

Article

Optimisation of Operation of Adsorption Chiller with Desalination Function

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Abstract: The demand for electricity is growing rapidly along with economic development and increasing population. At present, its production is mainly based on non-renewable sources, which has negative impacts on the environment and contributes to global warming. A large proportion of the produced electricity is consumed by refrigeration equipment. Climate change and the progress of civilisation are additionally increasing the demand for cooling, with increasing electricity consumption as a consequence. One of the options for obtaining eco-friendly cooling is the use of adsorption chillers. These devices are powered by low-temperature heat and their operation only requires a small amount of electrical energy. The source of low-temperature heat can be, e.g., waste heat generated in many industrial processes. Its use allows one to increase energy efficiency and achieve additional financial benefits. However, adsorption chillers are characterised by low coefficients of performance. This paper presents possibilities to improve their performance. It also presents the results of tests carried out on a three-bed adsorption chiller with desalination function. The aim of the investigation was to determine the effect of the cycle time on the coefficient of performance (COP) and specific cooling power (SCP). The working pair was silica gel and water. The results confirmed the effect of the duration of adsorption and desorption on the COP and SCP of the adsorption chiller. Increasing the duration of the cycle led to an increase in the COP.



Citation: Sztekler, K. Optimisation of Operation of Adsorption Chiller with Desalination Function. *Energies* **2021**, *14*, 2668. <https://doi.org/10.3390/en14092668>

Academic Editor: David Borge-Diez

Received: 29 March 2021

Accepted: 4 May 2021

Published: 6 May 2021

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Keywords: adsorption; chiller; desalination

1. Introduction

Dynamic economic development, population growth and observed climatic changes imply that the demand for cooling will be growing every year. Cooling processes are used in many industries, such as in the food industry for food production and storage, the pharmaceutical industry, heavy industry and power generation [1]. Refrigeration units using thermal compression and using adsorption and desorption processes are modern alternatives to the most commonly used conventional electrically driven compressor refrigeration systems. The need to seek innovative solutions for the refrigeration industry has been dictated, among other things, by the necessity to save electricity and reduce the environmental impact.

The market for refrigeration equipment is growing steadily. Data from the International Institute of Refrigeration (IIR) show that there are currently over 5 billion refrigeration units and heat pumps in operation globally [2]. In 2016, more than 1.6 billion air conditioning units were in use, of which more than half were located in the United States and China alone [3]. Middle Eastern countries are a particularly important market. The demand for cooling is extremely high there due to the very warm climate. It is estimated that almost 100% of households in the Middle East are equipped with air conditioning [3]. The data quoted above clearly show the scale of the use of cooling devices and, consequently, the energy consumption related to their operation. In this context, it is particularly important that the vast majority of the units in use are compressor systems driven by electricity [1]. According to the report of the International Institute of Refrigeration in Paris, the refrigeration sector consumes approximately 20% of the world electricity production [2]. On the

other hand, estimates of the International Energy Agency (IEA) indicate that the share of air conditioning equipment in the global electricity demand was approximately 10% in 2016 [3]. During peak cooling demand in summer, this value can increase significantly [3]. Taking into account that global electricity production is mainly based on non-renewable sources, it can be concluded that the refrigeration sector indirectly contributes to accelerating the rate of adverse climate change [4].

Adsorption chillers can be powered by the low-temperature waste heat with temperatures in the range of 60 °C to 90 °C or by the heat from solar energy, and therefore they are characterised by very low electricity consumption [1,5,6]. Furthermore, adsorption chillers can operate at low temperatures, which additionally contributes to the reduction in thermal energy losses. Many processes in various industries emit energy which is lost to the atmosphere unless it is recovered. In thermal power plants, approximately 50–70% of the energy value of the fuel is rejected as waste heat [6]. In such cases, one of the possibilities of using waste heat is the production of cold energy in adsorption chillers [1]. The use of this type of equipment offers the possibility of creating polygeneration systems capable of producing electricity, heat and cold simultaneously [7]. In addition to reducing the negative impact of greenhouse gas emissions, energy recovery can also bring significant financial benefits [1]. A very important feature of adsorption chillers in the context of environmental care is the use of non-ozone-depleting refrigerants such as water [5]. It is a cheap, widely available, safe and the most thermally stable adsorbate which extends the applicability of adsorption chillers to water desalination [8,9].

Moreover, in addition to several previously mentioned advantages, adsorption chillers are characterised by easy and quiet operation and a small number of moving mechanical parts, which makes them especially valuable in applications where reliability of the devices is very important [8,10]. Replacing an electric compressor with a thermal compressor has the advantage of no vibration, thus opening up many new application possibilities [11]. Despite there being so many advantages of using adsorption chillers, there are also some limitations. These include the low coefficient of performance (COP) compared to conventional refrigeration systems, which is usually between 0.5 and 0.6, the low specific cooling power (SCP), and the small mass and heat flow inside the bed [8,12]. All of these are related to the large mass and dimensions of adsorption chillers [6,13]. Continuous research is being conducted to improve the efficiency of adsorption chillers so as to make them more attractive and competitive in the market. In a later part of the paper, a number of methods to improve the performance parameters of adsorption chillers are presented.

One of the disadvantages of the materials used is that the highly porous adsorbents have relatively lower thermal conductivity [8]. At the same time, this is a field of searching for new solutions that take into account the balance between good thermal conductivity and sufficiently high sorption capacity [8,14]. Sorption materials that can work with water are, e.g., silica gel, zeolite and activated alumina [15]. Some very important characteristics of the sorbents are the ability to adsorb a maximum amount of adsorbate per unit mass and a low specific heat [8,15]. Particularly important from the point of view of the heat source and chiller operation is the bed regeneration temperature. This is also one of the characteristics of the sorption materials and can be different for different materials [12,15]. Furthermore, adsorbents must be non-toxic, durable, readily available and cheap [8,14,15]. The high porosity of such materials is an important characteristic from the point of view of sorption properties, but it negatively affects heat conduction [15].

An adsorption chiller with desalination function can be characterised by several key parameters. These include the coefficient of performance (COP), the specific cooling power (SCP) and the specific daily water production (SDWP) [16,17]. These indicators depend on many factors. Some of them, such as bed regeneration temperature, chilled water temperature or cycle time, can be easily modified in order to obtain the optimal values. These will vary depending on the design of the chiller, the resources available and the desired effect. This paper analyses the impacts of these factors on the COP. In addition to the above-mentioned possibilities of enhancing performance, there are also some other

factors which are strictly related to the design of the chiller and the properties of the adsorbent bed. These include improving the heat exchange efficiency inside the bed and the utilisation of heat and mass recovery in the system [6,7,14]. The former method can be divided according to the three keyways of its implementation:

- Improving heat transfer between the heat exchanger and the sorbent [12,18];
- Improving heat transfer in the sorbent [7];
- Using modern porous materials as sorbents [12].

A typical material that heat exchangers are made of is copper, characterised by a high thermal conductivity coefficient of 380 W/(mK) [12]. Additionally, the most commonly used adsorbent is silica gel, which has a thermal conductivity coefficient of merely 0.17 W/(mK) [12]. The significant difference in the value between these two materials means that heat transport in the boundary zone is hindered. One possible way to improve heat transfer in this area is, e.g., by coating the silica gel layer in contact with the heat exchanger surface with a binder [12]. In addition, increasing the heat transfer area as a result of using different exchanger designs also results in greater heat transfer between the exchanger and the adsorbent. Various design options for heat exchangers in an adsorbent bed have been presented in the paper [18].

An effective way to enhance heat transfer inside the bed is by doping the sorbents with materials with a higher coefficient of thermal conductivity [7,12]. Increasing the thermal conductivity of the bed can shorten the cycle time [19]. These can be, e.g., metal powders with a smaller grain size than the sorbent grains, which additionally allows one to reduce the amount of voids filled with still air in the bed [12]. The results of research on increasing the coefficient of thermal conductivity of the bed by doping silica gel with aluminium, copper and carbon nanotube powders are presented, among others, in the article [7]. The aim of that study was to check the influence of additives characterised by a high coefficient of thermal conductivity on the sorption kinetics of the mixture obtained [7]. Improved heat exchange in the bed can also be achieved by using modern sorption materials which combine good thermal conductivity with high sorption capacity. An example of this type of materials can be hybrid MOFs (metal–organic frameworks) [12].

Improved chiller performance can be achieved by using a number of methods related to heat recovery [6,20]. The idea of heat regeneration is to use the heat from the warmer bed being cooled in order to preheat the next bed. Likewise, the fluid circulating in the cooling circuit can be used to preheat another bed after the cooling of one bed [20]. Many advanced heat recovery cycles have been proposed in various publications. These include, e.g., the thermal wave cycle, the forced convection thermal wave cycle and the cascade cycle [6].

The right cycle time is one of the most important parameters of an adsorption chiller. Its length determines the amount of adsorbate flowing from the evaporator to the bed or from the bed to the condenser. It is absolutely vital to prevent a situation where this time will be too short because too little adsorbate will then evaporate into the bed or into the condenser. Too low a time of adsorption and desorption results in the inadequate temperature of chilled water and reduced production of desalinated water. On the other hand, too long desorption time may lead to unnecessary energy consumption for heating the bed and its components without resulting in more desorbed adsorbate. As a result, the number of cycles that can be performed during one day is also reduced [21]. COP increases with longer cycle time, because the increasing time is associated with the reduction in heat consumption, which powers the adsorption chiller [22,23]. Moreover, longer cycle times contribute to achieving a lower cooling capacity (CC) [24]. The effect of the cycle time on the value of the cooling capacity was investigated by Saha et al. [24]. In this study, the highest value of CC was obtained for the duration of adsorption/desorption equal to 180–300 s [24]. One of the ways of influencing the efficiency of the adsorption chiller by manipulating the cycle time is to shorten the bed regeneration time in relation to the time allocated for adsorption, due to the fact that it can run 2–3 times faster than adsorption (for monolayers) [25]. The influence of the ratio of desorption time to adsorption time on the

efficiency of the refrigerator was investigated by El-Sharkawy et al. [26]. It was indicated that the optimal value of the coefficient f will be variable for various operating conditions and the design of adsorption chillers. However, it has been noticed that the efficiency will increase if this coefficient is lower than one [26].

Adsorption chillers are the solution that can not only become a source of eco-friendly cooling but also contribute to reducing the problem of freshwater scarcity. The shortage of potable water is becoming an increasingly common problem globally. It is estimated that freshwater available to humans only accounts for approximately 0.75% of the Earth's total water supply [27]. The UN predicts that nearly 5.7 billion people could be affected by water scarcity by 2050 [28]. Continued population growth, the expanding economy and ongoing climate change are all contributing to an increase in water demand [28]. Water treatment is therefore required to meet this demand. The oldest desalination technologies have been used for decades [29]. Nowadays, however, conventional desalination processes are considered the most energy-intensive water treatment options [30]. For this reason, it is necessary to develop modern technologies that do not require such high energy inputs. One such possibility is the use of adsorption chillers for water desalination. Table 1 shows the specific energy consumption (SEC) for different desalination methods. The adsorption desalination technology is characterised by the lowest electricity consumption compared to conventional methods such as multi-stage flash (MSF), multi-effect distillation (MED) and seawater reverse osmosis (SWRO) [16,31].

Table 1. Comparison of energy consumption for selected desalination technologies. AD: adsorption; MSF: multi-stage flash; MED: multi-effect distillation; SWRO: seawater reverse osmosis.

Desalination Method	Electrical Energy Consumption (kWh/m ³)	Thermal Energy Consumption (kWh/m ³)	Ref.
AD	<1.5	39.8 (waste or solar heat)	[16,31]
MSF	3.5–5	69.44–83.33	[16]
MED	1.5–5	41.67–61.11	[16]
SWRO	4–6	-	[31]

Using saline water as adsorbate, after condensation in a condenser, purified and desalinated water is obtained, which is almost free of dissolved solids [32]. One example of an adsorption desalination plant in operation is the world's largest adsorption chiller with desalination function located in Solar Village near the capital of Saudi Arabia, Riyadh [33]. It has a desalinated water production capacity of 100 m³/day. The outstanding achievement in comparison to other desalination technologies in this case is the very low unit price of water, which is below USD 0.40/m³ of water. This is due to the very low power consumption of the plant, which amounts to about 1.2 kWh/m³ [34]. The cooling capacity of the unit is 1070 kW [33].

This paper presents the results of an experimental tests carried out for a laboratory three-bed adsorption chiller with desalination function in which the first and the second beds were synchronised carrying out the same adsorption or desorption processes at the same time while the third bed worked in the opposite phase. The study was designed to test the effect of cycle time on the value of the coefficient of performance (COP) and specific cooling power (SCP).

2. Materials and Methods

2.1. Adsorption Chiller with Desalination Function

The investigation was carried out on a three-bed adsorption chiller with desalination function located at the Energy Centre of the AGH University of Science and Technology in Krakow, Poland. The system investigated can operate in either a cooling or a desalination mode. The adsorption chiller can operate with, both, two-bed or three-bed mode. Such a design of the device allows one to carry out tests in various configurations of beds with different beds synchronised with each other in each variant. The use of multi-bed systems

increases the stability of the chiller operation and enables the adsorption and desorption to be carried out in a cyclic manner. It has been proven that the use of a 4-bed chiller increases their recovery efficiency by 70% as compared with a 2-bed chiller operating under the same conditions [20]. At the same time, a six-bed design has a 40% higher recovery efficiency as compared with the four-bed design [20].

Table 2 summarises the basic parameters of the adsorption chiller investigated. The chiller can produce chilled water with a temperature of up to 7 °C and up to 1.5 kW of cooling. The pressure in the evaporator, condenser and beds reaches values in the range of 0.5–3 kPa, 3–7 kPa and 0.5–7 kPa, respectively.

Table 2. Basic nominal parameters of the investigated three-bed adsorption chiller with desalination function.

Chiller Components	Parameter	Value	Unit
Evaporator	Cooling capacity	1.10	kW
	Chilled water inlet temperature	12	°C
	Chilled water outlet temperature	7	°C
	Chilled water mass flow	0.052	kg/s
Condenser	Capacity	2.00	kW
	Cooling water inlet temperature	20	°C
	Cooling water outlet temperature	22	°C
	Cooling water mass flow	0.250	kg/s
	Daily distillate production	40	kg

The basic adsorbent used in the unit concerned is silica gel, which in this case is provided by KD Corporation from the Republic of Korea while the adsorbate is water regardless of the mode of operation of the chiller. Table 3 shows the basic properties of silica gel, while Figure 1 shows the water vapor adsorption–desorption isotherms of the tested silica gel, determined from the DVS Vacuum apparatus data.

Table 3. Properties of silica gel.

Sorbent	Granulation (µm)	Bulk Density (g/mL)	Specific Surface Area (m ² /g)	Pore Volume (cm ³ /g)	Pore Diameter (Avg. Value) (nm)	Thermal Conductivity (W/(mK))
KD Corporation—silica gel	700–800	0.73	750–800	0.44	1.0–3.0	0.177

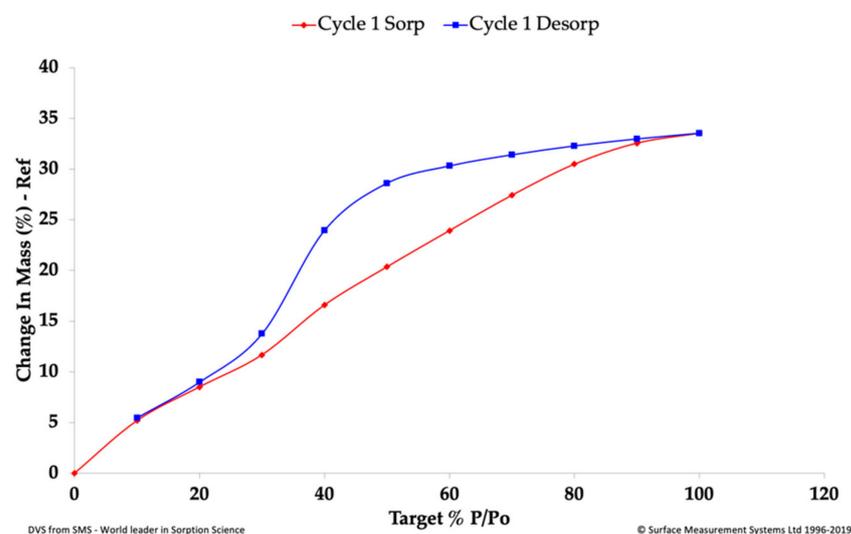


Figure 1. Water vapor adsorption–desorption isotherms on the SG sorbent for the temperature of 35 °C.

Figure 2 shows a simplified diagram of the investigated adsorption chiller with desalination function. The diagram shows its most important components, circuits and points representing measuring devices responsible for the measurements of temperature, pressure and flow rate.

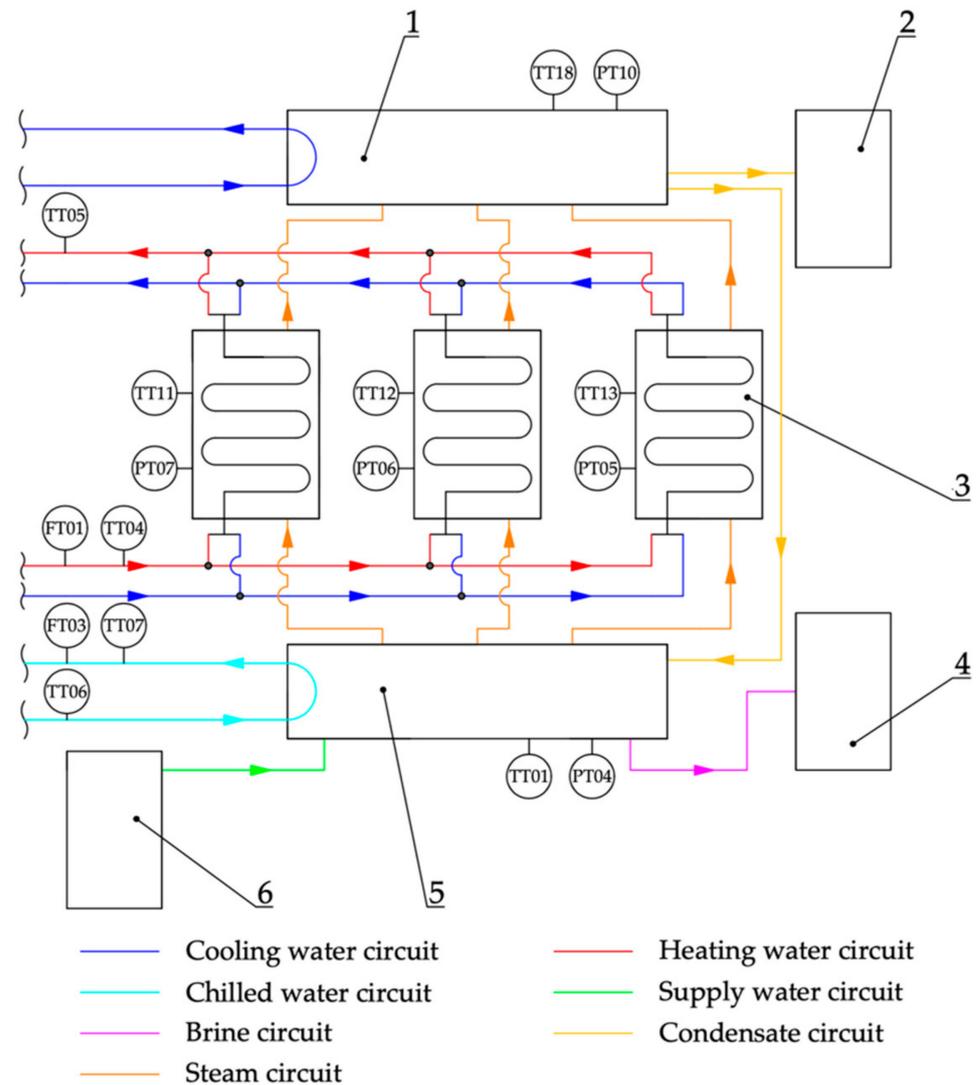


Figure 2. Simplified diagram of the three-bed adsorption chiller with desalination function used in the investigation. 1—condenser; 2—distillate tank; 3—adsorbent bed; 4—brine tank; 5—evaporator; 6—deaerator; TT01—temperature in the evaporator; TT04—hot water inlet temperature; TT05—hot water outlet temperature; TT06—chilled water inlet temperature; TT07—chilled water outlet temperature; TT11—temperature in bed 1; TT12—temperature in bed 2; TT13—temperature in bed 3; TT18—temperature in the condenser; PT04—pressure in the evaporator; PT07—pressure in bed 1; PT06—pressure in bed 2; PT05—pressure in bed 3; PT10—pressure in the condenser; FT01—hot water flow; FT03—chilled water flow.

The main components of the chiller are three adsorption beds (3), an evaporator (5) and a condenser (1). Each bed is equipped with a finned Tichelmann lamella exchanger with a total length of 880 mm and a total width of 450 mm. The construction of the evaporator and condenser is cylinder-shaped with a length and diameter of 1500 and 350 mm and 1450 and 220 mm, respectively. In addition, the system is equipped, among other things, with a distillate tank (2), a brine tank (4), a deaerator (6) and an expansion valve not shown in the figure. Fluids in various forms and under different conditions flow through the system in seven main circuits.

In the first stage, the salted water is deaerated in the deaerator and flows to the evaporator. In the evaporator, there is a system of pipes responsible for absorbing the heat from the outlet chilled water and transferring it to the supplied salt water. As a result, water in the evaporator changes its state of matter and evaporates. This process takes place at a low temperature, which is made possible by the appropriately low absolute pressure inside the evaporator. The evaporated water is transported from the evaporator to the adsorbent bed, thus starting the adsorption phase. Adsorption is an exothermic process. Therefore, the heat generated in the bed must be dissipated into the cooling water. This ensures that the correct adsorption temperature is maintained so that vapour adsorption occurs most efficiently [32]. Once adsorption is complete, the valve between the evaporator and the bed is closed and the adsorber pre-heating phase begins. Three-way valves are set so as to allow heating water to flow through the bed. The heating water reaches the required temperature in an 18-kW electric boiler simulating a source of low-temperature heat. The heated water flows into the buffer tank, from which it is then led to the beds in the regeneration phase. The boiler works periodically, keeping the water temperature at the set value. When the temperature in the bed reaches the required value, the desorption process takes place. Water in the heating circuit is still supplied to the heat exchanger in the bed. Water previously adsorbed on the surface of the silica gel desorbs and increases its pressure due to the thermal energy supplied. The valve between the bed and the condenser is opened and the resulting gas phase flows into the condenser, where it condenses by giving up its heat on the surface of the exchanger, through which cooling water flows. Depending on whether the adsorption chiller is in the cooling or the desalination mode, the condensate formed in the lower part of the condenser can flow through the expansion valve back to the evaporator to form a closed circuit, or it can be collected in the distillate tank. The expansion valve is responsible for maintaining the pressure difference between the condenser and the evaporator during the flow of condensate. The bed is then cooled before the next cycle. The cooler allows the heat to be recovered from the water that heats the adsorber during desorption. When the three-way valve is set correctly, cooling of the bed with cooling water begins. Then, water is supplied for some time to the heating water circuit so that as little as possible of the heat still gathered inside the bed is lost. Figure 3 shows photos of the investigated adsorption chiller with desalination function.

2.2. Measuring Instruments

The system in question is equipped with a system of measuring apparatus which allow the necessary parameters to be measured. During the testing, the temperature, pressure and flow rate were measured. Figure 2 schematically shows the location of the measuring points and they are marked with a description. Table 4 presents the parameters of the measuring instruments used. The measurements of temperature in the evaporator TT01, hot water inlet temperature at the beds TT04, hot water outlet temperature at the beds TT05, chilled water inlet temperature at evaporator TT06, chilled water outlet temperature the evaporator TT07, temperature in the beds TT11–TT13 and in the condenser TT18 were made using PT-1000 temperature sensors. Pressure values in the evaporator PT04, in the condenser PT10 and in the beds PT05–PT07 were measured using a pressure transducer. Flow rates of chilled water FT03 and hot water FT01 were measured using an electromagnetic flow meter.

Table 4. Characteristics of measuring apparatus.

Parameter Measured	Instrument	Operating Range	Accuracy
Pressure	Pressure transducer	0–99 kPa	0.50%
Flow rate	Electromagnetic flow meter	1–100 L/min	0.50%
Temperature	Temperature sensor PT-1000	−80 °C to 150 °C	0.1 °C

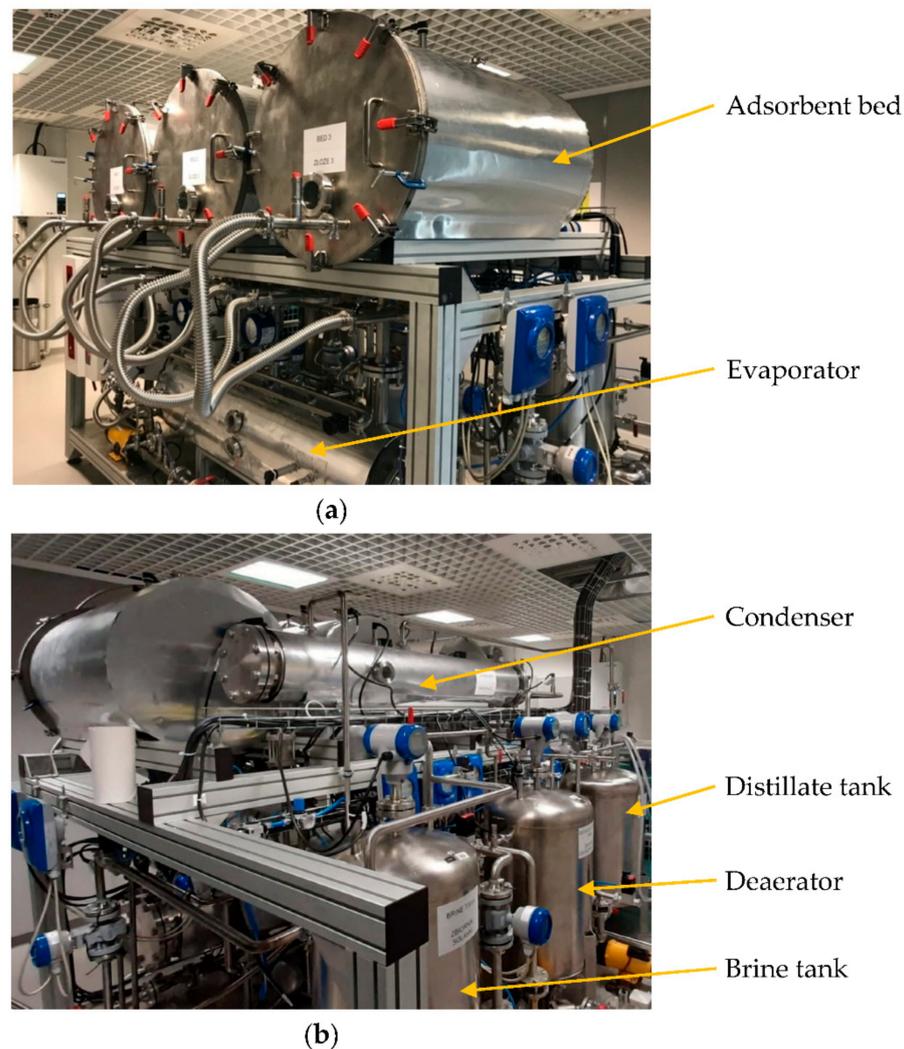


Figure 3. Three-bed adsorption chiller with desalination function used in the investigation: (a) front view, (b) back view.

All parameters were recorded during the steady-state operation of the adsorption chiller. The time from switching on the device to achieving steady-state parameters was approximately 1 h. The values displayed by the measuring instruments were saved every 5 s using the SCADA control system on a personal computer. Analysis of the results obtained was possible by exporting them to csv format in tabular form and then running them in Microsoft Excel.

The measuring devices and transducers are powered from a special switchgear. The system is equipped with control system software which enables the users to control all the pumps and valves and records the measurements. In addition, it is possible to set the duration of each phase, including half-cycle time and heat recovery time. The system includes manual ball valves (1/2-inch, 3/4-inch) and pneumatic valves between the evaporator and the beds, as well as the beds and the condenser. In addition, circulation pumps with a capacity of 0–500 L/h for heating, cooling and chilled water, are present in the plant.

2.3. Conditions for Conducting the Experiment

The study was designed to analyse the effect of different cycle times on the performance of the adsorption chiller. The experiment was conducted on a chiller using all three of the available beds. Beds 1 and 2 were operated in synchronisation with each other, while bed 3 was operated in the opposite phase. This paper presents the results of tests for

heating water temperature of 80 ± 3 °C and for various cycle times conducted under the same conditions. This study is focused on the determination of COP and SCP for different cycle times. In article [5], the effect of different heating water temperatures in the range of 55 °C to about 80 °C on the COP and SCP of a three-bed adsorption chiller was investigated. The COP and SCP increased with increasing heat source temperature and have the high value for the temperature of heat water of about 80 °C [5]. Therefore, for this temperature, tests were performed. Thus, adsorption occurred at the same time in the first and second beds while desorption was carried out in bed 3, or the other way around. Six different cycle times were analysed: 100, 200, 300, 500, 600 and 900 s. The dependence of the COP, SCP and other parameters of the adsorption chiller on the cycle time was tested.

The COP and SCP were calculated, based on [35], according to Equations (1) and (5) which are shown below:

$$\text{COP} = \frac{\text{CC}}{\text{HP}} \quad (1)$$

$$\text{CC} = \dot{m}_c \cdot c_{p,c} \cdot \Delta T_c = \dot{m}_c \cdot c_{p,c} \cdot (T_{i,c} - T_{o,c}) = \text{FT03} \cdot c_{p,c} \cdot (\text{TT06} - \text{TT07}) \quad (2)$$

$$\text{HP} = \dot{m}_h \cdot c_{p,h} \cdot \Delta T_c = \dot{m}_h \cdot c_{p,h} \cdot (T_{i,h} - T_{o,h}) = \text{FT01} \cdot c_{p,h} \cdot (\text{TT04} - \text{TT05}) \quad (3)$$

$$c_{p,h} = c_{p,c} = 4200 \frac{\text{J}}{\text{kg} \cdot \text{K}} \quad (4)$$

$$\text{SCP} = \frac{\text{CC}}{m_a} \quad (5)$$

Equations (1)–(5) use symbols with the following meanings: CC—cooling capacity, (W); HP—heating power supplied to the system, (W); m —flow rate, (kg/s); c_p —specific heat of water; T —temperature, (°C); m_a —the mass of sorbent, which was 12 kg. The indices used in the equations are: c—chilled water; h—heating water; i—inlet; o—outlet.

The cooling capacity is determined from the parameters of chilled water flowing through the evaporator. A 2 °C difference in evaporator inlet and outlet temperatures allows one to achieve a cooling capacity of 1.5 kW.

3. Results

Figures 4–9 show the distribution of pressures in all of the three beds, the condenser and the evaporator for each cycle time tested.

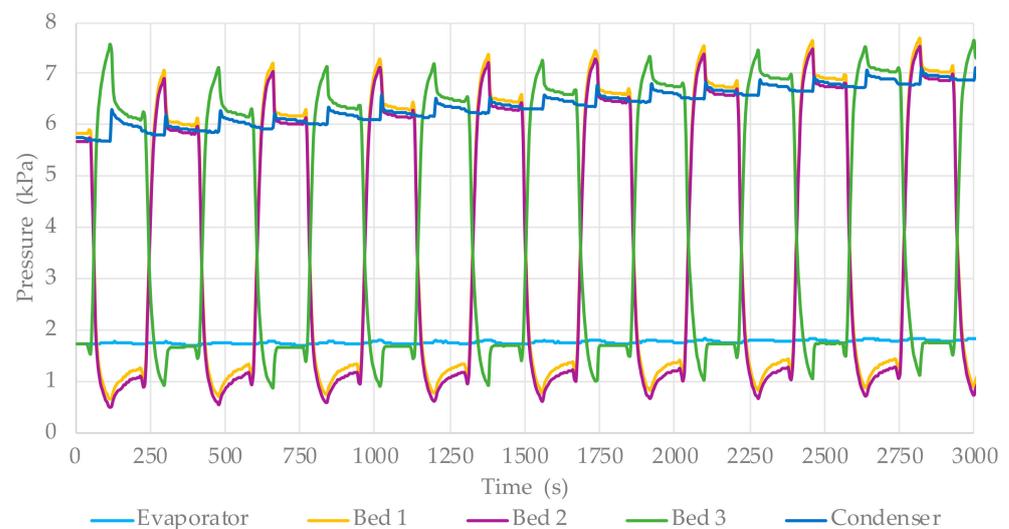


Figure 4. Pressure for cycle time = 100 s.

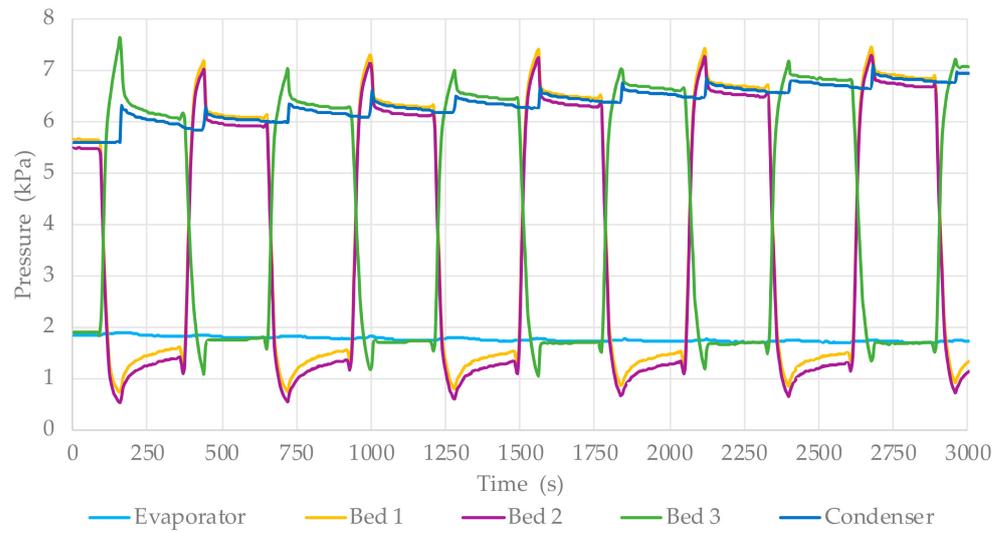


Figure 5. Pressure for cycle time = 200 s.

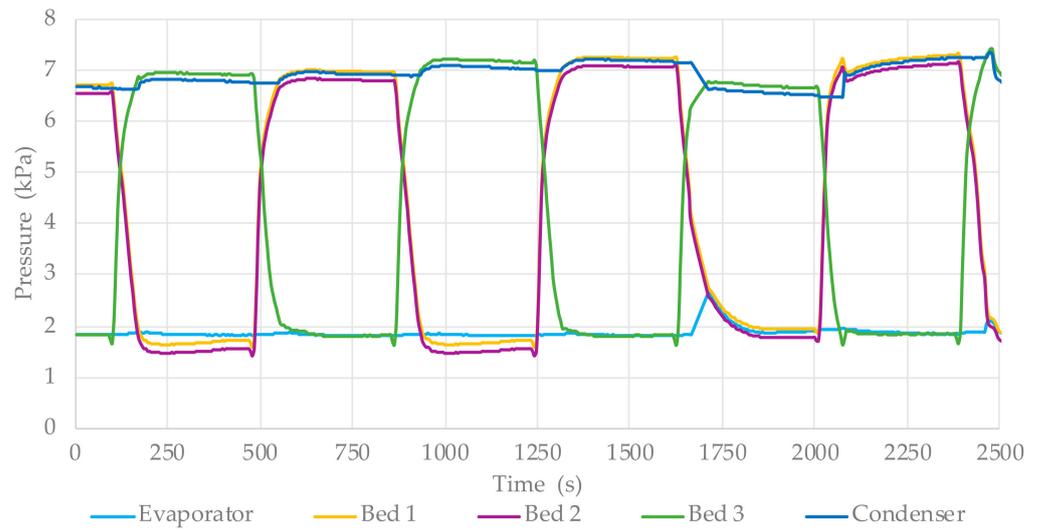


Figure 6. Pressure for cycle time = 300 s.

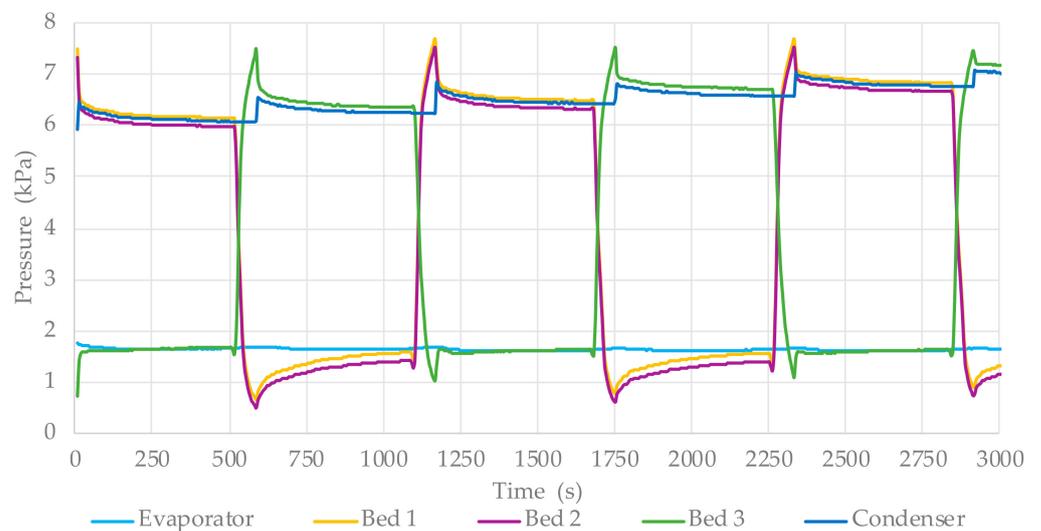


Figure 7. Pressure for cycle time = 500 s.

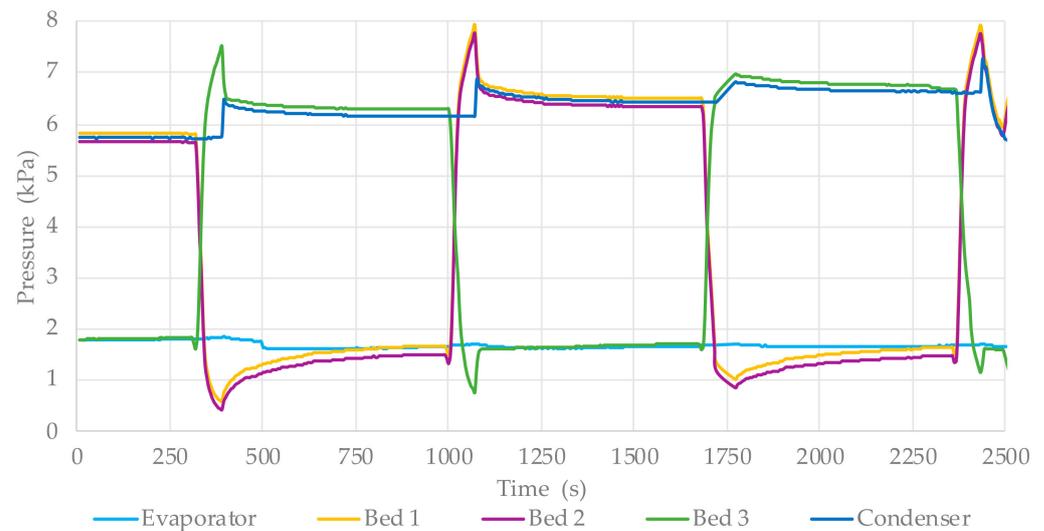


Figure 8. Pressure for cycle time = 600 s.

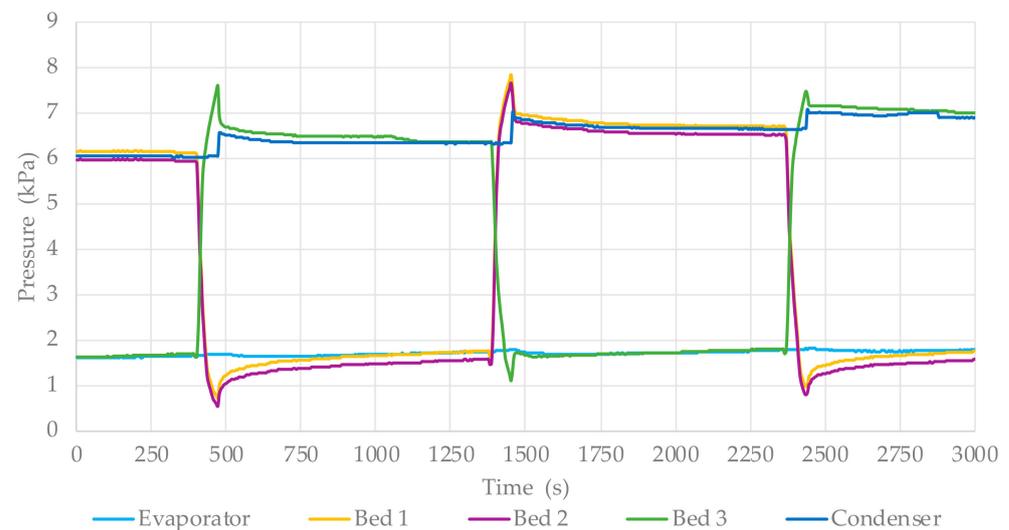


Figure 9. Pressure for cycle time = 900 s.

The beds marked with numbers 1 and 2 were synchronised with each other, which means that adsorption and desorption occurred at the same time. From the graphs above, it can be seen that the pressures in these two beds were similar. Bed 3 operated in the opposite way to the other beds. While adsorption was taking place in beds 1 and 2, desorption was taking place in bed 3. From the above curves, it can be deduced that the moment when adsorption started, the pressure in the respective bed increased and its value approached that of the pressure in the evaporator. In the case of the curves in Figures 4 and 5, for beds 1 and 2, the cycle time was too short for the bed pressure to approach the value of the evaporator pressure. When the bed was switched to the state proper for the desorption process, the pressure in the bed was equal to the condenser pressure.

Figures 10–15 show temperature changes in the beds, the evaporator and the condenser, and the changes in hot water inlet temperature at the beds for each cycle time.

The temperature curves clearly indicate the moments at which the adsorption and desorption phases in the beds start. These processes occur rapidly, which is confirmed by the dynamic temperature changes. In the case of adsorption, cooling water flows through the adsorbent bed, thus lowering its temperature. In this way, the course of the process becomes easier. During the desorption phase, hot water flows through the heat exchanger

in the bed, causing an increase in temperature inside the bed and evaporation of water molecules. The temperature of the water that heated the bed was 80 ± 3 °C.

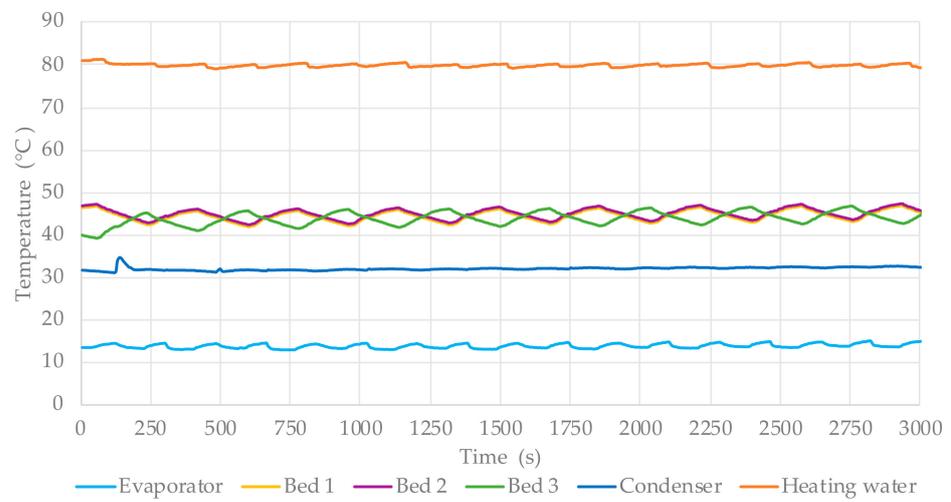


Figure 10. Temperature for cycle time = 100 s.

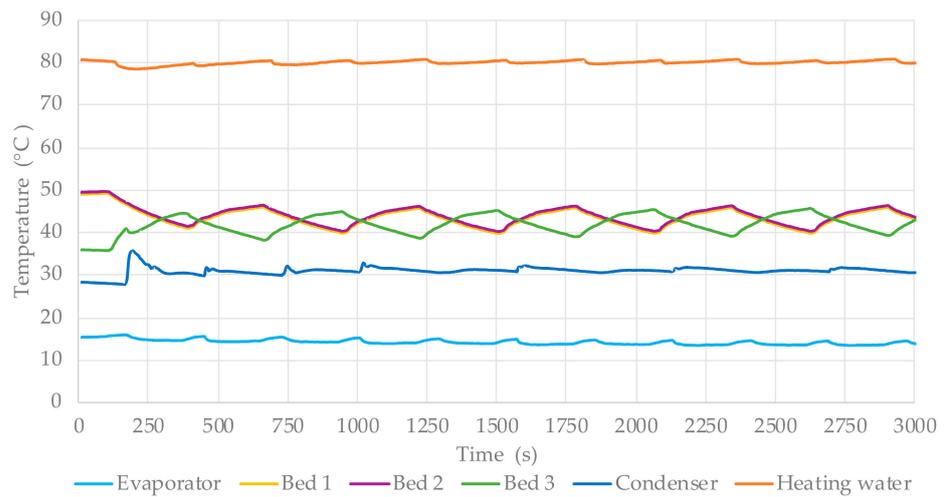


Figure 11. Temperature for cycle time = 200 s.

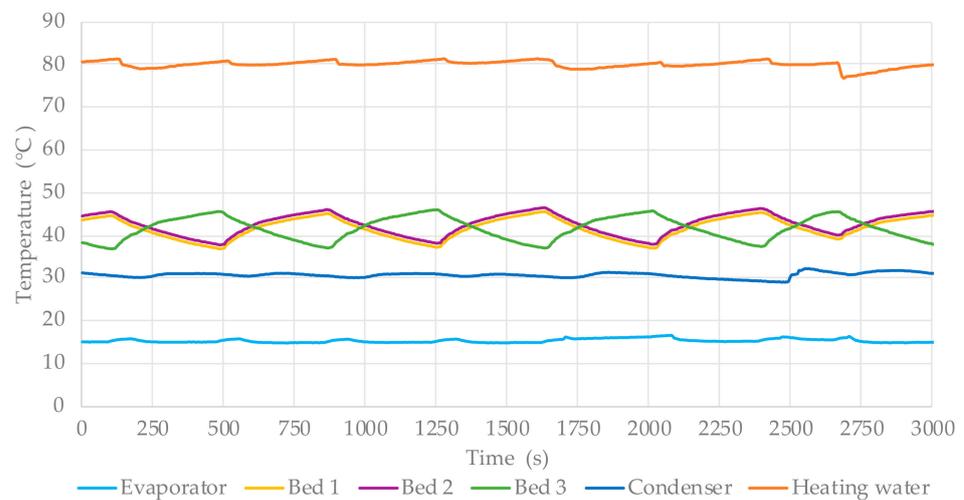


Figure 12. Temperature for cycle time = 300 s.

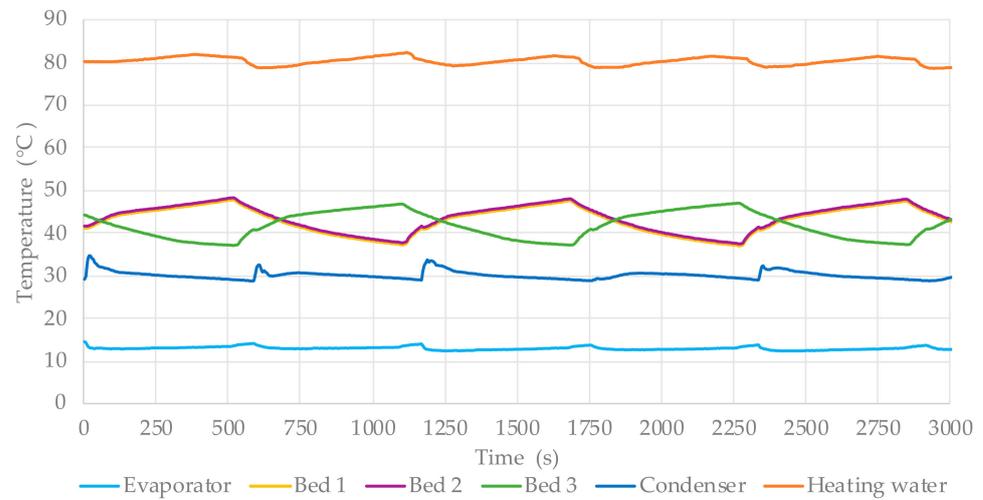


Figure 13. Temperature for cycle time = 500 s.

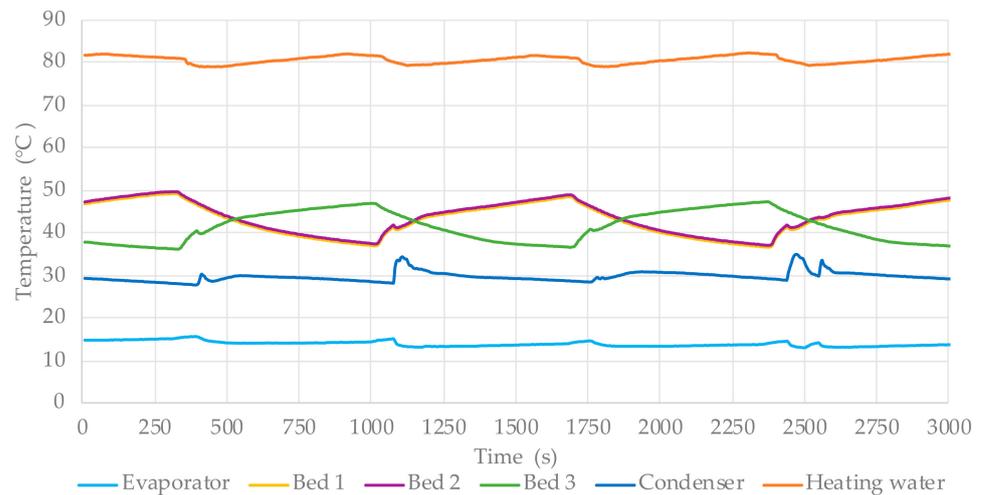


Figure 14. Temperature for cycle time = 600 s.

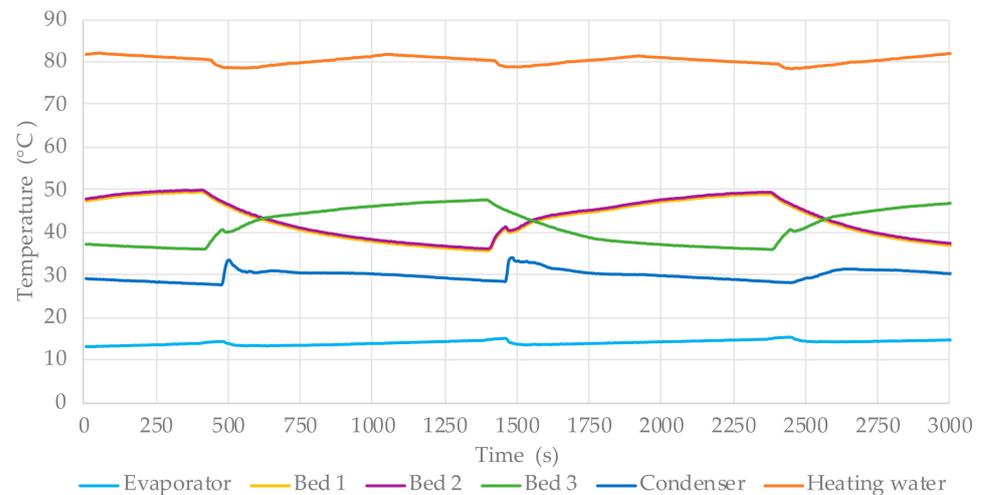


Figure 15. Temperature for cycle time = 900 s.

Figures 16–21 show the chilled water temperature at the evaporator inlet and outlet and the chilled water flow rate for each cycle time.

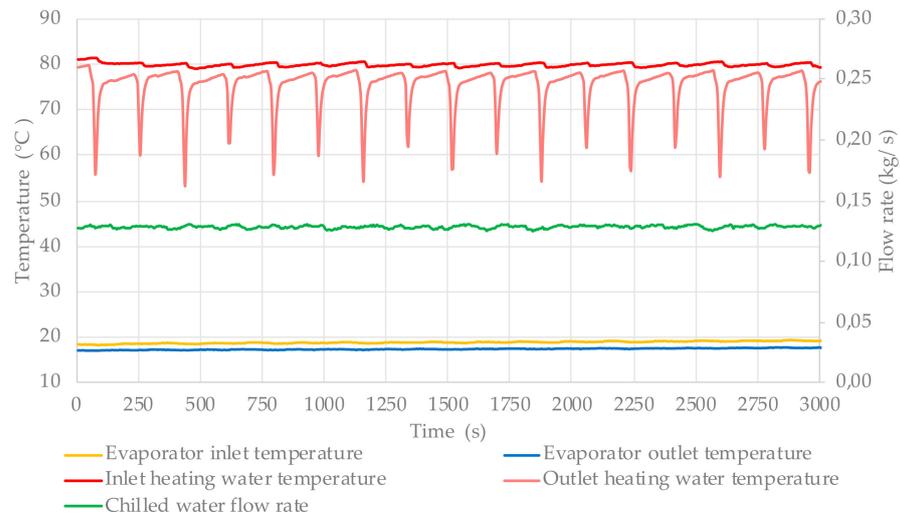


Figure 16. Evaporator inlet and outlet temperature and chilled water flow rate for cycle time = 100 s.

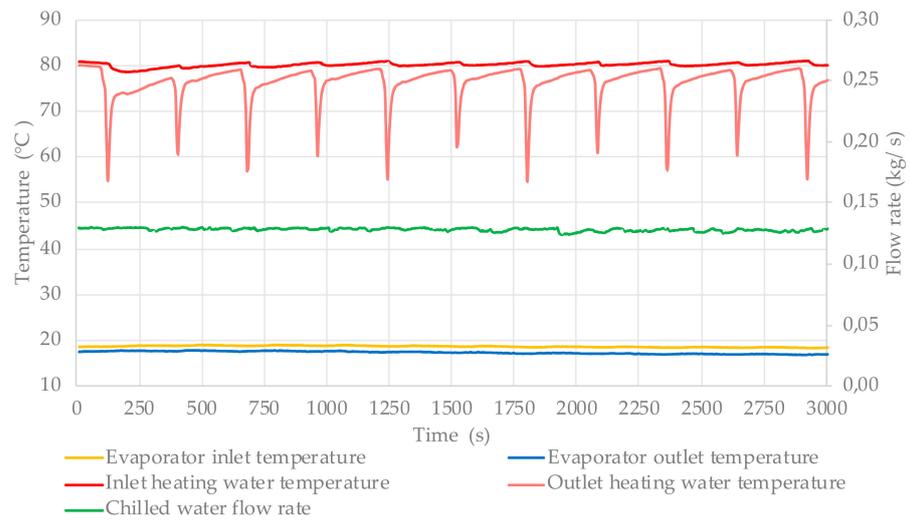


Figure 17. Evaporator inlet and outlet temperature and chilled water flow rate for cycle time = 200 s.

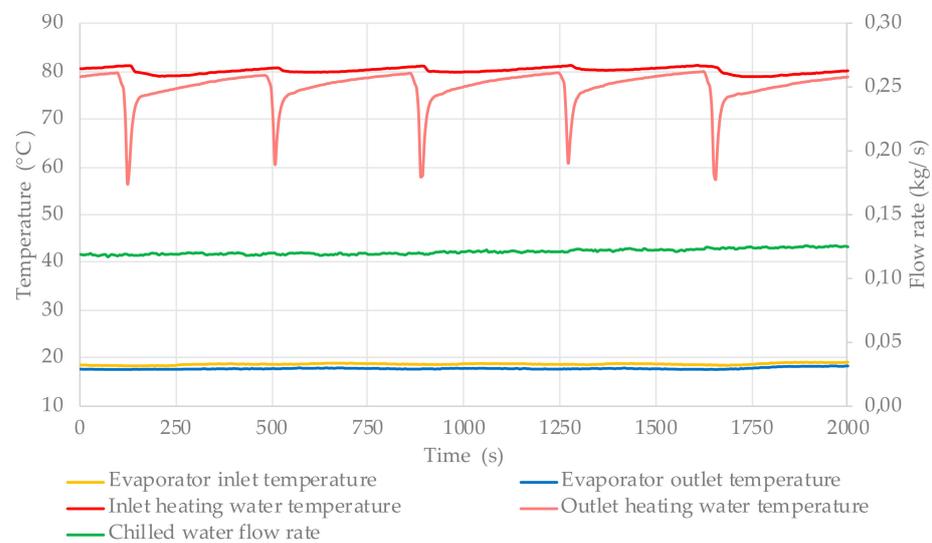


Figure 18. Evaporator inlet and outlet temperature and chilled water flow rate for cycle time = 300 s.

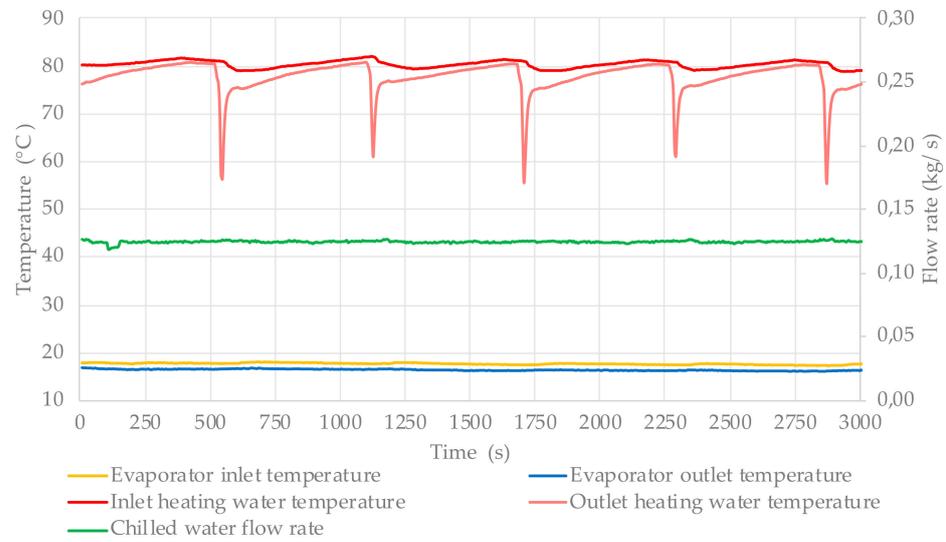


Figure 19. Evaporator inlet and outlet temperature and chilled water flow rate for cycle time = 500 s.

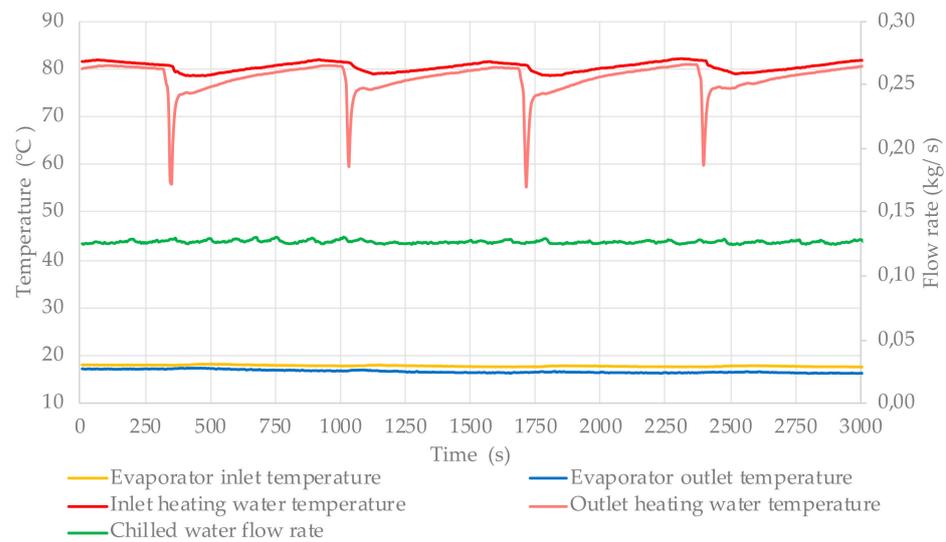


Figure 20. Evaporator inlet and outlet temperature and chilled water flow rate for cycle time = 600 s.

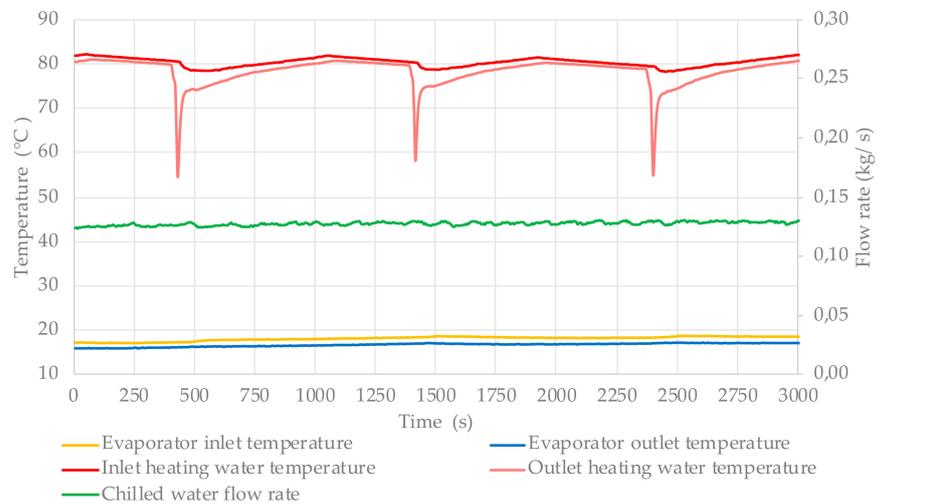


Figure 21. Evaporator inlet and outlet temperature and chilled water flow rate for cycle time = 900 s.

During the testing process, the evaporator was supplied with chilled water at a rate of approximately 0.13 kg/s. The temperature of chilled water at the evaporator inlet is maintained depending on the pressure value in the evaporator. When flowing through the evaporator, chilled water lowers its temperature as a result of giving up thermal energy to the adsorbate which then changes its state of matter and evaporates. Then, the temperature in the evaporator equals the value corresponding to the evaporation temperature of the adsorbate.

4. Discussion

From the results obtained, the effect of the cycle time duration on the COP and SCP can be assessed. An analysis of Figures 10–15 leads to the conclusion that longer cycle times meant higher temperatures in the bed during desorption and lower temperatures during adsorption. With longer cycle times, the heating and cooling times of the bed also increase, which is confirmed by the graphs. For cycle time of 100 s, the temperature during desorption phase is approximately 45 °C and approximately 40 °C during adsorption while for cycle time of 900 s, the corresponding temperatures are approximately 50 °C and 36 °C, respectively.

The lowest value of chilled water temperature obtained during this investigation was 16 °C. The difference between the evaporator inlet and outlet temperatures is approximately 1.5 °C and is stable throughout the cycle.

A graphical representation of the COP values depending on the cycle time is shown in Figure 22. The COP values were calculated according to Equations (1)–(4) as the quotient of the cooling capacity (CC) and the heating power (HP).

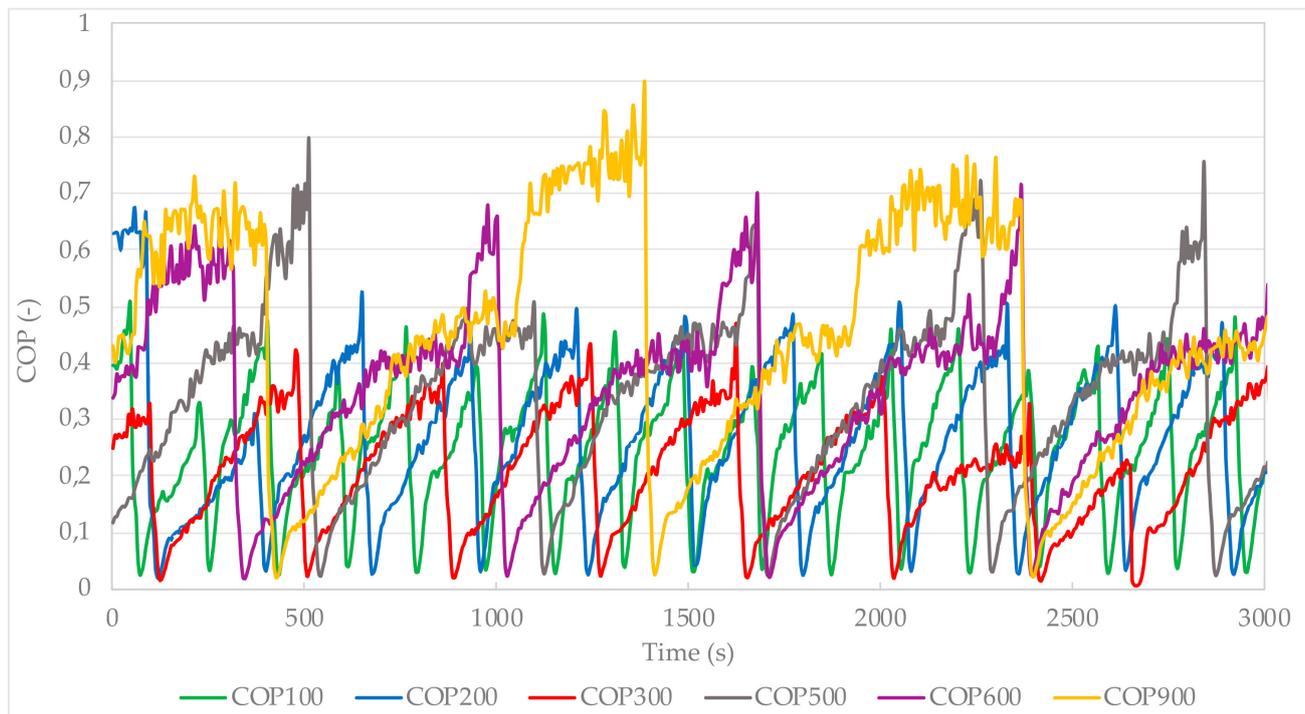


Figure 22. Comparison of the changes in the COP values for all cycle times tested.

The characteristic points in the above graph are the extremes of the curves corresponding to the particular cycle times. The COP reaches its minimum values with the start of the desorption process. At this point, the most intense heat exchange takes place between the hot water and the bed. This is the so-called bed pre-heating phase during which the temperature difference between the bed inlet and outlet is the greatest and reaches up to 35 °C. This is due to the fact that during adsorption, the temperature inside the adsorbent bed is much lower than the temperature required for the desorption phase. This difference

decreases as the bed is heated, so the cooling of the water becomes less and less intense. At the end of desorption, when the temperature difference between the bed inlet and outlet is the smallest, the heating power (HP) also reaches minimum values. Then, according to Equation (1), the COP is highest. In addition, it has been noted that for the longer cycles when the bed heating time is longer, the system reaches higher maximum values of the COP.

Figure 23 shows a comparison of COPs for cycles of 100 and 900 s, i.e., the extreme values.

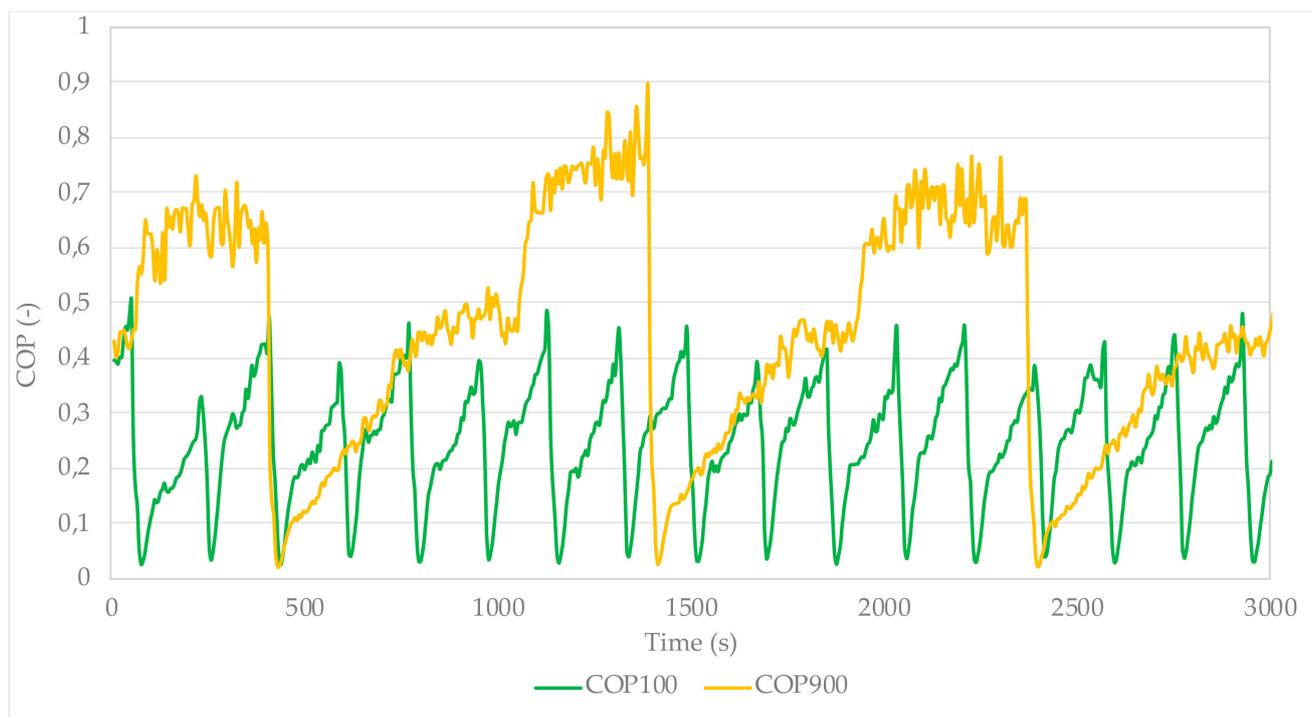


Figure 23. Comparison of changes in COP values for cycle times of 100 s and 900 s.

For a cycle of 100 s, this time is too short for the adsorption and desorption processes to occur in the most efficient manner. The short cycle time also means that it is not possible for the chiller operation to become steady-state. The adsorbent bed is not sufficiently heated and cooled then.

The longest cycle time contributes noticeably to the stable operation of the chiller. Increasing the adsorption and desorption times results in a greater amount of adsorbate being adsorbed and also a greater amount being desorbed from the surface of the sorption material.

Figure 24 shows influence of cycle time on SCP and COP. In accordance with the studies of other authors, COP increases with increasing time, while SCP increases until reaching a certain maximum value, and then decreases with increasing cycle time duration. The lowest values of SCP and COP were obtained for the cycle that lasted for 100 s and they are, respectively, 115 W/kg and 0.37. The highest SCP value of 154 W/kg was obtained for 500 s. The COP for this cycle duration is 0.55. The maximum obtained COP value during these studies is 0.64. It was achieved for the longest cycle duration of 900 s and SCP for this time is about 130 W/kg. However, such a long cycle time is disadvantageous since it is important for this type of device to achieve the highest possible efficiency with the shortest possible cycle time. Based on Figure 24, it can be concluded that the optimal cycle duration for the conditions in which the experiment was conducted is 500 s.

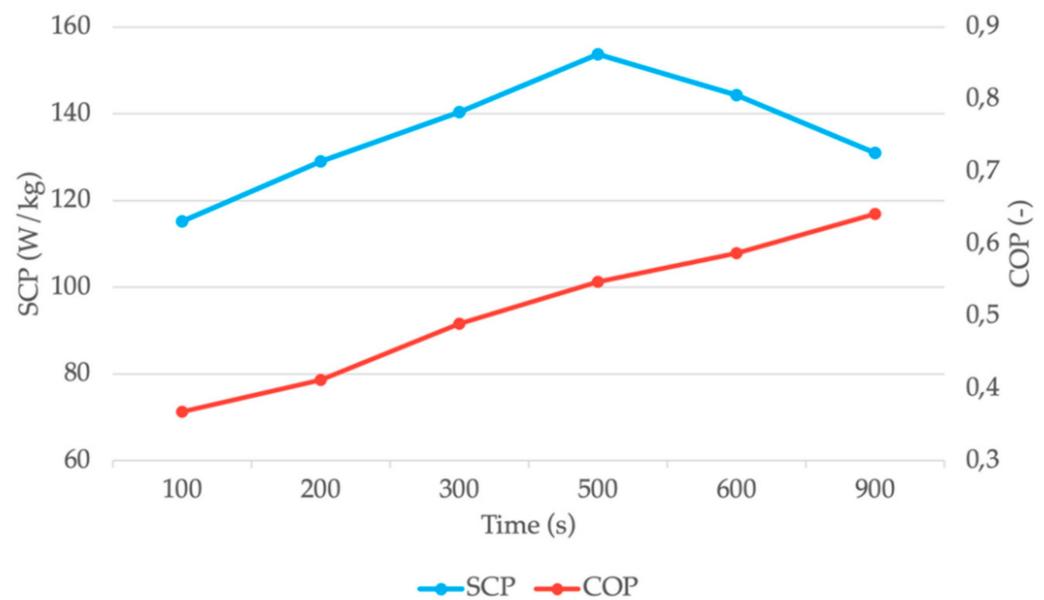


Figure 24. Influence of cycle time on the SCP and COP.

5. Conclusions

This paper presents various possibilities for improving the performance of an adsorption chiller. Experimental results relating to one of the methods are presented. The aim of the study was to investigate the effect of the duration of the adsorption and desorption processes on the COP and SCP of an adsorption chiller with desalination function. An analysis of the results obtained for the test device located at the Energy Centre of the AGH University of Science and Technology in Krakow confirmed that the duration of the entire cycle affects the performance of the adsorption chiller. The results obtained show that an increase in the cycle time can lead significant increase in the COP value. The SCP grows up to the maximum value for a cycle duration of 500 s. Then, the SCP value drops. Furthermore, the course of the cycle for longer adsorption and desorption times is characterised by greater stability of operation. It has also been noted that adsorption and desorption are most effective at the beginning of the cycle.

In the operation of the adsorption chiller, the key is to reduce the mass of the device and one of the ways is to optimally select the time of adsorption/desorption cycles where an appropriate balance between the SCP and COP value is achieved. Based on the data from the experiment, it can be summarised that the time of 100 s is too short because the heat exchanger was not heated evenly and not all of the water during the desorption process was desorbed. On the other hand, during the adsorption process, not all of the water vapor produced in the evaporator was adsorbed, which limits the evaporator's power and thus the device's power COP. When the adsorption/desorption time is increased above 600 s to 900 s, an increase in the COP of the device is observed; however, SCP decreases. This means that too long adsorption/desorption time of cycle causes that because after saturation of the sorbent water, no adsorption occurs and extending the time does not increase the cooling power of the device. However, after desorption of all the water from the bed, an increase in the cycle time does not cause an increase in the chilled power but the use of energy for desorption increases and the process becomes very energy consuming. Therefore, based on the experimental data for a three-bed chiller, it can be concluded that the cycle time of 500 s is the most appropriate because a good balance between COP and SCP is maintained, and the desorption/adsorption process is the most effective. It is important to shorten the cycle time for adsorption–desorption to achieve the highest cooling capacity and COP. The process of adsorption/desorption can be carried out in a shorter time than 900 s. For example, when the cycle time is 500 s, similar COPs and a higher SCP compared to 900 s are achieved.

The search for the optimal parameters of the adsorption chiller is crucial to improve its performance. The application of the right duration of the adsorption and desorption phases greatly affects the performance coefficients. Improving the efficiency of the operation of adsorption chillers will ultimately lead to an increase in their competitiveness in the market.

Funding: The paper was funded by subsidy for research Faculty of Energy and Fuels number 16.16.210.476.

Data Availability Statement: The data that support the results reported in this study are available from the corresponding author upon request.

Conflicts of Interest: The authors declare no conflict of interest.

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