

OPERATION OF AN ADSORPTION CHILLER IN DIFFERENT CYCLE TIME CONDITIONS

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This paper is devoted to application of adsorption process for cooling power generation in a cooling devices. Construction and working principle of a water-silica gel adsorption chiller has been presented and the basic refrigeration cycle has been discussed. The article outlines behavior of a single-stage adsorption system influenced by changes in cycle time. The effect of cycle time and inlet chilled water temperatures on the main system performance parameters has been analysed.

Keywords: adsorption chiller, coefficient of performance, silica gel adsorption, single stage system

1. INTRODUCTION

Sorption phenomena have widely been applied in various industrial-scale technologies, mainly in purification of flue gases. They could also be implemented in thermochemical cooling technologies being an alternative for compressed refrigeration in terms of proecological solution leading to primary energy savings as well as to reducing pollutant emissions into the atmosphere. The idea of thermochemical cooling in closed systems is based on making use of heat for achieving compression effect of refrigerant vapour circulating in a closed circuit.

Both absorption and adsorption involve sorption of refrigerant vapour accompanied by its subsequent desorption. The latter process requires heat supply. The origins of the use of thermochemical phenomena for cooling production date back to the mid-nineteenth century; when first absorption chillers were constructed (Asdrubali and Grignaffini, 2005). The first patents on utilisation of adsorption for this purpose were filed in the 1920s (Loh, 2010). Mainly due to a more efficient use of heat to produce cooling, absorption chillers have been widely commercialised on an industrial scale, whereas the number of manufacturers of adsorption-based equipment is still limited. Continuous research on improving efficiency of these devices should reveal the innovative nature of this technology.

Many thermodynamic models can be found in the literature aiming at developing systems that would provide prediction of performance at different work conditions, *inter alia* in Chua et al. (2004), Gräber et al. (2011), Loh et al. (2010) or Thu et al. (2013). An obvious advantage of adsorption chillers in respect to devices based on absorption is a possibility of supplying energy with heat carrier at lower temperature, thereby creating greater opportunity to make use of low-temperature heat sources (also waste heat). A performance analysis of a novel dual evaporator type, a three-bed adsorption chiller was

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presented by Miyazaki et al.(2010). Simulation results with hot water temperature of 65–85 °C can be found in that paper. Energy conversion processes take place together with inevitable energy losses, mainly in the form of heat dissipated in the atmosphere, thus the application area of sorption chiller equipment in technological solutions seems potentially to be very wide. They are used in air conditioning systems cooperating with solar collectors and polygeneration systems. Wherever there is a simultaneous demand for heat, cooling and electricity, thermochemical chillers can be successfully applied by creating local combined trigeneration systems. Selected trigeneration installations combined with adsorption chillers were presented by Wu and Wang (2006). Such solutions can be most commonly met in distributed energetics. However, if a source of electricity and heat (CHP) for the production of cooling is located at a considerable distance from the cooling system, which necessitates using district heating system, a trigeneration system (CCHP) will have central character. The knowledge and understanding of processes taking place in adsorption devices are very important aspects for their further performance improvement. Many investigated pairs of adsorbent-adsorbate systems can be found in the field of cooling technologies. Water as a cooling medium and solid silica gel as an adsorbent are the most commonly used substances in adsorption chillers. Kinetics of water adsorption on Fuji Davison RD silica gel was investigated in (Aristov et al., 2006). A zeolite–water adsorption chiller has recently been experimentally investigated by Myat et al. (2013). The adsorption kinetics of activated carbon/R134a and activated carbon/R507A pairs was investigated by Habib et al. (2010). Experiments carried out by Loh et al. (2009) provided data for alternative adsorbent/adsorbate pairs working at partial vacuum and pressurised conditions.

This paper presents design, construction, working principle and operation of a single-stage, water-silica gel adsorption chiller and analyses the performance of cooling production.

2. EXPERIMENTAL SETUP

A scheme of the experimental setup is presented in Figure 1. The adsorption cooling device consists of the following main components: evaporator, condenser, and four adsorption beds.

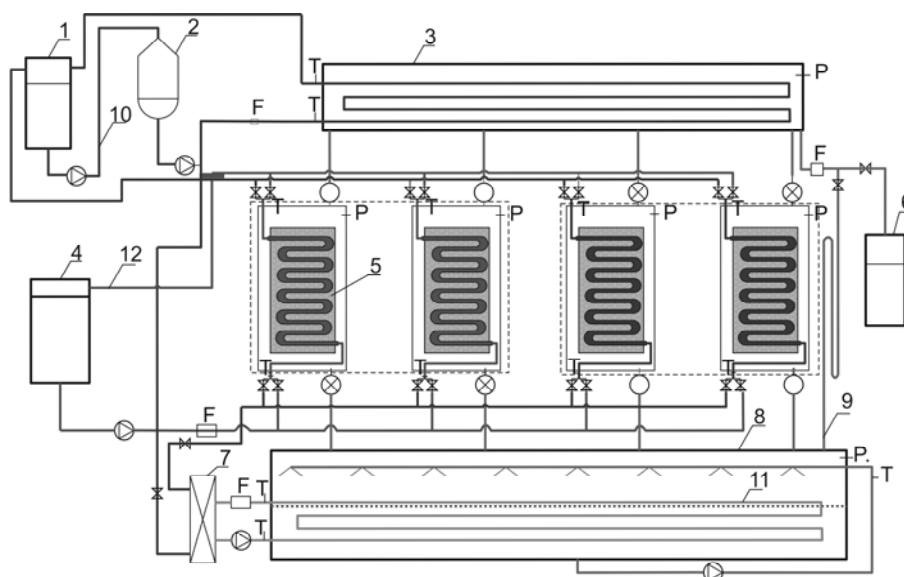


Fig. 1. Scheme of research station;

1 – tank of cooling water, 2- cooling tower, 3 – condenser, 4 – tank of hot water, 5 – silica gel, 6 – tank of refrigerant, 7 – heat exchanger of chilled water, 8 – evaporator, 9 – refrigerant circuit, 10 – cooling water circuit, 11 – chilled water circuit, 12 – hot water circuit, T/P – temperature/pressure sensors, F – flowmeter, O/⊗ - refrigerant valve open/closed

Single-stage or two-stage systems can be operated by means of appropriate valve manipulations. In the conducted investigations the chiller was working as a single-stage system of heat and mass transfer.

For the proper operation of the chiller, systems of adsorber and condenser cooling fed from the cooling tower as well as a control panel for measuring, recording and data acquisition were installed. The automation system consisted of the main control panel and sensors integrated into the data logger and computer. The location of sensors is presented in Figure 1. Temperature readings were taken every 3 seconds with an accuracy of $\pm 0.2^\circ\text{C}$. Flow measurements were made using electromagnetic transducer with an accuracy of $0.5\% \pm 0.05 \text{ dm}^3/\text{min}$. The pressure measuring sensors had the accuracy of $\pm 0.125 \text{ kPa}$. The measurement system was able to achieve the accuracy of the average cooling capacity determinations $\pm 3.5\%$, $\pm 3.9\%$ for *COP* and ± 1.7 for heating power.

3. WORKING PRINCIPLE

Cooling capacity is achieved in an evaporator via cooling water flowing through tubes placed inside it. The temperature of chilled water is reduced as a result of heat taken up by a refrigerant which changes its state during evaporation. There are two ways of accomplishing heat transfer between coolant (refrigerant) and cooled water (chilled water). The first one involves complete immersion of the tubes, in which chilled water flows cooled by the refrigerant. In the second, more efficient method, the tubes are partially submerged, and the refrigerant is sprayed on the external tubes through spray nozzles. Since at lower pressures water evaporates at lower temperatures, depending on the temperature of chilled water at the inlet to the evaporator (being a heat source for evaporation), pressure and temperature inside the evaporator are maintained. Consequently, the physical state of the refrigerant can be changed into vapour. The condition for the evaporation process to occur is to reach the refrigerant saturation point inside the evaporator, lower than that of the inlet chilled water flowing through the evaporator tubes, so that the refrigerant can receive heat from chilled water. The refrigerant supplied to the evaporator evaporates and flows further to the reactor (adsorber). Since the sorption capacity of the silica gel bed in the reactor is limited and the process of evaporation of the refrigerant takes place continuously, in order to ensure a continuous production of cooling capacity in a single-stage device at least two beds operating alternately must be installed. After the adsorption process has been completed, regeneration of the bed is required. Thus, when one of the reactors is operating in desorption phase, vapour generated in the evaporator flows into the second reactor, previously prepared for adsorption. In the system presented in Figure 1, two beds work as desorbers, while at the same time in two others adsorption takes place. Bed regeneration is preceded by its preheating for a short time (switching time). The vapour released during desorption flows into the condenser, where it is condensed when it comes into contact with cold walls of the condenser and releases heat of condensation to the condenser cooling water circuit. The cooling water temperature in the condenser has to be lower than that of the refrigerant vapour in the condenser. After passing through the throttling valve or U-tube, the refrigerant in the liquid state is returned to the evaporator. When desorption has finished, the bed is prepared for adsorption by pre-cooling in a short time (switching time). A system of bed connections with the condenser and the evaporator in successive phases of the cooling cycle is shown in Table 1.

A theoretical adsorption cooling cycle is shown in the Dühring diagram for a single-stage circuit of refrigerant contacted in the bed (Fig. 2). Values of the refrigerant vapour pressure are denoted on the ordinate, while the abscissa shows changes of the adsorbent temperature. The oblique lines depict changes in the amount of vapour adsorbed by the bed. An ideal adsorption cycle consisting of four stages: (a-b) pre-heat of the bed, (b- c) desorption, (c-d) pre-cooling of the bed, and (d-a) adsorption is marked by dashed lines.

Table 1. System of bed connections

Cycle phase	Position of valves connecting with beds	
	Evaporator	Condenser
Adsorption	Open	Closed
Pre heating/cooling time for bed	Closed	Closed
Desorption	Closed	Open
Pre heating/cooling time for bed	Closed	Closed

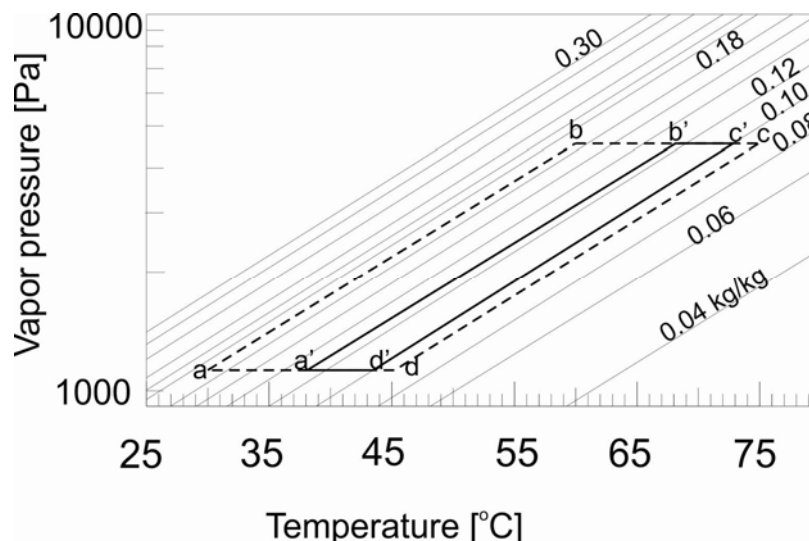
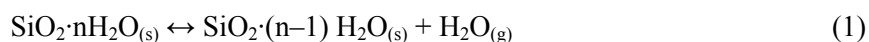


Fig. 2. The basic adsorption cycle for the single-stage adsorption chiller (Akisawa and Miyazaki, 2010)

Adsorption and desorption take place under a constant pressure. The adsorption process is exothermic and according to Fig. 2 the greatest changes in the refrigerant concentration at the surface of adsorbent can be noted at lower temperatures (more oblique lines crossed the area of trapezoid in lower temperatures). Therefore, to improve adsorption conditions and to maintain a constant vapour pressure, adsorption heat should be removed by the adsorber cooling water circuit. The bed is packed around a coil inside the reactor as shown in Fig. 1, so that it enables supply of hot or cold water, depending on the process taking place in the reactor.

During the pre-heating/cooling of the bed, adsorbent is brought to a temperature allowing easy process of desorption/adsorption. The real adsorption cycle is marked by a solid line (Fig. 2), and is only a part of the previously outlined theoretical cycle. Narrowing of the trapezoid area showing changes in the real cycle reflects the dynamism of changes taking place in the water vapour-silica gel system. The uptake of water vapour by silica gel ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$) can be described as follows:



where „s” denotes solid phase and „g” – gaseous phase.

In theory, equilibrium in the water vapour-silica gel system should be achieved, if the bed is fully saturated by refrigerant at the end of adsorption as well as at the end of desorption processes - when as a result of heat supplied to the bed it will be completely cleaned of the adsorbed vapour (Akisawa and Miyazaki, 2010). When the system approaches its equilibrium the sorption rate slows down, which in turn affects evaporation. This is not a desirable effect because of the requirement to maintain the operational stability of the device at a constant intensity. The slowdown of adsorption/desorption results in a decrease of the refrigerant circulation in the device cooling cycle, exerting direct impact on

the process of heat removal from the chilled water (cooling capacity generation). Therefore, because of the necessity of maintaining a constant cooling capacity generation via evaporation process, at a constant amount of circulating refrigerant in the adsorption cycle, the state of theoretical/ideal-equilibrium vapour - silica gel will not be attained. Hence the real refrigeration cycle (see Fig. 2) is a fragment of theoretical cycle located in the area where the adsorption process runs with the greatest rate.

4. OPERATION CYCLE OF ADSORPTION CHILLER

The operation cycle of an adsorption cooling device can be described as follows:

1. The evaporator is filled by refrigerant (water), and the pressure in the evaporator is maintained in the range of about 1.1 to 2.9 kPa.
2. A system of tubes is installed inside the evaporator. By means of chilled water (which flows inside the tubes) it provides heat necessary for refrigerant evaporation. The inlet temperature of the chilled water fed to the evaporator may be set from the control panel.
3. When temperature inside the evaporator is equal to the refrigerant evaporation temperature at a given pressure and also the temperature of the chilled water- fed into the evaporator via the system of tubes, is higher than the evaporation temperature of refrigerant, the evaporation process occurs. As a result the chilled water temperature leaving the evaporator via the system of tubes decreases.
4. The evaporator is connected to the beds, on which the adsorption of refrigerant vapour takes place. However, to ensure vapour flow towards the reactors (adsorbers) the pressure inside them must be lower than that in the evaporator. Therefore, before connecting beds to the evaporator, the reactor is pre-cooled in order to achieve a proper pressure level. The time of pre-cooling/pre-heating (switching time) was set at 45 seconds.
5. The valves connecting the evaporator with the reactors during the adsorption stage are opened, so that the vapour generated in the evaporator is adsorbed on silica gel bed. The adsorption process is exothermic, and to maintain a constant pressure in the bed the heat of adsorption should be removed by the cooling water circuit supplied from a cooling tower. The adsorption process takes place during a preset time cycle. After completing adsorption period the reactor is isolated from the evaporator and pre-heated during the switching time. During that period the pressure inside the reactor reaches a level allowing vapour discharge to the condenser and after that the valve connecting the reactor with the condenser is opened.
6. By the heat supply by means of hot water circuit, typically at temperatures lower than 95 °C, the previously adsorbed vapour is released in desorption. Desorption time is the same as that of adsorption. Beds are regenerated by heating.
7. Desorbed refrigerant vapour flows to the condenser. To ensure condensation of refrigerant, heat accompanying the phase change has to be removed from the system, therefore the cooling water system of condenser is applied, while the inlet temperature of cooling water must be lower than the refrigerant condensation temperature at a given pressure. Higher pressure than that in the evaporator is maintained in the condenser thus allowing condensed refrigerant to flow to the evaporator.
8. After condensation the refrigerant with high pressure flows through the U-tube and after reaching the pressure level equal to that in the evaporator enters the evaporator, where a system of nozzles is spraying refrigerant on the tubes with chilled water and the refrigerant cycle is repeated.

5. AIM OF THE RESEARCH AND CALCULATION METHODOLOGY

The experiments were aimed at monitoring the main operational parameters and performance evaluation in the present adsorption system. Based on the registered readings for water flow rates on the adsorption refrigeration system, the parameters defined by Equations (2), (3), (4), and (5) were calculated to determine their changes during the cycle period.

The coefficient of performance, COP , is a parameter that characterises performance of an adsorption cooling device

$$COP = \frac{CC}{HP} \quad (2)$$

It is defined as the ratio of the generated cooling capacity (CC):

$$Q_c = CC = \dot{m}_{ch} c p_{ch} \Delta T_{ch} \quad (3)$$

to the supplied heating power (HP)

$$Q_{des} = HP = \dot{m}_h c p_h \Delta T_h \quad (4)$$

The performance ratio of the adsorption system, defined as the quotient of the thermal power output from the system to the total thermal power supplied to them is calculated from Equation (5):

$$PR = \frac{Q_{cond} + Q_{U-tube}}{Q_{des} + Q_c} \quad (5)$$

All the the above calculations were carried out for each 3-second reading for a cycle which had previous been chosen as a representative (the most stable) in an experimental path for every preset cycle time. Since the calculations results were averaged for the representative cycle for certain cycle time conditions only three points for two different chilled water temperatures are shown on the graphs.

$$PR_{av} = \frac{1}{N} \sum \int_0^{T_{cycle}} \frac{Q_{cond} + Q_{U-tube}}{Q_{des} + Q_c} dt \quad (6)$$

$$CC_{av} = \frac{1}{N} \sum \int_0^{T_{cycle}} \dot{m}_{ch} c p_{ch} \Delta T_{ch} dt \quad (7)$$

$$COP_{av} = \frac{1}{N} \sum \int_0^{T_{cycle}} \frac{CC}{Q_{des}} dt \quad (8)$$

6. OPERATION PARAMETERS

Since the effectiveness of vapour release in desorption depends on heat flux supplied for bed regeneration, and one of the parameters regulating the thermal power of stream is the inlet temperature of the heat carrier fed into the reactor, the efficiency of cooling capacity generation will grow with the increasing temperature of the heat source used to regenerate the bed. This relationship has been confirmed experimentally e.g. by Sekret and Turski (2012). Therefore, in the experiments a constant regeneration temperature of 85 °C was applied, which, as pointed out by Chua et al. (2004) is a typical regeneration temperature for water-silica-gel systems. Other operational parameters are listed in Table 2.

Table 2. Operating parameters

Parameter	Temperature [°C]	Flow [l/min]	Other
Hot water inlet (desorber)	85	48	–
Cooling water inlet (adsorber)	29.5	48	–
Cooling water inlet (condenser)	29.5	120	–
Chilled water inlet (evaporator)	10 - 20	48	–
Mass of silica gel per bed	–	–	36 [kg]
Pre heating/cooling time for bed (switching time)	–	–	45[s]
Cycle time (adsorption/desorption)	–	–	480 - 900 [s]

Due to the specific construction of the device, which enables optional operation of beds, adsorption and desorption periods were the same.

7. RESULTS AND DISCUSSION

Results are presented in Figs. 3, 4, and 5. Square points reflect experimental conditions at which chilled water temperature at the inlet to the evaporator was 20 °C, while the circles correspond to 10 °C. The experiments were conducted for three time cycles: 480 s, 600 s, and 900 s.

In general, higher values of investigated parameters were obtained for experiments with the 20 °C inlet chilled water temperature. It can be justified by better effectiveness of evaporation occurring at a higher temperature. It also means stronger effect of chilled water (at higher ΔT_{ch}) in comparison with 10 °C inlet chilled water temperature, which has a significant influence on the values of investigated parameters. Other experiment settings for both cases were identical.

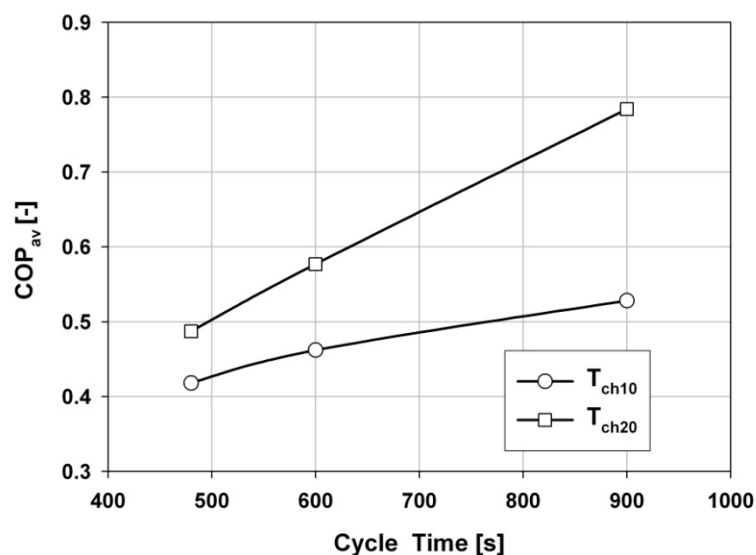


Fig. 3. COP_{av} dependence on the cycle time

Figure 3 shows a dependence of COP_{av} on the cycle time at different temperatures of chilled water entering the evaporator. As can be seen in the figure, when increasing the cycle time COP_{av} increases. This dependence can be explained by differences between sorption and desorption rates as well as by

changes in the dynamism of adsorption progressing with time. Together with extension of the cycle time the concentration of the refrigerant on the adsorbent increases, while adsorption slows down. To achieve a substantial increase in the amount of vapour adsorbed by silica gel (corresponding to concentration changes depicted by solid lines in Fig. 2) the process must proceed for a long time, because, as stated earlier, when the system tends to reach an equilibrium, sorption processes slow down.

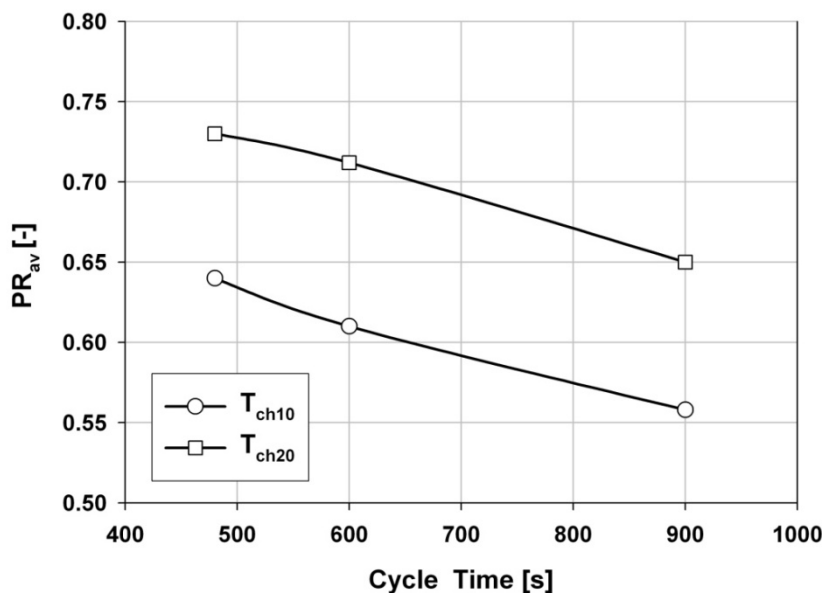


Fig. 4. PR_{av} dependence on the cycle time

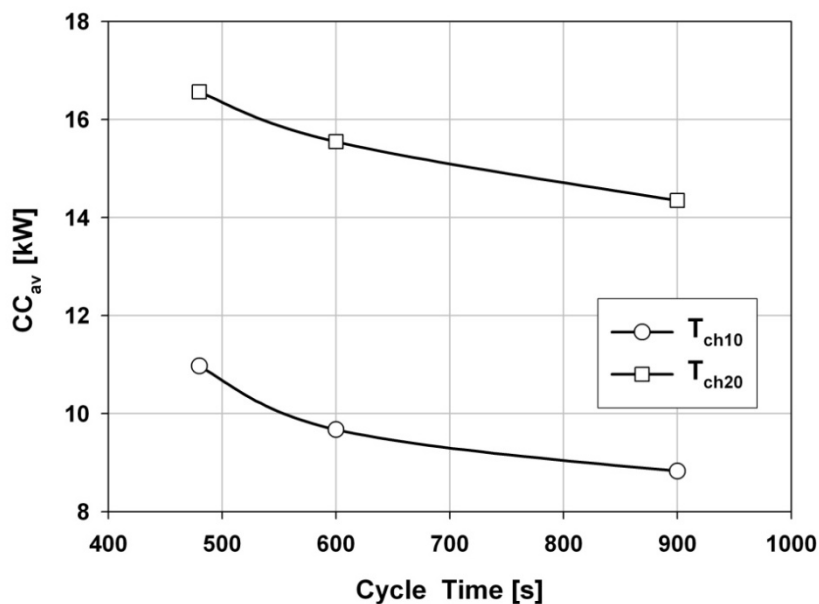


Fig. 5. Dependence of CC_{av} on the cycle time

In addition, desorption runs faster than adsorption (due to higher temperature), which means that after a given time the heating power supplied to the bed may not be consumed by desorption. Then, the cooling rate of the hot water fed to the desorption unit will be smaller, which at a constant flow of hot water reduces the instantaneous value of the output stream HP constituting the denominator in Eq. (2). This affects the final mean values of COP_{av} for the test cycles of adsorption and may result in nearly monotonic increase in COP values with the cycle time of the adsorption/desorption steps.

The lines shown in Figs. 4 and 5, show that regardless of chilled water temperature there is a general trend indicating a decrease in average cooling capacity and the average performance ratio when extending the cycle time of adsorption/desorption steps. This relationship is justified, as adsorption slowdown when the water vapour-silica gel system tends to reach equilibrium may also have an impact on the process of generating cooling capacity. The coolant mass transfer between the condenser and the evaporator is also slowed down, resulting in disturbances in the coolant evaporation process. For both investigated cases the highest value of CC_{av} was obtained for the shortest time cycle - 480 s.

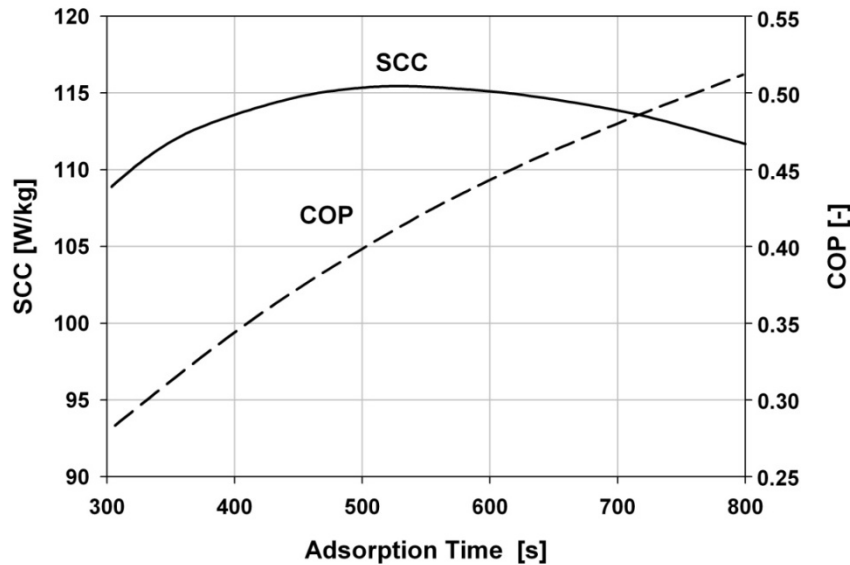


Fig. 6. Effect of adsorption time on COP and appropriate adsorption chiller cooling capacity (Akisawa and Miyazaki, 2010)

The average cooling capacity reaches a maximum in a shorter time, because the set of arguments, from which it is evaluated did not contain too many arguments "decreasing the average". It will be the moment preceding that adjusted for the maximum cooling capacity, CC , for a given cycle. Therefore, an extension of adsorption time will also result in extending time during which vapour adsorption in the bed will become increasingly slower. This will cause a reduction of the final value of CC_{av} and in consequence a decrease of PR_{av} . In the set of instantaneous measurements of the cooling power, taken for the average value calculations there are also the data from the "slow adsorption period," lowering the values presented in the graphs.

In the paper of Akisawa and Miyazaki (2010) devoted to single-stage adsorption chillers, the curve showing the generation of cooling capacity per kilogram of silica gel (SCC) versus cycle time has a maximum (Fig. 6).

As shown in Fig. 5, the curves do not reveal any points of inflection. This means that to find an optimal time of the adsorption cycle, corresponding to a maximum cooling capacity of the device, additional experiments should be conducted in order to check the system behaviour within a shorter cycle time.

8. CONCLUSIONS

From the experimental results carried out in this study it could be concluded that the variability of all (CC , COP , PR) parameters depends on the cycle time of adsorption/desorption steps. It is therefore evident that adsorption/desorption cycle time is an important parameter for productivity of adsorption chillers. All parameter changes occurring with increasing time of adsorption/desorption are related to

the achievement of dynamic equilibrium state in the water vapour-silica gel system, which affects mass transfer in the refrigeration device.

Maximising cooling capacity production per kg of silica is a desirable effect enabling cost reduction and size minimisation of future.

In order to achieve the greatest production of cooling capacity under operating conditions, optimal adsorption/desorption cycle time should be sought.

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SYMBOLS

CC	cooling capacity, W
COP	coefficient of performance
cp	specific heat of water at the inlet temperature, $\text{kJ}\cdot\text{kg}^{-1}\cdot\text{deg}^{-1}$
HP	heating power supplied for desorption, W
\dot{m}	flow of water, $\text{kg}\cdot\text{s}^{-1}$
N	number of readings in cycle
PR	performance ratio
Q_c	heat supplied to evaporation process by chilled water circuit, W
Q_{cond}	heat released to condenser cooling water circuit, W
Q_{des}	heat supplied to bed regeneration process by hot water circuit, W
Q_{st}	heat of adsorption, $\text{kJ}\cdot\text{kg}^{-1}$
Q_{U-tube}	heat released in condensation process, transported by refrigerant, W
t	time, s
T_{cycle}	cycle time, s
T_s	temperature, K
ΔT	temperature difference (between inlet and outlet) for water flow

Subscripts

av	average value for cycle,
ch	chilled water,
h	hot water

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