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AN EXPERIMENTAL STUDY ON HEAT AND MASS TRANSFER IN A CLOSED ADSORBENT BED OF AN ADSORPTION HEAT PUMP

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ABSTRACT

Heat and mass transfer in an adsorbent bed of an adsorption heat pump play an important role on the efficiency of the system. In this study, heat and mass transfer in an adsorbent bed of an adsorption heat pump is experimentally investigated during the isobaric adsorption process. An experimental setup was constructed and silica gel-water pair was chosen as working pair. By using the obtained experimental data during the adsorption process, the amount adsorbed, pressure change in the adsorbent bed and in the evaporator, the evaporator temperature and the temperature profile along radius of the adsorbent bed are shown via graphics, and necessary discussions are performed.

INTRODUCTION

Because of limited conventional energy sources and problems of ozone layer thickness, development of thermal heat pump has gained attentions of researchers in recent years. Adsorption heat pump, which is a kind of thermal heat pump, can operate with low temperature heat sources such as geothermal and solar energies [1-3]. Moreover, it has ability to store energy which can be utilized later on. Despite the considerable advantages of adsorption heat pump, its COP and specific power values are low compared to the mechanical and absorption heat pumps, however its primary COP is comparable with them.

A slow heat and mass transfer process in the adsorbent bed is the one of the important drawbacks in the adsorption heat pump. The enhancement of heat and mass transfer rate reduces the period of cycle and consequently increases the power. Mass is transferred due to transfer between particles in the adsorbent bed (i.e. interparticle mass transfer) and due to transfer in the absorbent particle (i.e. intraparticle mass transfer). The interparticle mass transfer mainly occurs because of the pressure difference of adsorbate vapor in the adsorbent bed. That's why most of studies employ Darcy Law to represent the flow of adsorptive between the adsorbent particles. However, some researchers [4-6] include Knudsen and molecular diffusions for determination of adsorptive transfer in the adsorbent bed. Although it may increase the resistance of interparticle mass transfer, the use of small size particles decreases heat transfer resistance. The mechanism of mass transfer in the adsorbent bed is highly influenced from the porosity, temperature, and pressure of the bed as well as thermophysical properties of the adsorbent and the adsorbate. The intraparticle mass transfer mechanism can be explained by the transfer of the adsorptive in an adsorbent particle. In porous structures, the intraparticle mass transfer mainly arises due to the inner surface rather than the external one. The intraparticle adsorptive transfer is generally described as a diffusion process since the convective flow through the pore of adsorbent is negligible. Hence, Fick's Law with proper concentration gradient and mass diffusivity is used in the description of adsorptive transfer.

Numbers of experimental studies are performed by researchers on adsorption heat pump systems. Boelman et al. [7] experimentally investigated the performance of a chiller manufactured by the Nishiyodo Kuchouki Co. Ltd. Douss and Meunier [8] proposed and analyzed a cascading adsorption cycle in which an active carbon–methanol cycle is topped by a zeolite–water cycle. They found that around 250^{o}C, the COP of the setup reached 1.06. Di et al. [9] performed numerical and experimental studies to investigate the effect of heat source temperature on the coefficient of performance of an adsorption heat pump. Hajji et al. [10, 11] have presented a numerical and experimental analysis for the adsorption process. They reported that if the rate of heat transfer to or from the adsorbent is very slow, the system can be assumed as a uniform pressure system.

In this study, an experimental setup was designed and constructed to investigate heat and mass transfer in an adsorbent bed of an adsorption heat pump during the isobaric adsorption process. The study was performed for silica gel-water pair. As is known, because of heat of adsorption the temperature of granules increases during the adsorption process. By measuring the temperatures and the pressure of adsorptive in the adsorbent bed, temperature and bed pressure profiles during the adsorption process were obtained and plotted. The change of amount of adsorption in the silica gel with time was measured. The evaporator temperature and pressure are also plotted and necessary discussions are performed.

NOMENCLATURE

P	[kPa]	Pressure
Q	[J]	Heat transfer
T	[K]	Temperature
W	$[kg_v kg_s^{-1}]$	Adsorbate concentration

Subscripts

ads	Adsorption
bed	Adsorbent bed
cond	Condenser
eva	Evaporator
reg	Regeneration

THE WORKING PRINCIPLE OF AN ADSORPTION HEAT PUMP

A basic intermittent adsorption heat pump consists of an adsorbent bed, a condenser, an evaporator, and an expansion valve as seen in Figure 1.

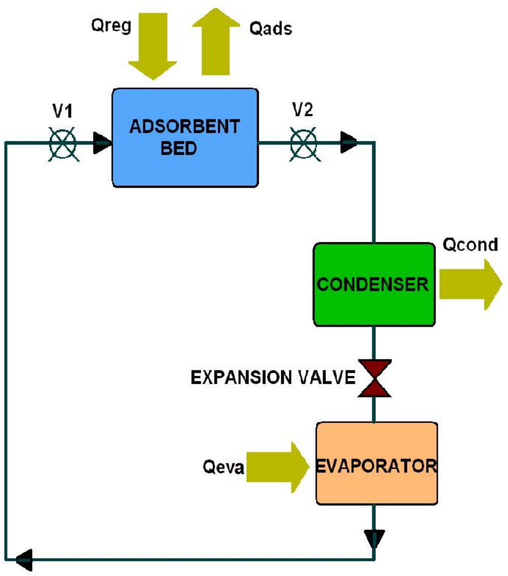

Figure 1 An adsorption heat pump cycle

A cycle of an adsorption heat pump consists of four processes as isobaric adsorption (d-a), isosteric heating (a-b), isobaric desorption (b-c), and isosteric cooling (c-d). The cycle can be schematically represented on the Clapeyron diagram (ln(P) vs. -1/T) as shown in Figure 2.

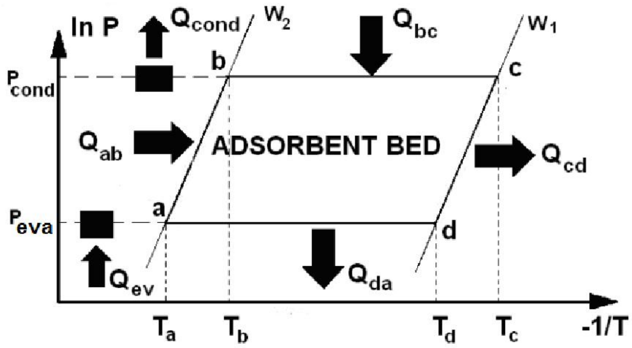

Figure 2 Clapeyron diagram of an adsorption cycle

At the beginning of adsorption process (point d) all valves are closed. Both the adsorbent bed and evaporator are at the evaporator pressure, P_{eva}. By opening the valve V1, the evaporator starts to get heat from the space required to be cooled. The evaporated adsorbate in the evaporator is adsorbed by the adsorbent granules in the adsorbent bed. The process continues until the concentration of adsorbate in granules attains to W_2 level. The process (d-a) is known as the isobaric adsorption process. During the adsorption process, heat of adsorption is released in the adsorbent bed. The cooling effect in the cycle arises during the isobaric adsorption process when the adsorptive is evaporated by gaining heat from the environment. After isobaric adsorption process, valve V1 is closed and then isosteric heating process starts (a-b). During this process the adsorbent bed is heated and the temperature of the adsorbent bed rises from T_a to T_b while the adsorbate concentration of the bed remains constant at W_2. In the isosteric heating process, the adsorbent bed is heated at a constant adsorbate concentration and the pressure of the bed increases from the evaporator to the condenser pressure (P_{eva} , P_{cond}). The next process is desorption process (b-c) which starts by opening of valve V2 placed between the adsorber and the condenser. The heating effect occurs during the isobaric desorption process when the adsorptive is condensed by releasing heat to the surroundings. During the desorption process, the temperature of adsorbent bed is increased from T_b to T_c while its pressure remains at P_{cond}. The desorbed adsorbate leaves the adsorber is condensed in the condenser and as a result the adsorbate concentration falls from W_2 to W_1. Finally, both valves V1 and V2 are closed and adsorbent bed is cooled to reduce its pressure from P_{cond} to P_{eva}. The adsorbent bed is cooled during the isosteric cooling process from T_c to T_d to reduce the pressure and temperature of the adsorbent bed at constant amount of adsorbate. The pervious experimental results [7-11] showed that adsorption and desorption processes take the most of period of an adsorption heat pump cycle. Thus, investigation on adsorption and desorption processes is very important, and that's why the present experiments were held only for the isobaric adsorption process.

THE EXPERIMENTAL SETUP

The setup was mainly composed of an adsorbent bed and an evaporator. The components of the setup are shown schematically in Figure 3.

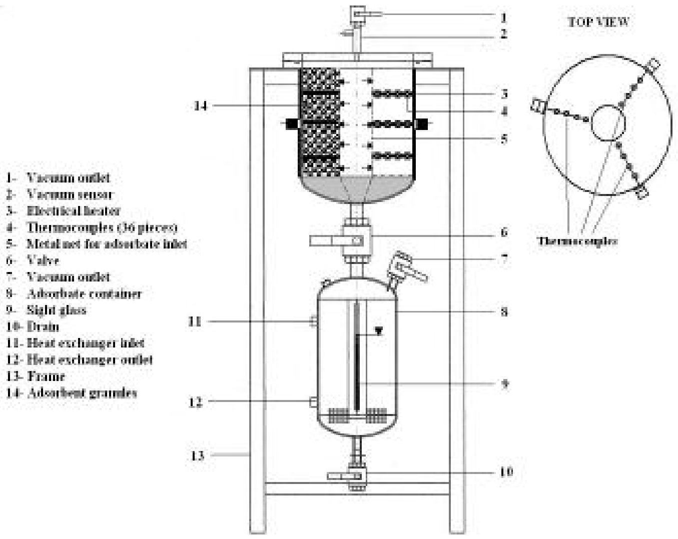

Figure 3 The schematic view of the experimental setup

The Adsorbent Bed

The adsorbent bed was constructed from a stainless steel pipe with 4 mm thickness and 309 mm inner diameter. The height of adsorbent bed is 290 mm. On the adsorbent bed, there are a valve used to connect the adsorbent bed to vacuum pump and a pressure transducer to measure the pressure of adsorbent bed. There are three different outlets for the thermocouples on the circumference of adsorbent bed. The thermocouples are located at 0, 120, and 240 degrees in θ direction and the distances between the thermocouples in axial and radial direction are 90 mm and 25 mm, respectively. The locations inside of the adsorbent bed and the codes of the thermocouples are shown in Figure 4.

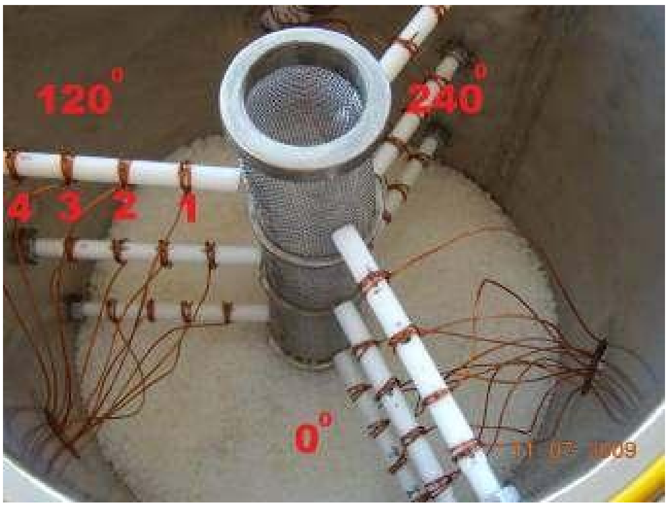

Figure 4 An inside view of the designed adsorbent bed and locations of the thermocouples

The letters U, M, and B represents the upper, middle, and lower part of the adsorbent bed. The numbers 0, 120, 240 are used to represent the θ direction of a thermocouple. Finally, the location of the thermocouple in radial direction was given by numbers as 1, 2, 3, and 4. Therefore, U-120-3 thermocouple represents the thermocouple in upper part of the adsorbent bed with 120 radial angles and the third one from the inner hollow. There are 36 thermocouples in the adsorbent bed. This configuration enables to measure the temperature at 36 points in the adsorbent bed during isobaric adsorption process.

A metal mesh made of steel with 50 mm diameter in vertical direction was located in the middle of the adsorbent bed for transferring of the adsorptive into the adsorbent bed in the radial direction easily. Then, the adsorbent bed was filled with 17.4 kg silica gel particles. The equivalent diameter of the silica gel granules which was used in the adsorbent bed varies between 3 - 5 mm. It is reported that the used silica gel has 25% water adsorption capacity by weight. The average pore diameter of silica gel was given as 2.0-2.5 nm.

The circumference of the adsorbent bed was covered with an electrical heater with a power of 1 kW. The heater is controlled by a PID temperature controller during evacuation period. The control panel is used to control the electrical heater on the adsorbent bed. The adsorbent bed was cooled naturally during the adsorption processes. The temperature and pressure were measured and acquired by using data loggers. The constructed experimental setup is illustrated in Figure 5.

Figure 5 The constructed experimental setup

The Evaporator

The setup has one evaporator/condenser tank which has volume of 10 lt. The evaporator basically consists of a stainless steel container, a pressure transducer, a thermocouple, and four vacuum valves (a valve for water supply inlet, a valve for vacuum connector, a valve to drain water and a valve between the evaporator and the adsorbent bed) as shown in Figure 6. A helical coil is located inside the evaporator. The water coming from the constant temperature bath is circulated through the coil to evaporate the adsorptive in the evaporator. The inlet and outlet pipes of the helical coil are connected to water bath. The length of the coil is 12 m with the diameter of 6 mm. The water level in the evaporator can be followed from the sight glass located in the front of the evaporator. A thermocouple located inside the evaporator measures the temperature of the water in the container. A vacuum tight valve was located between the adsorbent bed and adsorbate container. A small wet/dry RV rotary vane vacuum pump was used for evacuation process.

Figure 6 The evaporator and its components

The Temperature and Pressure Measurement

The thermocouples in the adsorbent bed are K type and they are thermally insulated probes with a flexible wire. They measure the local temperature at the located position. The response time of the K type thermocouples is 0.5 sec. Their operation temperature is from -250 to 404^{o}C. For 36 K type thermocouples located in the adsorbent bed and for the other 5 K type thermocouple measurements, 6 data loggers and a module was used.

Two identical pressure transducers were used on the setup to measure the pressures of the evaporator and the adsorbent bed. These pressure transducers have ±0.25% accuracy and have a range 1 to 5 V output. The stainless steel pressure transducers have a measurement range 101.6 kPa to 0 kPa.

The software used for monitoring and data logging. The software provides an object based graphical interface that simplifies control and display setup. The software provides to configure the parameters and connect the toolbox. The data were saved automatically and then they were transferred to Excel data file.

THE EXPERIMENTAL PROCEDURE

As it was mentioned beforehand, in this study the experiments were performed only for the adsorption process. Before the adsorption process, the whole system should have to be evacuated.

For drying (or desorption process), the bed was heated by the electrical resistance, surrounding the adsorbent bed, up to 100^{o}C and held at 100^{o}C while the valve between evaporator was opened. The desorbed water vapor flows to the evaporator and it is condensed. In the helical coil inside the evaporator, water with -1^{o}C is circulated between evaporator and water bath to extract heat due to condensation. After desorption of water vapor in the evaporator, the adsorbent bed was evacuated with the vacuum pump for 120 hours to reach the minimum adsorbate concentration in the particles.

While the adsorbent bed temperature was set to the adsorption process initial temperature (see Figure 2, point d) and the whole thermocouples in the adsorbent showed nearly the same temperature, the valve between the evaporator and the adsorbent bed was opened and the adsorption process was started. During the adsorption process, the evaporated water from the evaporator was adsorbed by silica gel and throughout the adsorption process, the adsorbent bed was cooled. After completing the adsorption process, the valve between the adsorbent bed and the evaporator was closed. The isobaric adsorption process was continued until the level of water inside the evaporator was not changed which indicates the saturation of the silica gel particles.

RESULTS AND DISCUSSION

The presented results are valid for an isobaric adsorption at 7.4 kPa. The initial temperature point of the bed (see Figure 2, point d) was 95^{o}C while the initial temperature for the evaporator was 40^{o}C. The period for adsorption process was 54 hours. At the end of the adsorption process the temperature of the bed was dropped to 25^{o}C.

Based on the observation of the level of water inside the evaporator, the change of amount of adsorbed vapor by silica gel during adsorption process was plotted and is given in Figure 7. As is seen, the adsorbed amount is 1.6 lt corresponding to 9.2% kg of water per kg of dry silica gel.

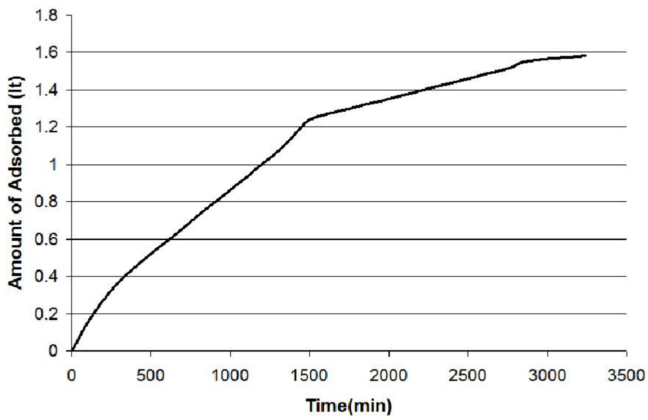

Figure 7 The variation of amount of adsorbed water vapor by silica gel with time

Figure 8 shows the variations of the evaporator temperature and the pressures of the adsorbent bed and the evaporator during the adsorption process. The adsorbent bed and evaporator pressures were approximately at 7.4 kPa during the adsorption process and this shows that no flow resistance exists during flow of water vapor from evaporator to the adsorbent bed. The evaporator temperature was 40°C at the beginning of process. When the valve between the adsorbent bed and the evaporator is opened, the evaporator temperature steeply decreases to 23°C. Then, it increases by time to 35°C and it remains constant during the wide period of adsorption process. There is no doubt that the steep drop of evaporator temperature occurs due to high adsorption rate at the beginning of process. However, this high rate of adsorption at the initial state of the process is not seen clearly in Figure 7. Unfortunately, high oscillation of water level in the evaporator at the initial condition of the adsorption process does not permit to sensitive measurement of amount of the water adsorbed.

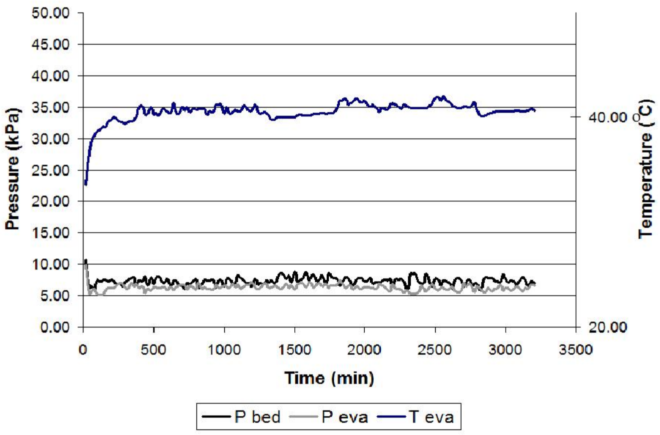

Figure 8 The variation of adsorbent bed and evaporator pressures and temperature of evaporator during adsorption process

The adsorbent bed temperature was set to 95°C at the initial of the adsorption process (point (d)). By the opening valve between the evaporator and the adsorbent bed, the water vapor is evaporated and the silica gel begins to adsorb the water vapor. The changes of temperature in thermocouple locations as 1 and 4 at the middle of the adsorbent bed for all angular directions with time are illustrated in Figure 9. As is seen, the temperatures having the same distance from the center of the bed are identical. This shows that heat and consequently mass transfer does not cause any change in the angular direction. The temperatures of the inner points (M-0-1, M-120-1, and M-240-1) are same with the temperature of the outer points (M-0-4, M-120-4, and M-240-4) at the beginning of the process. A difference in those temperatures is seen after starting of adsorption process and the temperature of the outer region decreases faster than the inner regions since the adsorbent bed is cooled from the circumferences. This figure also shows that, relatively, cold evaporator vapor does not have important effect on cooling of silica gel at the inner region of adsorbent bed. At the end of process, the temperature of the inner and the outer regions comes close to each other.

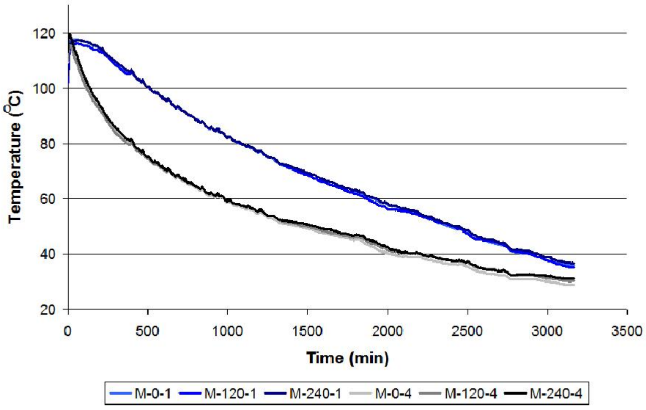

Figure 9 The temperature changes with time for points 1 and 4 at the middle of the adsorbent bed for all angular directions

The metal mesh located in the middle of the adsorbent bed causes that the adsorptive can be easily transferred into the adsorbent bed in radial direction. Consequently, the adsorptive touches the particles located in the inner region of adsorbent bed or the first points near to the metal mesh (numbered as M-0-1, M-120-1, and M-240-1). At the initial state of the adsorption process, the temperature of the first point's increases compared to the other points due to the heat of adsorption as seen from Figure 10 in which the temperature profile in radial direction for starting period of the process is shown.

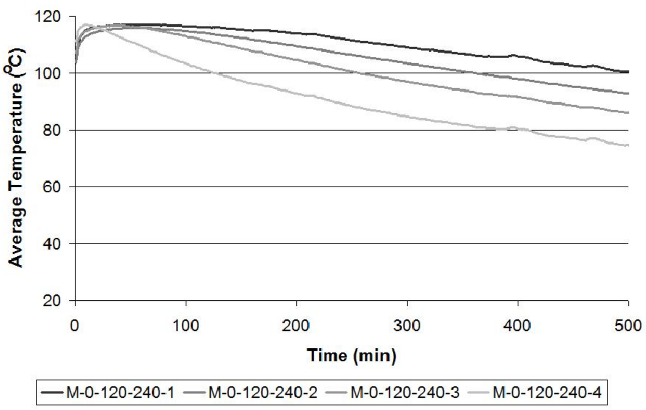

Figure 10 The variation of temperatures along radius of the adsorbent bed at the middle of the adsorbent bed for starting period.

CONCLUSION

The heat and mass transfer mechanism in the adsorbent bed should be recognized well in order to reduce the period of cycle of an adsorption heat pump. In order to understand the mechanism of heat and mass transfer in the adsorbent bed, an experiment is performed for the isobaric adsorption process.

Based on the obtained results following remarks can be concluded:

- When the adsorption temperature is started at high temperature and the adsorbent bed is cooled, the temperature at the inner region is higher than the outer region for most of the period.
- At the beginning the adsorption period, the temperature of the inner region increases due to heat of adsorption and starts to be decreases gradually.
- The obtained results show that for the designed adsorbent bed, heat and mass transfer does not depend on angular direction; however the small changes in the vertical direction was seen due to heat loss from the top and the bottom of the adsorbent bed.
- The adsorption period for the designed adsorbent bed and the silica gel particle was found around 3000 minutes to increase water concentration by 10%.
- One of important results of this study is that thermal equilibrium model is valid for the designed system.

The presented results are the first results of the designed adsorbent bed and further studies would be performed to find out the effects of different parameters such as initial temperature, bed pressure, particle radius, porosity, and cooling rate on the adsorption rate and the period.

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