

Article

The Effects of Using Steam to Preheat the Beds of an Adsorption Chiller with Desalination Function

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Abstract: Adsorption chillers are a promising alternative to traditional compressor-based devices. Adsorption chillers can be supplied with low- or medium-temperature waste heat or heat from renewable energy sources. In addition, they can be used for water desalination purposes. Thus, the adsorption chillers are unique devices that meet essential problems of the modern world: a need to limit the negative impact of humankind on the natural environment and growing problems with access to drinking water. However, adsorption chillers also have disadvantages, including ineffective operation and large size. Therefore, in this paper, the influence of steam utilization on the operation of an adsorption chiller with water desalination function was investigated experimentally, which has not been done before. The research was carried out on the adsorption chiller, working on a silica gel–water pair, installed in the AGH UST Center of Energy. The chiller was modified to preheat the sorbent with the use of steam. The results show that the use of steam instead of water for preheating the bed leads to higher temperatures in the heat exchanger and the bed. As a result, heat transfer from the heating medium to the bed is more intense, and a significant shortening of the desorption process is observed. In the case of using steam for preheating, the desorption time was about 30 s, while for water, it was 300 s. Thanks to this solution, it is possible to reduce the size of the device and increase its efficiency. The proposed solution opens a new course of research on adsorption chillers and broadens the horizon of their applications, as steam is a by-product of many industrial processes.

Keywords: adsorption chiller; desalination; preheating; silica gel; steam



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1. Introduction

Cooling processes are used in many industries, including food, pharmaceutical, heavy and energy industries. The International Institute of Refrigeration (IIR) estimated that the total number of refrigeration, air-conditioning and heat pump systems worldwide in 2019 was around 5 billion [1], with electrically powered compressors being the most abundant. As a result, electricity consumption in the refrigeration industry accounts for around 20% of total electricity consumption in the world [1]. Moreover, the dynamically progressing economic development, population growth, observed climate changes and the increasing desire to increase thermal comfort among people mean that by 2050 the global demand for electricity in the refrigeration industry will double [1].

It should be noted that more than 65% of electricity in the world is generated by burning fossil fuels [2], which adversely affects the natural environment due, among others, to greenhouse gas emissions. Additionally, the operation of compressor refrigeration equipment is based on the appropriate thermodynamic transformations of refrigerants such as hydro-chlorofluorocarbons (HCFC) and chlorofluorocarbons (CFC). These refrigerants are characterized by a high ozone depletion potential (ODP) and a high global warming potential (GWP) [3]; therefore, various legal regulations are introduced regarding the possibility of using these refrigerants [4].

Another challenge faced by more and more people around the world is the growing problem of a lack of access to drinking water. It is estimated that currently around 3.6 billion people live in water-poor areas for at least one month a year, and this number could rise to 5.7 billion by 2050 [5]. Therefore, in order to meet the demand for drinking water, desalination of sea or ocean water seems inevitable. However, conventional methods of desalination of water, such as multi-effect distillation (MED) or reverse osmosis (RO), are energy-intensive processes. To obtain 1 m³ of desalinated water using MED and RO technologies, 14.2–21.6 kWh and 1.5–6.0 kWh of energy is required, respectively [6].

As a result, alternative and environmentally friendly technologies are being sought in both the refrigeration and desalination sectors. One of them is the use of adsorption chillers with the function of water desalination. Table 1 presents a comparison of water desalination using adsorption chillers and other technologies. Comparisons are made for solar energy coupled desalination technologies. As can be seen, water desalination using adsorption chillers is competitive with conventional water desalination technologies listed in Table 1.

Table 1. Comparison of selected water desalination technologies coupled with solar energy. Based on [6].

Desalination Technology	Electrical Energy Consumption, kWh/m ³	Thermal Energy Consumption, kWh/m ³	Cost, USD/m ³	Heat Source Temperature, °C
Adsorption chiller	1.4	39.8	0.7	55–85
Multi-stage flash desalination	2.5–5.0	81.0–144.0	1–5	90–110
Multi-effect distillation	1.5–2.0	60.0–70.0	2–9	79–90
Passive solar still	0	1106 ¹	1.3–6.5	-
Reverse osmosis	41–45	0	3–27	-

¹ Calculated with the assumption that the latent heat of water vaporization is 2390 kJ/kg [7] and the thermal efficiency of the solar still is 60% [8].

Adsorption chillers, unlike compressor chillers, are supplied with low-temperature heat, the minimum required temperature of which is only 55–80 °C [9]. Therefore, to power adsorption chillers, low-temperature waste heat from industrial processes [10] or heat obtained from solar energy [11] can be used. Moreover, the adsorption devices do not use harmful HCFCs and HFCs, but are based on environmentally friendly sorbent-sorbate pairs, such as silica gel–water [12], zeolites–water [13], activated carbon–ethanol [14]. Additional advantages of adsorption chillers include low noise level, lack of system vibrations and no moving parts [15]. On the other hand, one of the main disadvantages of adsorption refrigeration equipment is discontinuity of operation and low coefficient of performance (COP), usually not exceeding a value of 0.6 [16], as well as a low specific cooling power (SCP) [17].

The solution to the first problem, i.e., the discontinuity in the operation of adsorption chillers, is the use of two- [11], three- [18], four- [19] or even six-bed chillers [20]. On the other hand, efforts to improve the COP and SCP include many different methods, some of which only consist in changing the operating conditions of the device, and some require interference with the construction of the chiller.

The simplest methods of improving the COP and SCP of adsorption chillers, which do not require modification of the chillers' structure, are the selection of the appropriate time of the adsorption/desorption cycles [21], or the use of a heat source with a higher temperature [18]. However, it should be kept in mind that the heat supplying adsorption chillers is usually waste heat with a given temperature, which usually cannot be changed. Therefore, another solution to improve COP may be, for example, the use of mass recovery, which requires the connection of sorbent beds [22]. As demonstrated by Ng et al. [22], the use of mass recovery can improve the COP of the chiller by up to 20%. Another possibility is to use heat recovery, which takes heat from the bed during the adsorption process and transfers it to another bed, which is in the desorption or preheating phase [23]. Such action can improve the COP of the chiller by about 40% [23].

The heat exchange between the sorbent and the bed heating/cooling medium has a significant impact on the course of the desorption/adsorption process and, therefore, on the effectiveness of adsorption chillers [24,25]. The intensification of heat transfer

in beds can be implemented in several ways: Firstly, by using a heat exchanger of an appropriate design [26], as well as being made of an appropriate material, which should be characterized by a high thermal conductivity coefficient, low heat capacity and low density [27]. Secondly, the intensification of heat exchange can take place by reducing the thermal resistance between the sorbent layer and the heat exchanger, which can be achieved through the use of various types of glues [25]. The heat transfer can also be intensified in the bed itself by adding various materials with high thermal conductivity to it, such as graphite flakes [28], copper, aluminum or carbon nanotubes [29,30].

Therefore, based on the above paragraph, it can be concluded that much attention is paid to the intensification of heat transfer within the bed itself or between the bed and the heat exchanger. However, the rate of heat flow from the heat transfer medium (the medium heating the bed during desorption) to the bed is also dependent on the thermal resistance between the medium and the heat exchanger as well as on the temperature difference between the medium and the bed [24]. Therefore, it seems justified to look for the possibility of intensifying heat transfer on the side of the heat transfer medium.

The effectiveness of desorption depends on the inlet temperature of the heating medium, and the abovementioned effectiveness augments with increasing temperature of the heating medium [31]. This observation was also reported by Ghilen et al. [32], who concluded that desorption is much faster for high temperatures of the heating medium compared to low temperatures. As a result, when the heating water inlet temperature increased from 55 °C to 95 °C, the chiller COP increased by up to 80%. A similar result was obtained experimentally by Sekret and Turski [33], as well as Sztékler et al. [18]. Sekret and Turski [33] found that the chiller COP increased by 17% when the heating water inlet temperature increased from 80 °C to 95 °C, while Sztékler et al. [18] reported a COP improvement of 190% when the heating water inlet temperature increased from 57 °C to 85 °C.

It is worth noticing that in most cases of adsorption chillers, the medium that heats or preheats the bed is water and, in some cases, also thermal oil [34,35]. Ng et al. [36] suggested that adsorption chillers can be driven by low-temperature steam, but they did not provide any information about the effects of using steam for bed regeneration on the operating parameters, e.g., temperatures, pressures and COP, of the chiller. In turn, Shahzad et al. [37] investigated the performance of the adsorption chiller integrated with two ejectors driven by steam at a pressure of 2 bar. However, to the best of the authors' knowledge, the literature lacks research concerning the effect of using steam to directly preheat the bed of the adsorption chiller, without using additional devices such as ejectors. Steam can have a much higher temperature than water, which, as shown in the above paragraph, is expected to improve the performance of the adsorption chiller. Such an innovative solution has not been investigated before.

This article presents the results of experimental research on the use of steam for the preheating of the beds of a three-bed adsorption chiller with water desalination function. Such a solution has never been used in the technology of adsorption chillers and is undoubtedly a novelty that will contribute to the development of this direction of research. As a result of using high-temperature steam, the heat exchange between the medium and the bed takes place faster, thanks to which the desorption process can take place in a much shorter time. Additionally, steam is generated in many technological processes and, therefore, the use of steam for preheating adsorption chiller beds can significantly expand the scope of their applications, as well as develop a new direction of research on adsorption chillers.

2. Methodology

2.1. Test Stand

The test stand, the basis of which is an adsorption chiller with a water desalination function, is located at the AGH UST Center of Energy. The tested chiller is a three-bed chiller in which silica gel and water are used as a sorbent–sorbate pair. A detailed description of the test stand and the general principle of operation of the tested chiller can be found in

the papers [18,21]. Nevertheless, for the needs of this experiment, the chiller worked in a two-bed configuration, and the test stand was modified so that it was possible to investigate the effect of bed preheating with steam on the parameters of the chiller operation. The diagram and photos of the test stand with applied modifications are presented in Figures 1 and 2, respectively.

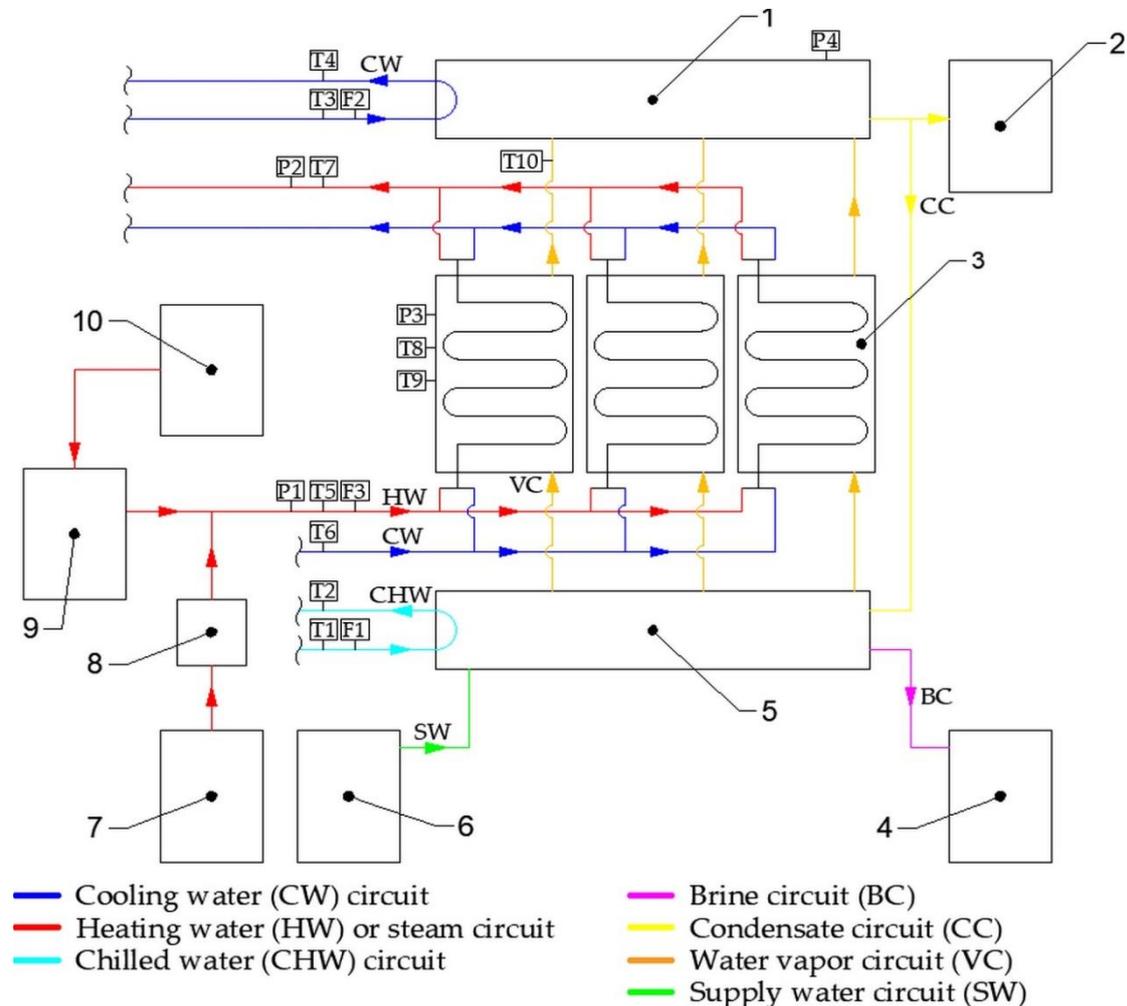


Figure 1. Simplified diagram of the test stand. 1—condenser; 2—distillate tank; 3—adsorption bed; 4—brine tank; 5—evaporator; 6—degasification tank; 7—steam generator; 8—manifold; 9—hot water tank; 10—electric heater; T1—chilled water inlet temperature; T2—chilled water outlet temperature; T3—cooling water inlet (to the condenser) temperature; T4—cooling water outlet (from the condenser) temperature; T5—heating water/steam inlet temperature; T6—cooling water inlet (to the bed) temperature; T7—heating water/steam outlet temperature; T8—temperature inside the heat exchanger; T9—temperature of the free space of the bed; T10—temperature of water vapor leaving the bed and flowing to the condenser; F1—chilled water flow rate; F2—cooling water flow rate; F3—heating water/steam flow rate; P1—steam inlet pressure; P2—steam outlet pressure; P3—pressure inside the bed; P4—pressure inside the condenser.

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 heat 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 (evaporator) and 1450 and 220 mm (condenser), respectively. In addition, the system is equipped, among other things, with a distillate tank (2), a brine tank (4), a degasification tank (6) and an expansion valve not shown in Figure 1. Additionally, a steam generator (7) and manifold (8) were installed at the test stand to enable investigating the use of steam for preheating the bed. In addition to the main components, the investigated unit is equipped

with three circulating pumps (not shown in Figure 1), one for heating, one for cooling and one for chilled water circuits. However, these pumps are not an integral part of the adsorption chiller in contrast to, for example, a compressor in the case of compressor chillers. Theoretically, it is even possible to completely exclude the above-mentioned pumps thanks to the gravity flow of water. Fluids in various forms and under different conditions flow through the system in seven main circuits, as marked in Figure 1.

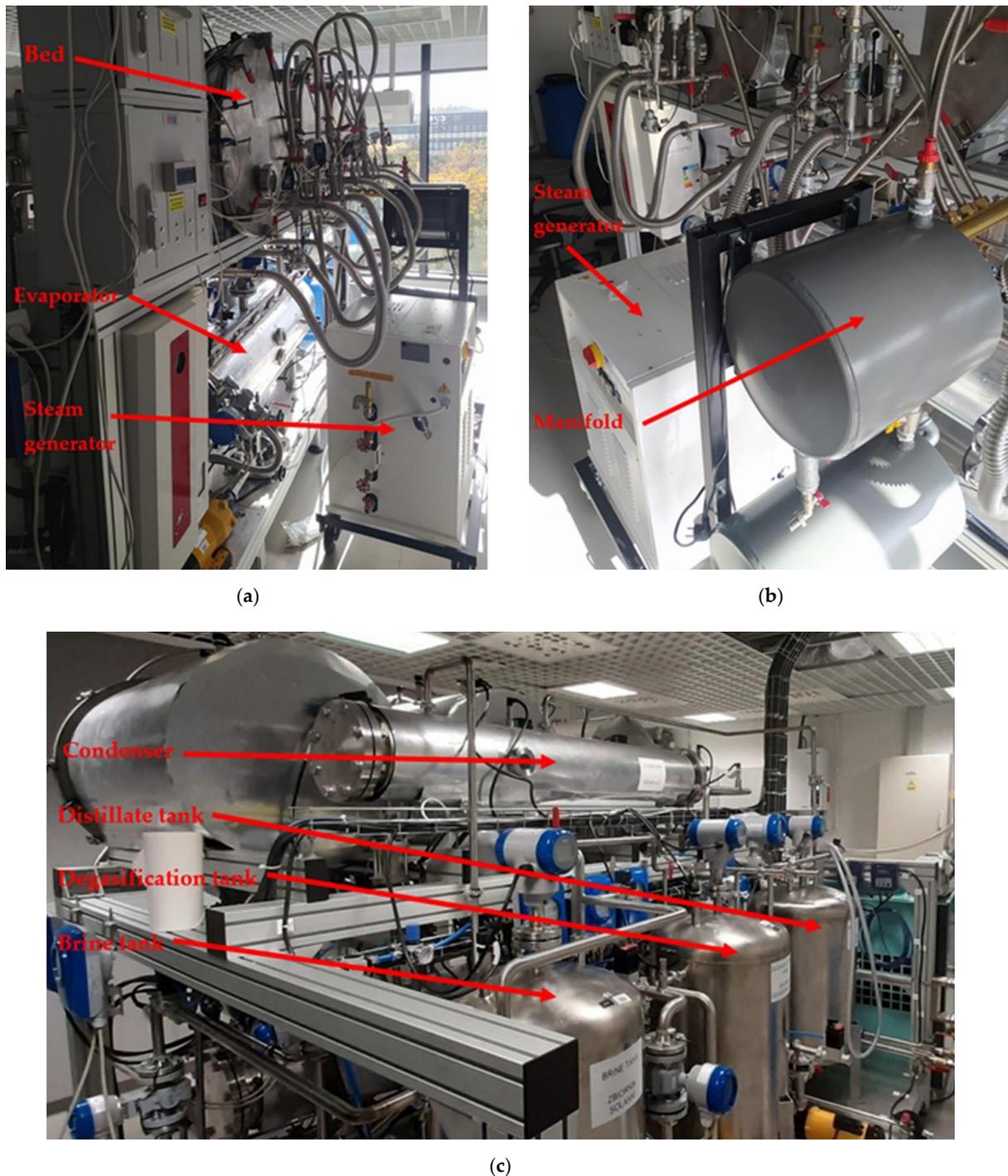


Figure 2. Pictures of the test stand: (a) front view on the beds, evaporator and steam generator; (b) front view on the steam generator and manifold; (c) back view on the condenser, distillate tank, degasification tank and brine tank.

In order to test the use of steam for the preheating of the chiller beds, the electric steam generator MAXI 24 (marked with the number 7 in Figure 1) was installed on the test stand. Detailed technical parameters of the steam generator are summarized in Table 2. The device has modulated power, thanks to which it is possible to control the parameters of the steam supplied to the chiller. The steam generator was connected to the distribution manifold (8), which in turn was connected to the heating water circuit. Thanks to this, two variants of bed preheating are possible:

1. With the use of hot water: the water is heated in the electric heater (10) and directed to the hot water tank (9) and, then, to the bed (3), while the steam generator (7) is not used and is cut off from the system by using special valves (not shown in Figure 1).
2. With the use of steam: steam is generated in the steam generator (7) and directed to the distribution manifold (8) and, then, to the bed (3). Steam flows through the bed for about 50 s (until its inlet and outlet temperatures are equal). Then, the supply of steam to the bed is cut off, and the supply of hot water, used for the desorption process, is opened. After leaving the bed, the steam is returned to the hot water tank.

Table 2. Technical parameters of the steam generator MAXI 24.

Parameter	Value
Maximum heating power	14 kW
Steam output	18.5 kg/h
Supply voltage	230 V
Boiler capacity	24.9 L
Maximum steam pressure	7 bar
Water pump motor power	0.55 kW

2.2. Measuring Devices and Uncertainty Analysis

The following parameters were measured during the experiments:

- The inlet and outlet temperatures of heating water or steam (depending on the operation variant of the chiller);
- The temperature inside the heat exchanger;
- The temperature of the free space in the bed;
- The temperature of the water vapor (sorbate) at the outlet of the bed;
- The pressure in the bed;
- The pressure in the condenser;
- The flow rates of heating water, cooling water, chilled water and steam.

The measuring sensors used are listed in Table 3.

Table 3. Technical parameters of measuring sensors.

Parameter	Sensor	Measurement Range	Measurement Uncertainty
Temperature	Pt-100 ¹	−80 °C to 250 °C	±0.1 °C
	Pt-1000	−80 °C to 150 °C	±0.1 °C
Pressure	Pressure transducer	0–99 kPa	±0.5%
Flow rate	Electromagnetic flow meter	1–100 L/min	±0.5%

¹ The Pt-100 sensor was used to measure the temperature of steam for the preheating of bed. The remaining temperatures were measured with Pt-1000 sensors.

All values were measured in the steady state of the chiller operation, achieved after about one hour from the moment of its start-up, and then, 300 adsorption/desorption cycles were performed. The values were saved every 5 s on a personal computer thanks to the use of special software. The test results were exported to csv files, which enabled their further processing. In addition, the test stand is equipped with an appropriate control system, thanks to which it is possible to fully control the parameters of the chiller.

The total measurement uncertainties were calculated as a quadratic sum of the random and systematic uncertainties [38]:

$$u(k) = \sqrt{\delta k_{ran} + \delta k_{sys}}, \quad (1)$$

where k , $u(k)$, δk_{ran} and δk_{sys} are the temperature or the pressure or the mass flow rate, the total measurement uncertainty, the random uncertainty and the systematic uncertainty, respectively. The systematic uncertainties are equal to the uncertainties of the measuring devices (Table 3), while the random uncertainties were calculated as follows:

$$\delta k_{ran} = \sqrt{\frac{1}{N \cdot (N - 1)} \cdot \sum (k_n - k_{avg})^2}, \quad (2)$$

where N , k_n and k_{avg} are the number of measurements ($N = 300$), the value of n -th measurement and average from 300 measurements, respectively.

The coefficient of performance of the investigated chiller was calculated as [39]:

$$COP = \frac{\dot{m}_c \cdot c_{p,c} \cdot (T_{i,c} - T_{o,c})}{\dot{m}_h \cdot c_{p,h} \cdot (T_{i,h} - T_{o,h})}, \quad (3)$$

where m , c_p and T are the mass flow rate, (kg/s), the specific heat capacity, (J/kg/K) and the temperature, (°C), respectively. The subscripts c, h, i and o correspond to the chilled water, heating medium, inlet and outlet, respectively. The uncertainty of the COP was calculated from the general formula for error propagation [38]:

$$u(COP) = \frac{\sqrt{\sum \left(\frac{\partial COP}{\partial k_i} \cdot u(k_i) \right)^2}}{COP} \cdot 100\%, \quad (4)$$

where k_i stands for quantities from Equation (3).

The calculated measurement uncertainty of temperatures, pressures, mass flow rates and COP is 0.2 °C, 0.1 kPa, 0.01 kg/s and 9.7%, respectively.

2.3. Experimental Procedure

During the experiments, the influence of the use of steam for preheating the adsorption chiller beds on its operating parameters was investigated. For this purpose, two variants of the chiller operation were investigated, during which the beds were preheated with hot water (variant 1) or steam (variant 2). The working parameters of the chiller in variants 1 and 2 are presented in Table 4.

As mentioned before, the investigated adsorption chiller has three beds. Nevertheless, for this study, the chiller operated in a two-bed mode. Thus, the adsorption and desorption processes occur in the beds periodically. Primarily, the refrigerant from the evaporator flows to the bed, and the adsorption, which is an exothermic process, begins. The cooling water flows through the bed and receives heat from the bed through the heat exchanger. When the adsorption is completed, the bed is firstly preheated with water (variant 1) or steam (variant 2) for 50 s (until its inlet and outlet temperatures are equalized). Next, the desorption starts. As desorption is an endothermic phenomenon, heat in the form of hot water is supplied to the bed through the heat exchanger. After finishing the desorption, the refrigerant (desorbed water vapor) flows to the condenser, while the heat recovery process starts in the bed. Then, the entire process (adsorption, preheating, desorption, heat recovery) repeats. During all processes (adsorption, preheating, desorption and heat recovery), supply water is continuously supplied to the evaporator, and to ensure the continuous cooling capacity of the adsorption chiller, two beds are being used and working alternately. That is, desorption takes place in one bed, while adsorption takes place in

the second bed. The preheating/desorption (adsorption)/heat recovery cycle time was 50/300/30 s in both variant 1 and 2.

Table 4. Chiller operating parameters in two variants of operation.

Parameter		Variant 1 (Water Preheating)	Variant 2 (Steam Preheating)
Evaporator	Cooling capacity	1.10 kW	1.10 kW
	The chilled water inlet temperature T1	20 °C	20 °C
	The chilled water outlet temperature T2	18 °C	18 °C
	The chilled water mass flow rate F1	0.125 kg/s	0.125 kg/s
Condenser	Capacity	2.00 kW	2.00 kW
	The cooling water inlet temperature T3	25 °C	25 °C
	The cooling water outlet temperature T4	27 °C	27 °C
	The cooling water mass flow rate F2	0.250 kg/s	0.250 kg/s
Beds	The heating water inlet temperature T5	80 °C	80 °C
	The heating water mass flow rate F3	0.250 kg/s	0.250 kg/s
	Steam inlet temperature T5	-	120 °C
	Steam inlet pressure P1	-	1.864 bar
	Steam outlet pressure P2	-	1.386 bar
	Steam mass flow rate F3	-	0.0021 kg/s
	The cooling water inlet temperature T6	25 °C	25 °C
Mass of the sorbent	12 kg	12 kg	
Cycle time	Preheating	50	50
	Adsorption/desorption	300	300
	Heat recovery	30	30

3. Results and Discussion

3.1. Preheating with Steam and Water

Figure 3 shows the temperatures of heating water (variant 1) and steam (variant 2) at the inlet to the bed, while the outlet temperatures of the media (heating water and steam) are shown in Figure 4. As the preheating process starts, the inlet and outlet temperatures of the media increase in the first 50 s due to the cooling water circuit closure and the heating water/steam circuit opening. When analyzing the preheating with steam, it can be noticed that after opening the valve supplying water to the bed (transition from high to low temperature and vice versa), there is a certain time shift related to the change in the medium. This shift time is approximately 5 s.

In the case of variant 1, the heating water temperature at the bed inlet reaches about 80 °C after 50 s and remains at this level throughout the desorption process (300 s). When steam is used to preheat the bed, it can be observed that its maximum temperature at the inlet to the bed is about 120 °C after about 50 s from the beginning of the process. Thereafter, a decrease in the temperature of the medium to about 80 °C is visible, caused by the closure of the steam flow and the opening of the flow of heating water.

After 300 s, the desorption process is completed and the cooling water flow is opened, as evidenced by the drop in its inlet and outlet temperatures. In about 320 s, a sharp rise in temperature is visible in the steam temperature curve. A possible reason for such an undesirable system behavior is improperly selected solenoid valves shutting off the steam circuit from the bed.

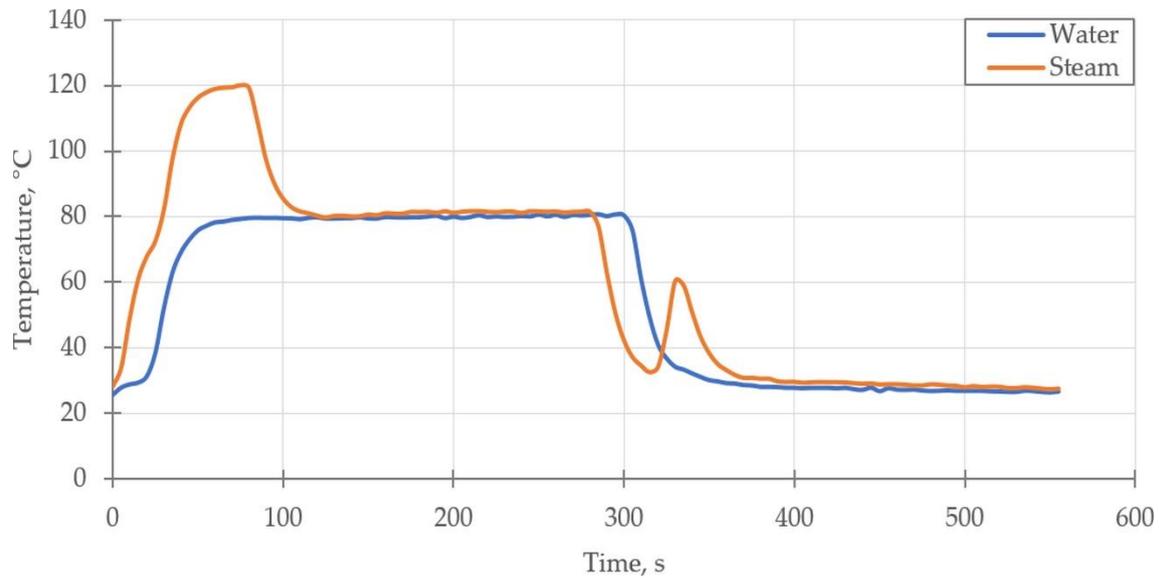


Figure 3. Temperature of the medium inlet (T5) to the adsorption chiller bed during desorption.

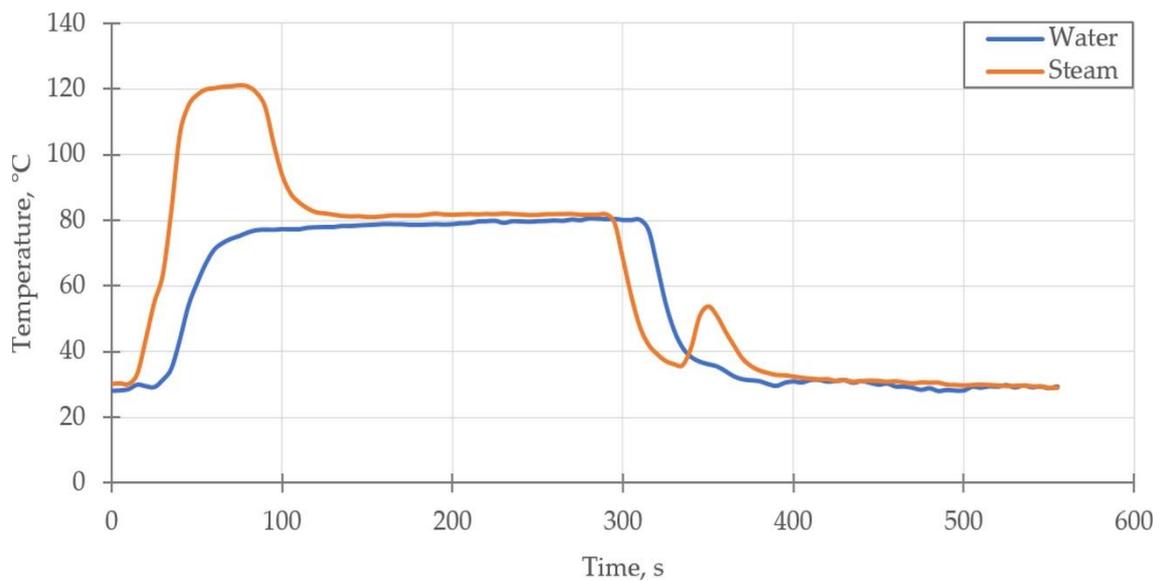


Figure 4. Temperature of the medium outlet (T7) from the adsorption chiller bed during desorption.

Figure 5 shows the change in pressure inside the bed as a function of time for preheating with water and steam. During steam preheating, the pressure in the bed increases much faster than in the case of water preheating. In addition, preheating the bed with steam leads to a greater maximum pressure inside the bed (about 12 kPa) than preheating with water (maximum pressure of about 8 kPa), which indicates that the desorption process is faster when the bed is preheated with steam.

Faster heat transfer between steam and silica gel than between water and silica gel is also confirmed by the temperature changes inside the heat exchanger, which is presented in Figure 6. The temperature rises and stabilizes faster for steam preheating. The use of steam to preheat the bed leads to higher temperatures inside the heat exchanger than in the case of the use of heating water. This is because the steam at the inlet to the bed has a higher temperature than heating water. Furthermore, the steam condenses in the heat exchanger, which additionally intensifies heat transfer. The high temperature of the steam enables faster heat transfer to the silica gel, which in turn leads to an intensification of the desorption process. It is also worth paying attention to the time after which

the heat exchanger temperature reaches its maximum. In the case of steam preheating, the maximum temperature of the heat exchanger is about 70 °C, reached after about 100 s from the beginning of the process, and remains constant until the end of the desorption cycle. On the other hand, for water preheating, the temperature in the heat exchanger increases throughout the desorption phase until it reaches its maximum (approximately 65 °C) after about 300 s.

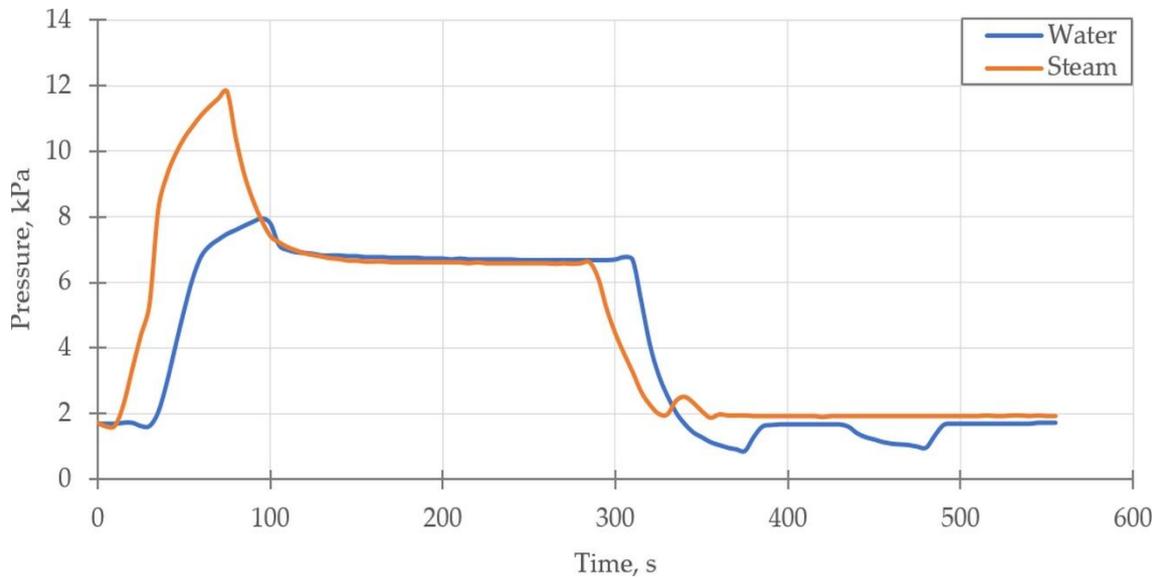


Figure 5. Pressure inside the bed (P3) during desorption.

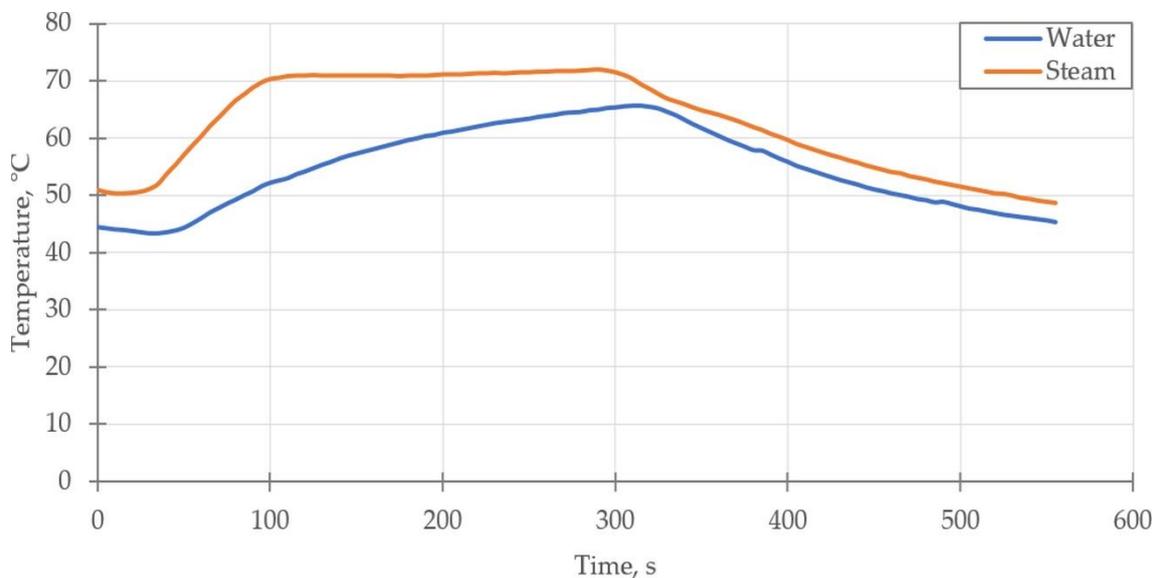


Figure 6. Temperature inside the heat exchanger (T8).

As already mentioned, the use of steam to preheat the bed leads to the intensification of heat transfer and acceleration of the desorption process. Therefore, in the case of preheating with steam, the desorption ends practically a few seconds after the preheating process. As a result, the desorption lasts for about 30 s for steam preheating, while in the classic cycle (water preheating), it lasts for about 300 s.

The temperature of the free space of the bed is presented in Figure 7. It can be noticed that the temperature of the free space in the bed preheated with steam increases and stabilizes faster and is higher than in the case of preheating with water. With the use of steam, the temperature of the free space in the bed reaches a constant value of 50 °C already

after 80 s from the beginning of the cycle. On the other hand, the temperature of the free space in the bed preheated with water increases gradually, reaching its maximum (about 48 °C) after 300 s.

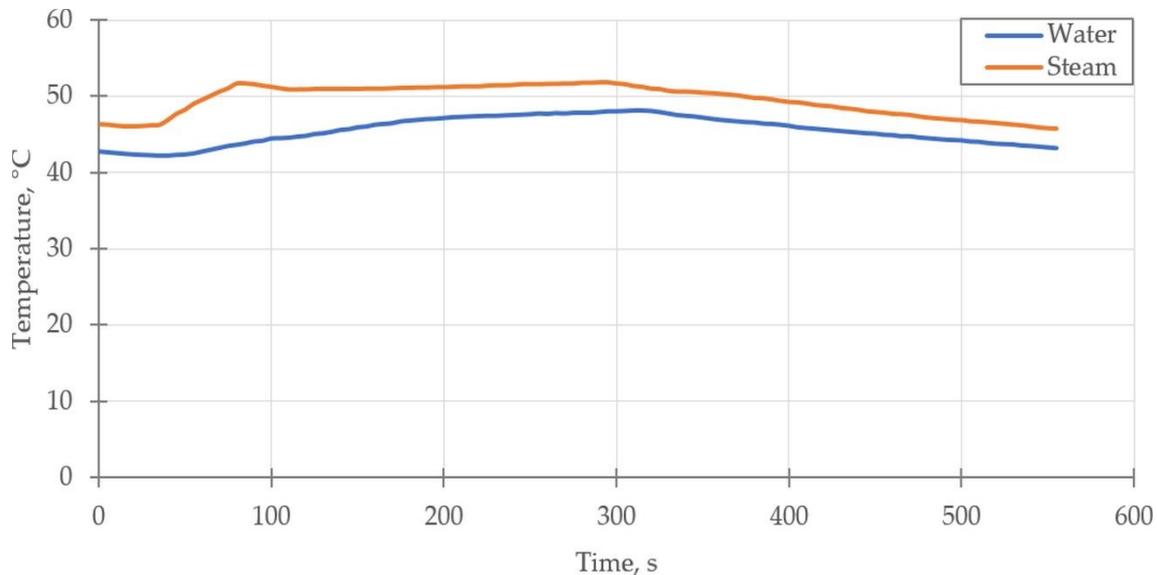


Figure 7. Temperature of the free space of the bed (T9) during desorption.

Figure 8 shows the temperature of water vapor, i.e., the sorbate after desorption, leaving the bed and flowing to the condenser. It can be noticed that the sorbate temperature increases faster in the case of steam preheating than water preheating. Such a course of the curves proves that the desorption of water vapor from the silica gel surface is more intense and occurs earlier in the case of steam preheating compared to the preheating with water. Thus, the transfer of sorbate from the bed to the condenser takes place more quickly, resulting in an increased COP (Equation (3)). The COP for water and steam preheating is 0.49 and 0.66, respectively, which means an increase of 35.2%.

As shown in the Introduction, numerous researchers reported that the COP of adsorption chillers increases with an increasing temperature of the heating medium. Among the works cited in the Introduction, the greatest improvement (by 190%) was obtained by Sztékler et al. [18]. Thus, the improvement of the COP achieved in this work (by about 35%) seems to be modest. However, it should be noted that the COP of adsorption chillers depends not only on the temperature of the heat source but on many other factors, including the number of beds, sorbent–sorbate pair, the temperature of chilled water, the pressure in the condenser and evaporator, the time of adsorption/desorption cycles, the construction of the chiller and others. Therefore, the improvements of the COP reported by different researchers cannot be compared directly, since, as explained above, the COP depends on several factors. Thus, the reported values of the COP enhancement could be compared only if the tests were carried out on the same chillers and with the same operational parameters. Additionally, the reference temperature of the heating source is meaningful, e.g., Sztékler et al. [18] compared the COP for the heat source temperatures of 57 °C and 85 °C, while in this paper, the temperatures of the heat source are 80 °C and 120 °C. As reported by Ng et al. [40], the rate of water desorption from silica gel is temperature-dependent but this relationship is not linear, i.e., the enhancement of desorption rate is much higher when the heat source temperature is increased from 40 °C to 80 °C than from 80 °C to 120 °C.

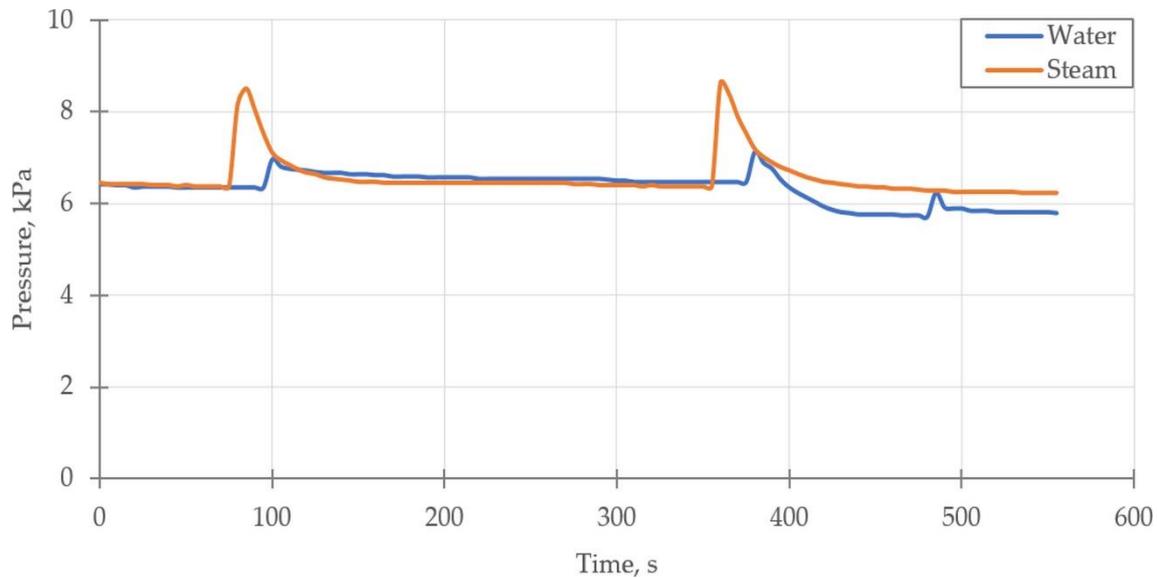


Figure 8. Temperature of the water vapor leaving the bed and flowing to the condenser (T10).

Such observations are confirmed by the pressure distribution in the condenser, which is shown in Figure 9. For bed preheating with steam, the pressure change in the condenser is more dynamic than in the case of water. Regarding steam preheating, after the initial pressure increase (facilitating the formation of condensate in the condenser), the pressure drops quite quickly, which leads to the flow of larger amounts of water vapor from the bed and, therefore, enhances the effectiveness of water desalination.

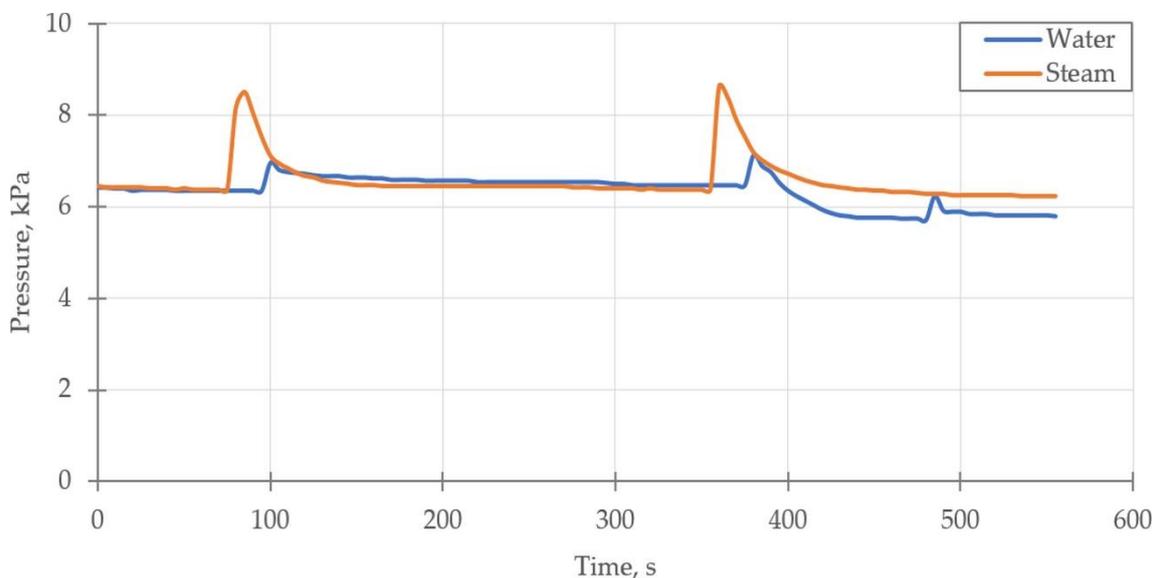


Figure 9. Pressure inside the condenser (P4).

3.2. Cost Calculation

As presented in Section 3.1., using steam for bed preheating can be beneficial in the terms of improving heat transfer and reducing the desorption time. Therefore, if free waste steam is easily available, the proposed solution seems to be cost-effective (ignoring the costs of chiller rebuilding). However, if there is no access to waste steam, the steam must be generated. Thus, a simple cost analysis is done to estimate the cost-effectiveness of this solution.

Assuming the initial water temperature T_0 , heating water temperature T_w and steam temperature T_s as 20 °C, 80 °C and 120 °C, respectively, their specific enthalpies are $i_0 = 83.9$ kJ/kg, $i_w = 335$ kJ/kg and $i_s = 2705.9$ kJ/kg. Therefore, the energy necessary to increase the temperature of 1 kg of water from 20 °C (initial condition) to 80 °C and to generate 1 kg of steam (120 °C) is $E_w = 251.1$ kJ/kg and $E_s = 2622$ kJ/kg, respectively. The cost of generating steam and preparing heating water can be calculated from Equation (5):

$$C = c_{fuel} \cdot \dots \cdot E/Q, \quad (5)$$

where C , Q and c_{fuel} are the cost of generating the steam (or preparing the heating water), the calorific value of fuel and the unit price of fuel, respectively. The assumed values of fuel unit price, calorific value and the results of calculation are summarized in Table 5.

Table 5. Cost calculation of generating steam and heating water from different fuels. Based on data from [41].

Fuel	Calorific Value, (kJ/kg)	Unit Price, (PLN/kg)	Cost of Generating the Steam, (PLN/kg)	Cost of Preparing the Heating Water, (PLN/kg)
Black coal	21,240	0.89	0.11	0.01
Lignite	9470	0.30	0.08	0.01
Oil	42,300	3.02	0.19	0.02
Natural gas	48,000	1805.56	98.63	9.45
Waste steam from industrial processes	-	0	0	-

Based on Table 5, it can be concluded that the cost of generating 1 kg of steam is approximately 10 times higher than the cost of preparing 1 kg of heating water with predetermined parameters. Nevertheless, if steam being a by-product of, e.g., the industrial process is available, then the cost of steam is zero.

3.3. Challenges and Design Guidelines

As explained in the Introduction and shown in the Results and Discussion, higher temperatures of the medium used for bed preheating, achieved by using steam instead of water, lead to faster heat transfer and shorten the desorption time from 300 s to 30 s. As a result, the COP of the adsorption chiller is improved by 35.2%, and more adsorption/desorption cycles can be completed in a given time. Therefore, the size of the chiller can be reduced maintaining the same cooling capacity. Nevertheless, using steam instead of water for bed preheating proposed in this paper involves a completely different approach to the desorption process and the material requirements of the device. Under given operating conditions of the chiller (Table 4), the average velocity of the steam is about 7.3 times higher than the average velocity of the water during the preheating. As a result, during the supply of steam to the bed, a very strong mechanical reaction of the system, especially of the pipelines supplying the steam to the bed, takes place, manifested by strong vibrations of the system.

The heat transfer rate between the heating medium and bed is directly proportional to the overall heat transfer coefficient, heat transfer surface area and temperature difference between the medium and the bed. Therefore, based on the results presented in this paper, the following general guidelines for designing steam-preheated adsorption chillers can be outlined:

- The steam supply system must be taken into account when designing new devices or, in the case of the existing ones, the adsorption chillers should be redesigned and rebuilt;
- An appropriate heat exchanger that enables the condensation of the steam should be designed or selected;

- Due to the condensation of steam, a heat exchanger should allow free drainage of the condensate and deaeration, which can be achieved by using straight pipes arranged parallelly and inclining the heat exchanger by about 3–5%;
- The steam inlet and water inlet should be on two sides of the heat exchanger to allow deaeration and condensate drainage;
- An appropriate heat exchanger and steam injection method that ensures uniform steam flow and reduces the vibrations should be designed or selected;
- Flow resistance during steam preheating is about 50 times greater than the flow resistance during water preheating. Therefore, it is advisable to increase the cross-sectional area of the pipes in the heat exchanger by at least 50%, which will result in a two-fold reduction in the flow resistance;
- The temperature difference between the steam and bed is about two times greater than the temperature difference between the heating water and bed. Additionally, the main barrier of heat transfer from the heating medium to the bed is the thermal contact resistance between the surface of the heat exchanger and silica gel grains [24]. Thus, changing the material of which the heat exchanger is made can be considered (e.g., from copper with high thermal conductivity to aluminum with lower thermal conductivity);
- Size reduction in the adsorption chiller, maintaining the same cooling capacity, should be kept in mind;
- The cost of preparing steam is about 10 times higher than the cost of preparing heating water using fossil fuels (Table 5). Thus, if there is a lack of waste steam from industry processes (or renewable energy sources), a thorough economic analysis should be conducted to ensure that using steam for bed preheating is cost-effective.

In addition to the design guidelines listed above, the results presented in this work may also be a basis for creating and validating a mathematical model of the desorption in the adsorption chillers, which may be a topic of the next paper. Furthermore, although the research was carried out for one adsorption chiller on a laboratory scale, it is expected that the presented results translate into other adsorption chillers, including the industrial-scale ones.

4. Conclusions

This article analyzes the possibilities of bed preheating with steam at a pressure of 3 bar and the maximum temperature of 120 °C.

During the experimental tests, a significant effect of the use of steam for preheating on the reduction in the desorption time was observed. The maximum temperature of the inlet steam to the bed was 120 °C, and a dynamic equalization of the outlet temperature to the inlet temperature was observed. The temperatures equalization lasted up to 30 s, which proves a very intense heat exchange process between the bed and the heating medium.

The heat exchanger temperature reaches its maximum after about 80 s from the start of the cycle (a few seconds after the end of steam feeding to the heat exchanger) and remains constant until the end of the desorption cycle, while the temperature in the case of water preheating slowly increases to reach its maximum at the end of desorption.

In the case of steam preheating, the pressure in the bed reaches a maximum value of 12 kPa, where in the case of heating water, it is 8 kPa. A higher pressure facilitates the desorption process, which is much more dynamic in the case of steam preheating.

When analyzing the use of steam, it should be noted that when using steam for preheating, the desorption process is shortened to about 30 s compared to 300 s for heating water. Reducing the desorption time to 30 s causes the device, using the same amount of sorbent, to increase its cooling capacity, because at the same time the sorption/desorption cycle can run several times in relation to the preheating the bed using hot water. Thus, the shortening of the desorption time can also lead to the reduction in the dimensions of the device. This is because the same cooling capacity can be obtained from a smaller amount of sorbent. Additionally, the COP of the chiller increased by 35.2% when steam is used instead of water for bed preheating.

If steam is used as a heat source for bed preheating, special preparation of the entire steam supply system to the device is required, and structural changes in the adsorption chiller are necessary. Nevertheless, using steam to preheat the beds of the adsorption chiller shows the potential of increasing its efficiency by reducing the desorption time.

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