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Analysis of the use of sorption and evaporative cooling as part of the preparation of ventilation air for Polish climatic conditions

Mikołaj RZĄŻEWSKI[1] and Andrzej GRZEBIELEC*[1]

[1]Warsaw University of Technology, Warsaw, Poland

Abstract

In this paper, the possibility of use of a DEC type air conditioning system, using solar energy, in Polish climatic conditions Polish, as an alternative to traditional systems based on compressor refrigeration equipment, was analyzed. At the beginning of the work, attention was paid to how important it is for users to maintain thermal comfort conditions and how these conditions can be determined. It also shows why the DEC system can be a good solution for the cases under consideration. In the next part of the paper, the analyzed system is described, presenting the individual processes of humid air transformation taking place in it, in which devices these processes can take place and how they were modeled in further calculations. Modeling the operation of the DEC system was based mainly on determining the efficiency of individual devices, i.e. the effectiveness of the processes taking place in them and the use of a psychometric graph. Similarly, the method of calculating the useful heat that can be obtained from solar collectors under known conditions is presented. For this purpose, meteorological data and the theory of similarity in heat transfer were used. In the next part of the work, an example of a calculation cycle was presented, along with the next steps of applying to the psychometric graph points corresponding to the states of moist air at individual points of the DEC system. On the basis of such calculation cycles, performed for different values of outdoor air parameters, the relationships of the obtained cooling power, the power supplied for adsorber regeneration, EER, temperature and relative humidity of the supply air to rooms, from the temperature and relative humidity of the outside air. Next, the calculation process for determining the useful heat obtained from solar collectors is presented. On the basis of several such processes, the average conditions of heat collection from the collector were determined, on the basis of which the amount of energy obtained from solar radiation was determined on the scale of the entire summer period. On the basis of this analysis, surpluses and shortages of energy obtained from collectors on individual days of the considered period were determined. In conclusion, it was stated that despite the fairly good cooperation of the system with solar collectors and its simple construction, the DEC system cannot be an alternative to compressor refrigeration equipment. This is mainly due to the unfavorable level of relative humidity in Polish climatic conditions, which does not allow the device to achieve the appropriate temperature of the air supplied to the rooms.

Keywords: DEC, SDEC, sorption and evaporative cooling in Polish conditions, solar cooling, alternative ways of cooling, preparation of ventilation air, thermal comfort

1 Introduction

Currently, in the vast majority of service architecture facilities, i.e. office buildings, shops or public buildings, cooling using compressor refrigeration equipment is used. This situation results from the lack of alternative solutions on the market that would show an appropriate ratio of cooling efficiency to the costs of energy supplied to the system [1]. Air conditioning and ventilation air preparation is an increasing share in the annual energy balance of facilities, so they have a great potential for energy savings and, consequently, operating costs [4]. In addition, compressor equipment, despite its high efficiency, is also not a very ecological solution, taking into account their electricity consumption and used refrigerants. Both of these features stand in opposition to current trends in reducing emissions of carbon dioxide and other greenhouse gases into the atmosphere [2]. Therefore, the search for and analysis of alternatives is perfectly justified. One of the alternative proposals may be sorption-evaporative cooling systems, which achieve a cooling effect by evaporating moisture in the air supplying the air conditioning system. The energy supplied to this system is mainly heat, needed to regenerate the sorption deposit, and electricity to drive the devices included in the

***Corresponding author:** E-mail address: (andrzej.grzebielec@pw.edu.pl) (Andrzej GRZEBIELEC)

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air conditioning unit. When considering the rationality of using a given system, it is first of all necessary to determine whether it is able to achieve the required parameters of supply air under the most common external conditions in the Polish climate. The second issue is the power source of the system, which will be cheaper than powering compressor. The best and actually the only option to obtain thermal energy other than from combustion, in the case of service facilities, seems to be solar energy, transformed into heat in solar collectors. An important aspect of the use of a given system is also the possibility of application in already existing facilities and the investment costs of the sorption and evaporation system competitive with compressor devices. Taking into account all the above-mentioned aspects, this paper analyzes such an air conditioning system, based on certain assumptions in modeling the operation of the system and on measurement data of outdoor air conditions obtained from the meteorological station of the Warsaw University of Life Sciences.

1.1 The ventilation air preparation methods

People spend the vast majority of their lives indoors, so it is natural that the conditions in them have a significant impact on the proper functioning of the human body and the related well-being [9]. A particularly important aspect of it is thermal comfort, understood as satisfaction with the thermal conditions of the space in which a person stays. Being outside the conditions of thermal comfort is associated with certain reactions of the body. The human body is equipped with mechanisms that regulate its heat exchange with the environment - sweat secretion, chills and narrowing or dilating blood vessels, so the range of ambient parameters in which a person is able to stay is quite wide. However, all these mechanisms are associated with a sense of discomfort, which in itself results in a decrease in work efficiency, difficulty in maintaining focus and the desire to change the place of residence. Extreme situations, on the other hand, will lead to a decrease or increase in body temperature, which results in serious symptoms such as weakness, dizziness, confusion, muscle tremor and others. Although our organisms can survive in very different conditions, the parameters in which we will feel good and function properly are quite narrow and at the same time necessary to meet. The energy efficiency of the human body is quite small - up to 20% [5], which, when it comes to maintaining a constant temperature, creates the need to drain excess energy produced in metabolic processes. This is done by radiation, convection from the surface of the skin and evaporation, with the effect on the participation of individual methods of heat transfer in the overall balance of the body, depending on the following aspects:

- air temperature;
- relative humidity of the air;
- the speed of air flow relative to the surface of the skin;
- average radiation temperature [5];
- physical activity;
- insulation of clothing.

1.2 Alternative ways of maintaining the thermal comfort of rooms

In the European Union, the vast majority of energy demand for cooling rooms is provided by service infrastructure – banks, hotels, office buildings and shops. This situation results primarily from the need to maintain appropriate storage conditions for products in supermarkets (refrigeration consumes 40% of energy in these facilities), a high demand for coolness also occurs in data centers for cooling servers, and in third place should be placed the energy used to ensure the appropriate temperature of rooms used by people - offices, hotel rooms, sales halls, etc. The vast majority of cold is produced by compressor refrigeration equipment, driven by electricity, which, depending on the generation structure of a given country, is more or less efficient in terms of the use of primary energy. In Poland, the efficiency of electricity generation is about 33%. In addition, it will be taken into account the fact that over 85% of this energy was generated in thermal power plants, obtaining cooling from compressor devices will turn out to be unecological, and with the possibility of obtaining energy from solar radiation or waste heat, also uneconomical [2]. Alternatives to mains-powered compressor equipment can be the same appliances, powered by photovoltaic panels, or sorption refrigeration units. The advantage of the first solution is the possibility of using in already existing systems based on devices powered by electricity. Photovoltaic panels can also power both small and larger systems, the limitation is only the area that we can allocate for the installation of cells. From the point of view of the entire facility, photovoltaic panels can also be a source of savings not only in the cooling system, but also in lighting, mechanical ventilation and all other systems that consume electricity. However, the disadvantage of this solution is the low efficiency of electricity generation in photovoltaic cells, which additionally decreases with increasing temperature. This results in the need to devote significant areas to the installation of panels, which in turn makes it problematic to keep them clean, which is necessary for optimal absorption of solar radiation. A large number of panels also makes it difficult to control their proper functioning, turning off a single cell results in the exclusion of the entire panel. The use of absorption or adsorption refrigeration equipment is associated with the need to provide an upper heat source with a temperature of 80-130 C. It can be waste heat, solar radiation energy converted into heat in collectors or heat obtained from combustion. The advantage of sorption devices is the ability to manage heat, which without it would be thrown into the environment. Sorption devices, due to their fairly simple design and a small number of mechanical elements, are also very durable, and maintain factory operating parameters throughout their operation. The disadvantage of sorption systems is the large dimensions of the equipment, which requires significant areas intended for engine rooms. Usually, solutions of this type are also used in very large systems, producing from several hundred kilowatts to several Megawatts of cold. Cooling in traditional sorption devices is used when a high demand for cooling goes hand in hand with the need or possibility of managing large amounts of heat. Thus, it excludes their use in service and residential infrastructure. In this area, another technology can find its place, also using the adsorption process - sorption-evaporative cooling, which is the subject of this work. What makes DEC systems attractive is the simultaneous supply of fresh air to the ventilated rooms of a given facility, heat or cold recovery and obtaining a cooling effect without the use of compressor equipment, and using waste energy or solar energy, which is very beneficial due to the coherence of the demand for coolness and high intensity of solar radiation [3]. Air handling units of this type are quite simple in design and consist of inexpensive components. On the other hand, the proper and economically justified functioning of sorption and evaporation systems using solar energy is strongly dependent on external conditions. Too little energy obtained in collectors results in the need to fill in the gaps by emergency heat sources, most often electric heaters, which in comparison to compressor devices, is very unfavorable.

2 DEC systems

The abbreviation DEC (Desiccant evaporative cooling) literally means sorption-evaporative cooling, which means that the cooling effect in such type devices is obtained by evaporating water in the dried air inside the sorption bed. Fig. 1 shows a general diagram containing the essential components of an air handling unit using this technology.

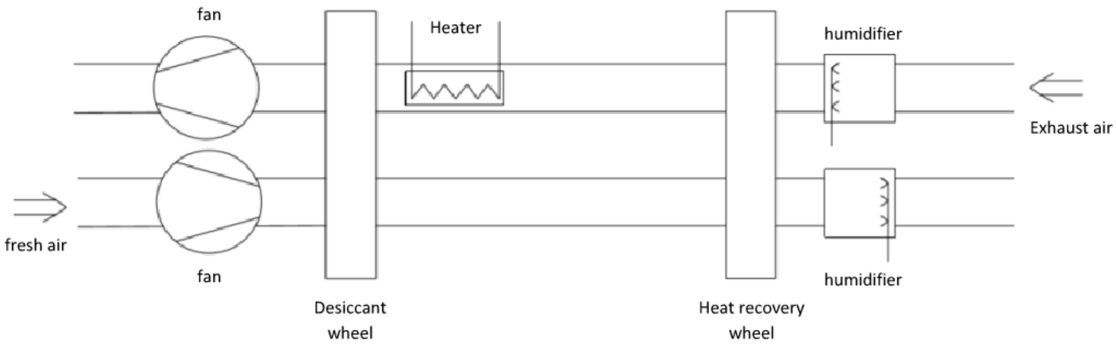

Figure 1. DEC system schema

Fresh air is sucked into the system by a supply fan and directed to the desiccant dehumidifier, where its moisture content is reduced and its temperature increases [13]. Then the stream goes to the heat exchanger, recovering the coolness from the room - its temperature drops, with a constant moisture content. Behind the exchanger, air flows through the sprinkler chamber, where in the adiabatic process its moisture content increases and the temperature decreases. The air prepared in this way enters the room, receiving heat and moisture gains, and then is sucked by an exhaust fan into the sprinkler chamber, in order to reduce the temperature of the stream flowing through the heat exchanger as much as possible [8]. The planer heated in the exchanger is then heated to an appropriate level, determined by the temperature required to regenerate the sorption dryer bed [6]. Hot air flows through the dehumidifier and then is removed to the environment. The following are the listed transformations of moist air on the psychrometric graph, and all the processes mentioned above are discussed. Figure 2 shows the full process of thermodynamic changes of air.

Process 1-2: Desiccant dehumidification.

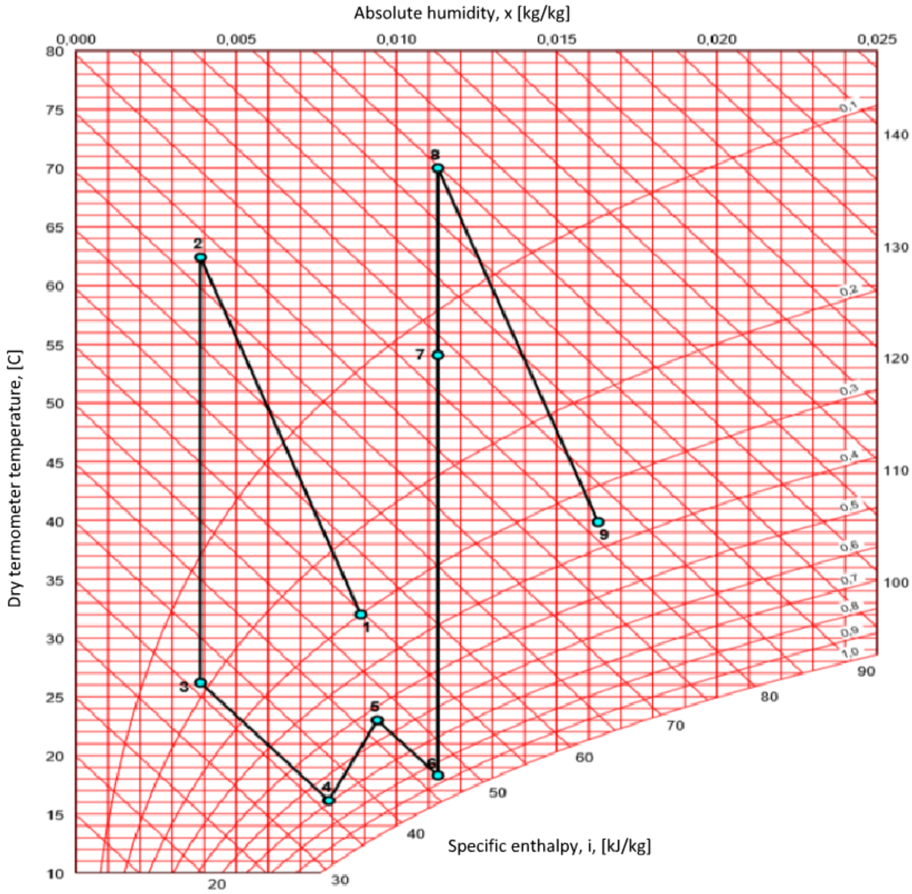

Figure 2. Thermodynamic changes of air taking place in a DEC type air handling unit

Rotary dehumidifiers are most often used to carry out this process. They are designed similarly to rotary heat exchangers, except that their cartridge is additionally covered with a layer of moisture adsorbing water. The materials used are silica-gel, lithium chloride, zeolites, active alumina and other substances, mainly based on silicon [7, 11]. These materials are characterized by very small pore sizes, which are associated with significant pressure drops in the flowing air stream and a higher regeneration temperature. In addition to rotary dryers, absorption with aqueous solutions of hygroscopic salts such as lithium chloride, lithium bromide or calcium chloride is used. The use of liquid sorbent is characterized by a smaller drop in air pressure in the dehumidifier and lower temperature required for regeneration than in adsorbers, the possibility of postponing regeneration until energy is available, a lower risk of dirt and the development of microorganisms in the device and the possibility of connecting multiple dehumidifiers to one regenerator. In contrast, this technology is less compact than sorption rotors and requires a slightly more complicated installation. It also requires the use of more expensive materials, resistant to corrosion caused by the salts used. Small amounts of sorbent are also lifted with air, which is not dangerous to the health of people staying inside the ventilated room, but results in the need to supplement it from time to time.

Air with a decrease in moisture content also increases the temperature, because as already mentioned, the sorption bed, in order to be able to remove moisture from the pores of the sorbent, must be heated to the level of 60-90°C, depending on the used adsorbing material. An increase in air temperature is also associated with the absorption of adsorption heat by them.

Process 2-3. Cooling with constant moisture content, in a counter-current heat exchanger.

After drying and heating in a desiccant dehumidifier, the hot air is directed to the heat exchanger, where its temperature is reduced as much as possible. On the other hand, the exchanger is powered by a stream exhaust from the room, so there is a recovery of energy supplied to the air in the sorption rotor. Possible technical options for the implementation of this process are a rotary, cross-plate exchanger, heat pipes, with an intermediate liquid or a spiral exchanger with longitudinal flow. There are also solutions with a built-in heat pump, however, due to the fact that the DEC system is intended to be an alternative to compressor refrigeration equipment, it is not taken into account in this work. The rotary heat exchanger is the most commonly used option due to its high efficiency and low complexity of the structure, which makes rotary heat exchangers inexpensive. In devices of this type, it is also possible to achieve a smooth or step-by-step adjustment of the performance, depending on the method of powering the motor driving the rotor. The disadvantages of this solution are the need to provide an external power supply and the lack of separation of fresh and removed air, which disqualifies them in systems that emphasize hygiene. The rotary regenerator is made of a drum made of sheet steel, filled with accumulation material. These are tightly rolled corrugated sheets or mesh, most often aluminum, because it is characterized by high thermal conductivity, which positively affects the efficiency of the entire device. The front section of the rotor is divided into three parts - fresh air flow, removed air flow and sluice. The use of a lock allows to minimize the ingress of exhaust air into the supply air. A better hygienic solution is a cross-plate exchanger. A device of this type is built of corrugated sheets arranged alternately, in such a way that they form channels set relative to each other at right angles. In these channels, the air removed and fresh flow, respectively. In addition to tightness, the advantage of the solution is the lack of the need to supply power from the outside, and the lack of mechanical elements, which increases the reliability of the exchanger. The simple design also results in a small price. On the other hand, cross-plate heat exchangers are characterized by low efficiency, high sensitivity to frosting and have quite large dimensions, which increases the size of the entire air handling unit in which it is placed.

Tight solutions also include a group of devices using an intermediary liquid. One of them is heat pipes. One part of it is located in the exhaust duct, where it receives heat from the exhaust air. As a result of this process, the refrigerant in the device evaporates, filling the second part of the tube, located in the supply duct. There, the refrigerant condenses and heat is emitted into fresh air. The liquefied medium under the influence of gravity or capillary forces returns to the heated part of the tube. This solution is characterized by one hundred percent separation of the supply stream from the exhaust stream, without the possibility of leaks. Thanks to the use of phase transition, the process is also close to isothermal and has a large heat capacity. Capillary tubes are a very simple and reliable design, without external power supply, resistant to frosting and which can be easily cleaned. However, a heat exchanger made of heat pipes is relatively expensive and its efficiency is lower than that of a rotary heat exchanger. Where the supply and exhaust ventilation ducts are separated from each other, or where there are more, it is a good idea to use heat recovery via liquid flowing in the exchangers in the appropriate ventilation ducts. In addition to high flexibility, this option is characterized by easy adjustment by means of liquid flow control and high frost resistance. The disadvantages are the need to power the pumps, the high cost of installation compared to other recuperative exchangers, low efficiency and toxicity of glycols, which are most often used as an intermediary liquid.

3 Modeling the operation of a DEC system

This section presents calculations regarding the efficiency of the DEC type air conditioning system in various environmental conditions. The aim of this analysis was to find parameters characterizing the operation of the system, such as cooling power, EER coefficient or achieved parameters of supply air to rooms, in conditions that can be meet in Poland. The analysis is based on the Mollier psychrometric graph, with the help of which air transformations in the air conditioning unit were mapped. The operation of solar collectors was also modeled, in conditions corresponding to the results of measurements from the actual meteorological station located in Warsaw. The aim of this analysis was to determine whether the Polish conditions are sufficient to drive the DEC system, whether the intensity of solar radiation is really consistent with the demand for cooling power and what possible problems are associated with the selection of collectors to cooperate with the considered system. Here, the aforementioned measurements and the theory of similarity in heat transfer were based.

Analysed system is shown in Fig. 3. It should be noted that the Fig. 3 contains only the elements of the device to be analyzed in this work, and not a complete list of devices included in the air conditioning unit. Below are listed the operating parameters of the devices that will take part in the further analysis of the system:

- Pumps and fans - energy consumption at the level of 10% of energy consumption in heaters has been assumed.
- Desiccant wheel - the efficiency of energy recovery was assumed at the level of 0.8, while the amount of moisture absorbed was assumed on average equal to 5 g/kg of dry air.
- Heat recovery wheel - assumed heat recovery efficiency at the level of 0.75.
- Humidification chamber - humidification efficiency at the level of 0.75.

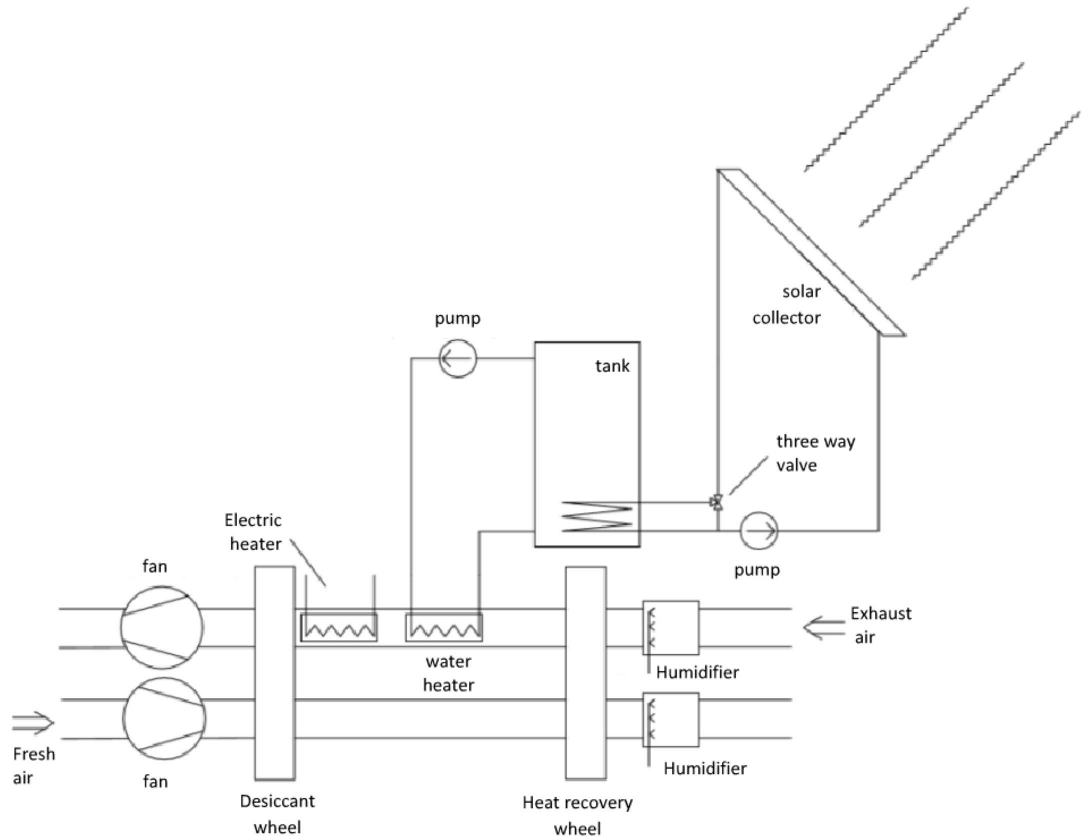

Figure 3. Analysed DEC system

- Water heater - The assumed water temperature at the inlet to the heater is 80°C, the power is controlled by adjusting the amount of water flowing through the heat exchanger.
- Electric heater - as a backup heat source for the device, it is activated in the event of a drop in the temperature of water flowing into the exchanger below 70°C.
- Accumulation tank - designed to increase the system's resistance to possible insufficient sunlight in some summer days. The water temperature in the tank should be maintained at such a level that it is possible to reach the required temperature for the heater as soon as possible, and at the same time that the heat losses from the tank are not too high. It is possible to collect water from the tank for domestic hot water purposes, especially outside the period of energy demand for cooling.
- Flat solar collector - it is assumed that the working medium receiving heat from the collectors circulates in the absorber tubes until it reaches the right temperature 90°C. Then it is directed through a three-way valve to the accumulation tank.
- A 45% solution of propylene glycol was taken as the working medium [12].

3.1 Analysis of the effectiveness of the operation of the DEC device

In addition to the parameters, mentioned in previous chapter, characterizing the considered DEC type systeml, it was also assumed that the air temperature maintained in the room is 24°C, while the absolute humidity of the removed stream is greater than the relative humidity of the supply air, by the following value:

$$x_5 = x_4 + 2 - \frac{2}{25}(70 - \phi_4) \tag{1}$$

This is a fictitious formula, expressing the assumption that at the relative humidity of the supply air equal to 70%, its stream is able to receive 2g/kg of moisture, while at the value of 95% it no longer receives moisture. The amount of latent heat output received depends on the relative humidity of the supply air, because it is one of the parameters affecting it, but it should be noted that this is definitely a more complicated process. Therefore, it was decided to use simplification. Another assumption made for the calculation is that the temperature difference between the supply stream behind the rotary recuperator and the exhaust stream in front of this exchanger (points 3 and 6) is 8 K (2).

With this set of information, a mapping of moist air transformations taking place in the DEC type system was carried out. Below are the next steps of this process, for the parameters of external air 30°C and 30% relative humidity.

Determination of point 2 on the basis of the assumption about the amount of moisture adsorbed from the air, dependence on the efficiency of the regenerator and the known temperature of regeneration of the sorption bed.

$$x_2 = x_1 - 5 = 7.91 - 5 = 2.91\frac{g}{kg} \tag{2}$$

$$t_2 = \epsilon_{reg}(t_8 - t_1) + t_1 = 0.8(70 - 30) + 30 = 62°C \tag{3}$$

Determination of point 4 on the basis of the assumption of adiabaticity of the humidification process and the efficiency of humidification.

$$i_4 = i_3 = 34.6\frac{kJ}{kg} \tag{4}$$

$$x_4 = \epsilon_{hum}(x'' - x_3) + x_3 = 0.75(8.85 - 2.91) + 2.91 = 7.36\frac{g}{kg} \tag{5}$$

Determination of the fifth point based on the assumed temperature of the removed air and the calculated absolute humidity.

$$t_5 = 24°C \tag{6}$$

$$x_5 = x_4 + 2 - \frac{2}{25}(\phi_4 - 70) = 7.36 + 2 - 0.08 \cdot (65.7 - 70) = 9.71\frac{g}{kg} \tag{7}$$

Determination of point 6 on the basis of the assumption of the adiabaticity of the humidification process and the efficiency of humidification. Verification of the assumption with a minimum temperature difference of points 3 and 6.

$$i_6 = i_5 = 48.8\frac{kJ}{kg} \tag{8}$$

$$x_5 = \epsilon_{hum}(x'' - x_5) + x + 5 = 0.75 \cdot (12.39 - 9.71) + 9.71 = 11.72\frac{g}{kg} \tag{9}$$

Knowing the parameters of point 6, it is necessary to check the veracity of the assumption with a minimum temperature difference between points 3 and 6.

$$t_3 - t_6 = 27 - 19 = 8K \tag{10}$$

The condition in this case has been met. In case the difference is too small, it would be needed to raise the assumed temperature value of point 3 slightly, and perform operations 4-6 again. If the difference is too large, this should also be corrected so that all the processes compared take place under the same conditions.

Determination of the temperature of point 7 based on the dependence on the efficiency of the recuperator. The moisture content of point 7 is known, and it is equal to the moisture content of in point 6.

$$x_7 = x_6 = 11.72\frac{g}{kg} \tag{11}$$

$$t_7 = \epsilon_{reg}(t_2 - t_6) + t_6 = 0.75(62 - 27) + 27 = 51.25°C \tag{12}$$

Determination of point 8 based on the required adsorber regeneration temperature.

$$x_8 = x_7 = 11.72\frac{g}{kg} \tag{13}$$

$$t_8 = 70°C \tag{14}$$

Determination of point 9 on the basis of the assumed level of moisture absorption by the desiccant dehumidifier and the difference in transformation enthalpy 1-2.

$$x_9 = x_8 + 5 = 16.72\frac{g}{kg} \tag{15}$$

$$i_9 = i_8 - (i_2 - i_1) = 101.2 - (69.9 - 50.4) = 81.7\frac{kJ}{kg} \tag{16}$$

Similarly, two series of calculations were made, estimating the effect of relative humidity and outside air temperature on the EER, cooling power, power supplied for adsorber regeneration and temperature and relative humidity of the air supplied to the rooms. For the purposes of calculations, the volumetric air flow in the ducts was assumed at the level of 1500 m3/h (approx. 0.5 kg/s). This amount of fresh air is sufficient for 75 people, which corresponds, for example, to a small office building or a medium-sized store. The cooling capacity of the device was determined as follows:

$$\dot{Q}_{ch} = \dot{m}_{air} \cdot (i_5 - i_4)[W] \tag{17}$$

where m is the mass flow of the ventilation air. Similarly, the power of energy supplied to the regeneration of the sorption rotor was calculated from the following relationships:

$$\dot{P}_{in} = \dot{m}_{air} \cdot (i_8 - i_7)[W] \tag{18}$$

On the other hand, the cooling efficiency of the EER process was defined as the ratio of cooling power to the power with which energy is supplied to the entire device. This power is the amount of energy supplied to the system to regenerate the adsorber at a given time $\dot{P}_{reg}$ and the electrical power consumed by the elements of the control panel, simply taken as 10% of $\dot{P}_{reg}$.

$$EER = \frac{\dot{Q}_{ch}}{\dot{P}_{reg} + 0.1 \cdot \dot{P}_{reg}} \tag{19}$$

The power supplied to the system for the regeneration of the $\dot{P}_{reg}$ sorption rotor bed, in the case of which there is no access to energy from any renewable sources, is equal to $\dot{P}_{in}$, while when the heat obtained, for example, from solar collectors completely covers the demand of the system, The $\dot{P}_{reg}$ is 0. The first series of calculations concerned the impact of relative humidity of the outside air. The external temperature was set at 30°C as a constant output parameter, while the relative humidity was increased by 5 percentage points each calculation cycle from 30% to 60%, what is shown in Fig. 4.

In the second series of calculations, a constant value of relative humidity was maintained at level of 30%, while the temperature was changed every two degrees from 26 to 38 °C, what is shown in Fig. 6.

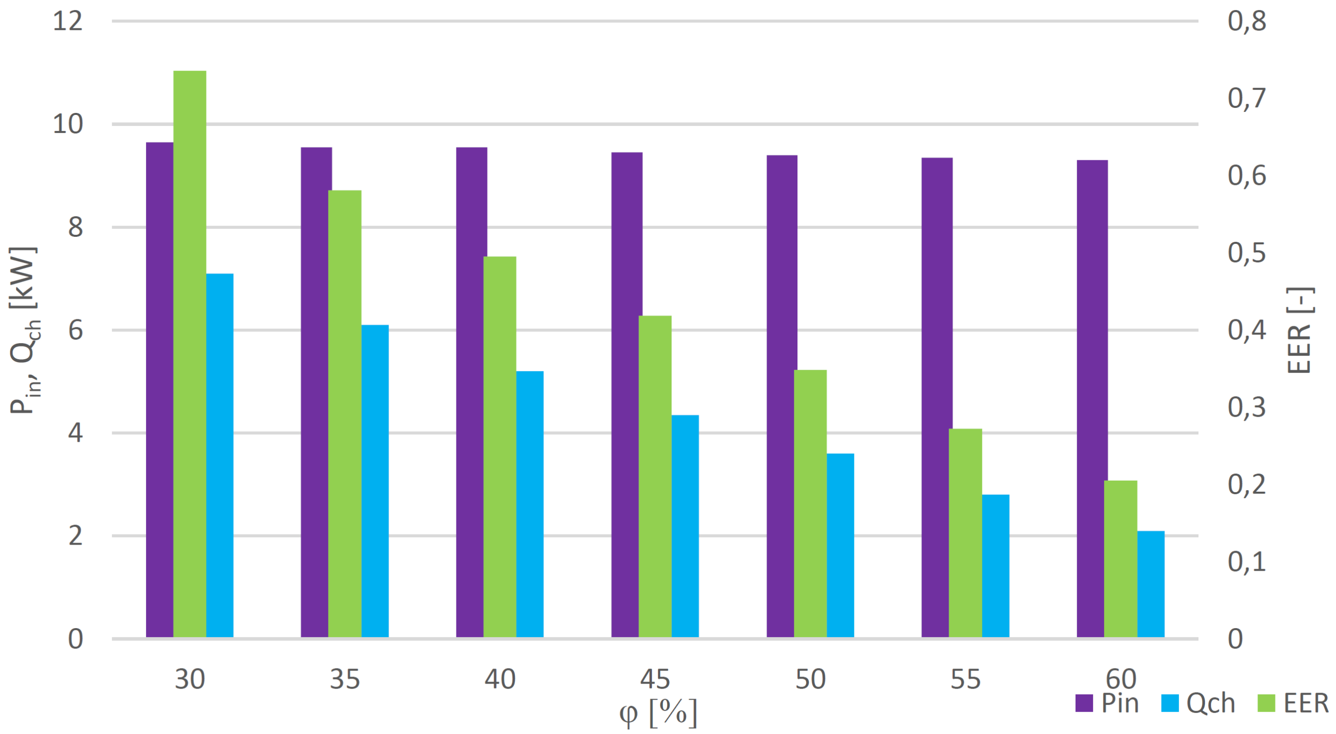

Figure 4. The influence of the relative humidity of the outside air ϕ on the cooling power Qch, the power supplied for the regeneration Pin and EER for analysed DEC system

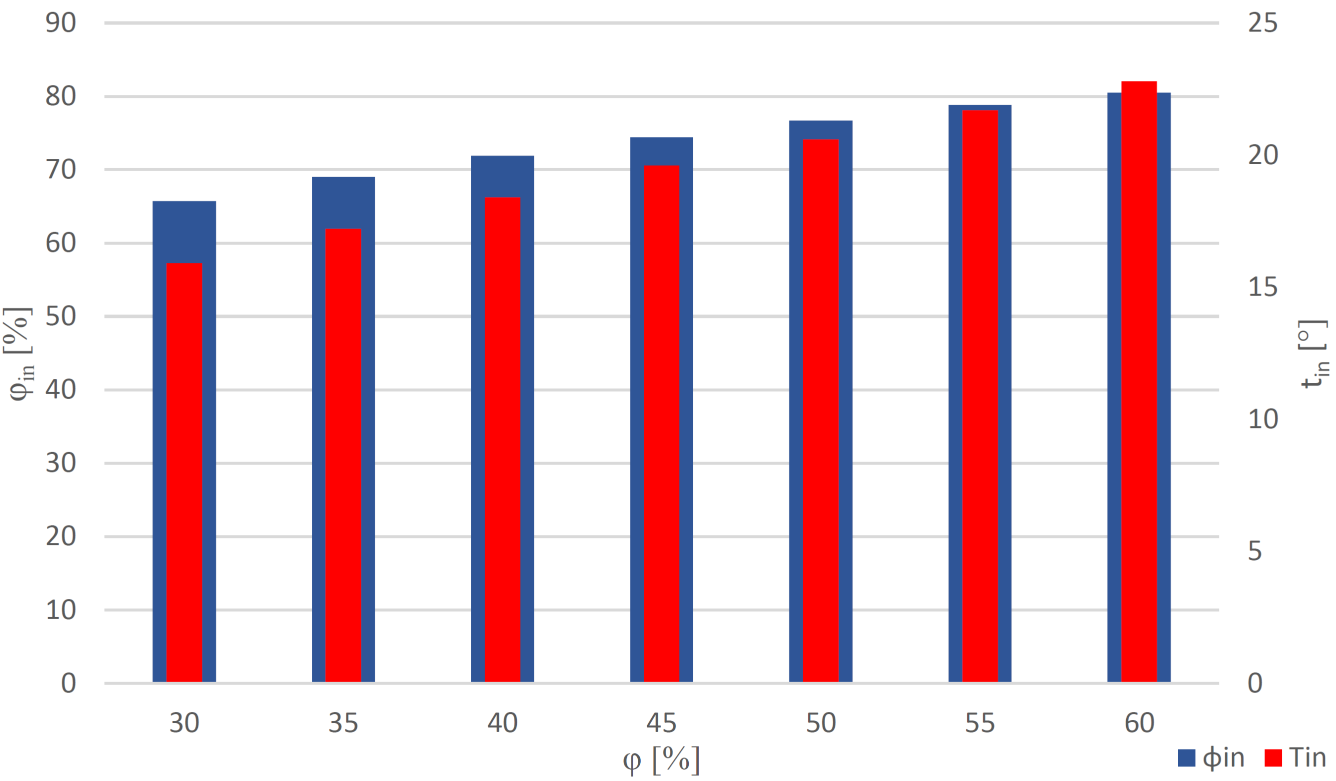

Figure 5. Influence of the relative humidity of the outside air ϕ on the temperature t_{in} and the relative humidity ϕ_{in} of the supply air to the rooms

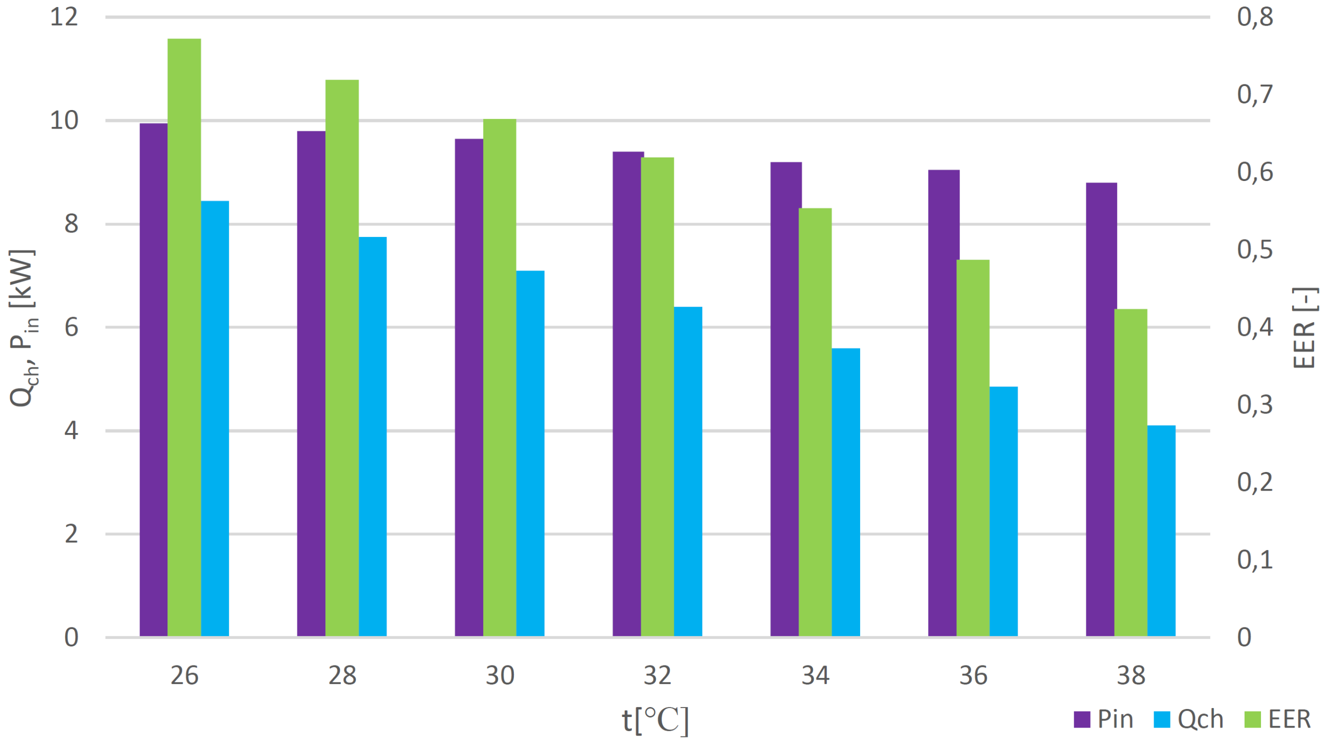

Figure 6. Influence of outside air temperature t on Q_{ch} cooling power, power supplied for regeneration of the P_{in} and EER of sorption rotor for analysed DEC system

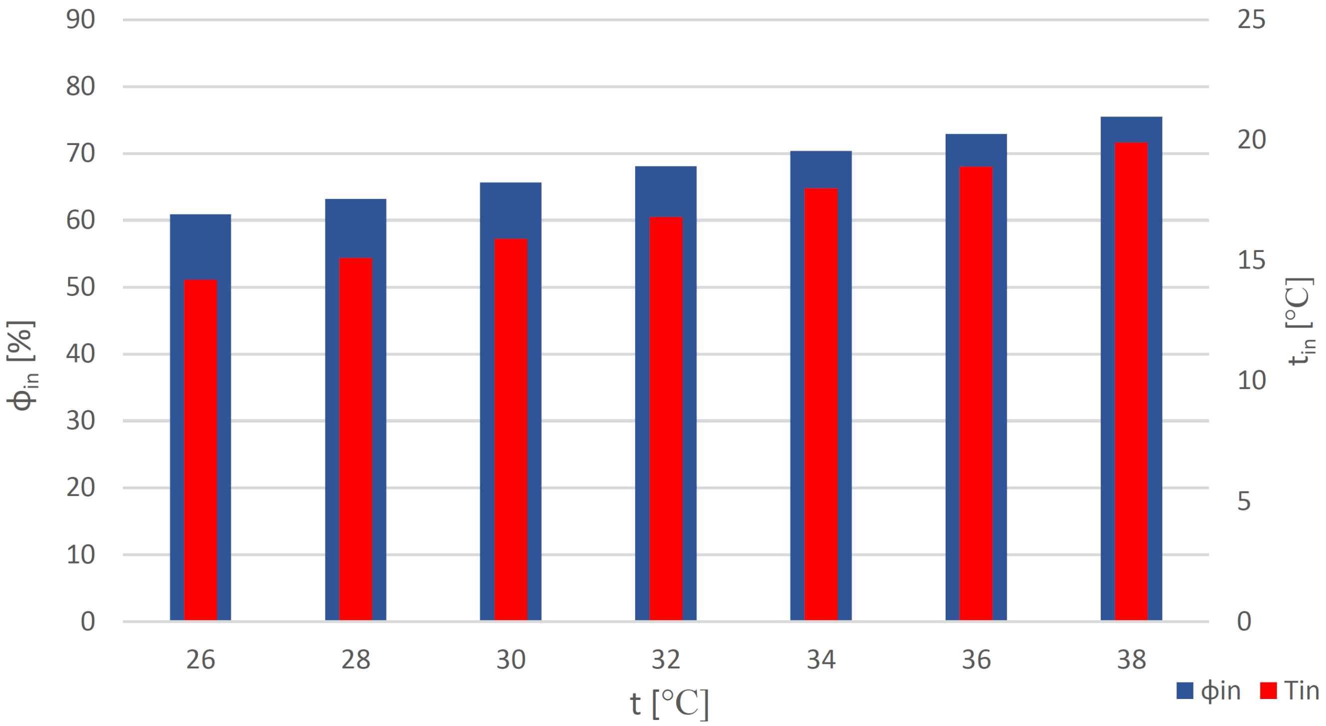

Figure 7. Influence of outdoor air temperature t on temperature t_{in} and relative humidity $\phi_i n$ of room air

3.2 Analysis of the cooperation of the DEC system with the solar collectors

The first step in this part of the analysis of the cooperation of the DEC system with solar collectors was to determine the average heat dissipation coefficient from the Fr_r collector, the mass flow of the $\dot{m}_r$ factor and its specific heat $c_{p,r}$.

The F_r coefficient depends on such parameters of the circulating medium in the absorber tubes as density, viscosity or heat capacity, and these values differ from each other for different values of the temperature of the medium [10]. In turn, this amount depends on the intensity of solar radiation falling on the collector. It was decided to average the coefficient F_r by performing calculations for 8 values of radiation intensity - from 400 to 1100 W/m^2, changing it by 100 in subsequent cycles. Figures from 8 to 11 shows day by day energy consumption for analysed DEC system for summer season in Poland.

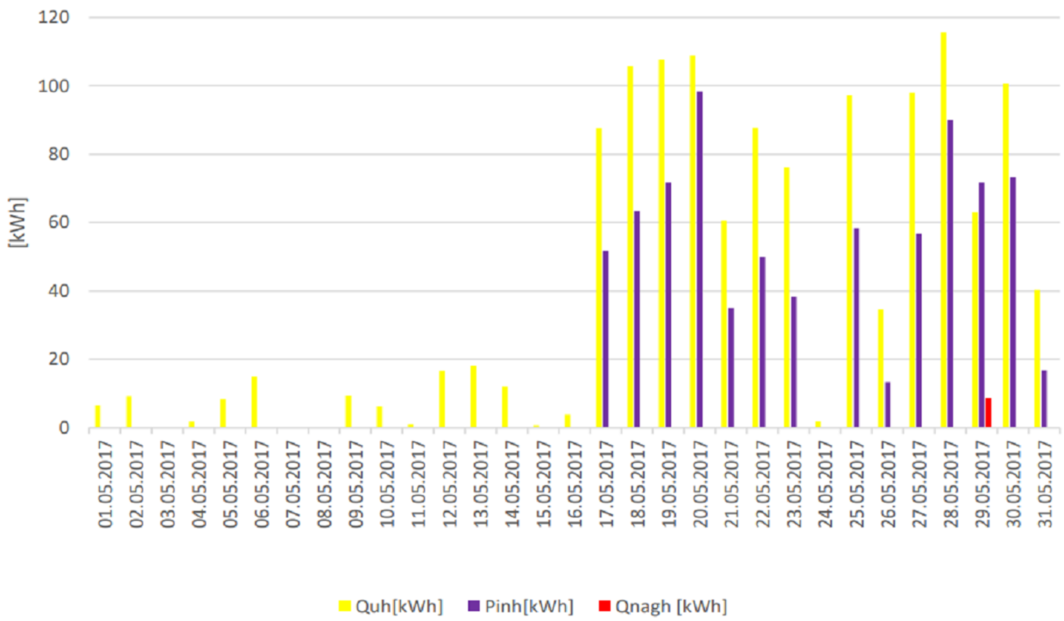

Figure 8. The amount of energy obtained in solar collectors, supplied to the electric heater and consumed by the DEC system in conditions corresponding to the days of May 2017. Q_{uh}- the amount of useful energy obtained in the collectors during the day, P_{inh} - the amount of energy supplied for the regeneration of the sorption rotor during the day, Q_{nagd} - the amount of energy supplied to the electric heater during the day.

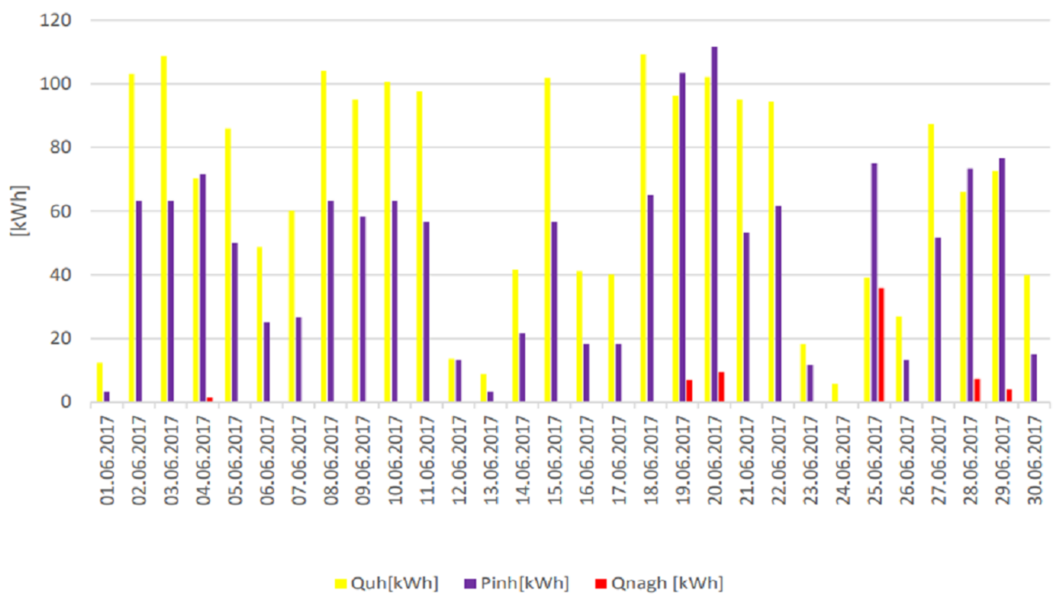

Figure 9. The amount of energy obtained in solar collectors, supplied to the electric heater and consumed by the DEC system in conditions corresponding to the days of June 2017. Q_{uh}- the amount of useful energy obtained in the collectors during the day, P_{inh} - the amount of energy supplied for the regeneration of the sorption rotor during the day, Q_{nagd} - the amount of energy supplied to the electric heater during the day.

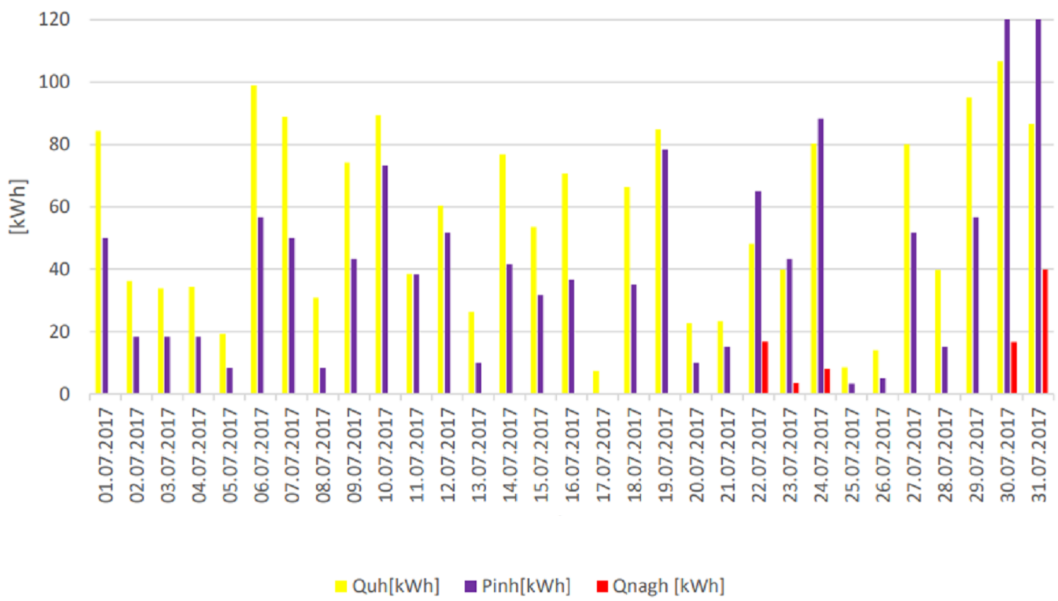

Figure 10. The amount of energy obtained in solar collectors, supplied to the electric heater and consumed by the DEC system in conditions corresponding to the days of July 2017. Q_{uh}- the amount of useful energy obtained in the collectors during the day, P_{inh} - the amount of energy supplied for the regeneration of the sorption rotor during the day, Q_{nagd} - the amount of energy supplied to the electric heater during the day.

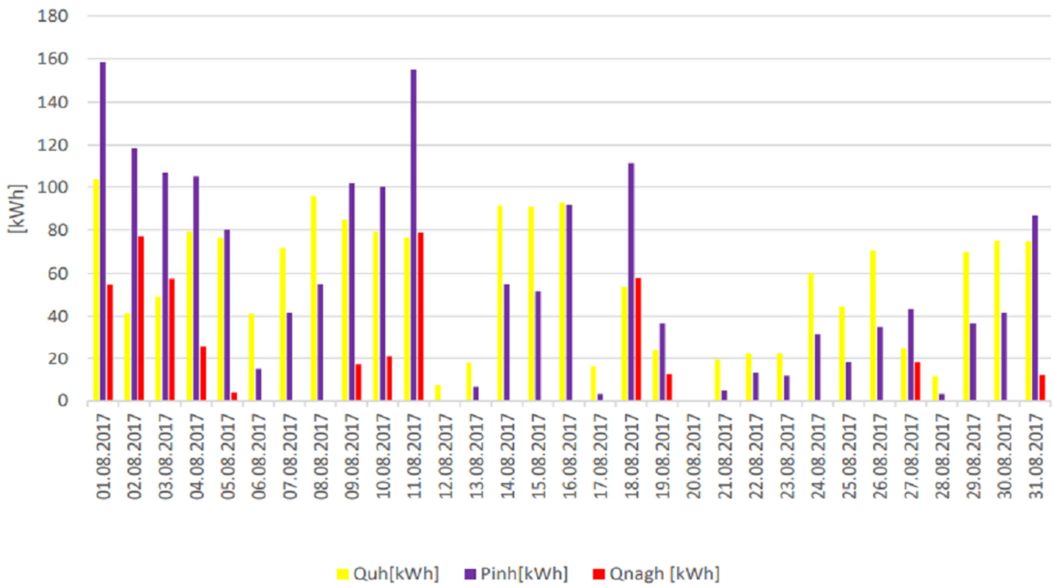

Figure 11. The amount of energy obtained in solar collectors, supplied to the electric heater and consumed by the DEC system in conditions corresponding to the days of August 2017. Q_{uh}- the amount of useful energy obtained in the collectors during the day, P_{inh} - the amount of energy supplied for the regeneration of the sorption rotor during the day, Q_{nagd} - the amount of energy supplied to the electric heater during the day.

The greatest demand for energy for the regeneration of the sorption rotor occurred in the first half of August, which, with slightly worse sunlight conditions, resulted in the frequent need to supplement energy deficiencies with an electric heater. In the rest of the summer - from May to the end of July, the heat obtained from solar collectors, except for a few days, was sufficient. Considering the diurnal periods, it can be ssen that the most problematic are the afternoons and evenings, when solar radiation is not available in sufficient quantity. This situation is especially bad for the second half of summer, when the sun sets faster and at the same time the outside air temperatures are still high, so there still occures cooling demand. By the end of July, this problem is solved by using a buffer tank, while already in August, or on the example in day 30.07 presented in Figure 12, the accumulated energy is still insufficient.

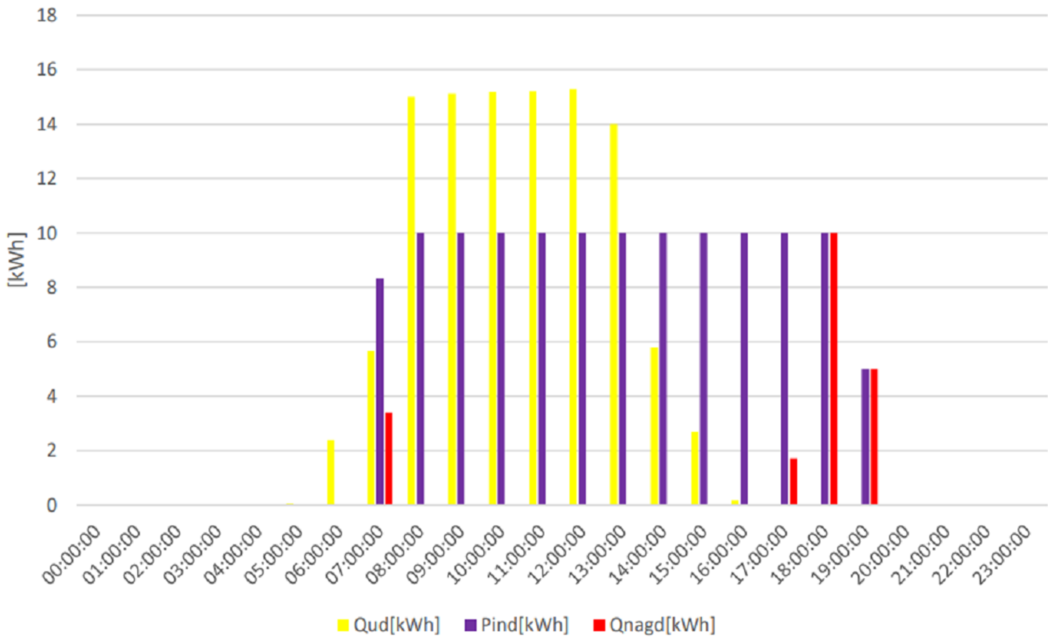

Figure 12. The amount of energy obtained in solar collectors, supplied to the electric heater and consumed by the DEC system in conditions corresponding to the next hours of 30.07.2017. Q_{ud} - the amount of useful energy obtained in the collectors in an hour, P_{ind} - the amount of energy supplied for the regeneration of the sorption rotor in an hour, Q_{nagd} - the amount of energy supplied to the electric heater in an hour.

4 Conclusions

The efficiency of a DEC air conditioning system depends to the greatest extent on the relative humidity of the outside air, which affects both the EER and the potential cooling capacity of the system. During the considered period of time – summer 2017 – the relative humidity of the air for all occurring temperatures rarely fell below 40%. For this value, the EER of the system is about 0.4 in the case of powering the regenerator with an electric heater and about 4.5 in the case of power supply from solar collectors. The obtained cooling capacity would be 5kW. Considering that this power is achieved for an air flow of 1500 m^3/h , this is very small value. The average outside air temperature during the periods DEC was active was 28.2°C, so this is an aspect that does not have a very negative impact on the functioning of the DEC system. The highest recorded value of the outside air temperature was 34.7°C, with a relative humidity of 43.6%, which allows to achieve about 4kW of cooling and EER 0.45 with energy supply electric and 5 with solar power. Analyzing the cooperation of the air conditioning system with solar collectors, it should be stated that in the latitude corresponding to Polish conditions, the coherence of energy generation from solar radiation is incomplete. The best conditions in terms of solar radiation intensity were observed at the end of May and in June, while the highest demand for energy for adsorber regeneration occurred in August. A similar phenomenon occurs both on the scale of the entire considered season and individual days in the afternoon. Energy is still needed for cooling, while there is no more solar radiation. Therefore, a good solution is to use an accumulation tank, which, using the surplus heat generation in the first half of the day, can cover at least part of the demand in the afternoon. The heat accumulator was considered in the perspective of one day, because the storage of heat at such a high temperature (80°C) can generate too much loss. In addition, with such a selected area of absorbers, all the energy obtained in July and August is dismantled on an ongoing basis, just in daily periods, while in May and June a fairly large surplus should be distributed. To sum up, the operation of the considered DEC system in Polish climatic conditions was assessed negatively, mainly due to the high average relative humidity of the outside air. Under such conditions, the system not only cannot offer adequate cooling power to receive heat gains from the rooms, but is also unable to reduce the temperature of the ventilation air to the appropriate level. A possible improvement in functionality would have to be associated primarily with an increase in the efficiency of the dehumidification process. However, the biggest problem of the system from the point of view of solar power is the surplus of energy generated in the first half of summer, and shortages in the second. This, of course, is due to the chosen method of selecting the surface of collectors. However, regardless of the surface of the absorber, it has to be faced either excess energy or its shortages. The first situation can be easily solved by allocating surpluses to, for example, the preparation of domestic hot water (if you have the right cutting), while the second situation actually destroys the raison d'être of the DEC system. Collectors are therefore a good source of power for the DEC system, but they should be selected according to demand in August conditions, assuming that we have an adequate reception of surplus energy.

The issue of the environmental friendliness of the considered system is also in question, paying attention to how much water it needs to work – in average conditions it is about 80 liters per day. It is true that all this amount goes into the natural circulation of water in the atmosphere, but a large cluster of DEC system can still be a problem, especially in areas less rich in water. In addition, the user has to pay for this water, which increases the operating costs of the system. Despite the simple construction and the associated low investment costs and sufficiently good cooperation with solar collectors, resulting in a high EER, it should be stated that the DEC system in Polish climatic conditions cannot be a rational alternative to compressor refrigeration equipment, and its adaptation can only take place to a limited extent, which will not necessarily be profitable.

References

1. Chojnacka, A. & Sudoł-Szopińska, I. Thermal comfort in office rooms in the aspect of standards. *Occupational Safety* **6** (2007).
2. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. EU strategy on heating and cooling, Brussels* 2016.
3. Dezfouli, M. Effective Parameters on the Performance of Solar Desiccant Cooling Systems. *Trends in Bioinformatics* **9,** 44–51 (2016).
4. Grudzień, A. M., Rusowicz, A. & Leszczyński, M. Analysis of air conditioning systems for different types of hotels. *Rynek Energii* **2,** 47–52. ISSN: 1425-5960 (2019).
5. Jones, W. P. *Air Conditioning Engineering* (Routledge, 2020).
6. Liu, L. *et al.* Numerical investigation of mass transfer characteristics for the desiccant-coated dehumidification wheel in a dehumidification process. *Applied Thermal Engineering* **160,** 113944. ISSN: 1359-4311 (2019).
7. Liu, Y. *et al.* Performance evaluation of a hybrid solar powered rotary desiccant wheel air conditioning system for low latitude isolated islands. *Energy and Buildings* **224,** 110208. ISSN: 0378-7788 (2020).
8. Pandelidis, D. *et al.* Numerical and experimental analysis of precooled desiccant system. *Applied Thermal Engineering* **181,** 115929. ISSN: 1359-4311 (2020).
9. Pełech, A. *Wentylacja i klimatyzacja. Podstawy* (Oficyna Wydawnicza Politechniki Wrocławskiej, 2013).
10. Pluta, Z. *Podstawy teoretyczne fototermicznej konwersji energii słonecznej* (Oficyna Wydawnicza Politechniki Warszawskiej, 2013).
11. Saputra, D. A. *et al.* Experimental investigation of desiccant wheel dehumidification control method for changes in regeneration heat input. *Energy* **205,** 118109. ISSN: 0360-5442 (2020).
12. Szelągowski, A. & Chwieduk, D. *Analysis of use a solar desiccant evaporative cooling systems in Poland climate conditions* in *Współczesne problemy termodynamiki* (eds Bury, T. & Szlęk, A.) (2017).
13. Tu, R., Li, J. & Hwang, Y. Fresh air humidification in winter using desiccant wheels for cold and dry climate regions: Optimization study of humidification processes. *International Journal of Refrigeration* **118,** 121–130. ISSN: 0140-7007 (2020).