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ON ADSORPTION OF WATER VAPOR ON SILICA GEL

BADANIE ADSORPCJI PARY WODNEJ NA SILIKAŻELU

Abstract

The aim of this work is to present the results of studies on heat and mass transfer in an adsorber, which is the main part of an adsorption chiller. The paper refers to adsorption of water vapor on silica gel grains. Adsorbent grains were coated on the outer surface of a copper pipe. The influence of grains diameter and flow rate of the gas phase on process intensity was considered.

Keywords: adsorption chiller, silica gel, water vapor

Streszczenie

Celem niniejszej pracy jest zaprezentowanie wyników badań dotyczących przenoszenia ciepła i masy w adsorberze stanowiącym podstawową część adsorpcyjnego urządzenia chłodniczego. Praca dotyczy adsorpcji pary wodnej na silikażelu. Ziarna silikażelu były naniesione na zewnętrzną powierzchnię miedzianej rurki. Badano wpływ wielkości ziaren oraz natężenia przepływu gazu na intensywność procesu.

Słowa kluczowe: chłodziarka adsorpcyjna, silikażel, para wodna

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1. Introduction

Nowadays, we can observe a steady increase in the level of pollution and the depletion of non-renewable energy sources. The development of new technologies that use environmentally friendly solutions is the answer to these problems. Refrigeration and air-conditioning are the fields where it is possible to reduce energy consumption. It was estimated that about 15% of world energy resources is used for cooling and refrigeration processes [5]. Because of this reason, an intensive development of chillers based on the adsorption process can be observed. They can be driven e.g. by solar energy, which can deliver the driving temperature difference.

The possibility of using environmentally friendly natural refrigerants is one the most important advantages of adsorption chillers. Water can be an example of such a refrigerant – it is ecologically clean, cheap and widely available. Moreover, automation and control of such systems is easy, the level of vibration and noise is low when compared with traditional compression systems and there are no corrosion problems as in the case of absorption chillers.

However, adsorption chillers have some disadvantages. The necessity to maintain vacuum in the system, their considerable size and weight, relatively low coefficient of performance COP and discontinuous operation resulting from alternating adsorption and desorption can be mentioned [2].

The aim of this paper is to present results of studies referring to enhancement of heat and mass transfer in an adsorber, which is one of the basic part of an adsorption chiller. Adsorption of water on silica gel was considered.

2. Operating principle of an adsorption chiller

Two adsorbent beds (adsorber and desorber), a condenser and an evaporator are the main components of an adsorption chiller. Heat exchangers are installed inside both beds. The operation of the chiller is cyclic. A cooling cycle is comprised of two adsorption/desorption steps and two switching steps.

In the adsorption period, adsorbate molecules are transported from evaporator to the adsorbent bed. This process is spontaneous as adsorbate molecules move from a gaseous phase to an adsorbed phase which is characterized by lower energy level and is more thermodynamically stable [4]. Transport of vapor molecules from the evaporator reduces the pressure. This causes boiling of the refrigerant and the production of the chilling effect. Adsorption is an exothermic process so it results in heat rejection. Therefore, in order to maintain the process, the adsorbent bed must be cooled by a cooling agent flowing in the heat exchanger and removing the rejected heat.

At the same time, the desorber, i.e. the second bed that is saturated with water vapor, interacts with the condenser. The bed is heated by a heating agent flowing in the heat exchanger as a result of which, the adsorbate molecules are desorbed from the bed and flow to the condenser where the vapor condenses. The liquid adsorbate flows back from the condenser to the evaporator.

When the adsorption/desorption period is complete, the switching step starts. The two reactor beds swap the roles. The path of the cooling and heating agent is changed. At this stage, there is no connection between the adsorber/desorber and the evaporator/condenser.

The adsorption pairs used in adsorption chillers can be divided in view of the adsorption type. The following pairs, based on physical adsorption, can be mentioned: activated carbon/ammonia, activated carbon/methanol, activated carbon/ethanol, zeolite/water, silica gel/water. Chemical adsorption occurs in the case of e.g. the metal chlorides/ammonia pair or metal hydrides/hydrogen pair. Adsorption can be enhanced by application of the pair with consolidated adsorbents e.g. zeolite and chlorides/water, porous substances and chlorides/ammonia or silica gel and chlorides/water.

3. Experimental setup

In this work, the silica gel/water pair is considered. Heat of adsorption, in this case, is equal to 2800 kJ/kg [6]. The degree of coverage (concentration of water in adsorbent grains) reported in literature is 0.2 g/g for typical working conditions of adsorbent chillers [7]. One of the advantages of silica-gel water pair is that such a system is non-toxic. Moreover, experiments were conducted under ambient temperature so there was no need to use adsorbates with evaporating point below 0°C. Silica gel can be regenerated after it has been used so the sample can be used many times.

The experimental setup was built from scratch. Its scheme is presented in Fig. 1. A 12×1 mm copper pipe of a length of 220 mm was the measuring element. Inside of the pipe, there was a coaxial PTFE rod of diameter 8.5 mm. The external surface of the pipe was covered with the commercial *Wikol* glue based on polyvinyl alcohol and then it was coated with silica gel grains [1]. The pipe was put into a glass pipe with double walls as presented in Fig. 2. Internal diameter of the glass pipe was 23 mm and the external one – 46 mm. Static air between the walls of the glass pipe played the role of insulation. The operation of the system is similar to the double pipe heat exchanger. There are two circuits – a circuit of air saturated with water vapor and a circuit of cooling water (Fig. 2c). Cooling water flows through the annular cross-section between the copper pipe and PTFE rod. Air flows between the copper pipe covered with silica gel grains and the internal wall of the glass pipe. Before it enters the system, it is saturated with water vapor in humidifiers. When the air flows around the adsorbent grains, water is adsorbed.

Adsorption in pellets covering the surface is much different from the classic adsorption in a bed. The size of pellets plays an important role when adsorption occurs in a bed. The smaller the grains, the faster the process, but on the other hand, the greater the pressure drop. In the considered case the thickness of an adsorbent grains layer is more important than the grains size. Actually, the size of grains does not influence the pressure drop of gas flowing along the surface covered with grains.

The setup was equipped with measuring and control instruments. Flow rate of the air was adjusted by the controller 4850 produced by Brooks Instruments. Sensors PC52 (Michell Instruments) allowed one to measure relative humidity and temperature at the inlet and outlet of the air. A Cu-CuNi thermocouple was used to measure temperature in the central point of the adsorbent layer (Fig. 2b). Sensors PC52 and the thermocouple were connected to a multi-channel electronic recorder MPI-D manufactured by Metronic.

Silica gel samples were regenerated in the chamber dryer Wamed with digital temperature controller. The mass of the adsorbent was measured with the use of an electronic laboratory AS/X produced by Radwag.

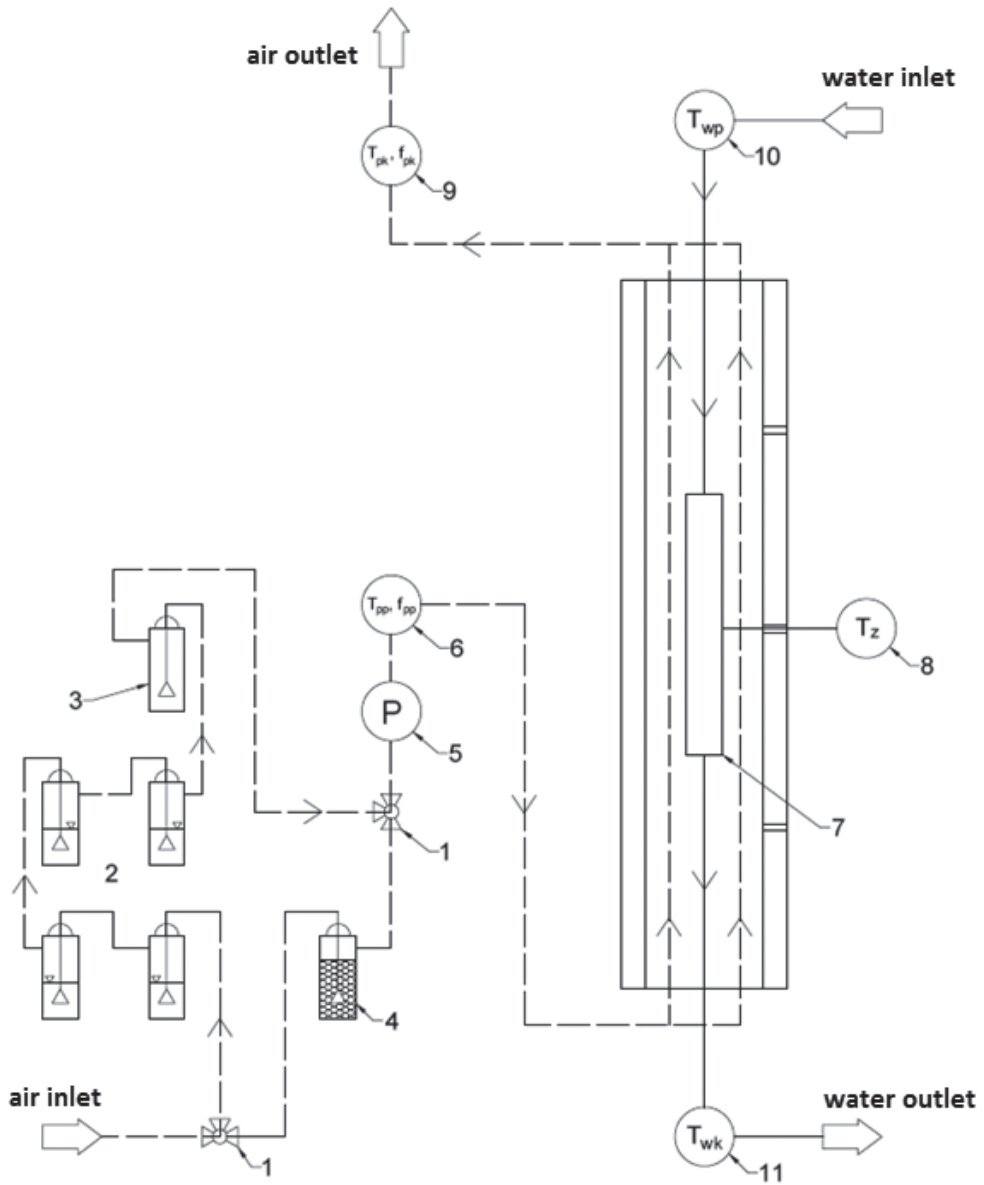


Fig. 1. Schematic diagram of the experimental setup: 1 – three-way valve, 2 – humidifiers, 3 – safety vessel, 4 – by-pass dryer, 5 – pressure converter, 6, 9 – air humidity and temperature sensors, 7 – measuring element, 8 – thermocouple measuring adsorbent temperature, 10, 11 – thermocouples measuring cooling water temperature

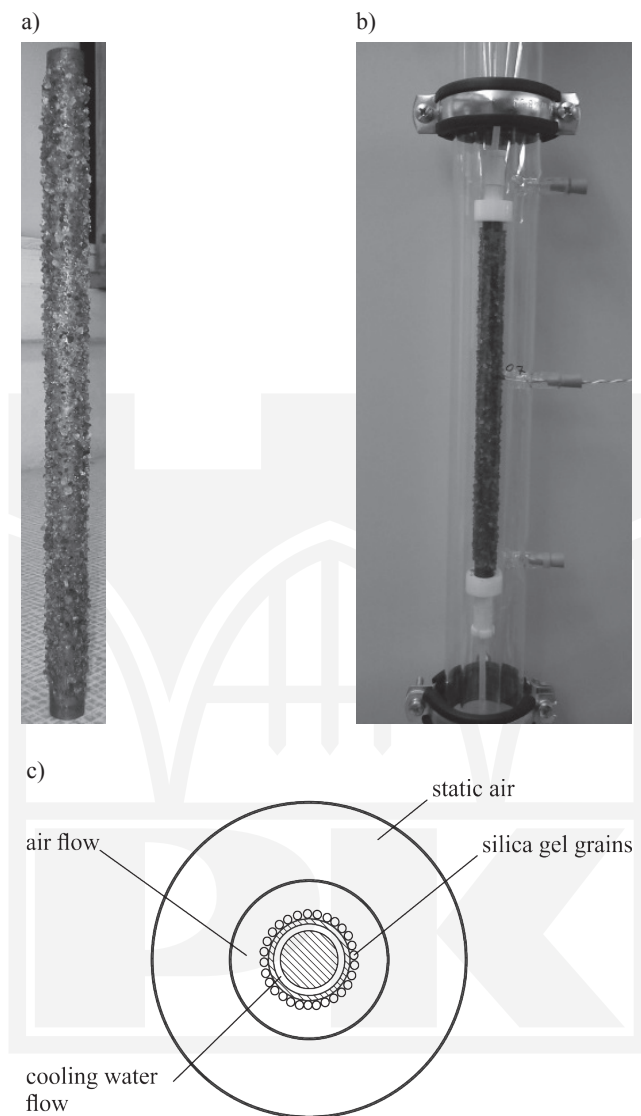


Fig. 2. Measuring element: a) after drying, b) after installation in the experimental setup, c) cross-sectional view

4. Experimental procedure

In the first step of the experimental procedure, the copper pipe was prepared. The pipe was weighed, its surface was degreased with acetone and then covered with glue and adsorbent grains. The pipe was then dried for 3 hours at 150°C in order to remove water from silica gel and glue. Then it was placed into the glass double-wall pipe. Before the measurements, air

flowing through the by-pass dryer packed with silica gel entered the installation in order to remove humid air from it. Then, the air flowed through humidifiers with water where it was saturated with water vapor and the measurements started. Recording of sensors indications was finished when the difference between inlet and outlet air humidity was steady for 10 min. The humid sample was then weighed and placed in the dryer to regenerate the adsorbent grains.

During the measurements, air temperature and humidity as well as mass of silica gel before and after adsorption of water was measured. Mass of adsorbed water was determined. Grains of diameters 0.63–0.8 mm, 0.8–1.0 mm and 1.5–2.0 mm were used. Inlet air humidity was 85%.

5. Measurement results

Two series of measurements were conducted. In the first series, the diameter of grains was constant. Air flow rate was the controllable parameter. The second series was based on changing grains diameter for the constant flow rate of inlet air. The obtained results are presented on the graphs in the form of symbols, however, only some of the results are depicted because of a high sampling frequency – sensors indications were recorded every 10 seconds.

In Fig. 3, the breakthrough curves (e.g. the relationships between outlet air relative humidity and time) for the first series of measurements are presented. Grains diameters are in the range 0.8–1.0 mm and air flow rates equal to 1 dm³/min, 3 dm³/min and 5 dm³/min (these

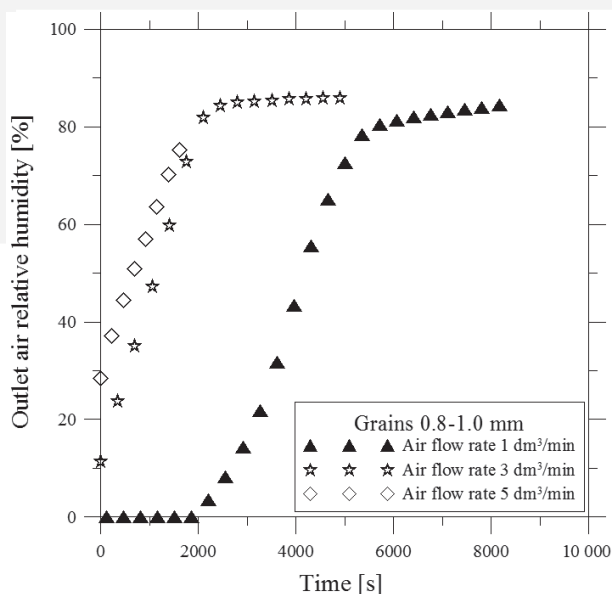


Fig. 3. Temporal variation of the outlet air relative humidity for different values of air flow rate and constant range of adsorbent grains diameters (breakthrough curves)

values refer to the air before saturation with water vapor in humidifiers). The flow rates refer to the air before saturation in humidifiers. On the basis of the graph, it might be concluded that in the case of flow rates equal to $3 \text{ dm}^3/\text{min}$ and $5 \text{ dm}^3/\text{min}$ the medium flows around the grains too fast so water vapor cannot be adsorbed effectively. When the flow rate was $1 \text{ dm}^3/\text{min}$, in the initial stage of the process there was no water vapor in the outlet air so there was no breakthrough at the very beginning of the process (i.e. for $t = 0 \text{ s}$).

In Fig. 4, the graph for the second series of measurements is presented. It refers to the constant flow rate of air equal to $1 \text{ dm}^3/\text{min}$ and different diameters of grains. It may be concluded that for this value of flow rate, the breakthrough was not observed for $t = 0 \text{ s}$ regardless of the grains size. Moreover, it should be noticed that the greater the grains, the longer the time after which the breakthrough of the bed occurs.

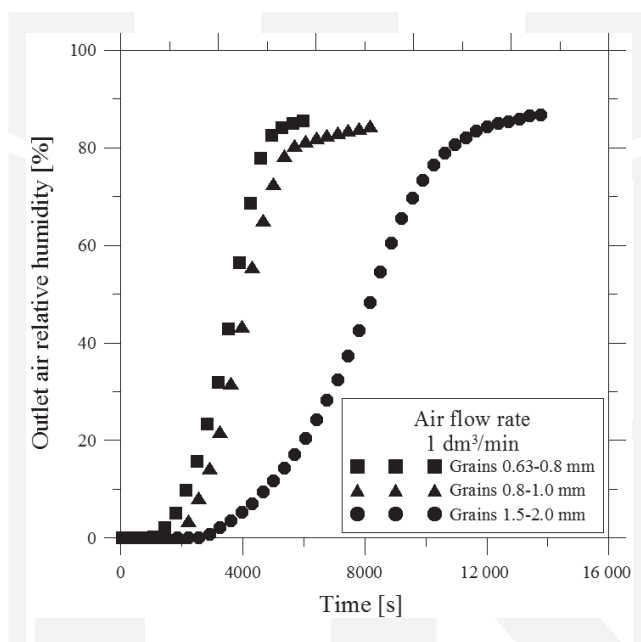


Fig. 4. Temporal variation of the outlet air relative humidity for different ranges of adsorbent grains diameters and constant air flow rate (breakthrough curves)

Graphs in Figs. 5 and 6 present temporal variations of the difference between the inlet and outlet air humidity. Fig. 5 refers to the constant grains size (0.8–1.0 mm) and different flow rates of air. According to the figure, the difference between inlet and outlet air humidity decreases over adsorption time. The result for grains 0.8–1.0 mm and air flow rate $1 \text{ dm}^3/\text{min}$ at the initial stage of the process is distorted, which is caused by the fluctuations of inlet air humidity and by the humid air that was left in the installation after a previous measurement. It may also be concluded that the greater the flow rate of air, the smaller the difference between inlet and outlet air humidity at a certain moment of time. In the case of flow rates $3 \text{ dm}^3/\text{min}$ and $5 \text{ dm}^3/\text{min}$, the initial humidity difference was relatively low because for high gas flow rates (high velocities) time of contact of the gas phase with the grains is too short to adsorb all of the water vapor contained in the air.

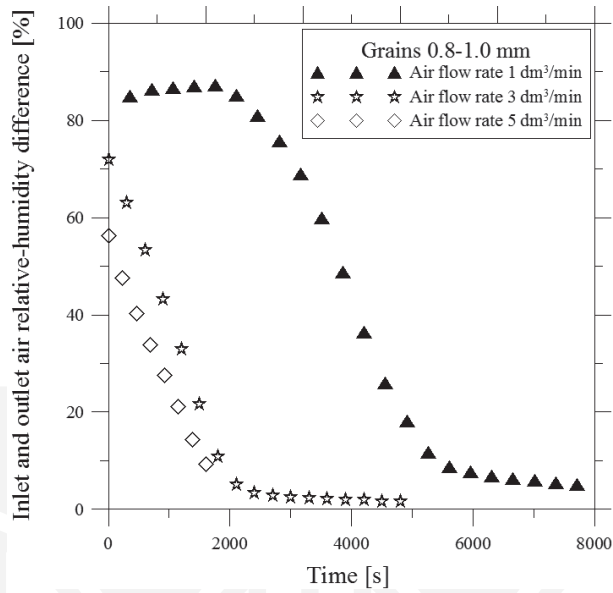


Fig. 5. Temporal variation of the difference between inlet and outlet air relative humidity for different values of air flow rate and constant range of adsorbent grains diameters

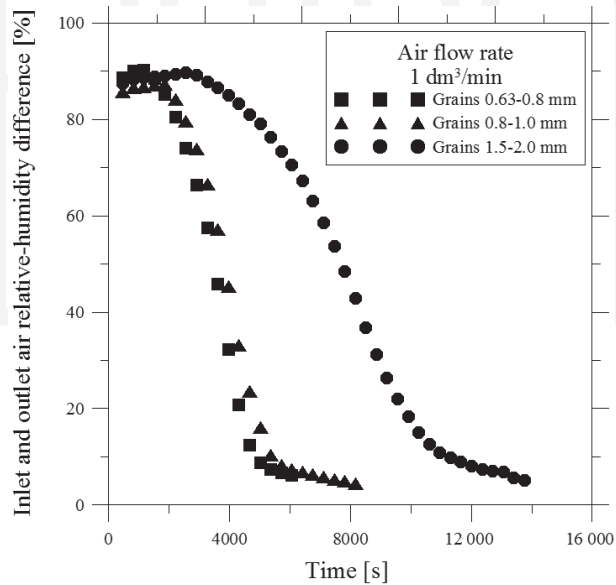


Fig. 6. Temporal variation of the difference between inlet and outlet air relative humidity for different ranges of adsorbent grains diameters and constant value of air flow rate

Fig. 6 refers to the constant flow rate of inlet air ($1 \text{ dm}^3/\text{min}$) and different sizes of grains. It comes from the figure that the inlet and outlet air humidity difference at a certain moment of time is the greater, the greater the grains size.

Therefore, on the basis of Figs. 5 and 6, it may be stated that the time after which the relative humidity difference reaches values close to zero is longer, the greater diameters of the grains and the lower flow rate of the air.

Fig. 7 presents variations of temperature in the central point of the adsorbent layer. It may be noticed that temperature increases at the initial phase of the process, which is consistent with predictions [3]. It is caused by the generation of the heat of adsorption. Then, the temperature decreases because the grains are cooled by the flowing stream of gas. The greatest temperature increase, in relation to the initial adsorbent temperature, was observed in the case of the flow rate equal to $3 \text{ dm}^3/\text{min}$. If the flow rate was high enough, the adsorbent would be cooled efficiently by the flowing stream and the shape of the curve would differ (temperature would only decrease).

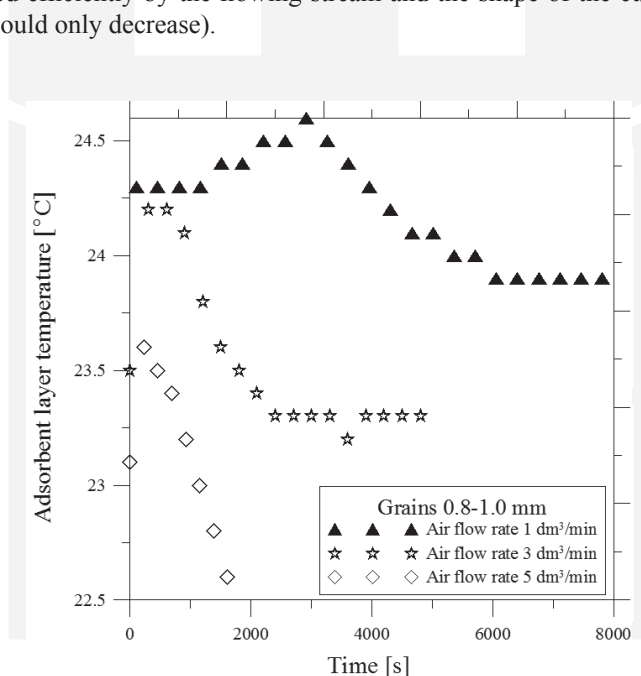


Fig. 7. Temporal variations of the adsorbent layer temperature for different values of air flow rate and constant range of adsorbent grains diameters

Results of measurements of mass of the adsorbed water are presented in Tables 1 and 2. It comes from the data contained in Table 1 that the final degree of coverage does not depend on the flow rate of the humid air. However, values from Table 2 allow one to conclude that greater size of grains gives the opportunity to adsorb greater amount of water regardless of the fact that the pipe cannot be covered with such grains as precisely as in the case of grains with smaller diameters.

Table 1

Results for the 1st series of measurements (constant range of grains diameters: 0.8–1.0 mm)

Air flow rate [dm ³ /min]	Air velocity [m/s]	Mass of dry silica gel covering the copper pipe [g]	Mass of adsorbed water [g]	Degree of coverage (concentration of water in grains) [g/g]
1	0.058	3.34	0.87	0.26
3	0.174	3.58	0.96	0.27
5	0.290	3.22	0.85	0.26

Table 2

Results for the 2nd series of measurements (constant inlet air flow rate: 1 dm³/min)

Grains diameters range [mm]	Mass of dry silica gel covering the copper pipe [g]	Mass of adsorbed humidity [g]	Degree of coverage (concentration of water in grains) [g/g]
0.63–0.8	3.06	0.79	0.26
0.8–1.0	3.34	0.87	0.26
1.5–2.0	5.96	1.70	0.29

6. Conclusions

On the basis of the collected data, one may state that for the air velocities that were under consideration the best results were obtained for low velocities (less than 0.174 m/s). Higher gas velocities reduce the adsorption effectiveness due to the short contact time. The contact time must be in the proper relation to the rate of adsorbate transport from the surface of grains to adsorption sites. Lower air velocities ensured the greatest temperature of the adsorbent, which is important because of the fact that the operation of adsorption chillers is based on thermal effects of the adsorption process.

The experimental data lead also to the conclusion that, for a certain velocity of air, the best results were obtained for grains diameters range between 1.5 mm and 2.0 mm. For such grains the breakthrough did not occur for the longest period of time. Moreover, in this case, a greater degree of coverage was observed.

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