2.1: Setup for calibrating pyranometers

9.3 Pressure loss

9.3.1 Equipment

Pressure loss is measured by means of the differential pressure transducer. This device converts electric signal into pressure difference. In the measurements different ranges of the transducers were used: 0-20Pa, 0-100Pa, 0-500Pa. They are connected with power supply equipment and with Fluke Helios Plus 2287A data logger.

Figure 9.3.1.1: Differential pressure transducer

9.3.2 Calibration

Differential pressure transducer was connected with reference micromanometer. On one cable there was a pump to create a pressure difference. That value was read by the transducer. This transducer was connected to a power supply which was next connected to a PC. All data could be read on the computer. By comparing those values with ones from the micromanometer the calibration was made.

Bibliography

[1] P. Grzelecki, P. Matuszewski, M. Sawicka „Ventilation In Aircraft Cabin", Aalborg University 2008

[2] O. Kalyanova, F. Zanghirella et el. "Measuring air temperature in glazed ventilated facades in the presence of direct solar radiation", Aalborg University, Politecnico di Torino.

10 APPENDIX – DETAILED RESULTS OF YEARLY PERFORMANCE

Here all results concerning yearly performance of the collector are presented. Every chart presents values for one month. The single values on a chart are daily averages.

10.1 Monthly energy balance

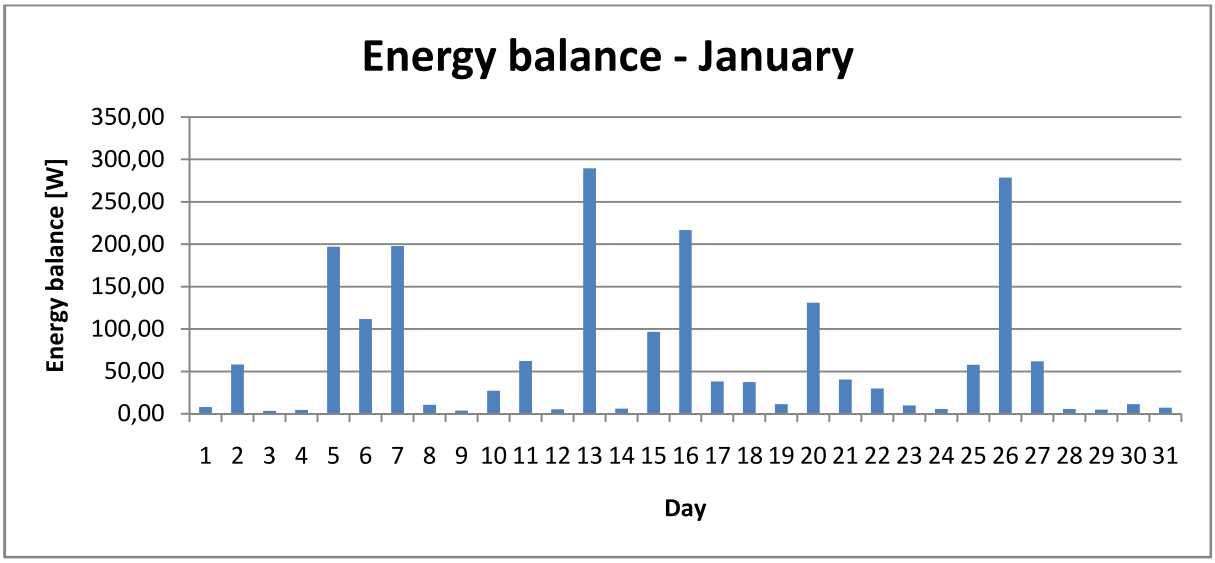

Figure 10.1.1: Monthly performance of the collector – energy balance in January

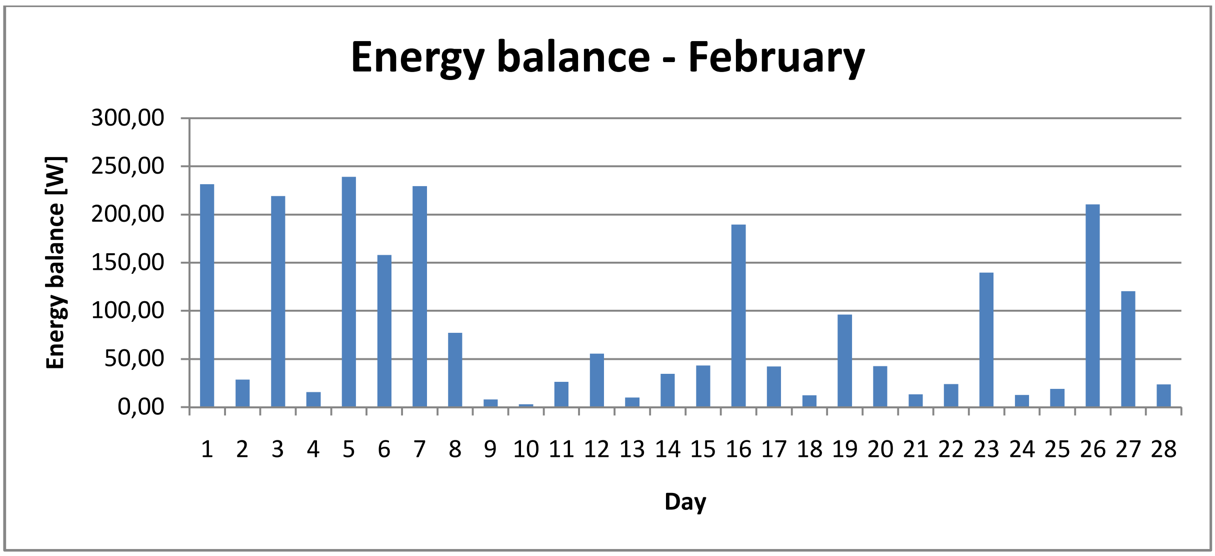

Figure 10.1.2: Monthly performance of the collector – energy balance in February

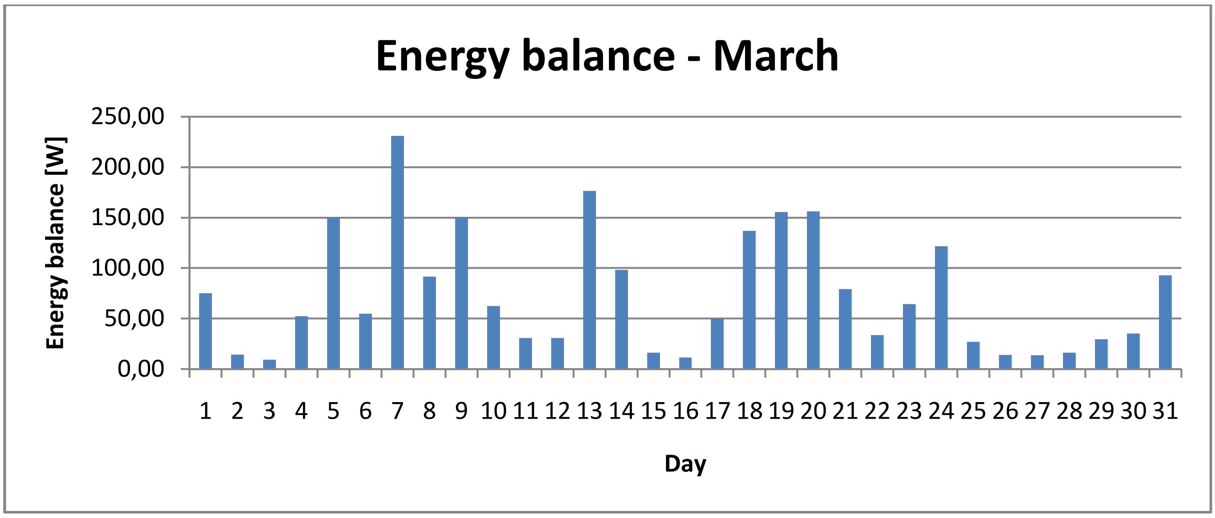

Figure 10.1.3: Monthly performance of the collector – energy balance in March

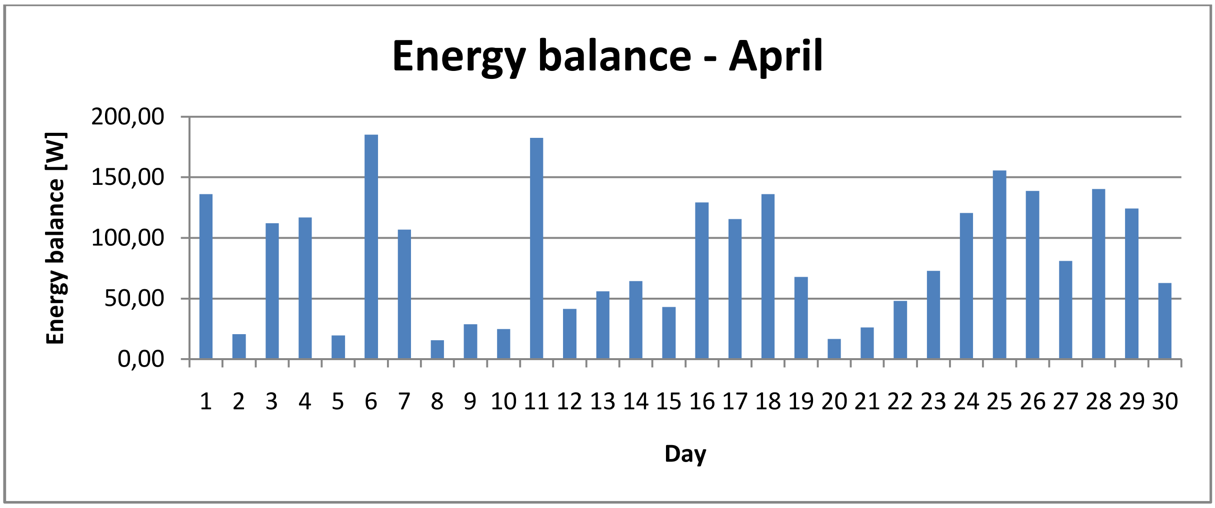

Figure 10.1.4: Monthly performance of the collector – energy balance in April

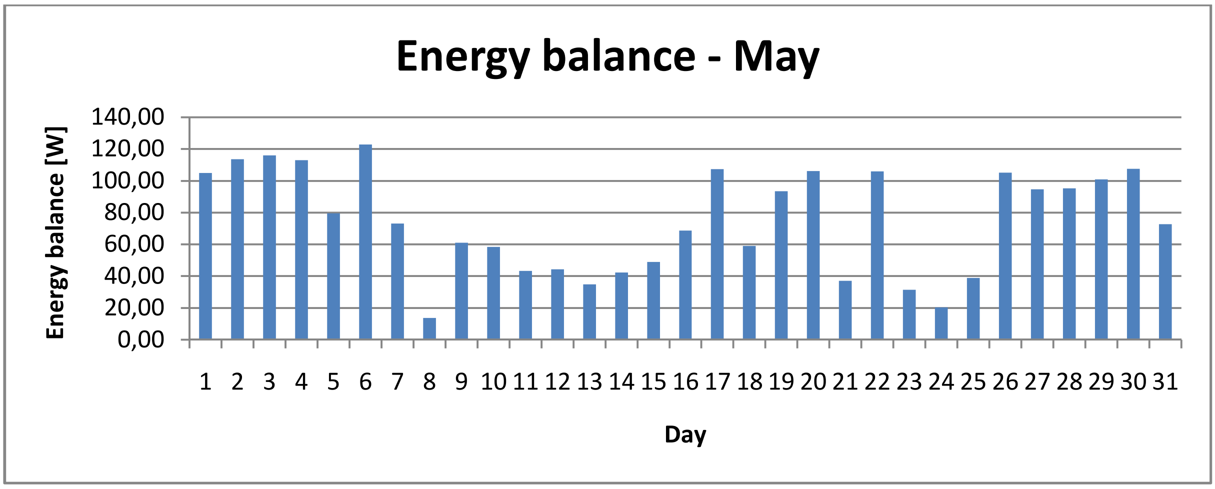

Figure 10.1.5: Monthly performance of the collector – energy balance in May

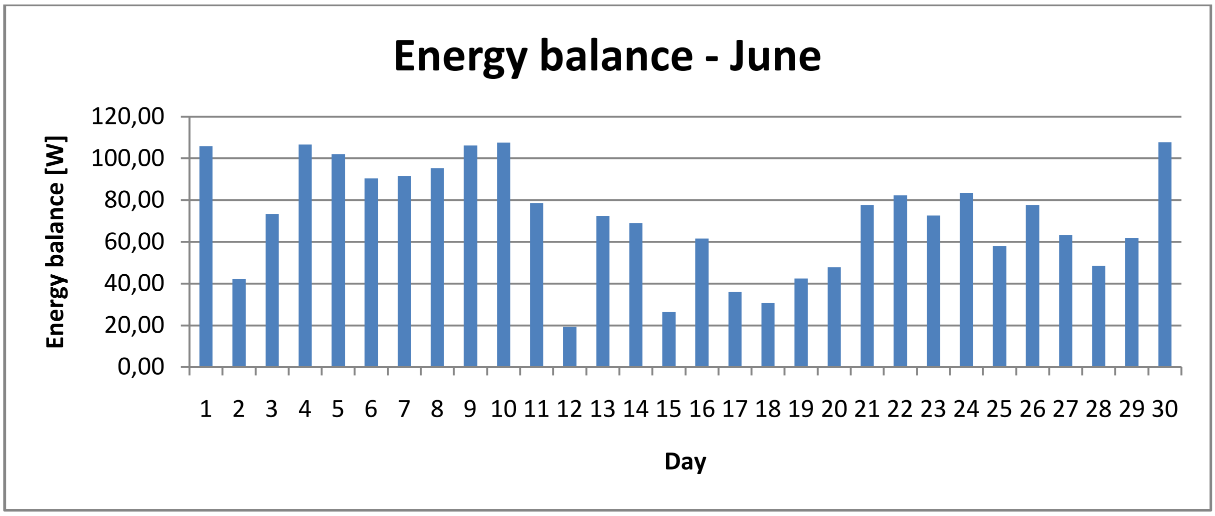

Figure 10.1.6: Monthly performance of the collector – energy balance in June

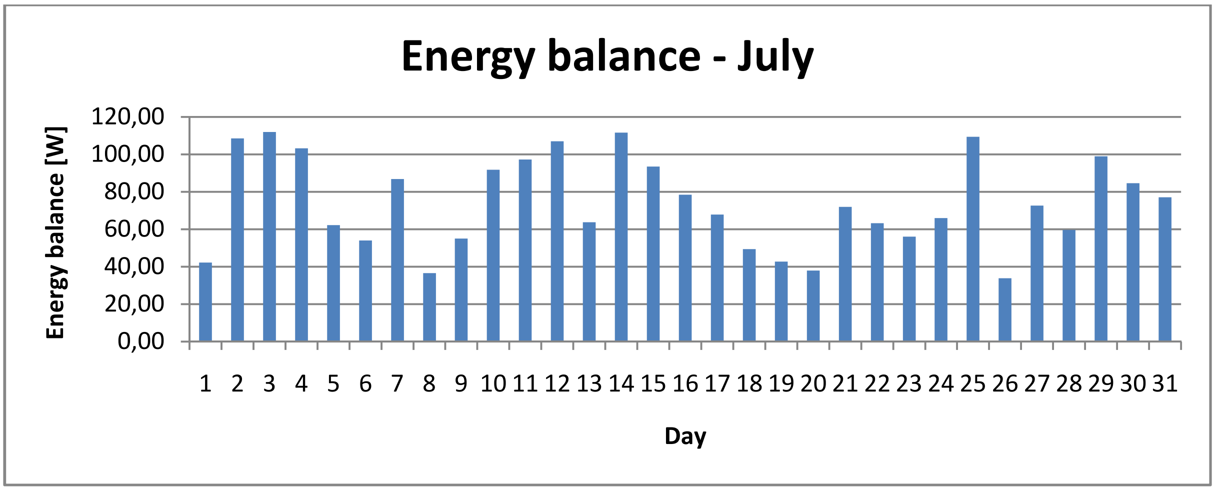

Figure 10.1.7: Monthly performance of the collector – energy balance in July

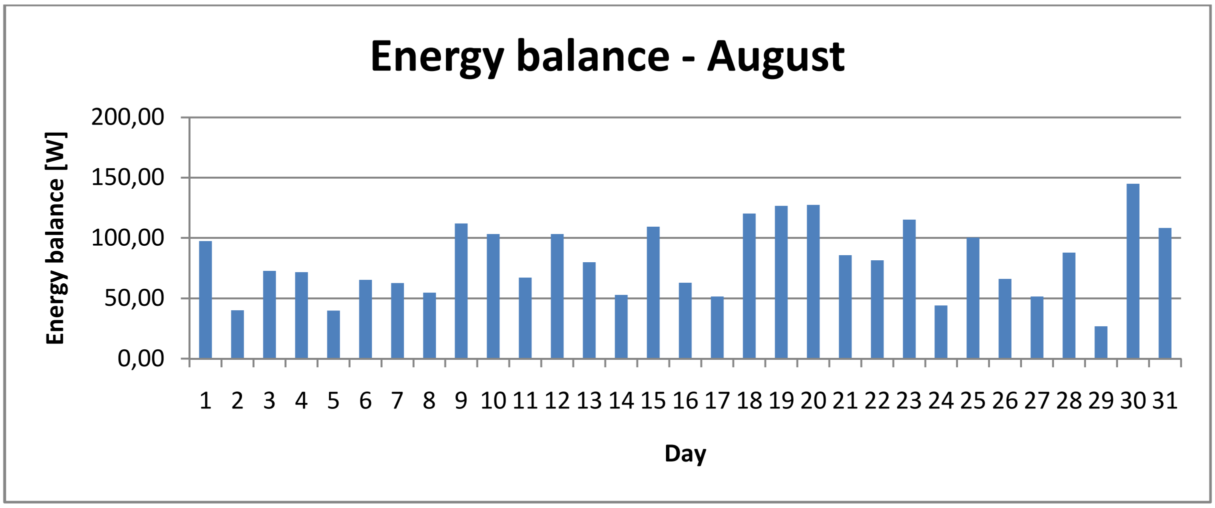

Figure 10.1.8: Monthly performance of the collector – energy balance in August

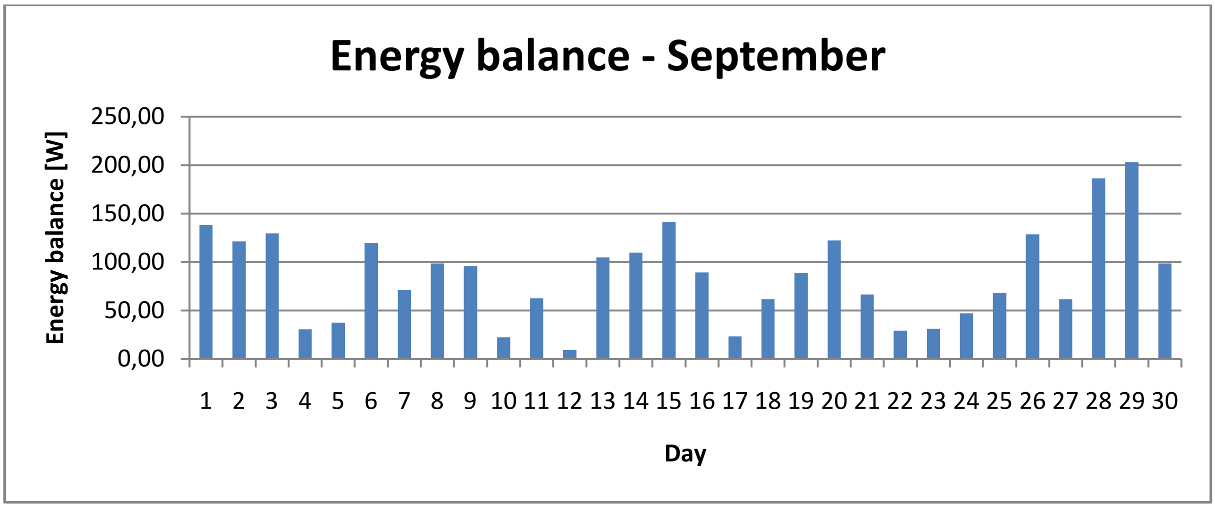

Figure 10.1.9: Monthly performance of the collector – energy balance in September

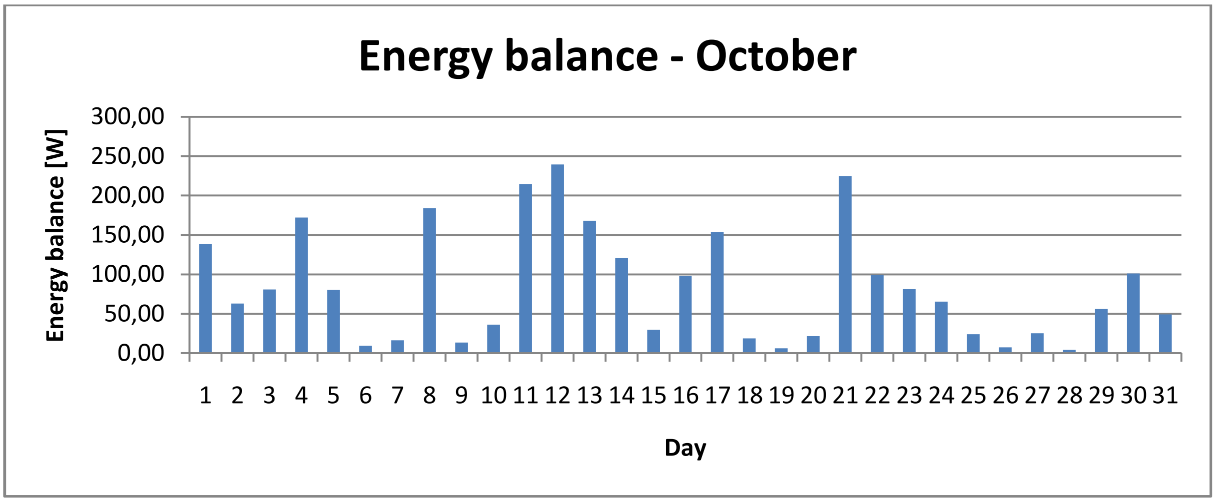

Figure 10.1.10: Monthly performance of the collector – energy balance in October

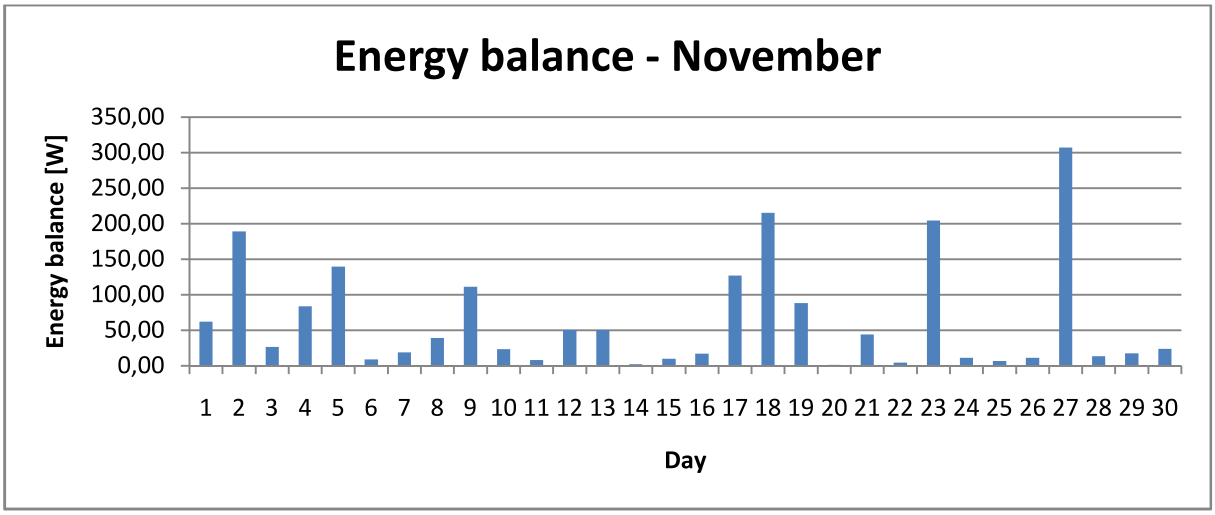

Figure 10.1.11: Monthly performance of the collector – energy balance in November

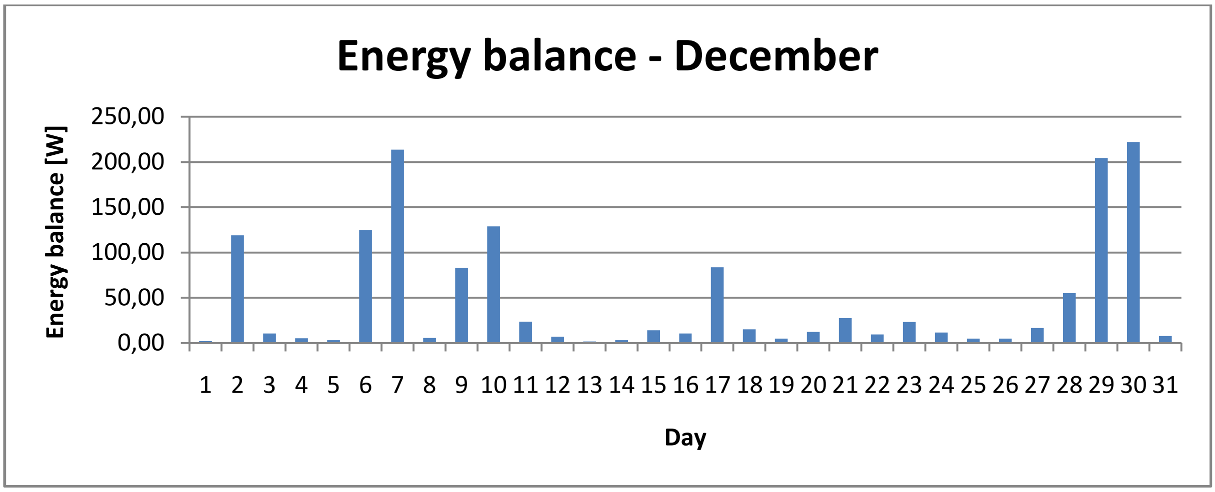

Figure 10.1.12: Monthly performance of the collector – energy balance in December

10.2 Monthly temperature increase

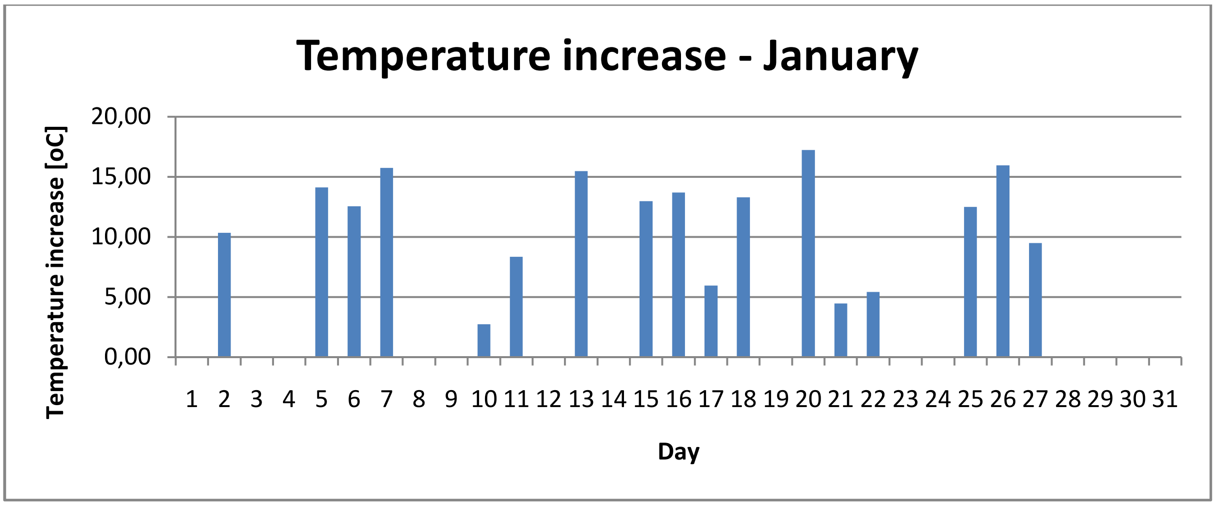

Figure 10.2.1: Monthly performance of the collector – temperature increase in January

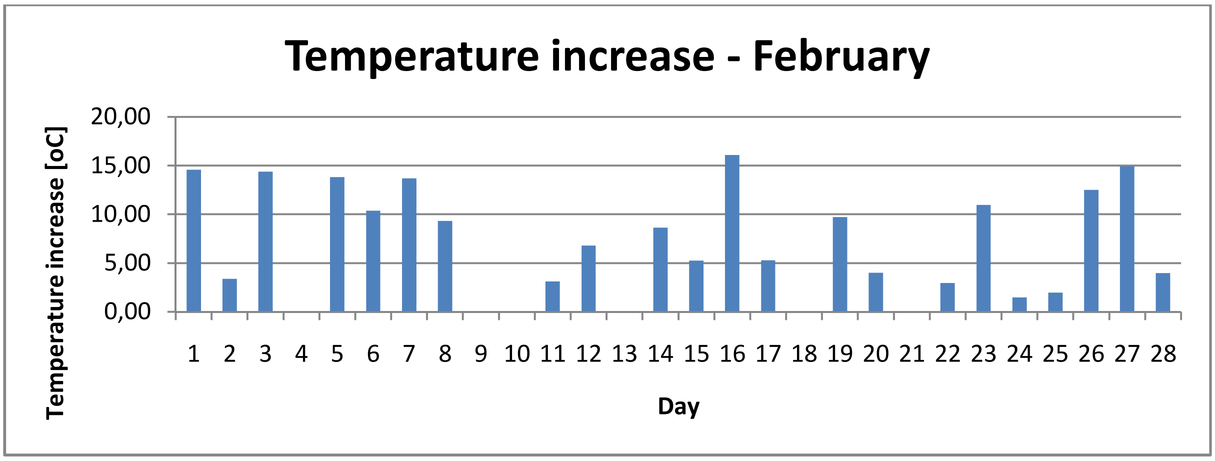

Figure 10.2.2: Monthly performance of the collector – temperature increase in February

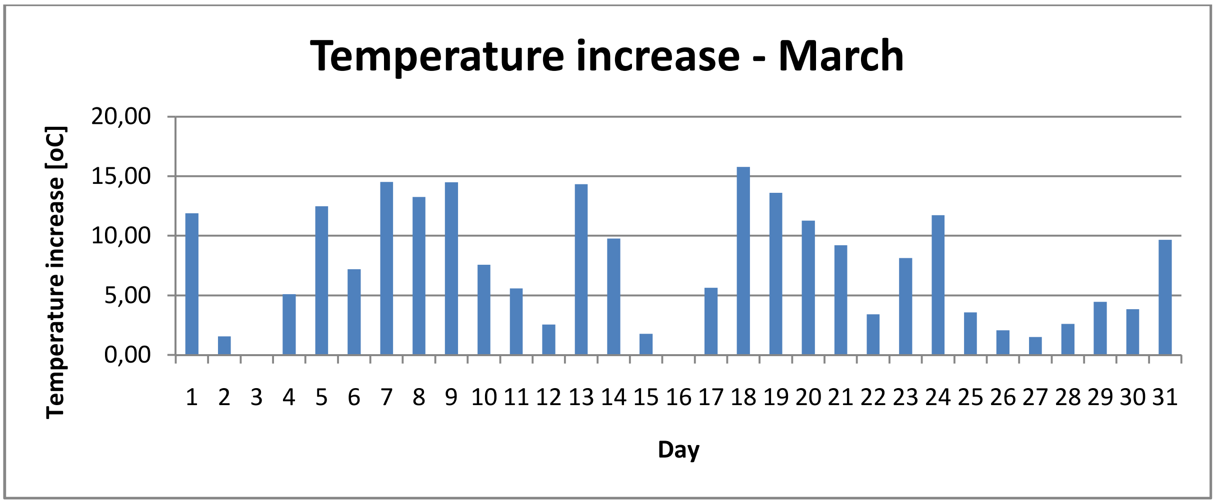

Figure 10.2.3: Monthly performance of the collector – temperature increase in March

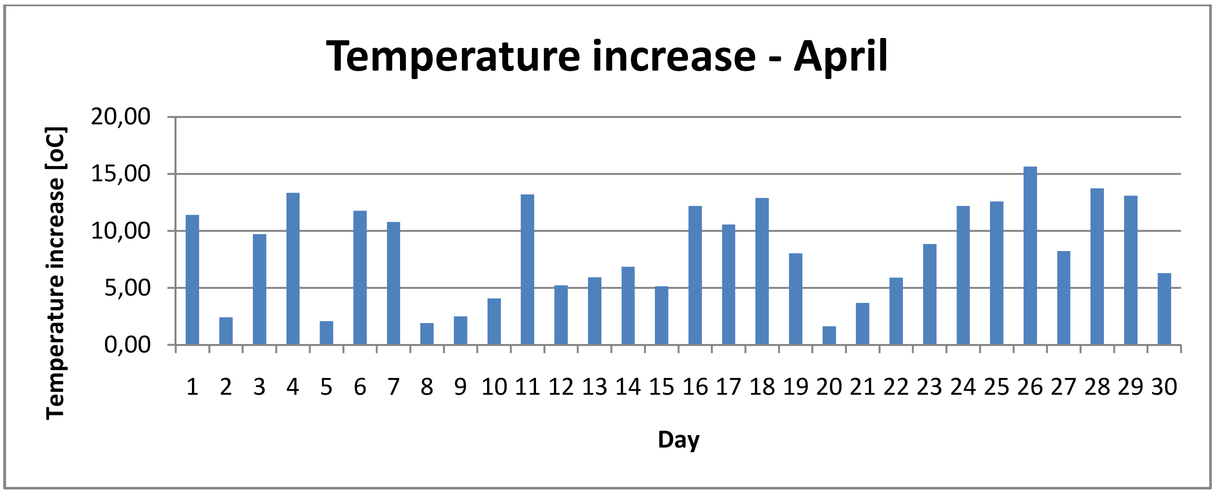

Figure 10.2.4: Monthly performance of the collector – temperature increase in April

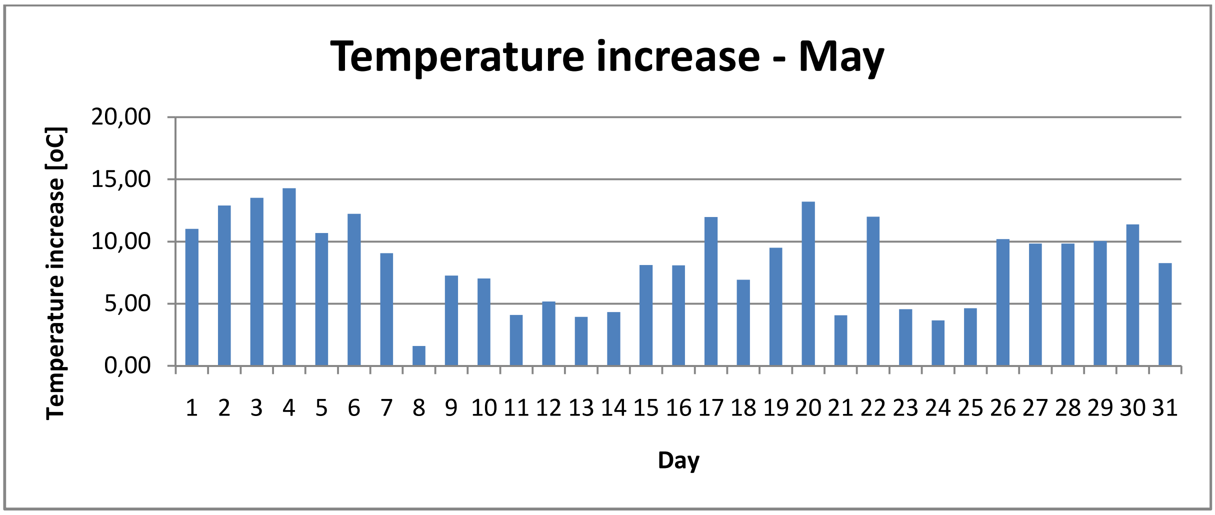

Figure 10.2.5: Monthly performance of the collector – temperature increase in May

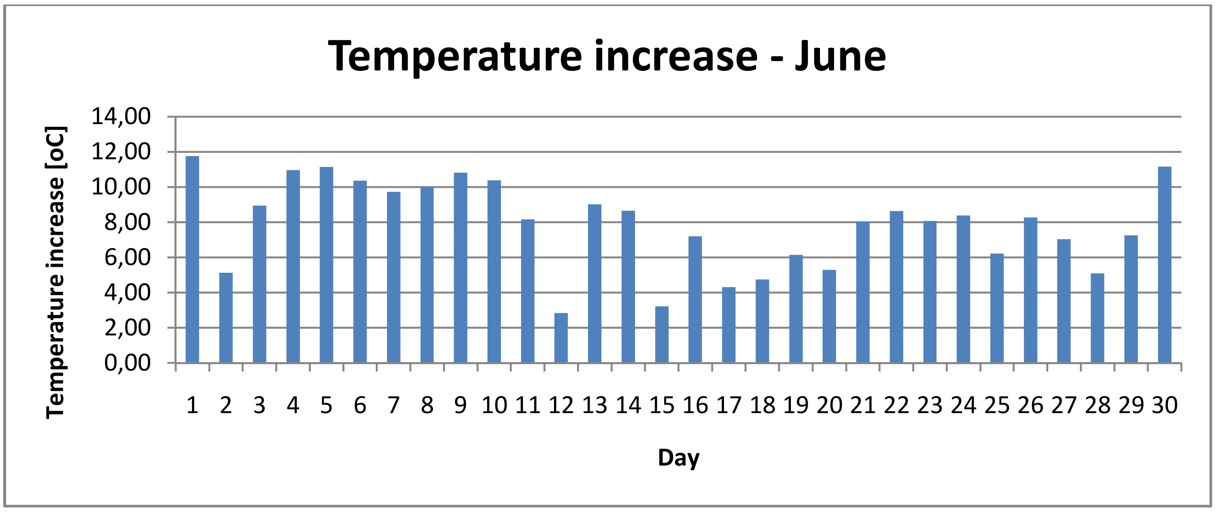

Figure 10.2.6: Monthly performance of the collector – temperature increase in June

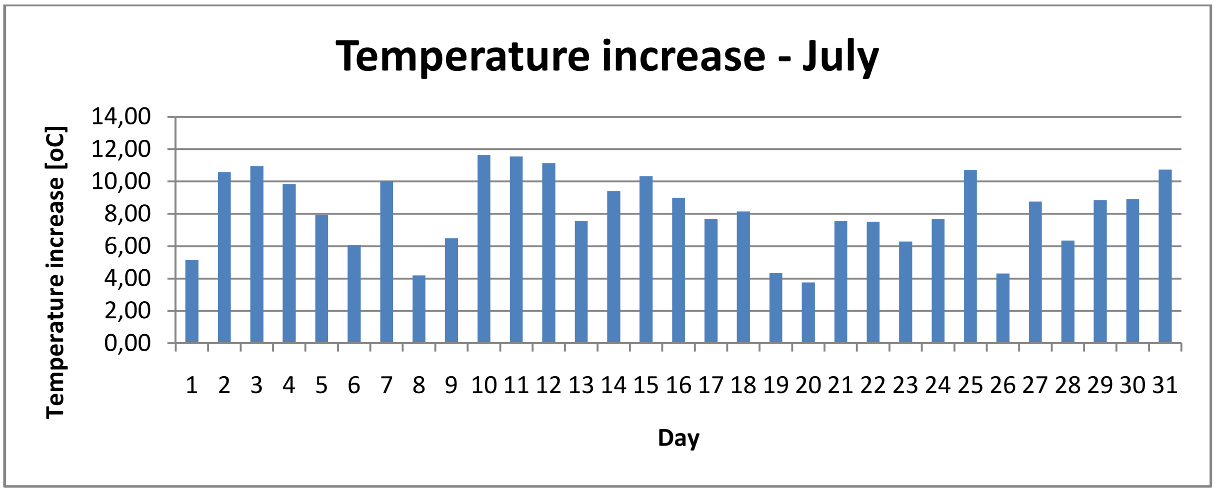

Figure 10.2.7: Monthly performance of the collector – temperature increase in July

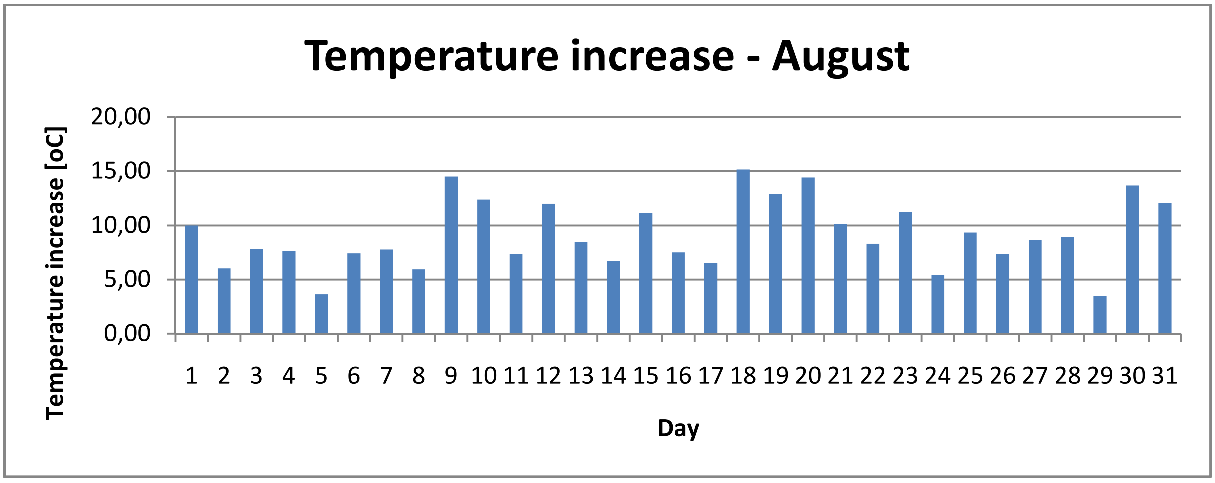

Figure 10.2.8: Monthly performance of the collector – temperature increase in August

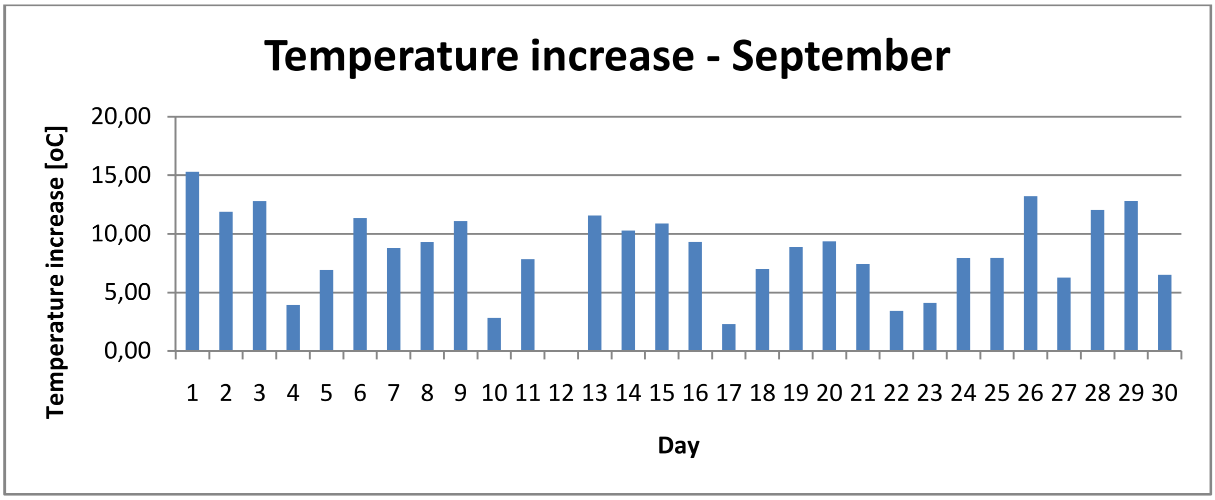

Figure 10.2.9: Monthly performance of the collector – temperature increase in September

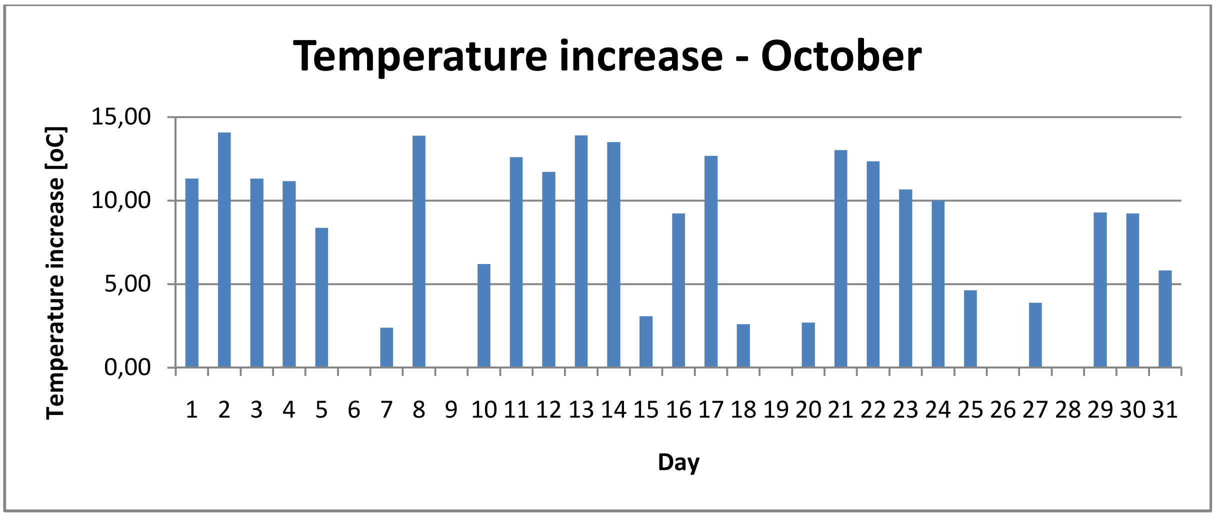

Figure 10.2.10: Monthly performance of the collector – temperature increase in October

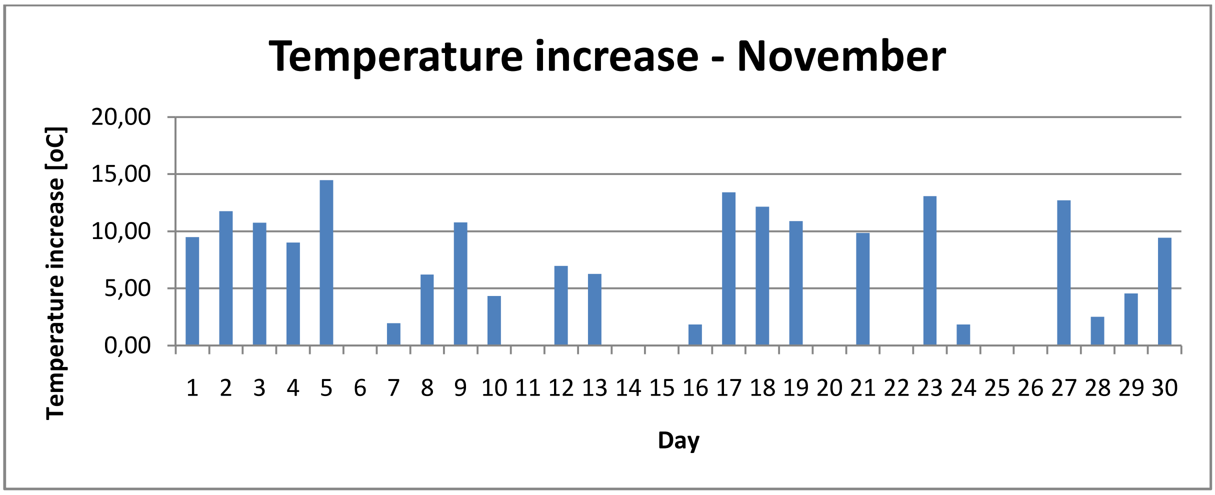

Figure 10.2.11: Monthly performance of the collector – temperature increase in November

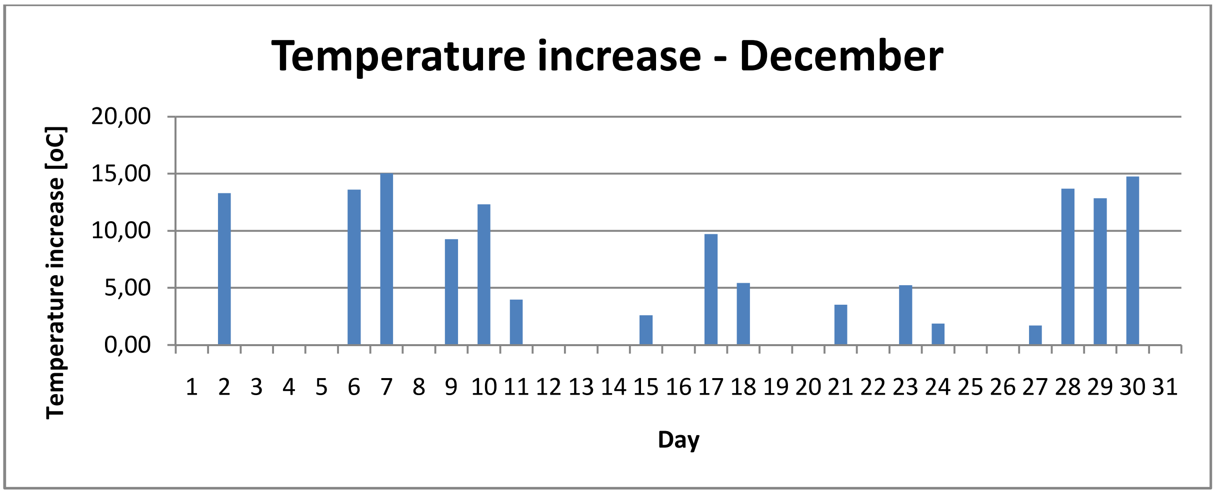

Figure 10.2.12: Monthly performance of the collector – temperature increase in December

10.3 Monthly airflow

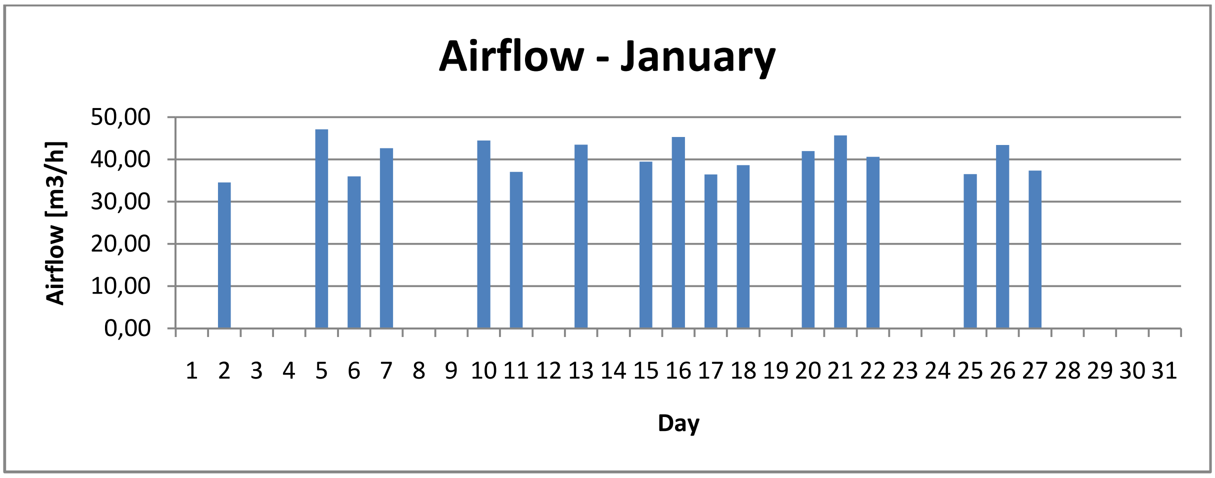

Figure 10.3.1: Monthly performance of the collector – airflow in January

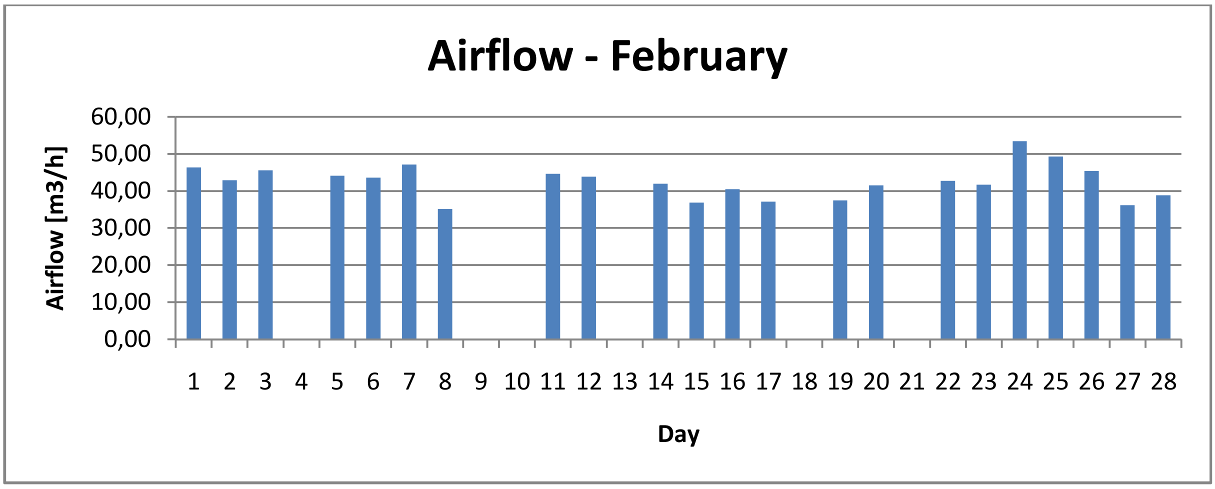

Figure 10.3.2: Monthly performance of the collector – airflow in February

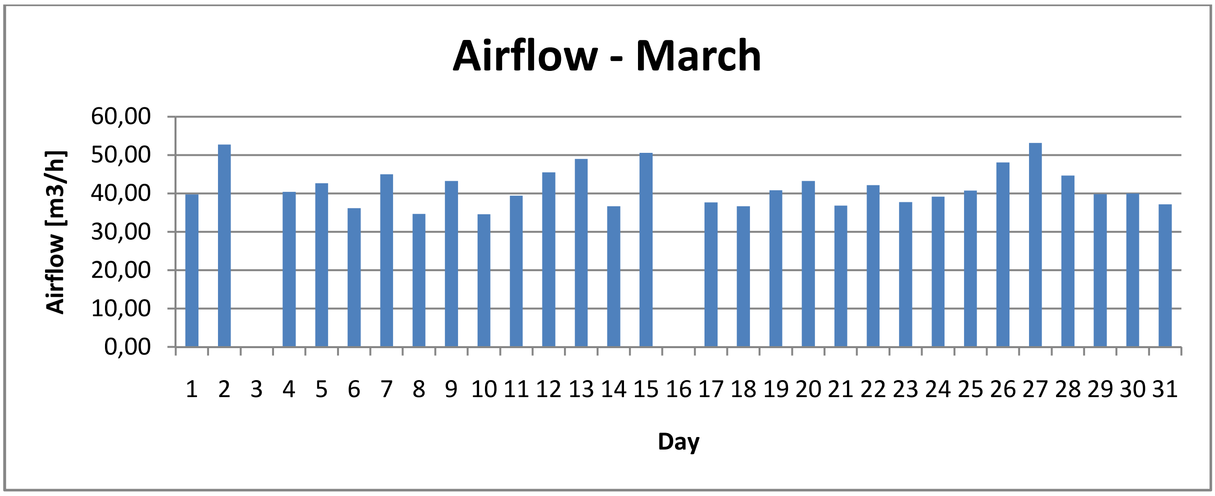

Figure 10.3.3: Monthly performance of the collector – airflow in March

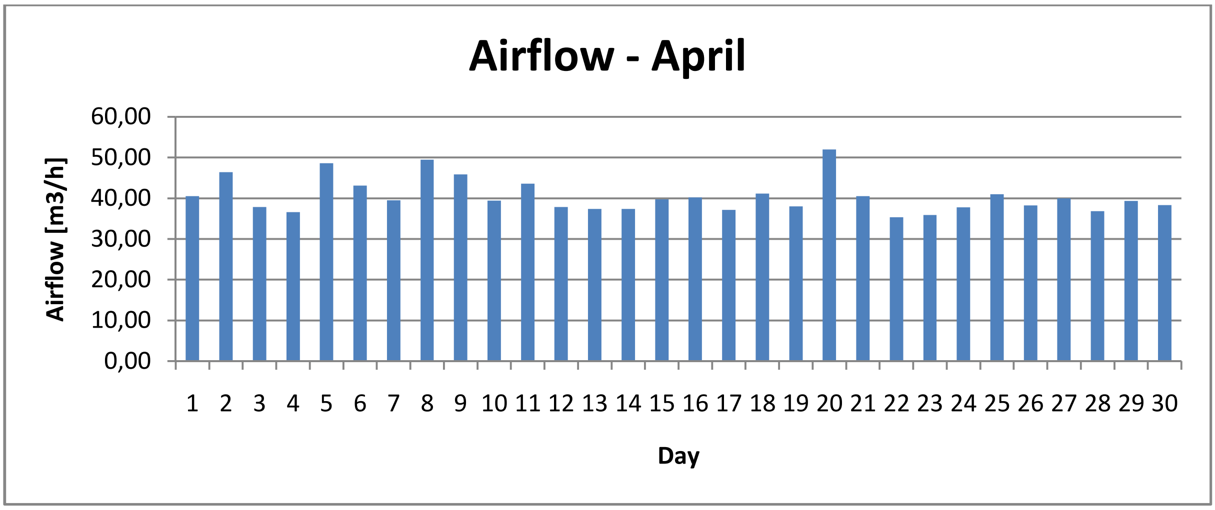

Figure 10.3.4: Monthly performance of the collector – airflow in April

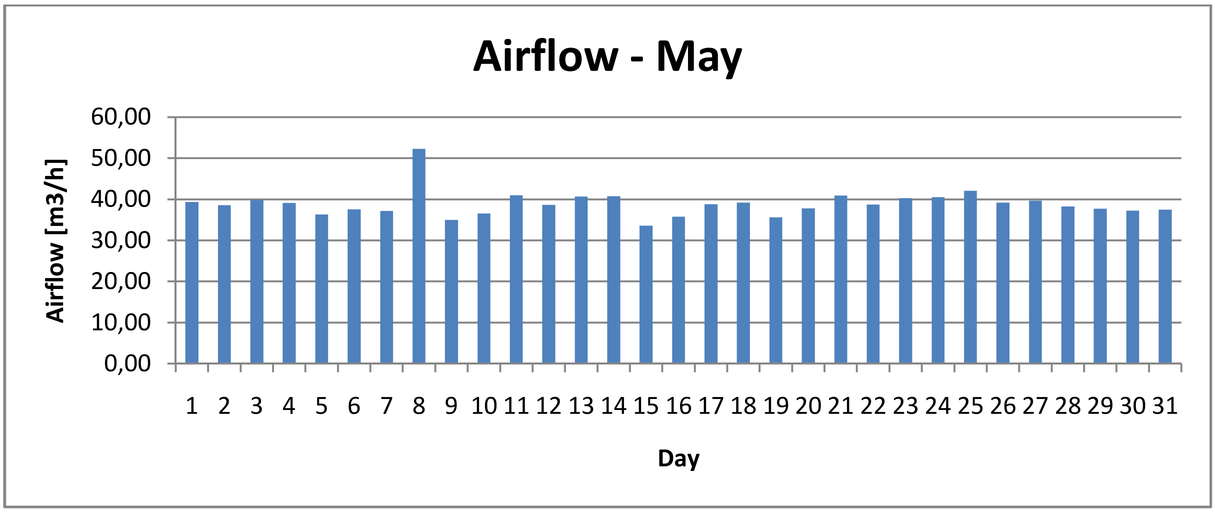

Figure 10.3.5: Monthly performance of the collector – airflow in May

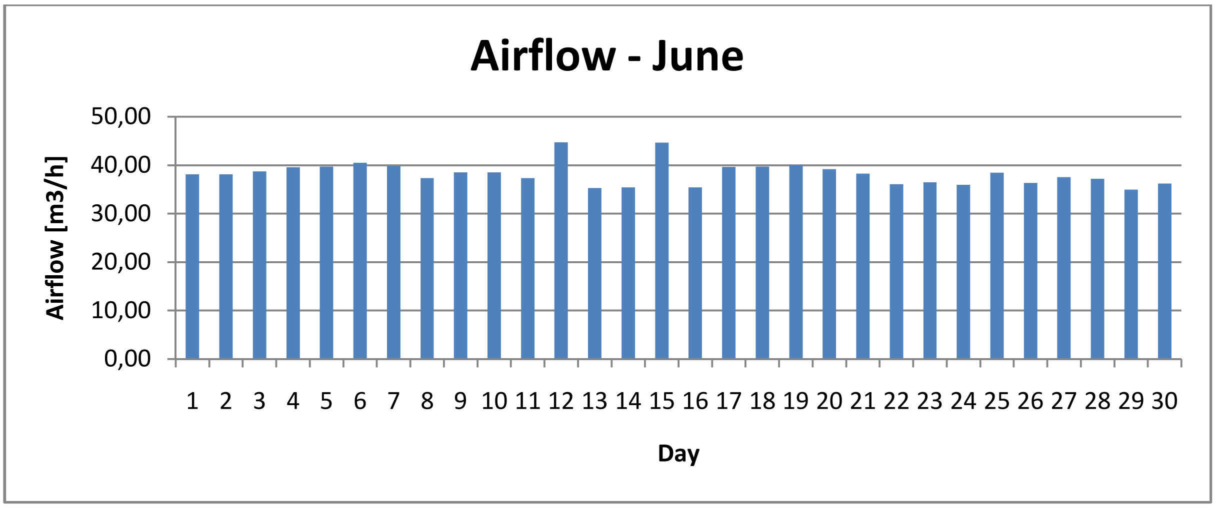

Figure 10.3.6: Monthly performance of the collector – airflow in June

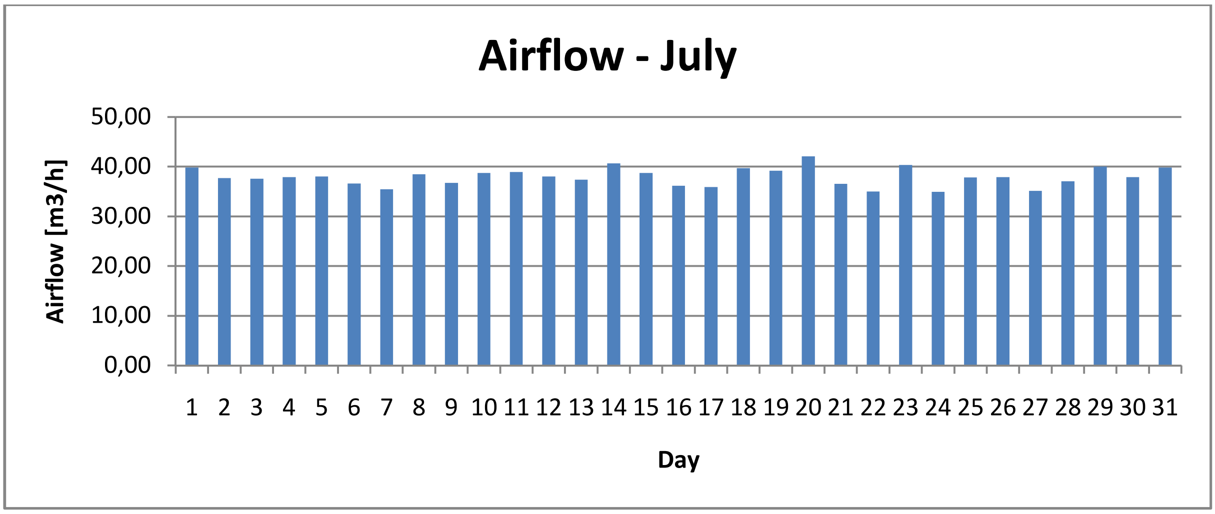

Figure 10.3.7: Monthly performance of the collector – airflow in July

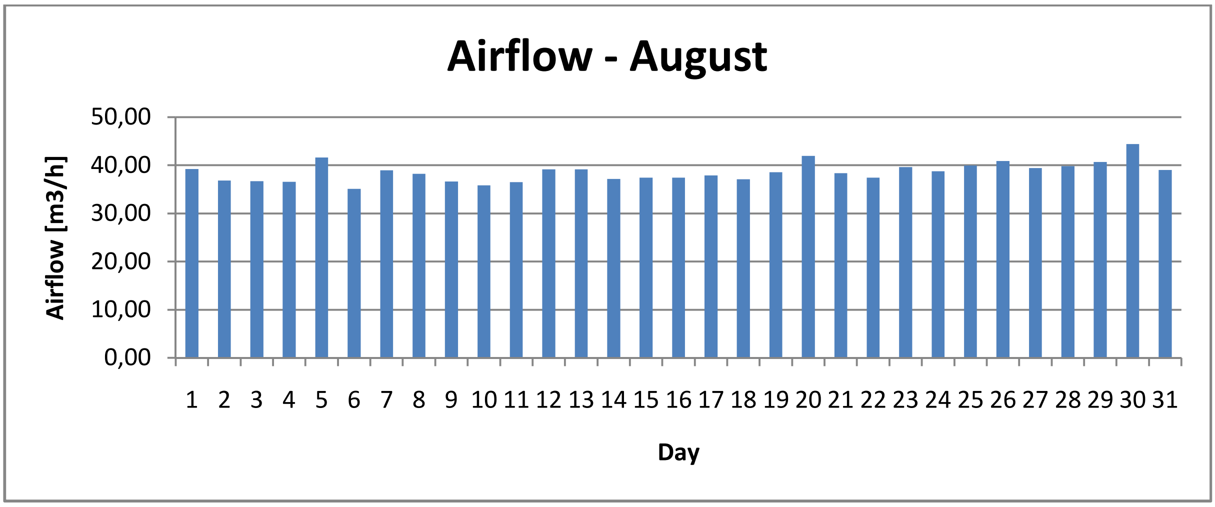

Figure 10.3.8: Monthly performance of the collector – airflow in August

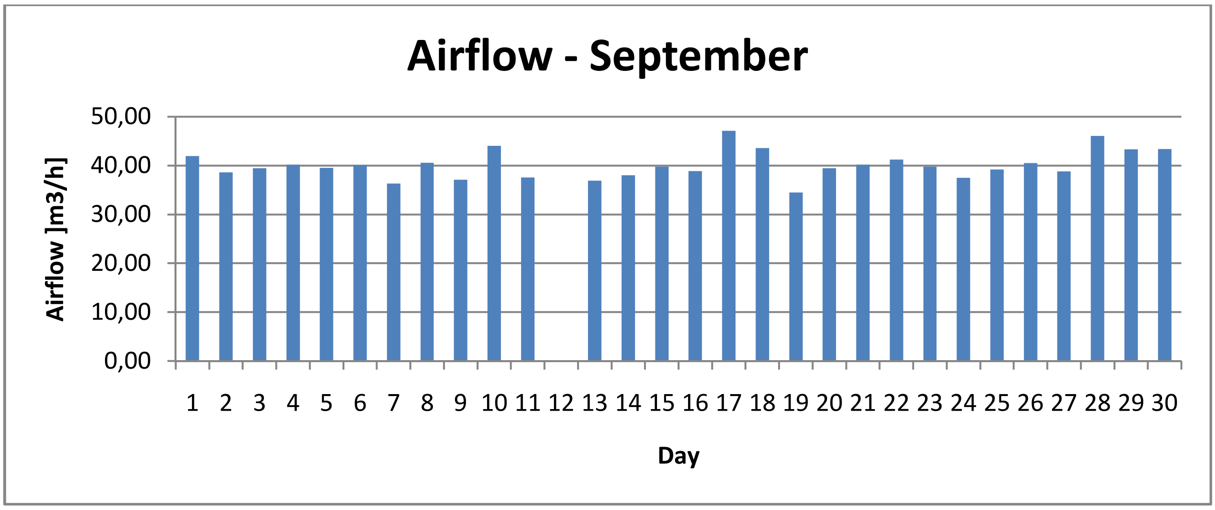

Figure 10.3.9: Monthly performance of the collector – airflow in September

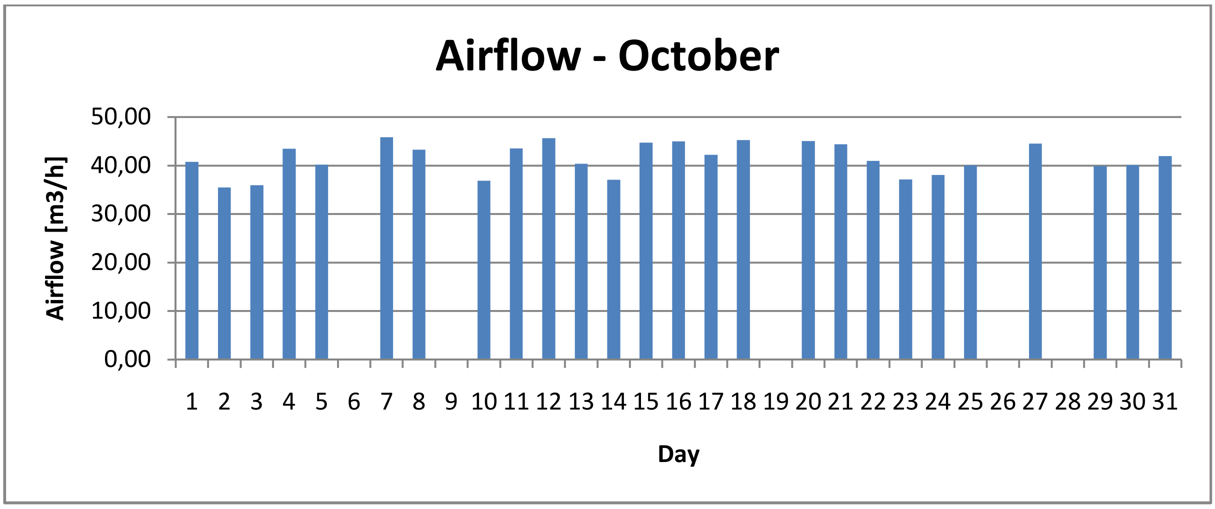

Figure 10.3.10: Monthly performance of the collector – airflow in October

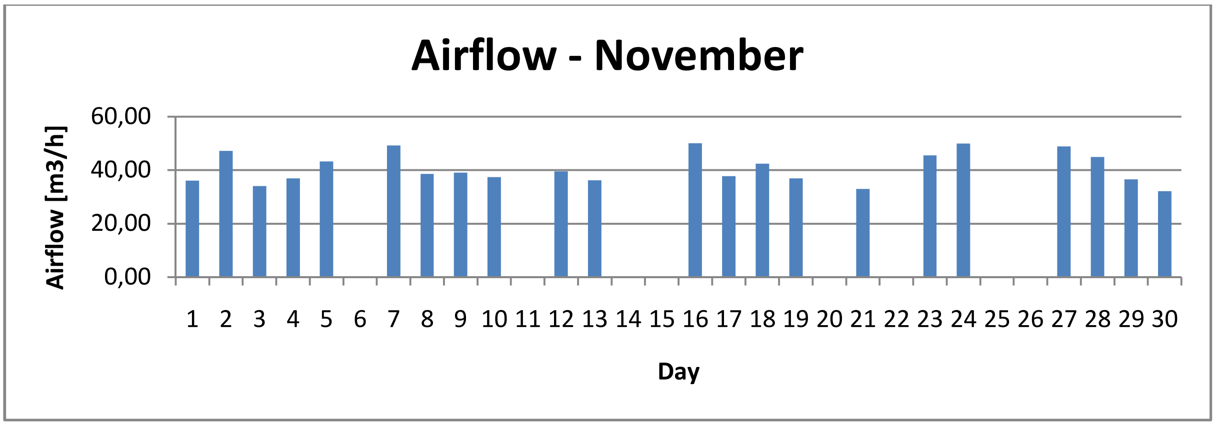

Figure 10.3.11: Monthly performance of the collector – airflow in November

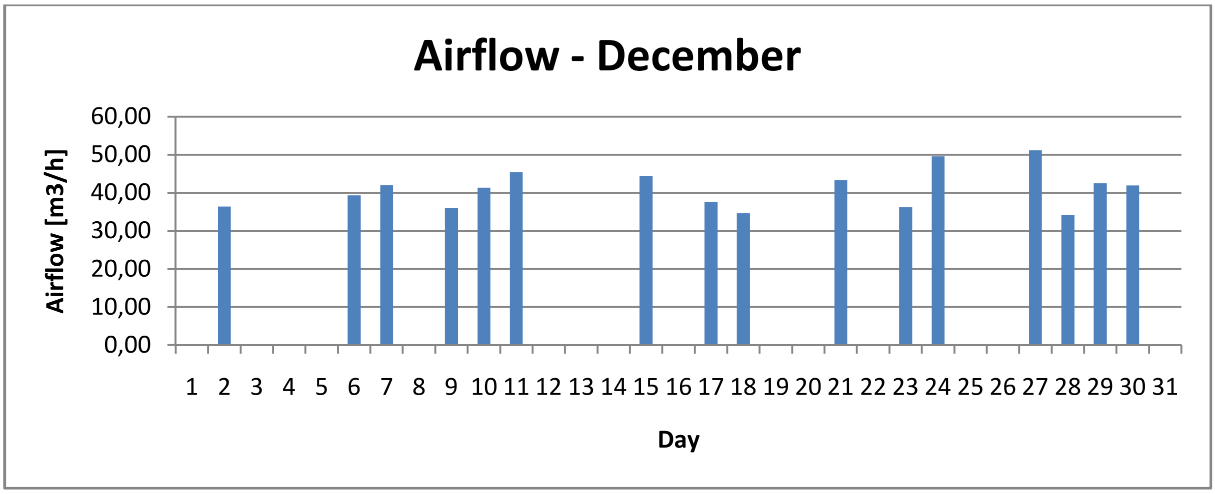

Figure 10.3.12: Monthly performance of the collector – airflow in December

10.4 Monthly efficiency

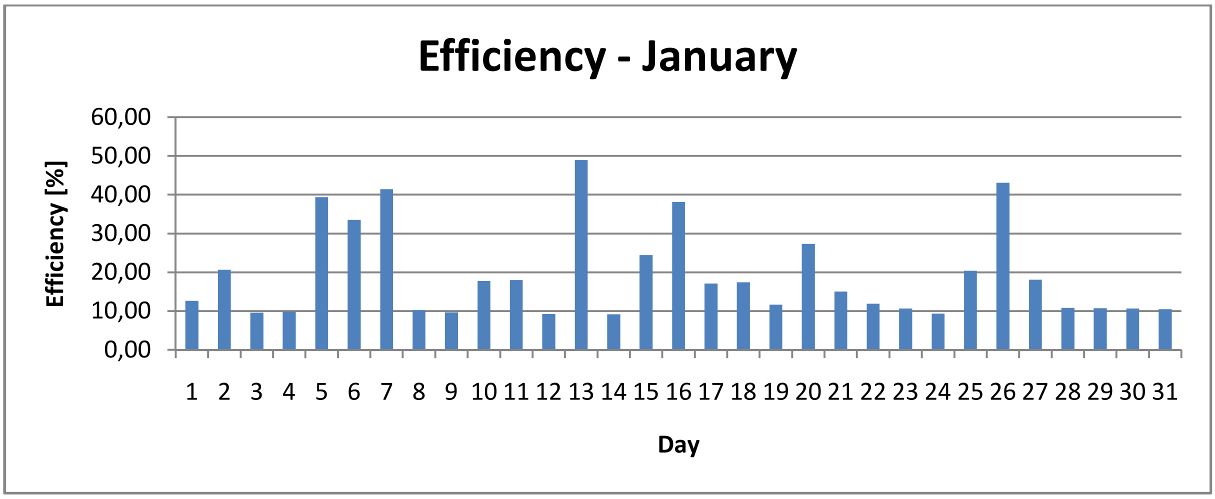

Figure 10.4.1: Monthly performance of the collector – efficiency in January

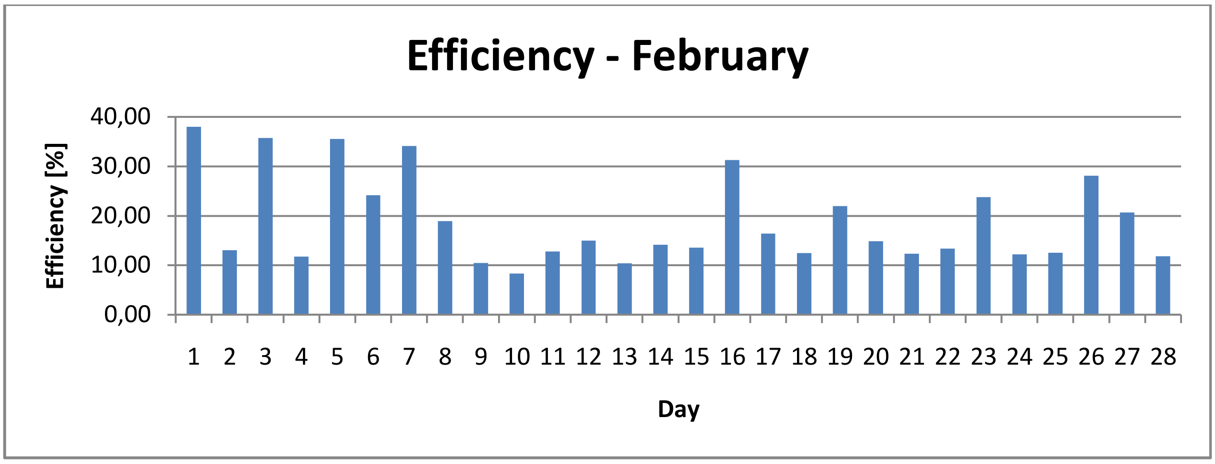

Figure 10.4.2: Monthly performance of the collector – efficiency in February

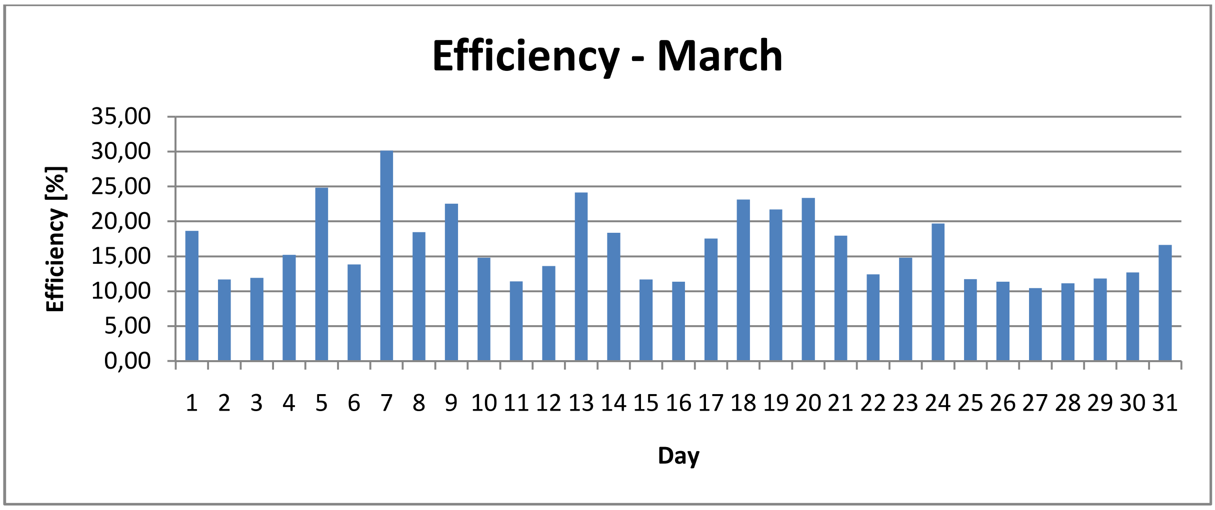

Figure 10.4.3: Monthly performance of the collector – efficiency in March

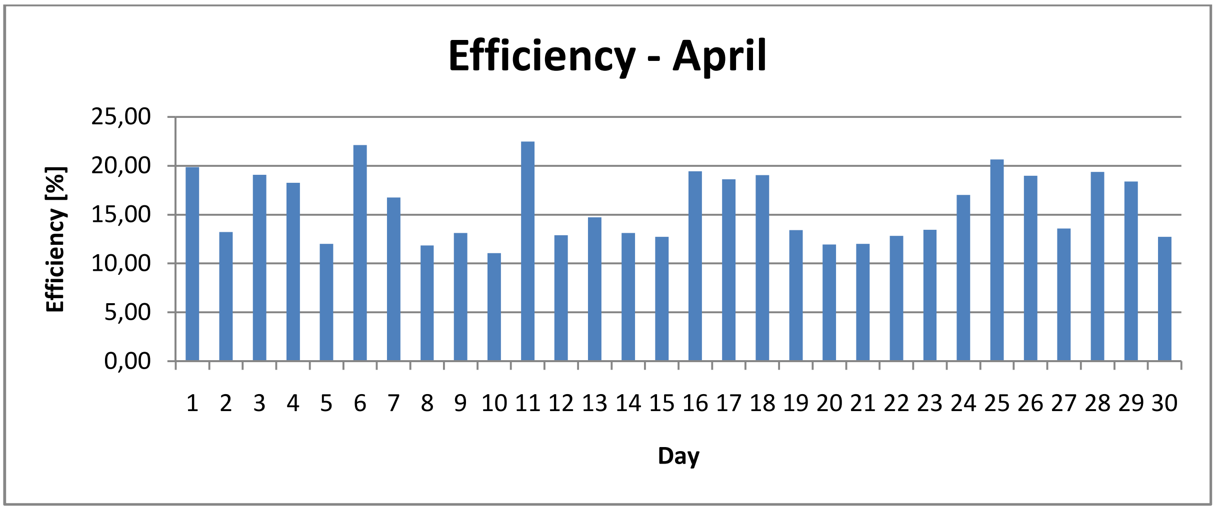

Figure 10.4.4: Monthly performance of the collector – efficiency in April

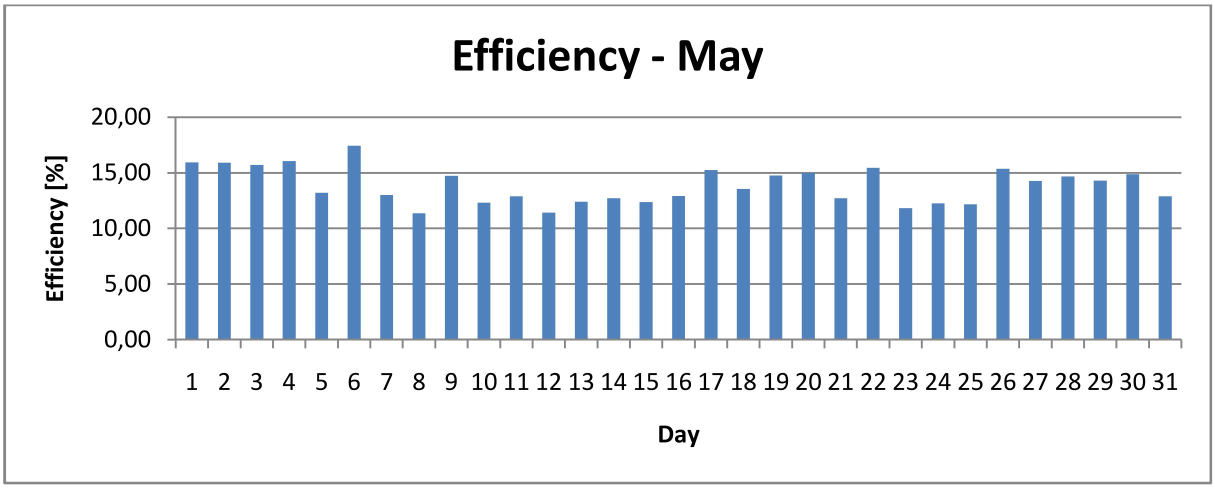

Figure 10.4.5: Monthly performance of the collector – efficiency in May

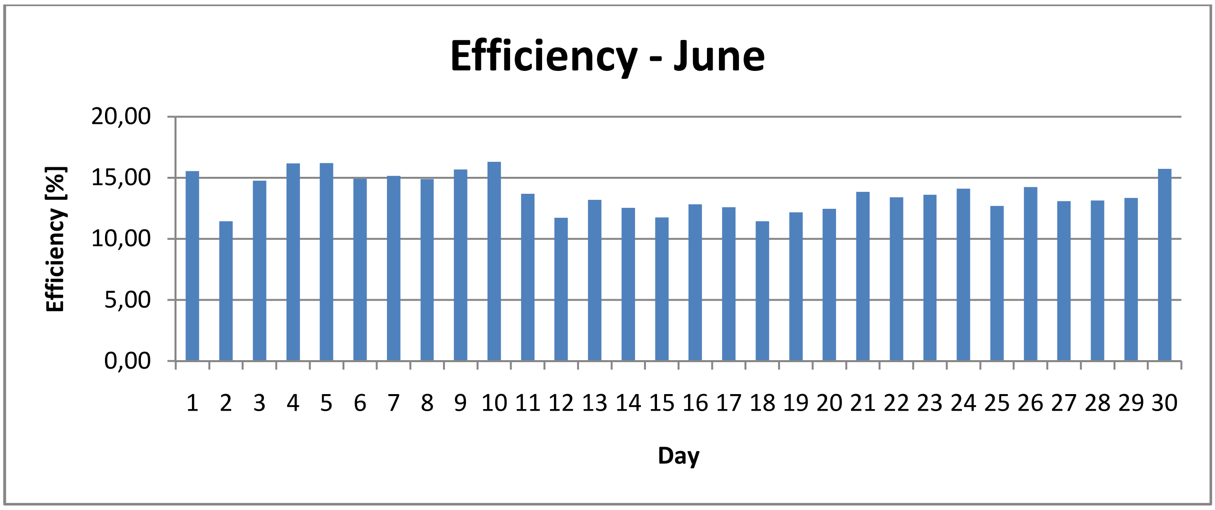

Figure 10.4.6: Monthly performance of the collector – efficiency in June

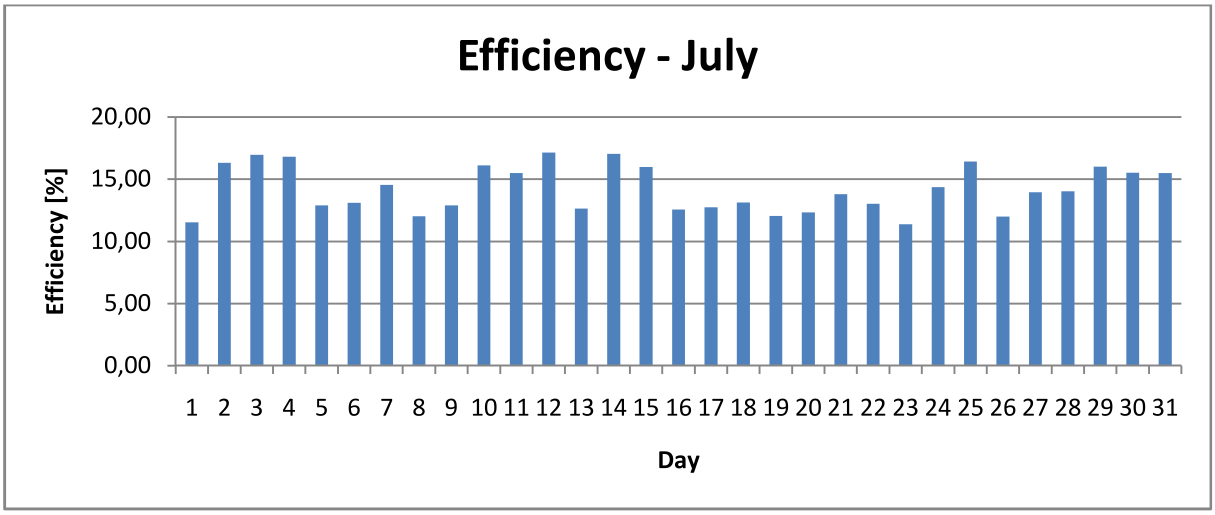

Figure 10.4.7: Monthly performance of the collector – efficiency in July

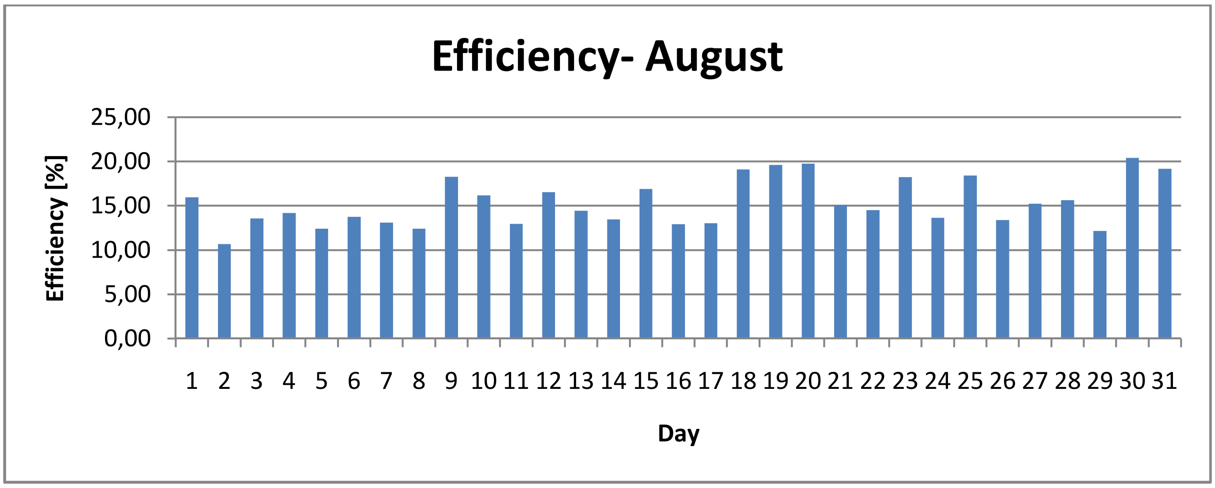

Figure 10.4.8: Monthly performance of the collector – efficiency in August

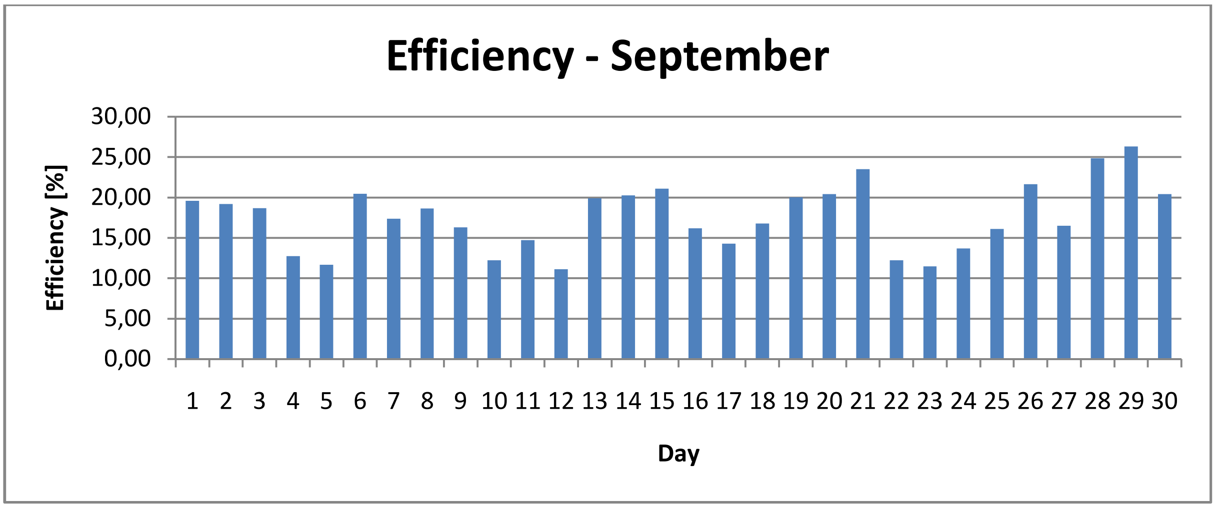

Figure 10.4.9: Monthly performance of the collector – efficiency in September

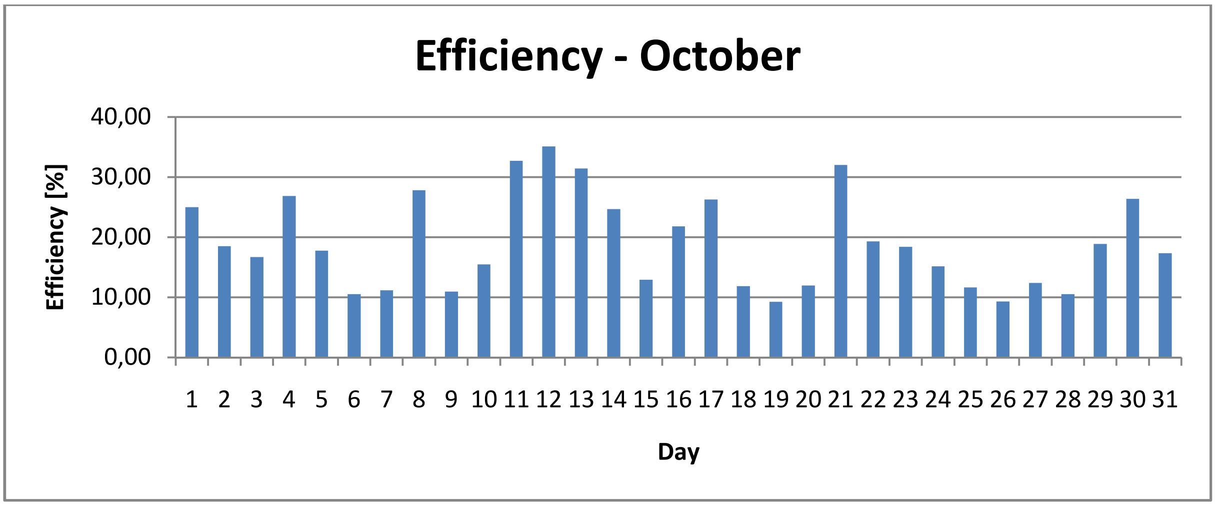

Figure 10.4.10: Monthly performance of the collector – efficiency in October

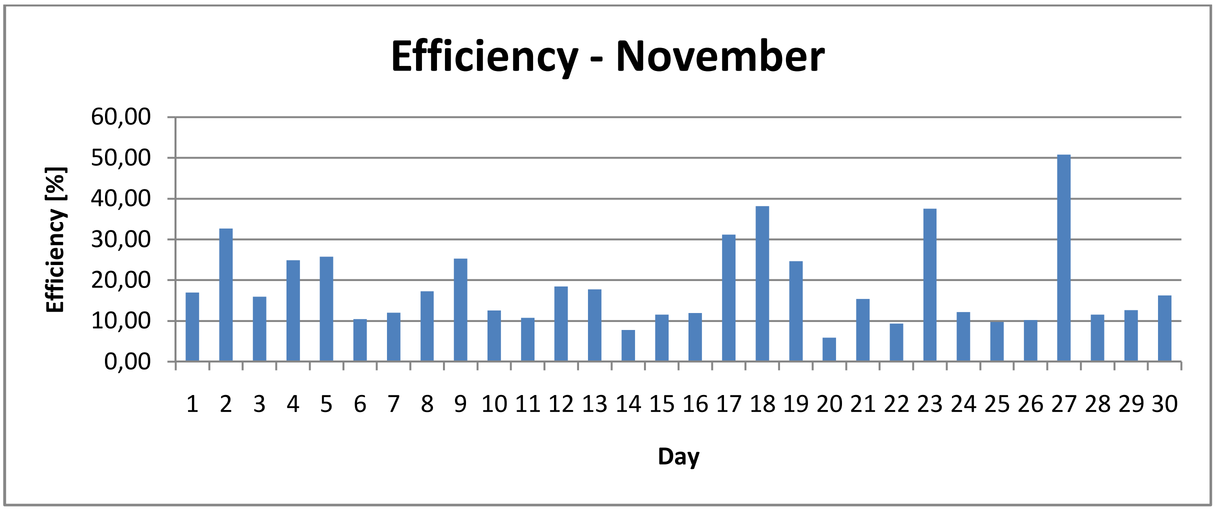

Figure 10.4.11: Monthly performance of the collector – efficiency in November

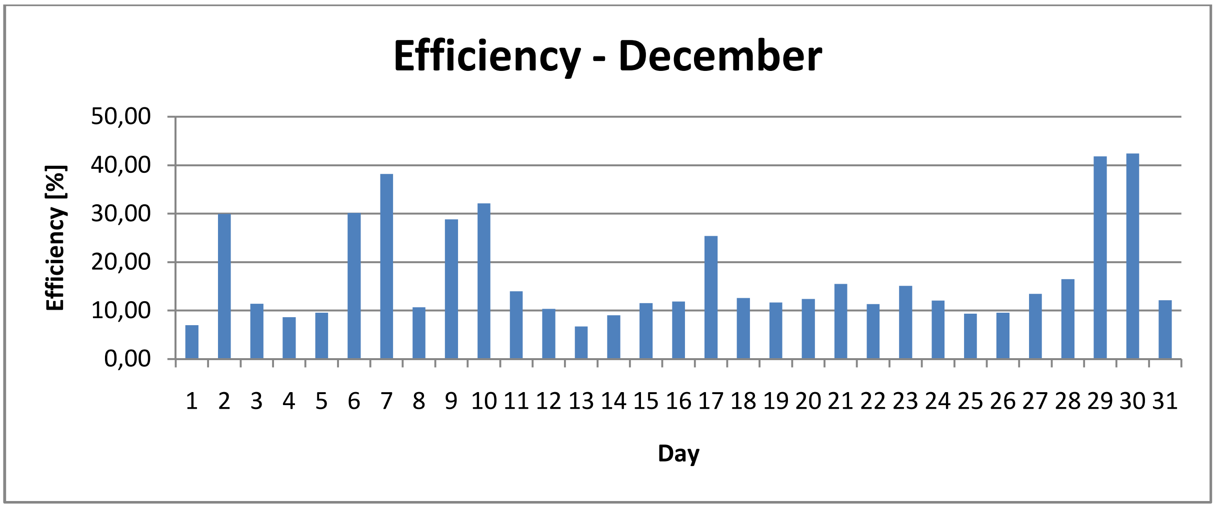

Figure 10.4.12: Monthly performance of the collector – efficiency in December