Centrum Rzeczoznawstwa Budowlanego

Open Access Journal
Modern Engineering 1 (2024) 23-39
journal homepage: https://mengineering.eu/

Analysis of Heat and Mass Transfer in the Elements of a Desiccant Evaporative Cooling (DEC) Air Conditioning System

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Abstract

The DEC system emerges as a sustainable alternative to conventional air conditioning systems reliant on compressor technology. Distinctively, this system circumvents the use of harmful refrigerants and minimizes electricity consumption. Its operational requirement, namely heat at approximately 70°C, can be sourced from solar collectors or reclaimed from industrial processes. Primarily tasked with air drying followed by cooling through humidification, this study delineates the burgeoning market for DEC and akin devices. Design adaptations catering to diverse weather conditions and operational needs are delineated. Notably, meticulous calculations spotlight mass and heat transfer dynamics within rotary exchangers. An empirical analysis of DEC performance under Polish weather conditions underscores crucial metrics including thermal power consumption, EER coefficient, indoor air parameters, system-wide water flow rates for humidification, and the influence of operational variables such as rotor speed, regeneration air temperature, air mass flow, and external air conditions. While the system effectively achieves desired cooling, it occasionally surpasses upper humidity thresholds during extreme weather conditions. Conclusions drawn from this study prompt potential resolutions to encountered challenges, promising advancements in DEC system optimization.

Key words: DEC, Desiccant Evaporative Cooling, sorption-evaporative cooling, solar cooling, air conditioning, DEC system.

1. Introduction

The task of air conditioning is to ensure appropriate temperature and air humidity in closed rooms. This is very important for the proper functioning of the human body. The optimal conditions for this purpose are a temperature of approximately 20-26ºC and a relative humidity in the range of 30-70%. The right temperature ensures people's well-being. Too low humidity may cause drying of the nasal mucosa, skin and eyes, and is often one of the causes of many upper respiratory tract diseases. Too high makes it difficult for sweat to evaporate from the skin surface, and therefore reduces the efficiency of the human natural cooling mechanism. It may also cause water to condense on cooler surfaces, e.g. windows, which may result in the formation of fungi or furniture deterioration [1].
Currently, the vast majority of air conditioners are compressor devices. The basic diagram of their operation is shown in Fig. 1.
This is a proven technology but has two main drawbacks. The first is energy consumption. The basic element of these devices is a compressor whose task is to compress the refrigerant. It uses significant amounts of electricity for this purpose. After being compressed, the refrigerant in gaseous form goes to the condenser, where it changes its state to liquid, while releasing heat to the surroundings. Then it is throttled in the expansion valve and flows through the evaporator, where it evaporates, removing heat from the room. The refrigerant condenses at higher temperatures and evaporates at lower temperatures so that it can absorb heat from the environment it is supposed to cool.

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Received 10 December 2023
Available online 31 March 2024
ISSN 2450-5501
Published by Centrum Rzeczoznawstwa Budowlanego

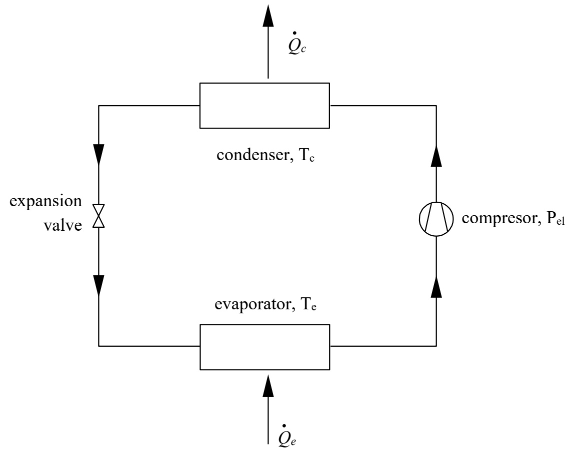

Fig 1. Operation diagram of the compressor cooling system (P_{el} – electrical power consumed by the compressor, T_c – temperature in the condenser, T_e – temperature in the evaporator, Q_e heat received from the cooled space, Q_c – heat released to the environment [2]

2. DEC system

The DEC sorption-evaporative cooling system seems to answer the above-mentioned problems. Firstly, it does not require the use of a refrigerant, and secondly, it can be much more economically profitable due to the lack of a compressor [3]. To power a DEC system, mostly thermal power is needed, not electrical power. The latter only powers secondary devices such as the pump in the heating circuit and fans. The temperature of the heat source, depending on the sorbent used, should range from 50 to 100ºC. This is another advantage because the summer period when there is a need for cooling is the period when heat is plentiful. In summer, the intensity of solar radiation is highest [7]. The basic source of heat for the DEC system may therefore be that coming from solar collectors. The combination of the DEC system with collectors also has another advantage compared to an analogous combination of photovoltaic panels as a power source and a classic compressor air conditioner [6]. Heat is much easier to store than electricity. All you need is an appropriate, well-insulated water tank, which is much cheaper and less complicated than electricity storage. This combination is shown in Figure 2.

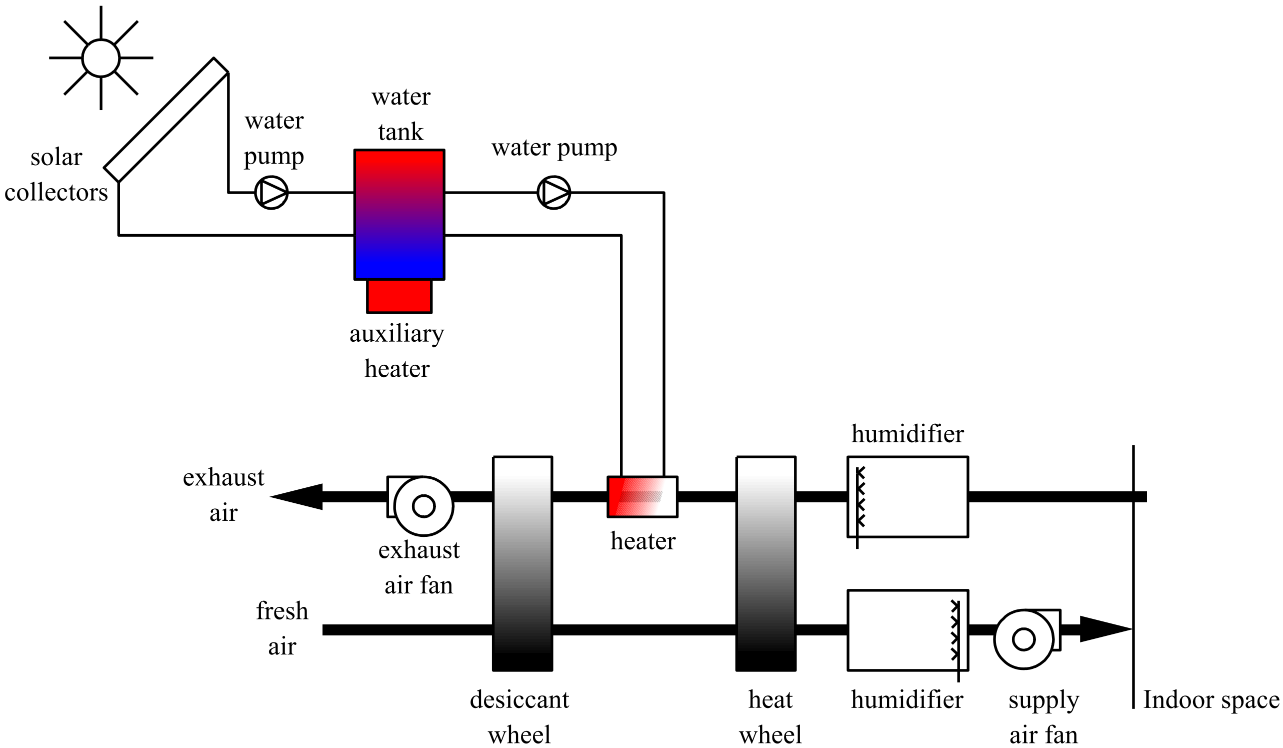

Fig. 2. Diagram of the DEC system connected to solar collectors and heat storage [5, 8]

Heat from renewable energy sources is not the only option. In the case of cooling industrial plants, the DEC system can be powered by waste heat from technological processes.
All of the above means that there is a growing interest in sorption-evaporative air conditioning systems around the world. They do not contain problematic refrigerants and can be much more profitable due to the easily stored heat coming from renewable sources or being "waste" from industry. The following chapters will present an overview of existing DEC installations and similar ones, the structure and principle of operation of the DEC system, along with an explanation of the functioning of its elements and the phenomena occurring in them, as well as example modifications for various purposes and situations. Calculations performed in MATLAB will be described, including: heat transfer and mass balance of the device, simulation of its operation in Polish climatic conditions and analysis of the impact of the most important parameters on its operation. The whole will be completed with a summary and conclusions.

3. Construction and principle of operation of the DEC cooling system

The system is based on cooling the air by humidifying it. Injecting water into the air stream causes the liquid to evaporate, and to change the state of matter, heat is needed, which is absorbed from the air and lowers its temperature. This phenomenon has been known and used since ancient times, but it has its natural limitations. It is impossible to cool and humidify the air forever, at some point the air will stop absorbing moisture. This will mean that the relative humidity of the air has reached 100% and the air temperature has equaled the wet bulb temperature. Relative humidity is the ratio of the partial pressure of water vapor in the air to the saturated vapor pressure or, in other words, the absolute humidity of the air (in kg H_2O per kg of dry air) to the maximum possible humidity in given conditions.

The wet bulb temperature is the lowest temperature that air at a given temperature and humidity can achieve using only evaporative cooling. The higher the air humidity, the higher the wet bulb temperature, so the fewer degrees it can be cooled. If the air, after lowering the temperature, is to be forced into rooms intended for people, the cooling limit is even higher, because for the comfort and proper functioning of human bodies, the relative humidity of such air should be in the range of 30 - 70%.

In order for the gas stream to be cooled further while maintaining the appropriate humidity, it must be dried beforehand. In the DEC system, this is done using silica gel, a porous material that can absorb significant amounts of moisture. This is possible thanks to the large specific pore surface in the range of 200-1000 m 2 g . It uses the phenomenon of physical adsorption, i.e. the accumulation of a specific substance on the interface of two phases. Silica gel is an adsorbent - an absorbing substance, and water vapor in the air is an adsorbate - an absorbed substance. A sorption rotor is used to intensify the sorption drying process in the DEC system. It is made of 0.2 mm thick aluminum sheets covered with a layer of silica gel. There are corrugated sheets between the straight sheets, which creates a very large specific surface. The distance between the straight sheets is 1.6 mm (Fig. 3).

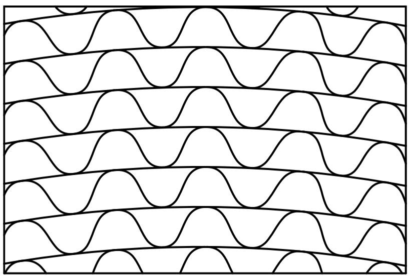

Fig. 3. Cross-section of the sorption rotor [8, 9]

A stream of external air flows through one part of the rotor's volume, and through the other part of the volume of the rotor flows the air blown out from the room. As a result of the rotational movement of the rotor, its subsequent "slices" pass alternately through one and the other stream, transferring heat and mass between them (Fig. 4.).

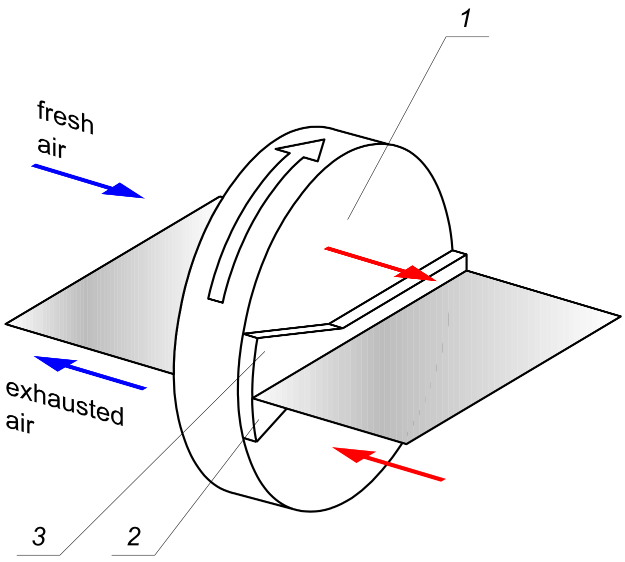

Fig. 4. Diagram of the sorption rotor (1-rotor, , 2 - shutter to prevent the ingress of exhaust air to the supply air duct, 3 - some fresh air cleans the rotor) [4, 8]

The DEC system also includes a heat rotor that serves as a heat recuperator. Its structure is identical to that of the sorption rotor except for the lack of the silica gel layer. Its function is only to exchange heat.

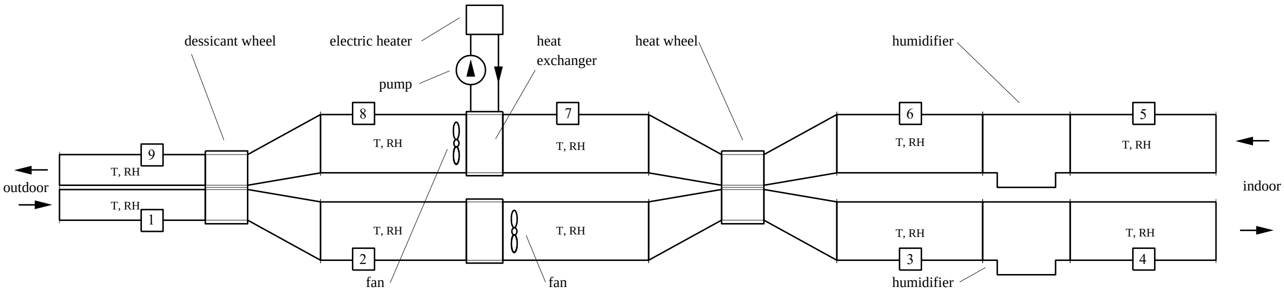

Fig. 5. Diagram of the DEC system (T – temperature sensor, RH – relative humidity sensor) [8]

Fig. 5. shows a diagram of the DEC system. The lower channel blows air from outside into the room, the upper channel blows air out of the room. The sorption rotor is located in the diagram between points 1 and 2 and 8 and 9, the thermal rotor is located between points 2 and 3 and 6 and 7. Between points 3 and 4 and 5 and 6 there are humidifiers that spray water into the air stream. The element that consumes most of the energy in the entire system is the heat source (7-8). In the laboratory case, for simplicity, it is a heater, ultimately e.g. solar collectors or waste heat from industry. The heater heats the air stream through the heat exchanger. Heating the return air before the sorption rotor is required to regenerate it, i.e. dry it, so that it can dry the outside air with the same intensity all the time. The whole is complemented by two fans ensuring air flow.

The subsequent transformations of humid air in the DEC system are shown in the Molière diagram (Figure 6) and in Table 1. Point P1 is the external air at a temperature of 30 °C and a relative humidity of 40. Between P1 and P2 it reaches the sorption rotor, dries and heats up. , due to the high temperature of the regeneration air and the impeller. Then it flows through the thermal rotor (P2-P3), lowering its temperature. The next transformation (P3-P4) is the injection of water from the humidifier, which approximately isenthalpically cools the air in the humidifier to a temperature of 22 °C and a relative humidity of approximately 60%. These are conditions that ensure comfort for people. Then, as a result of internal gains, its temperature and humidity increase. Air is sucked into the return duct and goes to the second humidifier (P5-P6). This cools the gas stream, this time as low as possible, i.e. to the wet bulb temperature and relative humidity of about 100%. The low temperature obtained in this process is used in the recuperator (P6-P7) to cool the air in the second channel. Then the stream flows through the heat exchanger (P7-P8), which transfers energy from the heater to it. It raises the temperature to 65 °C, this value is indicated in the literature as sufficient to regenerate the sorption rotor [13]. Air flowing through the sorption rotor (P8-P9) is cooled and moisturized, drying the rotor.

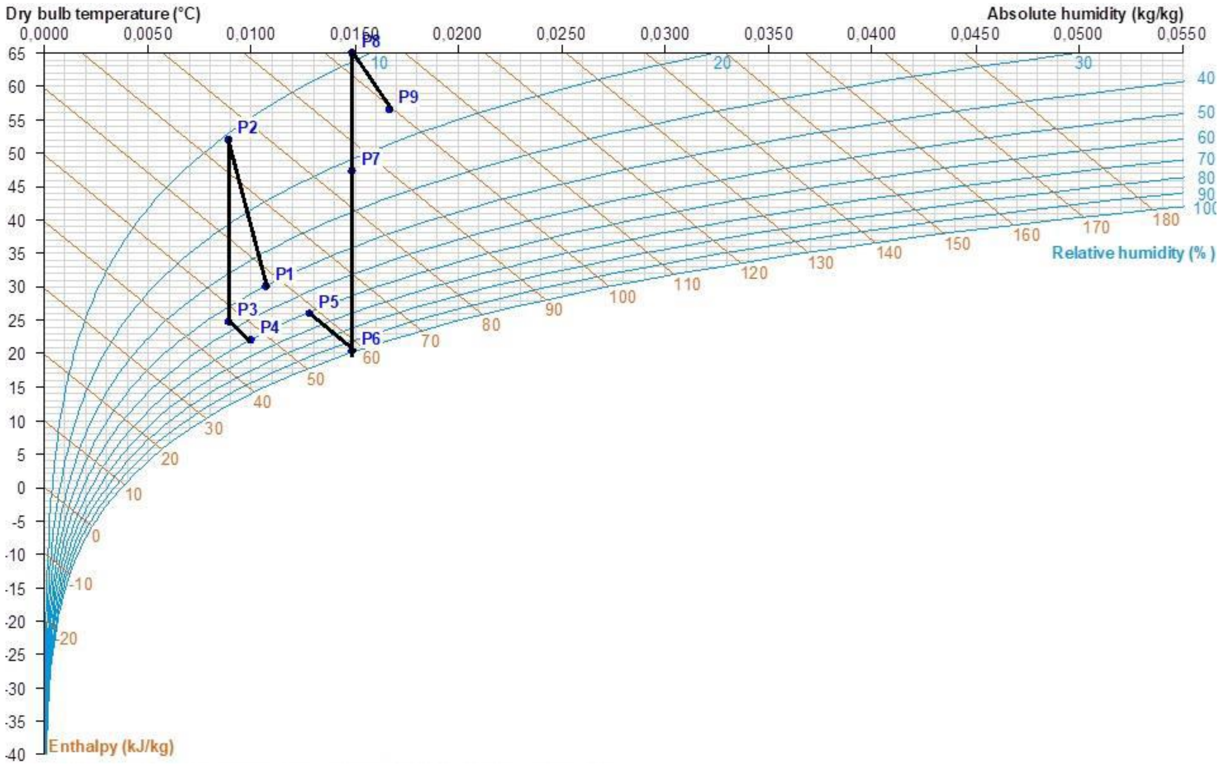

Fig. 6. Air paremeters in the DEC system

4. Calculations - heat and mass balance of the DEC system

4.1. Heat exchange in rotary heat exchangers

Figure 7 shows the coordinates used for calculations in the rotary heat exchanger. Two polar coordinates ri φ and a Cartesian coordinate x, coinciding with the rotor rotation axis, were adopted. The model will be divided into constant temperature pieces, for simplicity, only in the φ direction .

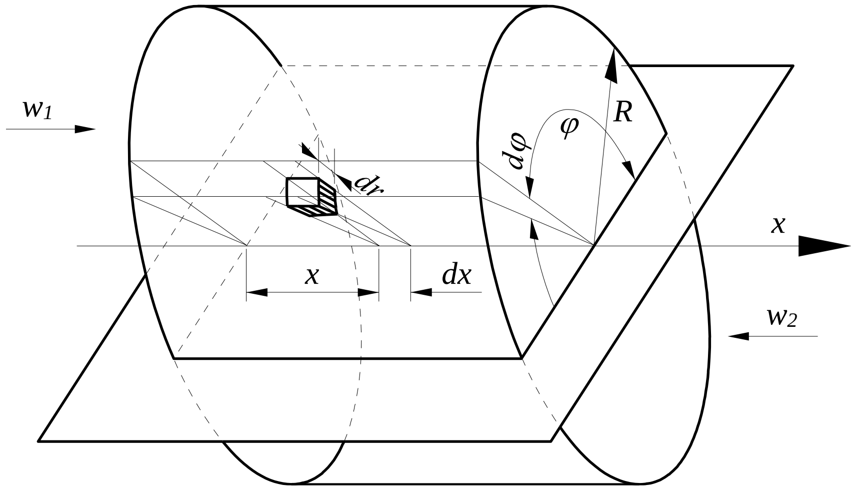

Fig. 7. Graphic model of the rotor [11]

The air filling the rotor together with the aluminum filling can be considered a porous material described by the porosity factor P and the specific surface area *s* defined as [10]:

$$P = 1 - \frac{G}{\gamma * V} \tag{1}$$

$$s = \frac{F}{V} \tag{2}$$

Where: G is the mass of the filling with density γ, F is the developed area of the filling and V is the volume of the rotor.
The equation describing the temperature at individual points of the rotor is as follows:

$$c_p \gamma_p \left(\frac{\partial t}{\partial \tau} + w_x \frac{\partial t}{\partial x} + w_r \frac{\partial t}{\partial r} + \frac{w_\varphi}{r} \frac{\partial t}{\partial \varphi} \right) = q_v + \lambda_{p,x} \frac{\partial^2 t}{\partial x^2} + \frac{\lambda_{p,r}}{r} \frac{\partial}{\partial r} \left(\frac{\partial t}{\partial r} \right) + \frac{\lambda_{p,\varphi}}{r^2} \frac{\partial^2 t}{\partial \varphi^2} \tag{3}$$

Further simplifications were used, due to only rotational motion:

$$\begin{aligned} w_x &= 0 \\ w_r &= 0 \\ w_\varphi &= \omega r \end{aligned} \tag{4}$$

A steady state was assumed, independent of time:

$$\frac{\partial t}{\partial \tau} = 0 \tag{5}$$

The heat absorbed from the air by the rotor is recorded as an internal heat source, in addition, for the sorption rotor, the heat from sorption should also be taken into account:

$$q_v = \alpha_1 s (t_1 - t_w) + q_{sor} \tag{6}$$

Due to the small thickness and high thermal conductivity of aluminum sheets, the following assumption was made:

$$t_w = t_m = t \tag{7}$$

For simplicity, heat conduction along the radius and x direction, i.e. the rotor axis, has been omitted:

$$\lambda_{p,x} \frac{\partial^2 t}{\partial x^2} + \frac{\lambda_{p,r}}{r} \frac{\partial}{\partial r} \left(\frac{\partial t}{\partial r} \right) = 0 \tag{8}$$

Taking into account all the above, equation (3)can be transformed into:

$$c_p \gamma_p \omega \frac{\partial t}{\partial \varphi} = \frac{\lambda_{p,\varphi}}{r^2} \frac{\partial^2 t}{\partial \varphi^2} + \alpha_1 s (t_1 - t) \tag{9}$$

Where:
t – rotor temperature, [°C];
t_1 – air temperature in duct in front of rotor, [°C];
c_p- specific heat of the material from which the rotor is made, $\left[\frac{J}{kg \cdot K}\right]$;
$\gamma_p = \gamma * (1 - P)$- effective density of the rotor, $\left[\frac{kg}{m^3}\right]$;
ω - angular velocity, $\left[\frac{rad}{s}\right]$;
$\lambda_{p,\varphi}$– effective heat conduction coefficient through the rotor in the φ direction, $\left[\frac{W}{m \cdot K}\right]$;
r – rotor radius, $[m]$;
α_1– heat transfer coefficient $\left[\frac{W}{m^2 \cdot K}\right]$;

Equation 9 was solved by using the finite difference method. Fig. 8. shows the simulation results for two rotations of the thermal rotor. Every half a turn, the air stream flowing through the rotor section changes. The rotor alternately is cooled and heated by air.

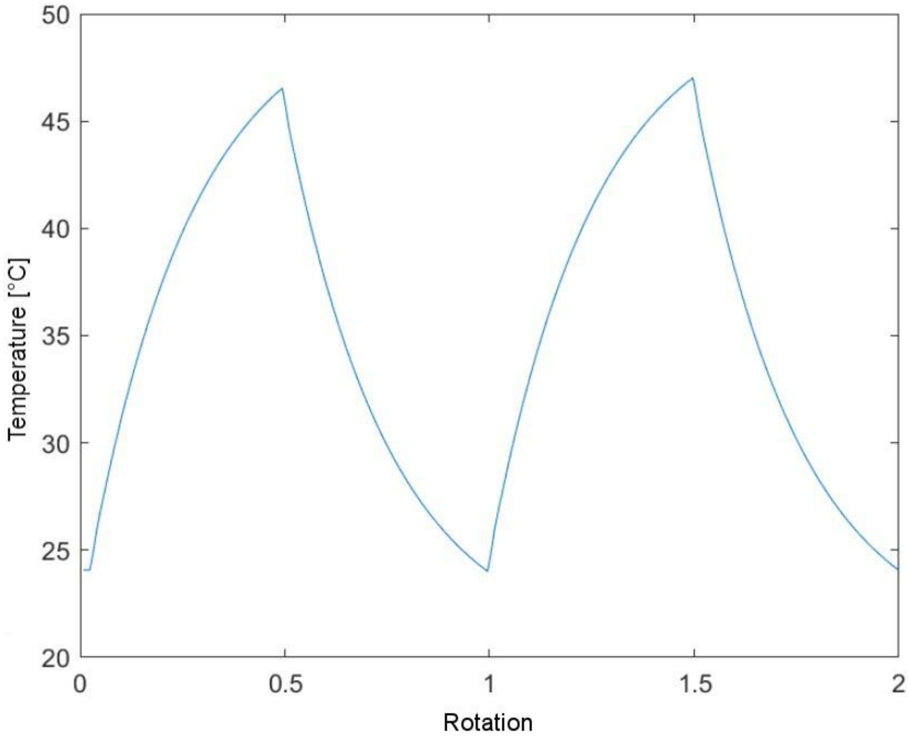

Fig. 8. Temperature distribution in the thermal rotor for t_1 = 50.7 ºC, t_2 = 20.4 ºC and T = 20 s

Where:
$t_{1,2}$ – air temperaute in ducts on inlet to rotor,
T – rotate time.

4.2. Mass exchange in the sorption rotor

The most important function of the sorption rotor is to dry the fresh external air. To correctly estimate the efficiency of the entire system, it is necessary to calculate how much water the rotor absorbs from air stream and how much it transfers to the other. In the literature [12] it can be found relationships and charts (Fig. 9.) describing the equilibrium values of moisture in silica gel, for given air parameters. The state of equilibrium is considered to be a situation when the sorbent has the same temperature as the surrounding air and there is no moisture exchange between them.

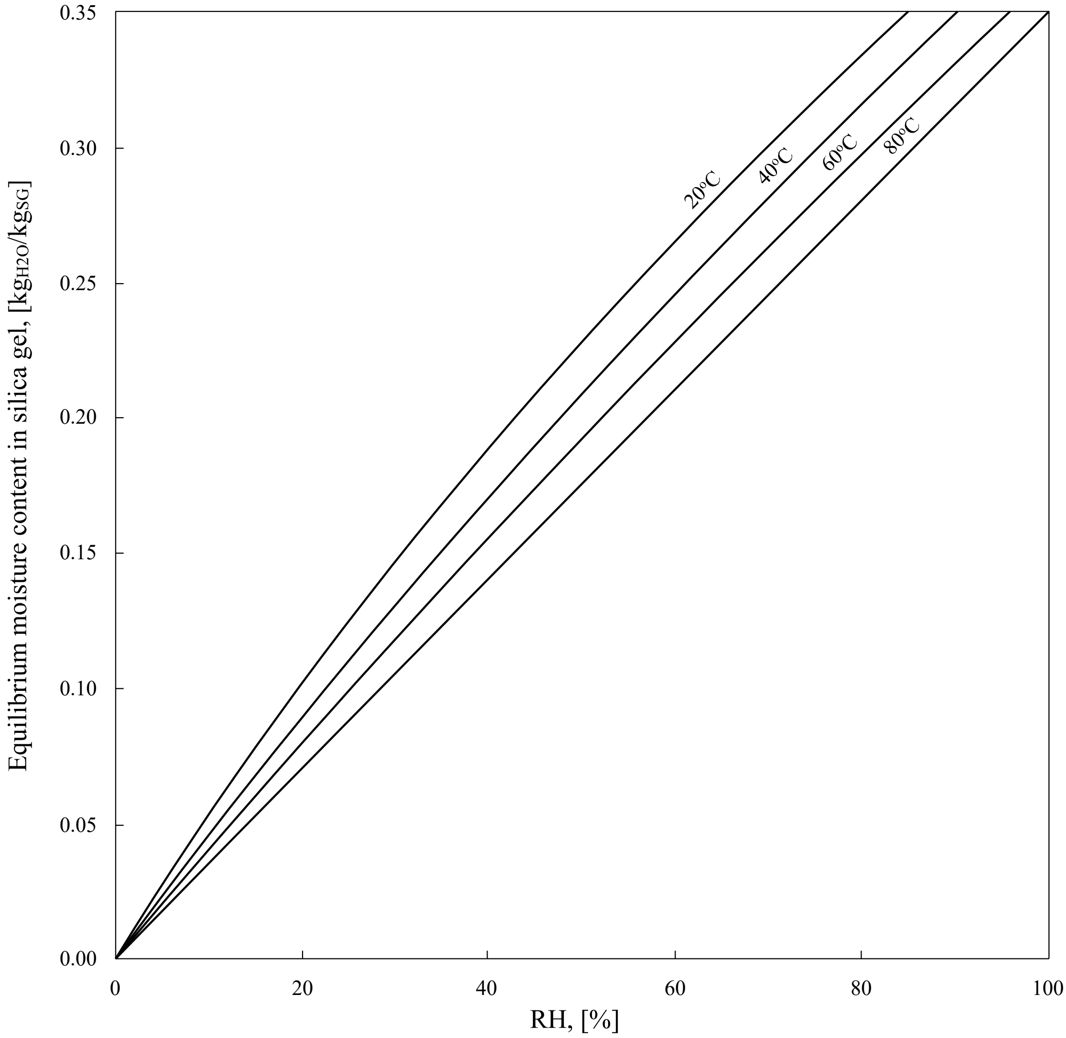

Fig. 9. Equilibrium diagram for moisture content in silica gel as a function of temperature and relative humidity of the air [12]

The equilibrium moisture content can be read from the graph (Fig. 9.) or can be calculated by solving the equation for RH according to the equilibrium content [12]

$$RH = (143.31 + 1.68678 \cdot T_w)X_e + (231.74 - 2.64006 \cdot T_w){X_e}^2 \quad (10)$$

Where:
RH - realtive humidity, [%];
X_e- Equilibrium moisture content in silica gel$\left[\frac{kg_{H2O}}{kg_{SG}}\right]$;
T_w– silica gel temperature [ºC];

A simulation was performed for two rotations of sorption rotor (Fig. 10.).

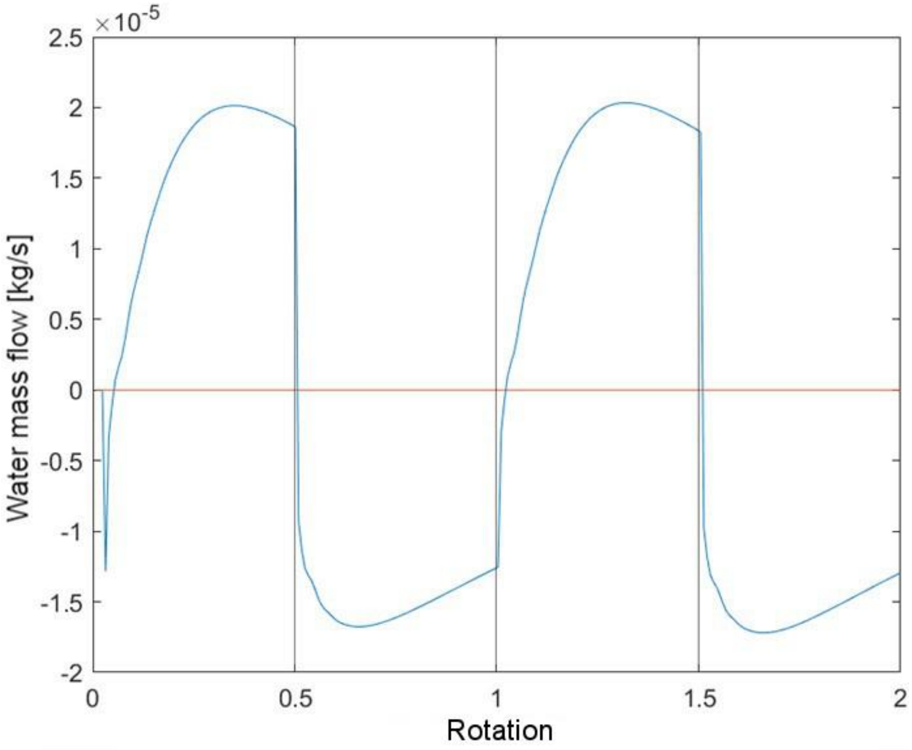

Fig. 10. Water mass flow rate for adsorption/desorption process, t_1 = 30[ºC], RH_1 = 40[%], t_2 = 70[ºC], RH_2 = 7.5[%], T = 60[s]

Results can be also shown as the relationship between the equilibrium and actual moisture content in the bed (Fig. 11.).

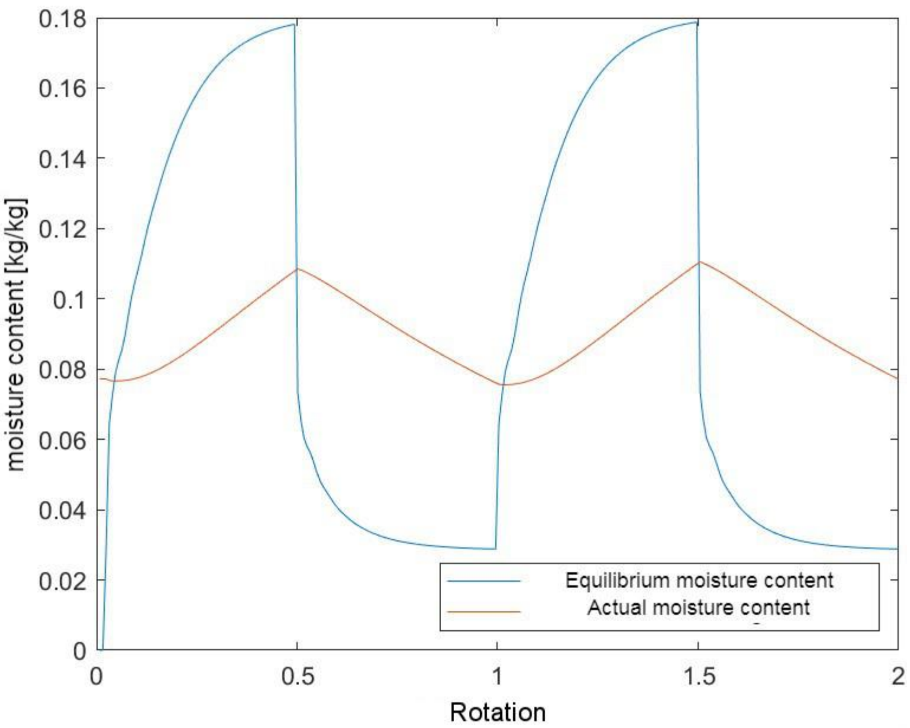

Fig. 11. Equilibrium and actual moisture content in the bed.

5. Results

5.1. DEC system performance for Polish weather conditions

The aim of the simulation is to check how the DEC system would cope with Polish weather conditions. The requirements are to cool the supply air to a temperature of 22 ºC and maintain its relative humidity in the range of 30-70%. For this purpose, data for typical meteorological years for Siedlce was implemented. Data present the temperature and relative and absolute air humidity with hourly accuracy. From the data, three consecutive very warm days of the year (June 28-30) were selected to pose a challenge to the cooling system. Then, data for hours when the temperature was lower than 22 ºC was discarded, i.e. for situations when the DEC system would not be needed. The outdoor air parameters are shown in Fig.12.

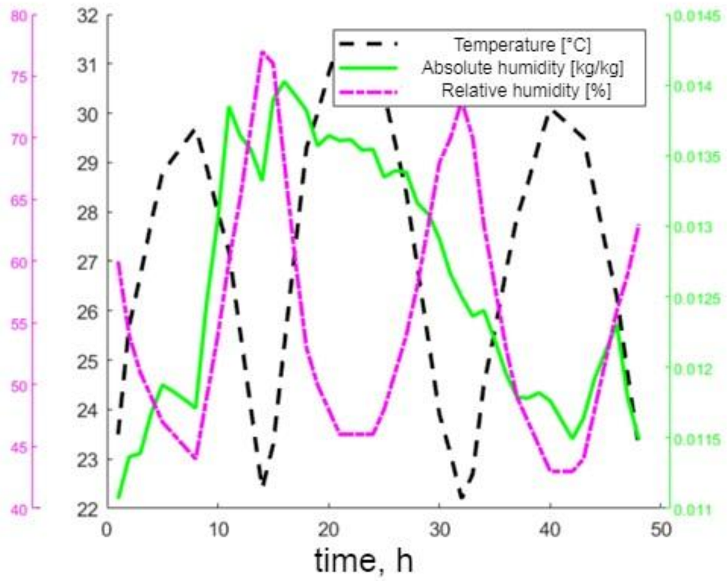

Fig. 12. Outdoor air parameters for a typical meteorological year in Siedlce, June 28-30 [14]

The absolute humidity at points P7 and P8 will be the same as at P6, there are no elements in between that would change this. The temperature of point p7 will be calculated later. Point P8 describes the regeneration air and its temperature is assumed to be 70ºC. According to this data calculation of the air at point P2, i.e. after passing the sorption rotor can be made. The air parameters are presented in the figure Fig. 13. It can be noticed a higher temperature and lower absolute humidity compared to point P1.

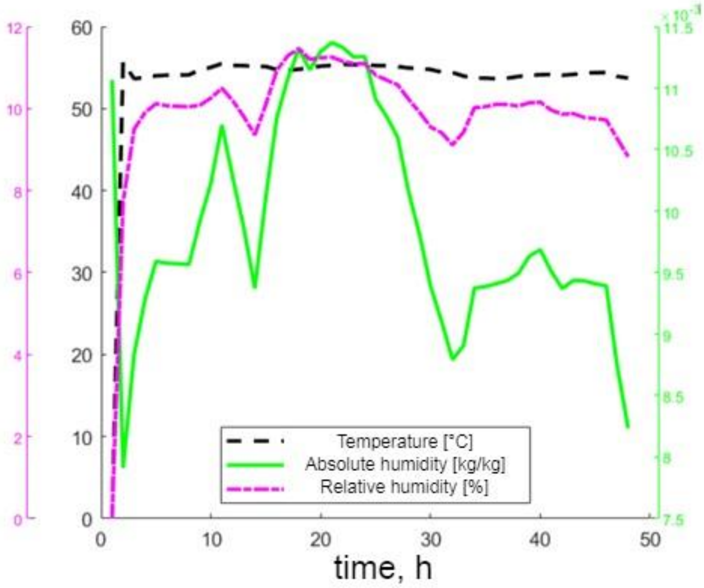

Fig. 13. Air parameters at point P2

In next step the air flows through the thermal rotor (P2-P3). The air parameters at point P3 are presented in the fig. 14. The air has the same absolute humidity and a lower temperature compared to point P2, but still too high for use in the room.

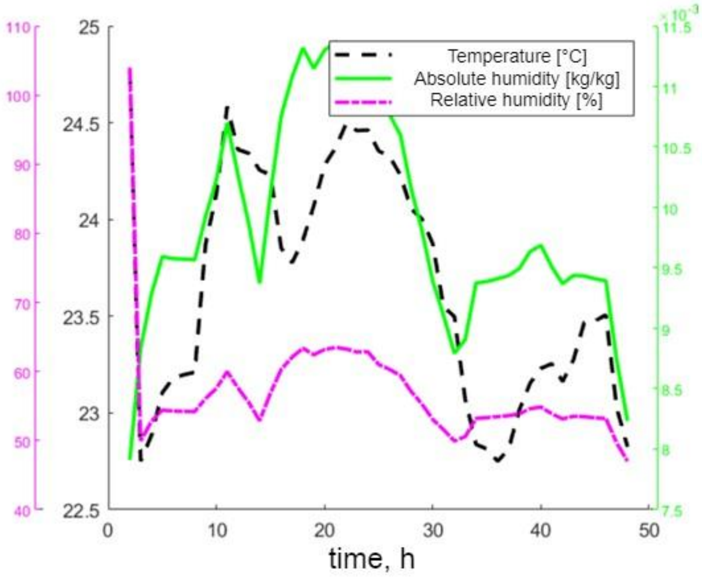

Fig. 14. Air parameters at point P3

In the P3-P4 transformation, the air goes to a humidifier, which cools it and, of course, humidifies it. The assumed room temperature was 22ºC. The mass flow of water from the humidifier is shown in Fig. 15. Fig. 16. shows parameters of air at point P4. It is the air supplied to the room.

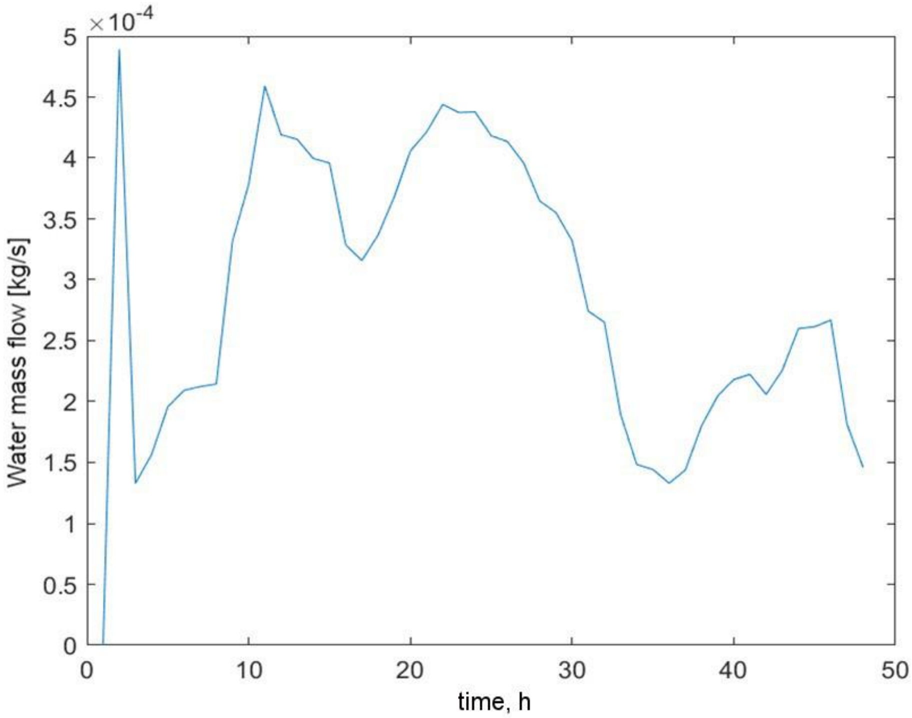

Fig. 15. Water mass flow in humidifier (P3-P4)

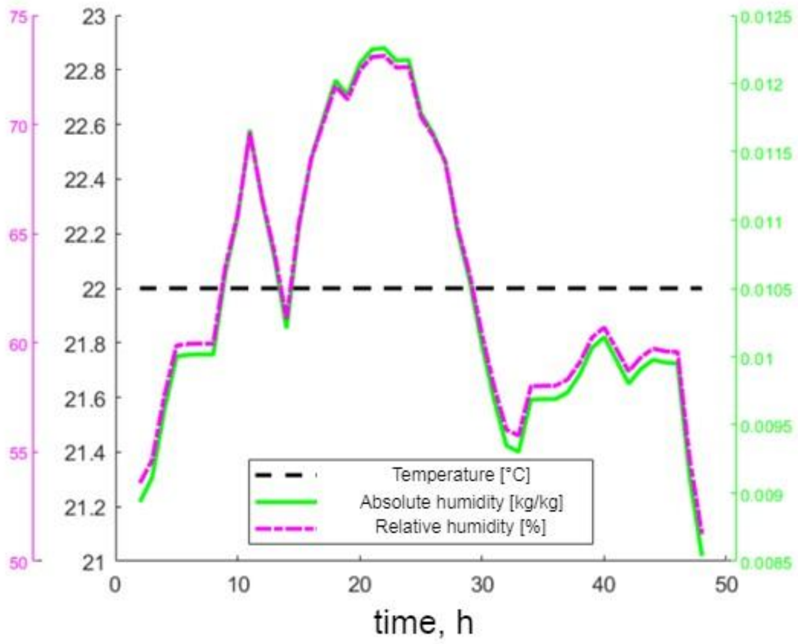

Fig. 16. Air parameters at point P4

In next step it should be calculated the previously omitted point P7, this is necessary to estimate the heat transferred by the heater and the cooling efficiency coefficient COP and EER. The results for calculated point P7 are shown in Fig. 17.

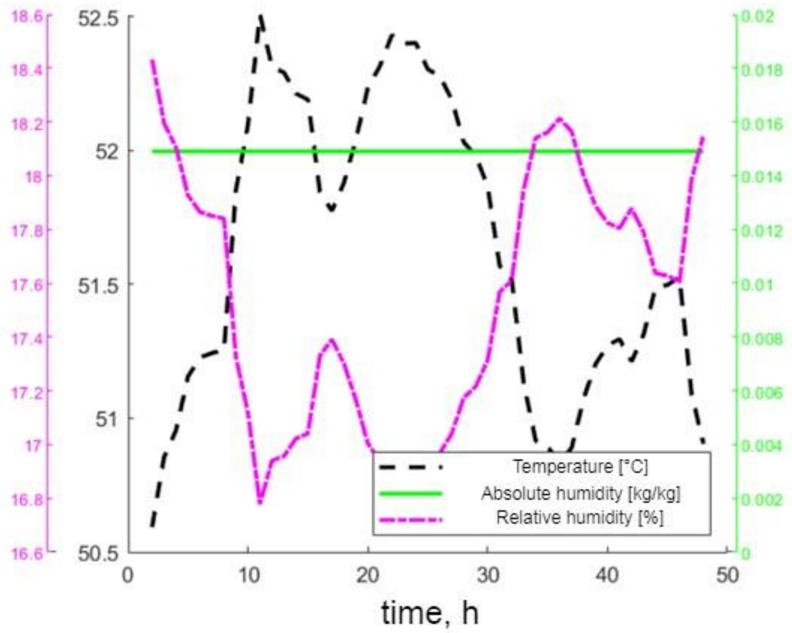

Figure 17. Air parameters at point P7

Then the air flows through the heat exchanger, which heats it to the temperature that regenerates the sorption rotor, using the heat from the heater. The heat capacity provided by the heater is described by the eqation:

$$\dot{Q}_h = (\dot{m}_{dry,air} \cdot c_{dry,air} + \dot{m}_{H2O} * c_{p,H2O}) * (T_8 - T_7) \quad (11)$$

Required heat capacity is shown in Fig. 18.

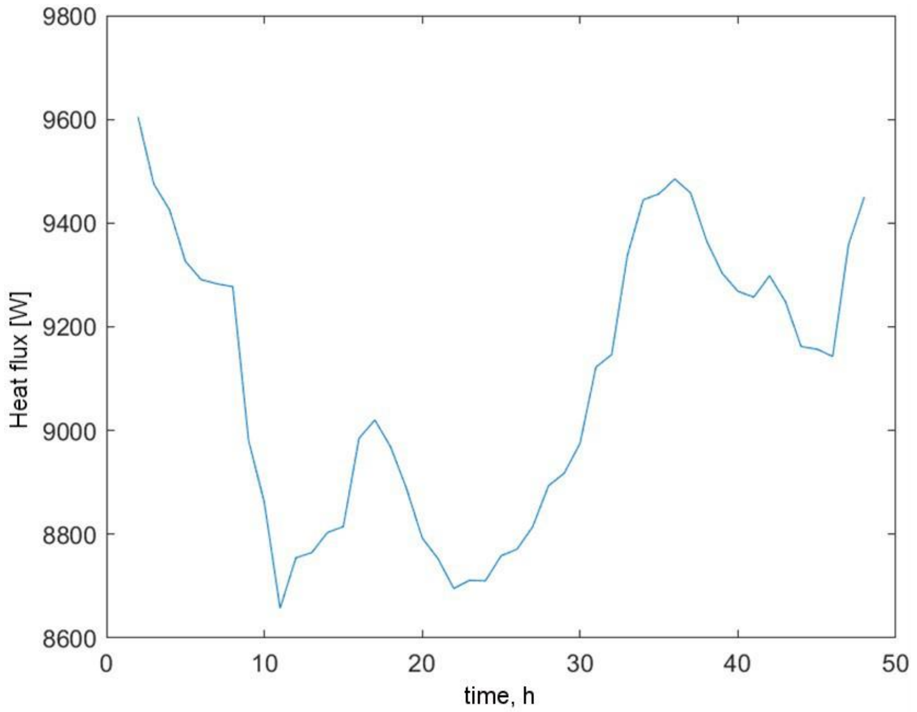

Fig. 18. Required heat capacity

In the next step there was calculated EER (Energy efficiency ratio). It is the ratio of the cooling power to the power consumed by the device. In this case, the cooling capacity depends on the temperature difference P1 and P4, and the capacity consumed by the the heater. The EER coefficient for the DEC system is described by the equation:

$$EER = \frac{\dot{Q}_{cold}}{\dot{Q}_h} = \frac{\dot{Q}_{P1-P4}}{\dot{Q}_h} \tag{12}$$

Obtained value of EER has been shown in Fig. 19.

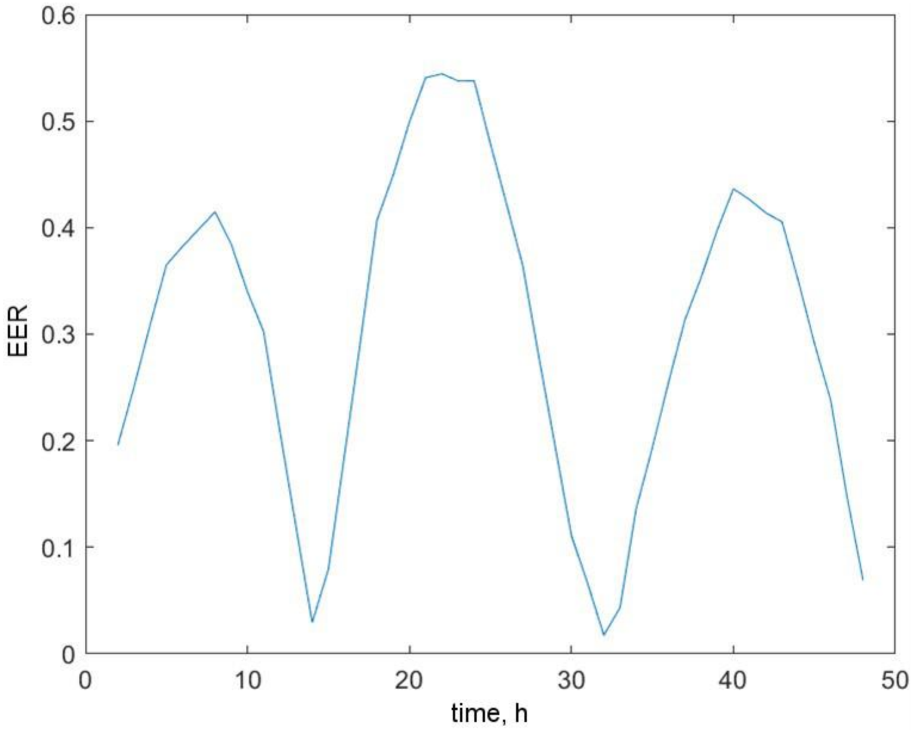

Fig. 19. EER coefficient of the DEC system

Such a large variability of the EER coefficient results from the characteristics of the simulation model. Although the cooling capacity changes significantly with changes in external air temperature, the capacity provided by the heater changes to a much lesser extent. The model assumes a constant regeneration air temperature, independent of the outside temperature and humidity. A real facility could have automation that manipulates the temperature at point P8 and, consequently, the capacity supplied by the heat source. For more favorable weather conditions, i.e. lower temperature and humidity, the regeneration air temperature could be lower. This would allow for an increase in the value of the EER coefficient when it is lowest. Similarly, in the opposite situation, for high external air temperature and humidity, the regeneration temperature could be higher than the assumed 70ºC.

5.2. The influence of parameters on the operation of the DEC system

This chapter will present an analysis of selected parameters influence on the DEC system. There will be considered:

- rotation time of desiccant and thermal rotors,
- regeneration air temperature,
- air flow rate,
- outdoor air humidity and temperature.

The role of the thermal rotor is to best transfer heat between the streams in order to cool the air directed into the room. Its rotational speed should be adapted to this purpose. The relationship between the rotor rotation time and its temperature distribution is shown in Fig. 20. It can be noticed that for longer rotation time the temperature of the rotor section begins to stabilize after some time after entering the air stream. This means that the average temperature difference between the rotor and the air flow rate is smaller and, consequently, the transferred heat capacity is also smaller. To maximize the efficiency of the heat rotor, aim for lower rotation time values.

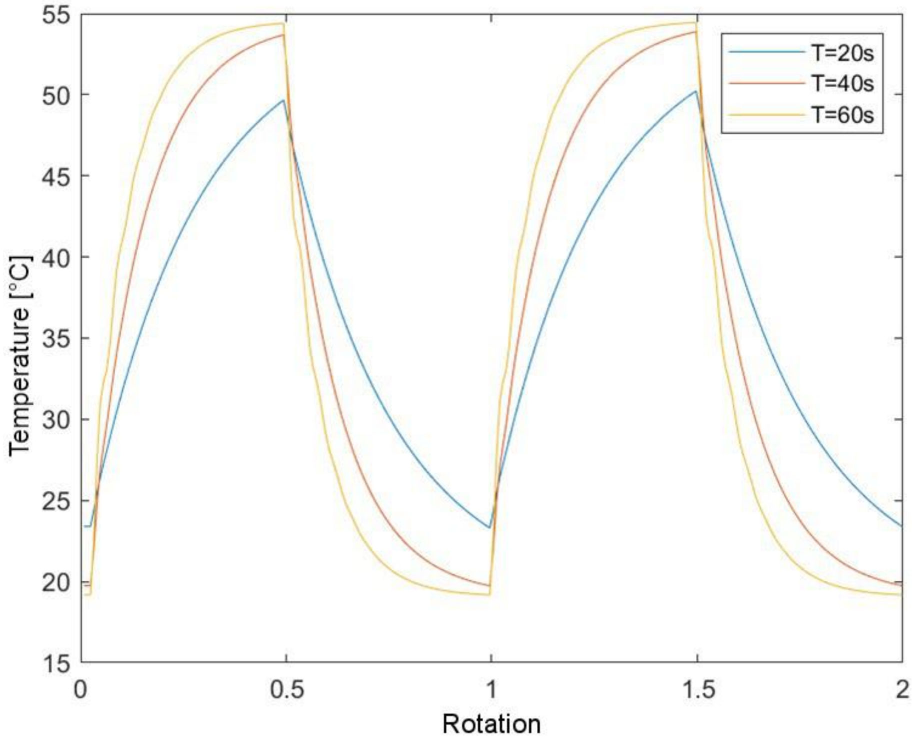

Fig. 20. The influence of the rotation time on the thermal rotor

The desiccant rotor also transfers heat, which is necessary for the sorption drying process, but the increase in air temperature in the rotor is a by-product and undesirable. The ideal rotational speed in this case should ensure the largest possible stream of moisture transferred between the streams. The dependence of this flux on the rotation period is shown in Fig. 21. It can be seen that longer rotation time ensure better moisture exchange without heating the air behind the rotor too much, so they will be more optimal for the desiccant rotor.

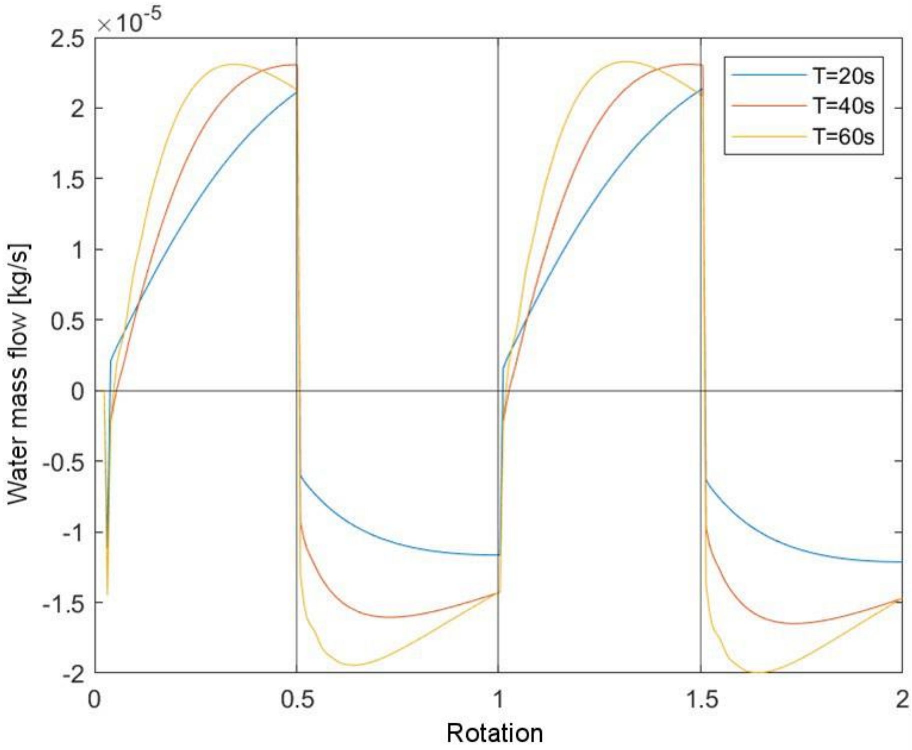

Fig. 21. The influence of the rotation time on the desiccant rotor

The stream of water transferred between air streams can also be made dependent on the temperature of the regeneration air. It can be controlled, for example, by turning the heater off and on, thereby changing the temperature of the medium flowing through the heat exchanger. This relationship is shown in Fig. 22.

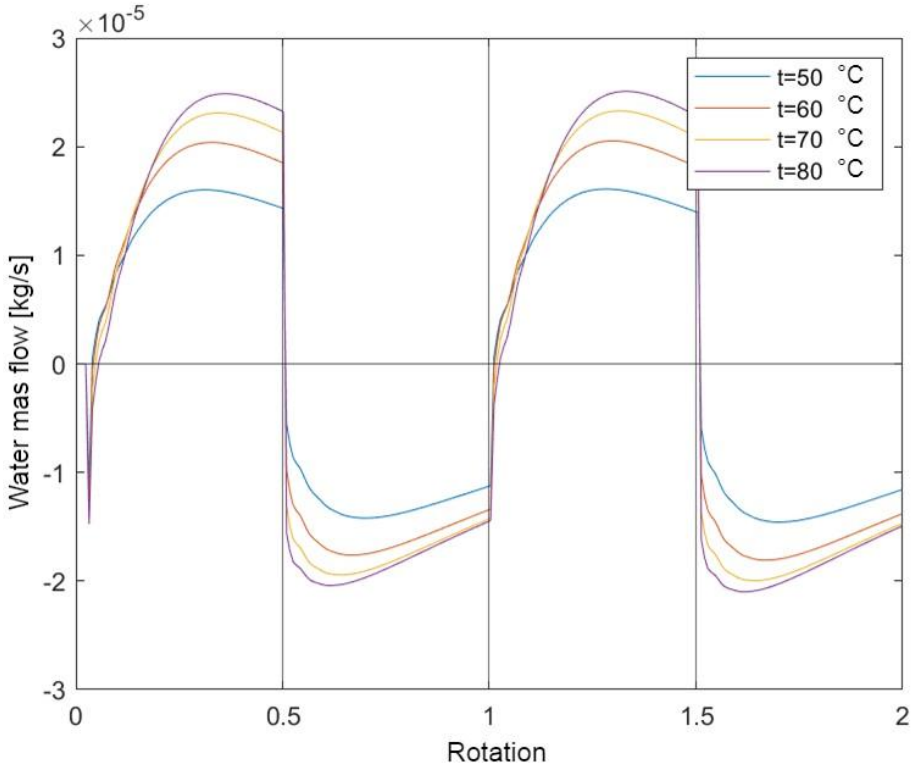

Fig. 22. The influence of regeneration air temperature on the adsorption/desorption process

Evidently, higher temperatures improve the desiccation drying process. However, the higher the temperature, the further its increase does not bring such benefits. At the same time, the energy consumption of the device also depends on this temperature. It can therefore be concluded that by increasing the regeneration temperature more and more, the positive effect on the sorption drying process would be smaller than the negative effect on the consumed heater power. 70ºC seems to be a reasonable compromise, but the best solution would be to manipulate this value depending on weather conditions.

6. Conclusions

In conclusion, this study sheds light on the intricacies of desiccant-based air conditioning systems and their optimization for energy efficiency. The research underscores the critical influence of ambient conditions, particularly temperature and humidity, on system performance.

Utilizing a comprehensive simulation model, factors contributing to the variability of the Energy Efficiency Ratio (EER) coefficient have been elucidated, emphasizing the need for dynamic control mechanisms.

Findings suggest that adjusting regeneration air temperature based on prevailing weather conditions holds significant potential for enhancing system efficiency. Manipulating regeneration temperature offers a favorable balance between desiccation drying effectiveness and energy consumption. Temperature-dependent control mechanisms provide a promising avenue for improving system performance while minimizing operational costs.

Furthermore, testing of desiccant rotor operation highlights the importance of optimizing heat transfer to maximize moisture exchange without undesired temperature elevation. Longer rotation time demonstrate superior moisture exchange capabilities while avoiding excessive heating of the air behind the rotor, presenting a more optimal solution for desiccant rotor operation.

Moreover, analysis reveals that while higher temperatures contribute to improved desiccation drying, a threshold exists beyond which further temperature increments yield diminishing returns. Maintaining a balance between temperature enhancement and energy consumption is paramount for achieving optimal system performance.

In summary, this study advocates for dynamic control strategies adapting to changing environmental conditions, thereby maximizing energy efficiency in desiccant-based air conditioning systems. Implementing temperature-dependent control mechanisms and optimizing desiccant rotor operation can realize significant advancements in system performance and energy savings..

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