EXPERIMENTAL STUDIES ON THE HYBRID SYSTEM OF HEAT AND COLD PRODUCTION FROM SOLAR ENERGY

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In recent years more and more energy is consumed in the European Union countries for summer air conditioning in buildings. This consumption will probably increase even more due to the predicted climate warming and the desire to improve the quality of life. At present final energy as heat and electricity is sourced mainly from fossil fuels. However, recently alternative renewable energy sources are increasingly taken into account as a result of efforts toward environmental protection and fuels savings. This paper presents results of the analysis of a hybrid solar-assisted heating and cooling system for buildings in the temperate climate of West and Central Europe. Solar energy potential was estimated. The investigation were performed using a large scale laboratory installation, which contains an evacuated solar collector, a single-stage NH3-H2O absorption chiller and a hot water tank. The impact of the main system parameters on its performance was analyzed on the basis of energy balances

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Keywords: *solar radiation, solar air conditioning, hybrid system, heating, cooling, energy-efficient building.*

1. Introduction

The demand for cooling and air conditioning in buildings continues to grow not only in hot regions of the Earth but also in areas with temperate climate. The conventional cooling systems are usually powered by electricity. It is estimated that, depending on the climate conditions, about 30 to 50 per cent of the global electricity production is used for air conditioning and cooling in buildings [1]. In Europe, energy consumption for these purposes is around 8% of annual electricity production and steadily increasing. It is expected that in 2020, about 60% of office and commercial facilities as well as about 40% of dwelling houses in European countries will be equipped with air cooling installations. To meet these needs will require mobilizing additional amounts of energy, approximately 2.4 EJ [2].

Reducing electricity consumption in air conditioning systems can be achieved, inter alia, by the use and distribution of thermal installations driven by heat obtained from the solar radiation energy. Two types of thermal technologies are proposed and investigated [1,3-9]: open and closed circuit technologies. In closed circuits, heat is transferred via chillers. Typically, water is cooled in chillers and used further for air conditioning. Liquid or solid sorbents are applied. The coefficient of performance depends on the heat source temperature and ranges from 0.7 for single-stage cycles to 1.3 for two-stage cycles [6,10,11]. Open circuits, also called dry-evaporative cooling systems, are a combination of the cooling process during moisture evaporation and the air drying process during its contact with a desiccant. The desiccant is regenerated through contact with ventilation air extracted from the building and through the heat from the solar collector or another heat source. The values of the coefficient of performance for open circuits are in the range 0.6 - 1.2 [6, 9-11].

A comprehensive installation operating in the temperate climate should allow for water heating all year round, space heating in winter and air conditioning in the hottest summer months. Utilization of the solar heat with the use of reasonable collector surface areas is limited under these conditions due to insufficient amounts of heat in autumn, winter and spring. A possible coverage of heat demand regarding thermal installations used for cooling purposes during summer months also needs further investigations. A solution is a hybrid system where heat is partly generated from the solar energy and partly from a conventional heat source, e.g. from fossil fuel or biomass combustion.

The paper presents some research of the hybrid system of air conditioning and water heating powered by solar radiation energy in the conditions of the temperate climate. Both cooling and heating systems can work simultaneously or alternatively. The main attention was focused on the cooling system with the (NH_3/H_2O) absorption chiller.

2. Solar energy potential

Investigations were conducted in the southern region of Poland, more exactly in Katowice with the geographical coordinates of 50.259°N and 19.020°E. The potential values of the solar energy radiation in this region were estimated. Figure 1 presents the calculated monthly values of the solar radiation energy reaching the Earth surface. Calculations were performed using the Excel spreadsheet and the mathematical relationships allowing to determine the following values [5,12-14]:

- declination of the Sun

$$\delta = 23.45 \sin\left(2\pi \frac{284+n}{365}\right) \tag{1}$$

- sunrise hour angle

$$\omega_s = \cos^{-1}(-\tan\varphi \tan\delta) \tag{2}$$

- daily extraterrestrial solar radiation energy on a horizontal surface in [MJ/m^2]

$$H_0 = \frac{0.0864}{\pi} G_{sc}\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right] \times (\sin|\omega_s| \cos\varphi \cos\delta + |\omega_s| \sin\varphi \sin\delta) \tag{3}$$

- daily global solar radiation on the Earth surface

$$H = H_0 \times K_T \tag{4}$$

Symbols used in Eqs. (1)-(4) are respectively: n – the day of the year (n = 1,2,3, … ,365), φ - latitude (φ = 50.259° - latitude of the city of Katowice), G_{sc} – solar constant (G_{sc} = 1367 W/m^2), K_T – clearness index. The calculations were performed for each day in the year. Finally, monthly values of the solar energy radiation were calculated as the sum of the daily ones. The most probable values of the clearness index were estimated on basis of the long-term observations[15]. They comprise a relatively narrow range ±0.04 around the mean value of 0.37. Figure 1 also contains the values taken from long-time measurements [15]. It can be seen that they are a little different from the calculated values but the differences do not exceed 13%. The calculated annual solar radiation is about 3500 MJ/m^2. Total difference between measured and calculated values for the whole year is only 6%.

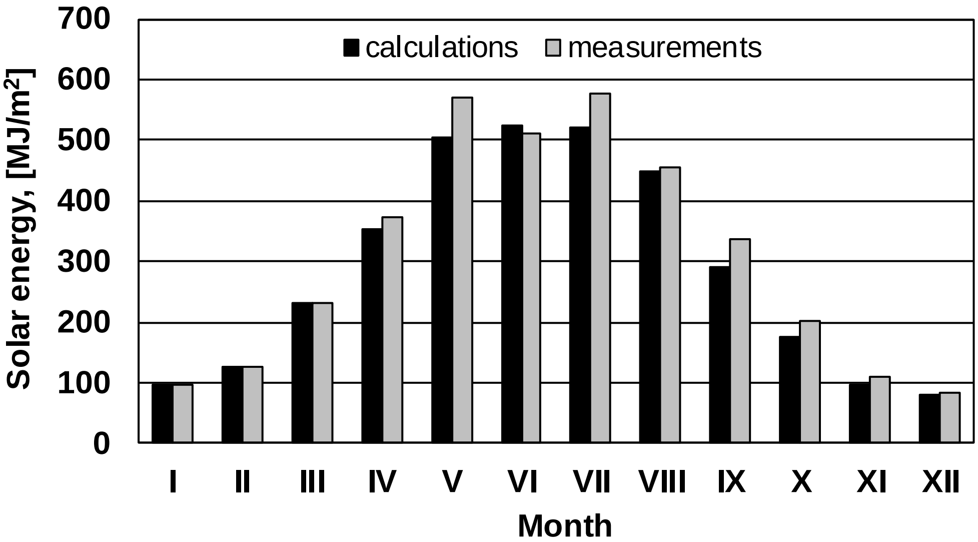

Fig. 1. Monthly solar radiation on the Earth surface at a latitude of 50.259°N

Hybrid solar installation in the temperate climate should be able to produce heat for heating system as well as heat as the energy driving air conditioning system in hot days. There is some evidence that for the central Europe climate and reasonable sizes of collectors, utilization of heat from the solar energy is practically limited only to tap water heating. However, also in this case, the so-called coverage ratio is about 50-60% for small installations and about 25-30% for large ones. An analogical ratio for central heating is only 10-15% [16]. Also instantaneous values of the irradiance can vary widely due to the apparent sun movement in the sky as well as the stochastic weather changes. In the hottest months: June, July and August, solar radiation at noon varies from about 320 W/m^2 with completely cloudy sky to about 900 W/m^2 when the sky is clear. Thus using an additional source of heat is necessary. Nevertheless, even a partial reduction in consumption of fuel for heat production may bring a substantial environmental benefit.

3. Installation

The research installation is shown in Fig. 2 and a general scheme of the cooling system is presented in fig. 3. The installation contains three major modules: a heat gain module, a water heating module and an absorption chiller. The key component of the heat gain module is an expanded Vaciosol CPC6 vacuum tube collector containing ten tubes with the total active surface area of 0.91 m^2. The heat medium is a 33% (wt.) solution of Henock blue ethylene glycol. The glycol flow rate is $1.67 \cdot 10^{-5}$ m^3/s. The stationary south oriented collector inclined at the stable angle of 30º was used. Such setting of the collector is commonly used in the small solar systems. Angle of inclination was estimated on basis of the theoretical modelling for the maximum value of the total annual solar radiation. Based on the preliminary experiments described further, the efficiency of solar to thermal energy conversion in the collector system is 62%.

In the collector, the solar energy is converted to heat that is delivered to the generator of the absorption chiller or to the hot tap water container via the circulating medium. The heat receiver selection is determined according to the three-way split valve setting. The circulating medium flow is forced by the pump system with a control unit. The control is based on measurements of temperature in the collector and the heat receivers as well as on the properly selected algorithm. The inverter delivers electrical energy to the pump drive with the automation system. The inverter accumulator is charged via a photovoltaic cell. The charging process is managed by the charging control unit. The installation is equipped with a check valve system and a flow indicator. The air is extracted from the flow system by means of a vent at the solar collector outlet. Additionally, the flow system can be managed by the control valve. The installation also contains circulating liquid containers on the side of the hot agent and on the return pipeline. The container on the side of the hot agent is intended to accumulate possible hot medium discharges resulting from the safety valve opening. It protects the installation from unacceptably high pressure in the system that may be caused by uncontrolled, excessive rise of the circulating agent temperature. The circulating agent container is connected (by the release valve) to the return pipeline of the agent that is cooled in the heat receivers. It is equipped with a manual pump for filling and replenishing the possibly depleted working agent. Increased volumes of the circulating medium due to its temperature rise are managed by the membrane vessel.

Fig. 2. General view of the installation

One of the receivers of heat gained in the solar collector is the hot tap water container that is supplied with cold water from the hydraulic network via an elastic connector with a quick release coupling at the end. The connecting system is equipped with the check valve, safety valve and the membrane vessel that prevents pressure increase due to water thermal expansion. Another heat receiver is the absorption chiller. The heat is delivered to the generator. The air is cooled in the evaporator coupled with the air conditioning system. The circulating agent in the cooling system is a 35% (wt.) aqueous NH_3 solution. The chiller is used for air cooling with a ventilator-forced flow. A general scheme of the cooling system is shown in Fig. 4.

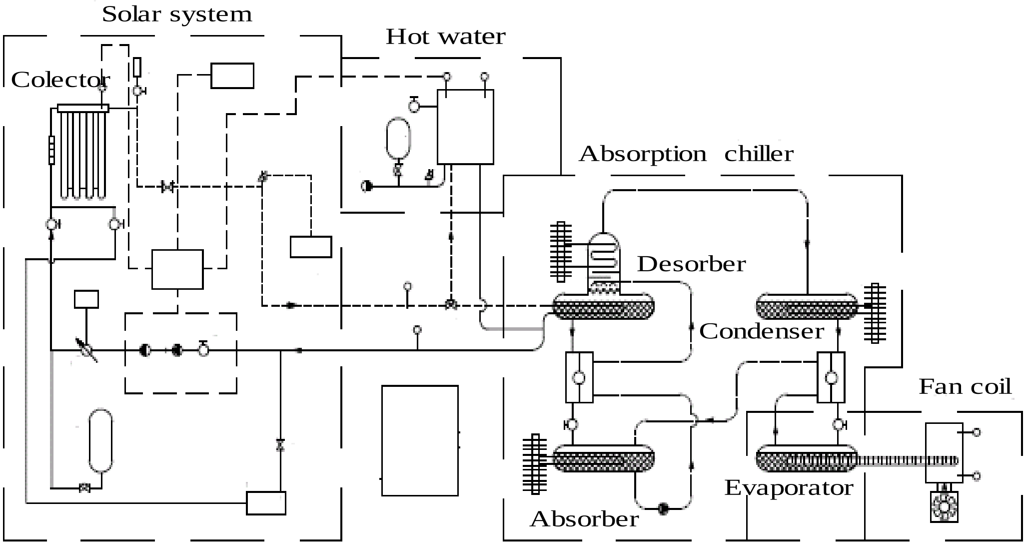

Fig. 3. Installation scheme

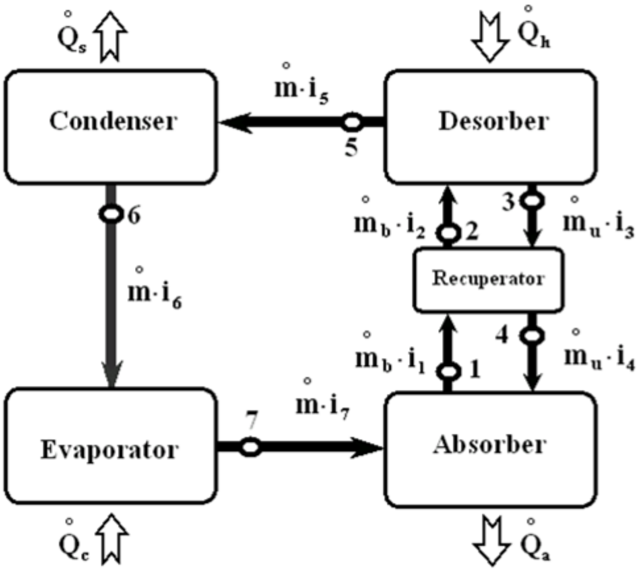

Fig. 4. Scheme of the chiller

The research stand was equipped with measuring systems, temperature and flow recording systems as well as a heat meter. Selection and positions of the measurement points were aimed at ensuring that the energy balance for the whole system could be determined.

In order to facilitate experiments, installation was designed as a compact version with wheels for easy transportation. A gas combustion chamber as an additional heat source could be easily connected.

4. Experimental investigations and energy analysis

Experimental investigations were carried out on some days of the following six months: April, May, June, July, August and September. The analysis of experiments was performed on basis of the measured media flow rates and temperature. The main processes are described by the following energy balances:

- the energy balance of the solar system

$$\dot{Q}_c = A_c[\tau\alpha\dot{e} - k_1(T_a - T_o) - k_2(T_a - T_o)^2], \tag{5}$$

where: $\dot{Q}_c$ is the heat flux from the collector, A_c=0.91 m^2 is the collector surface area, τ=0.9 is the coefficient of permeability for the collector cover plate, α=0.9 is the solar absorption coefficient for the absorption coating, $\dot{e}$ is solar irradiance on the collector surface, T_a is the temperature of absorber, T_o is the ambient temperature, k_1=0.721 W/m^2/K is the linear heat transfer coefficient and k_2=0.006 W/m^2/K^2 is the non-linear heat transfer coefficient;

- the energy balance of the hot tap water heating system

$$\eta_w\dot{Q}_w = \dot{V}_w\rho_w c_w(\Delta T_w) \tag{6}$$

where η_w is the system performance, $\dot{Q}_w$ is the flux of heat delivered to the system, $\dot{V}_w$ is the water volumetric flow rate, ρ_w is the water density, c_w is the specific heat of water and ΔT_w is the value of water temperature rise;

- a general energy balance of the cooling system

$$\dot{Q}_h + \dot{Q}_c = \dot{Q}_s + \dot{Q}_a, \tag{7}$$

where individual symbols denote the heat fluxes shown in Fig. 4;

- the energy balance of the desorber - recuperator system

$$\dot{Q}_h = \dot{m}[i_5 + (f-1)i_3 - fi_2], \tag{8}$$

where $\dot{Q}_h$ is the flux of heat delivered to the desorber from the collector or another heat source, $\dot{m}$ is the mass flow rate of the working medium (NH_3), f is the multiplicity of the circulating agent recirculation and i_2, i_3, i_5 are specific enthalpies in points presented in Fig. 4;

- the energy balance of the absorber

$$\dot{Q}_a = \dot{m}[i_7 + (f-1)i_4 - fi_1], \tag{9}$$

where $\dot{Q}_a$ is the flux of heat extracted from the absorber, $\dot{m}$ is the mass flow rate of the working medium (NH_3), f is the multiplicity of the circulating agent recirculation and i_1, i_4, i_7 are specific enthalpies in points presented in Fig. 4;

- the energy balance of the condenser

$$\dot{Q}_s = \dot{m}(i_5 - i_6), \tag{10}$$

Where $\dot{Q}_s$ is the flux of heat extracted from the condenser, $\dot{m}$ is the mass flow rate of the working medium (NH_3) and i_5, i_6 are specific enthalpies in points presented in Fig. 4;

- the energy balance of the evaporator

$$\dot{Q}_c = \dot{m}(i_7 - i_6), \tag{11}$$

where $\dot{Q}_c$ is the flux of heat extracted from the cooled air, $\dot{m}$ is the mass flow rate of the working medium (NH_3) and i_6, i_7 are specific enthalpies in points presented in Fig. 4. Symbol f in Eqs. (8) and (9) denotes the ratio of the strong working fluid mass stream flowing from absorber to desorber to the refrigerant mass stream flowing through condenser and evaporator. It shows then the necessary kg of working fluid in order to adjust the concentration difference of the strong and the weak working fluid.

The thermal coefficient of the performance with regard to the cooling system is described by the relationship:

$$COP = \dot{Q}_c / \dot{Q}_h. \tag{12}$$

Figure 5 presents a comparison between solar irradiance on the collector surface $\dot{e}$ and heat obtained from the collector $\dot{Q}_c$. Tests were carried in the days of middle in the month values of the solar radiation. Measurements were taken at noon under clear sky. As it was already mentioned the stationary collector was south oriented and inclined at an angle of 30º. The collector efficiency of about 62% was achieved. It can be seen from Fig. 5 that in a climate of eastern and central Europe, the best conditions for solar energy gain is only from May to August (300 W/m^2 on average).

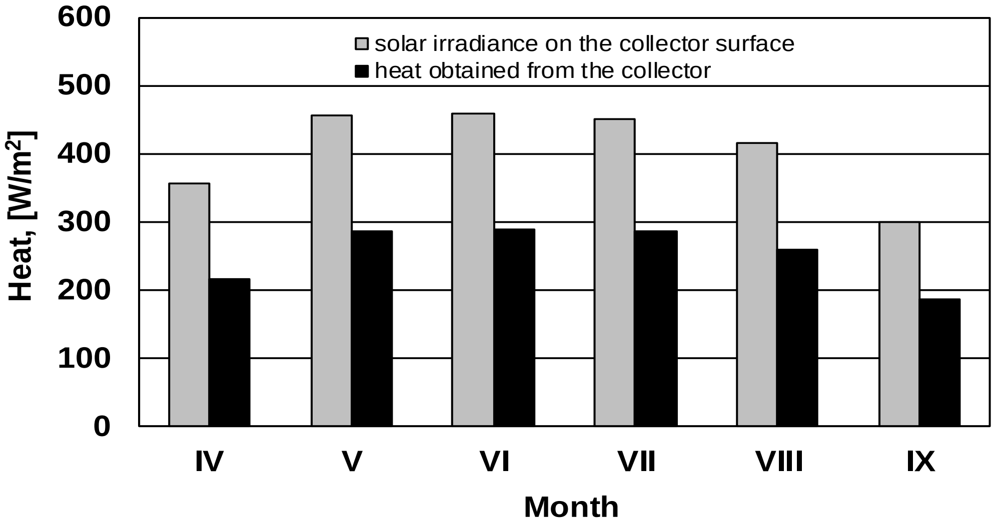

Fig. 5. Comparison between solar irradiance on the collector surface and heat obtained from the collector

Figure 6 presents comparison between absorber temperature and ambient temperature. The values of the absorber temperature in the figure was estimated from the equation $\dot{m}_g c_g \left(T_{g2} - T_{g1}\right) = A_c[\tau\alpha\dot{e} - k_1(T_a - T_o) - k_2(T_a - T_o)^2]$, where $\dot{m}_g$ is the glycol mass flow rate, c_g - the specific heat of the glycol, T_{g2} - glycol temperature at the solar collector outflow, T_{g1} – glycol temperature at the inlet to the collector and the other symbols are the same as in Eq. 5.

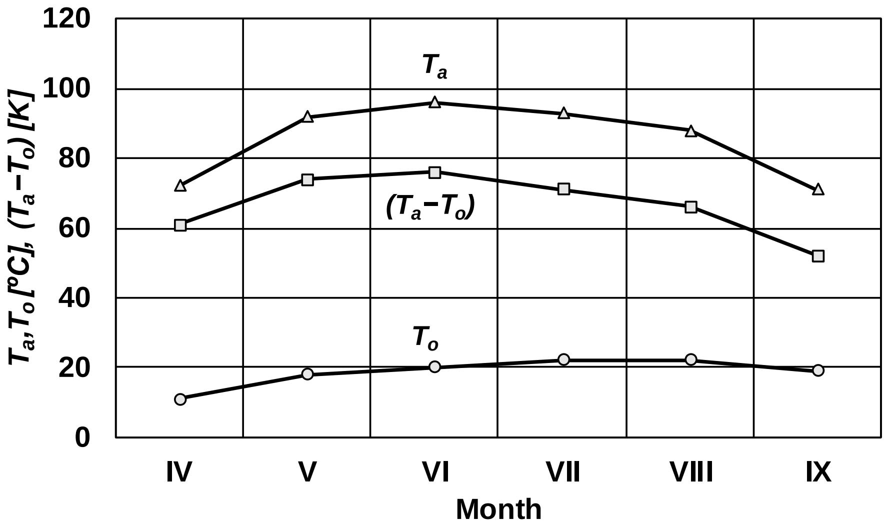

Fig. 6. Comparison between monthly average values of the ambient temperature (T_o) and absorber temperature (T_a)

The main attention was focused on the cooling system. Some selected results of calculations of this system are presented in Tab. 1. The installation was provided with valves and heat exchangers arrangement enabled to split heat from the solar collector into two streams. The setting was controlled manually, however further investigation with automatically controlled system are needed. The improved system should work based on selected criteria, such as ambient temperature. The results presented here were obtained in the arbitrary chosen case when a half of the heat obtained in the solar collector was delivered to the cooling system. The cooled air mass stream of 0.0057 kg/s was flowing along the evaporator cooling surface area of 0.161 m^2 with the average linear velocity of 0.7 m/s. The temperature of evaporator surface was app. -10 ÷ -5 ºC. The second half of the collector heat was delivered to the water tank of volume 0.02 m^3. The water temperature rose from 20 ºC to 40 ºC at the time about 8300 s in April but about 6500 s in June.

Tab. 1. Results of calculations of the main parameters of the cooling system

Parameter	Unit	Month					
		IV	V	VI	VII	VIII	IX
Air temperature before the cooling system	ºC	12	18	20	22	22	19
Air temperature after the cooling system	ºC	5	9	11	12	12	9
Heat supplied to the cooling system from the collector	W	100	130	132	129	119	84
Heat received from the cooled air	W	37.4	47.9	51.7	54.6	54.6	47.9
COP	-	0.37	0.37	0.39	0.42	0.46	0.57

Following the preliminary investigations of the cooling system, stable temperature values versus time were obtained, which is shown in Fig. 7 for selected points of the system. The temperature was measured continuously by thermocouples Pt100 and recorded by the multipoint recorder. Figure 7 simply presents fragment of the original print from the microprocessor recorder. It shows also profile of the glycol temperature at the solar collector outflow. This way of measurements was particularly important from point of view of process control. The effect of the air flow rates in the cooling system on its outlet temperature rise is presented in Fig. 8. For the calculations, a constant evaporator surface temperature of 263 K was assumed. For the flow rate changes within 0.003-0.01 kg/s, the cooled air temperature increased by approximately 12 K.

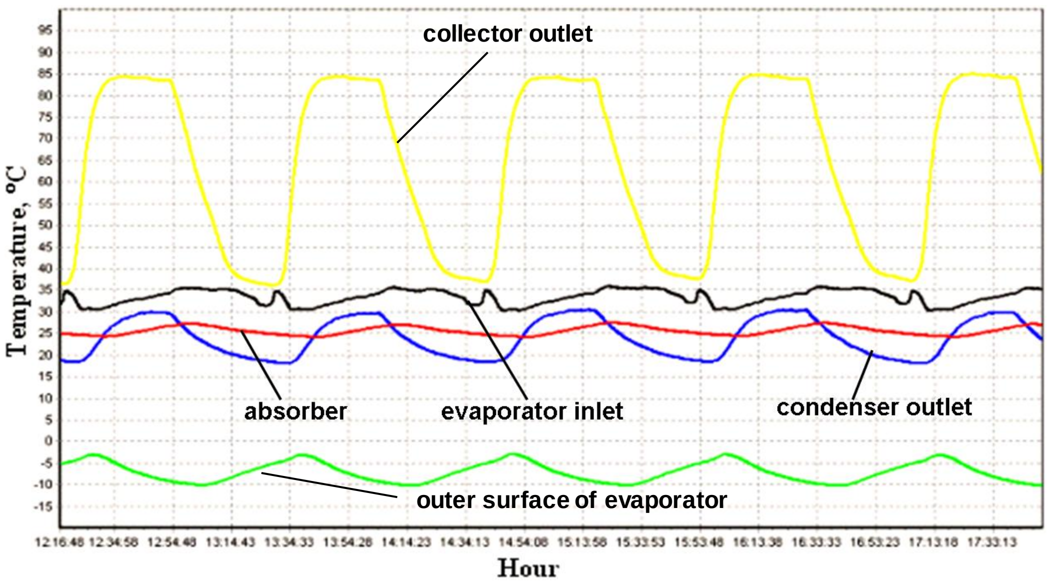

Fig. 7. Measured distributions of temperature at selected points of the cooling system

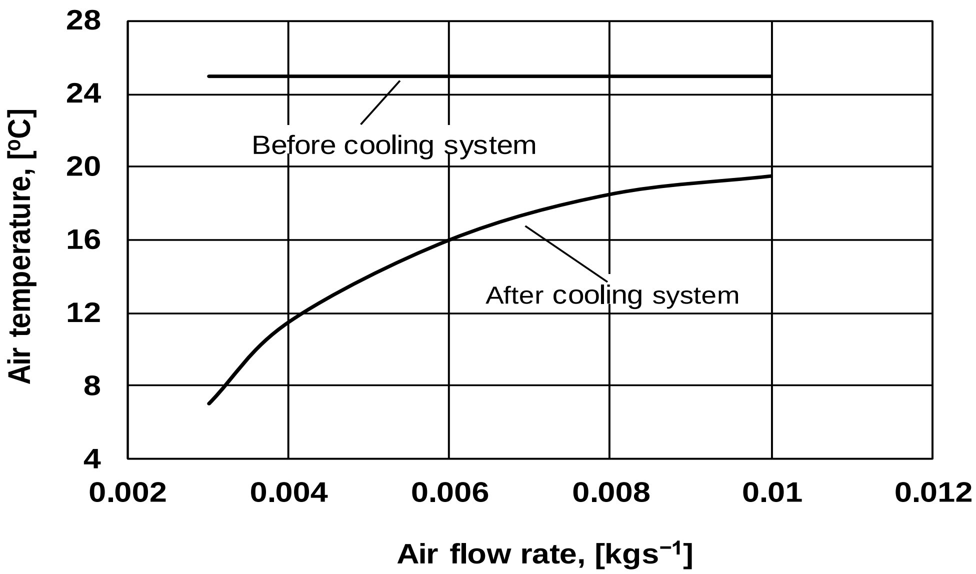

Fig. 8. The effect of the air flow rate on the cooled air temperature

As it was already mentioned investigations were mainly focused on the cooling system for air conditioning in small residential buildings although the production of heat for water heating simultaneously or alternatively was also taken into account. There are clear evidence that cooling demand in recent years is rapidly growing also in areas with temperate climates. It is estimated that the potential annual demand cooling in Europe is about 295.2 MJ/m^2 for the service sector and about 133.2 MJ/m^2 for residential buildings at the average climatic conditions specified by the European Cooling Index ECI = 100 [17]. Simple calculations show that in the case of residential buildings, the annual consumption of electricity needed to power conventional air conditioning systems may be at the level of 30 MJ/m^2. It also leads to the appropriate fossil fuel consumption and pollutant emissions. The use of small installations powered by solar energy can bring tangible benefits for the economy and the environment. The installation consumes only small amounts of electricity from the grid to power the pumps and recording devices, but also those amounts may be eliminated by adding a photovoltaic panel to the system.

5. Summary

A hybrid heating and cooling installation based on the thermal cooling technology with a solar collector was designed and built in laboratory scale. The preliminary experimental investigations and the energy performance analysis were performed on base of the mass and energy balances of all components of the system. Investigations were conducted in the southern region of Poland, more exactly in Katowice with the geographical coordinates of 50.259°N and 19.020°E. The potential values of the solar energy radiation in this region were estimated. The calculated annual solar radiation is on the level 3500 MJ/m^2. Investigations have shown correct interaction between all elements of the system. Regarding the cooling process, the estimated coefficient of performance was on the level of 0.45. This system can find the best application for air condition and water heating in single-family houses allowing to save fossil fuels and environment. Further systematic experimental studies will be continued particularly in terms of automatic control.

Acknowledgments

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