Analysis of Adsorption Thermal Storage Device for Solar Energy Storage

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Abstract: The main goal of this research was to develop the adsorption thermal storage device for domestic heating system charged by solar collectors and to indicate a new way of storing energy. Main characteristic of the storage system is to retain the energy for a longer period (seasonal storage), as long as the adsorbent and adsorbat are separated. In this research the influence of several parameters on the adsorption heat storage system is performed such as: the quantity of the stored heat, the inlet and the outlet water temperatures, the water mass flow and the saturation of the adsorbent. Adsorbent silica gel HX-13 (sodium aluminosilicate Na2O Al2O3 * 2SiO2) in the form of granule was used.

According to the results the conclusion can be made that the low adsorption heat storage is a consequence of low hydrophilic characteristic of the used adsorbent and therefore additional research is needed.

Keywords: Heat storage device, Thermo-chemical heat storage, Adsorbat, Adsorbents, Experiment.

1. INTRODUCTION

Increased use of energy, limited fossil fuels reserves and concern for a better environment tends to exploit energy from renewable energy sources. As a result, heat storage devices were developed to store energy from both, natural sources (solar, geothermal) [1], as well as industrial waste heat [2] what makes heat storage useful especially in industry where a lot of heating or cooling is needed [3]. Increasing emphasis is also given to heat storage systems for domestic heating and cooling [4-6]. Sorption technologies for solar heat storage gained a lot of interests in recent years due to their high energy densities and long-term ability for thermal energy preservation [7]. Sorption heat storage system is based on the principle of thermo-chemical storage. Ongoing research and development studies shows that challenges of the technology focus on aspects of different types of sorption materials [8,9], configurations of absorption cycles and advanced adsorption reactors. Booming progress illustrates that sorption thermal storage is a realistic and sustainable option for storing solar thermal energy, especially for long-term applications.

In the thermo-chemical energy storage methodology, sorption material and gas are chosen as the sorption working couple for energy storage, whereby thermal energy is stored in the form of chemical bonds resulting from the sorption process between the material and the gas [10]. The current state in the field of adsorptive heat transformation (AHT) cannot be considered as wholly satisfactory, due to inappropriate thermodynamic properties of adsorbent materials [3], therefore studies tends to improve materials. Developed composite sorbents made from active salts and porous materials showed improved sorption storage capacity when compared to water-based energy storage due to its high energy density [11-13]. Exergy analysis performed by Abedin et al. [14] showed that thermo-chemical sorption energy storage system may be as efficient as and even more stable than other types of thermal energy storage system.

Restuccia et al. [15] presented the experimental results of a lab-scale cooling module with the composite sorbent SWS-1L which is a promising alternative to the common zeolite or silica gel for application in solid sorption and compared experimental results with a theoretical simulation. Their approach was also used to study the influence of the main operating parameters on the system performance and to make recommendations on how to improve the chillers design and process parameters. Glaznev et al. [16] investigated how a gradual tuning of pore size affects the water sorption properties; composites with smaller pores are able to generate cold by rejecting the adsorption heat to hotter environment. Stronger bonds between water and salt which is limited to smaller pores results in the appropriate enhancement of the desorption temperature. It was shown that the small, micro porous aluminophosphates are among the most suitable materials for low temperature (solar) heat storage.

In the last two decades, several studies proposed different developed adsorption solar cooling systems...
that allows a good compromise between high reliability and good performance. From those studies, simple tubular module is considered as one of the most efficient configurations [17,18]. The adsorption tubular module is a tube casing in which adsorber, condenser and evaporator are placed and it presents a small-scale adsorption cooling unit. Heat pipes can also be used in adsorption refrigeration systems to improve the performance of the systems. Thermally driven adsorption chillers and heat pumps have received increased attention in recent years. Heat pumping devices which are operating on sorption effects, current trends and forthcoming applications were studied and discussed by Ziegler [19,20]. Henninger et al. [21] analysed current available active sorption materials (like silica gels and zeolites), recently developed materials (aluminophosphates) and silica-aluminophosphates (SAPO) as well as novel materials (like metal organic frameworks under continuous thermal cycling in a water vapour atmosphere) in order to evaluate their suitability for the use in a periodically working heat pump based on water as working fluid. Besides the solar cooling application for thermal cooling using waste heat at low temperature level (<80 °C for adsorption systems) the combination of co-generation units with sorption chiller is promising as described in [22].

Finck et al. [23] investigated a 3 kWh thermochemical heat storage module for solar energy storage as a part of an all-in house system implementation focusing on space heating application at a temperature level of 40 °C and a temperature lift of 20 K. Measurements showed a maximum water circuit temperature span (released by adsorption) of 20 – 51 K which is by all means suitable for space heating.

Engel et al. [24,25] experimentally and numerically investigated of a real scale seasonal solar closed storage sorption system which was analysed for several months under realistic conditions in the heating period. Heat is provided in evacuated tube collectors in combination with buffer storage. Several sorption storage modules are included in the system what offers 'charge boost' when vapour transfers between two of modules. This allows higher states of charge for a given charging temperature level. With validated developed numerical model it has been analysed that for a storage system with 6 m³ of material fractional energy savings up to 75% has been achieved for standard single family house in the middle Europe. In similar system using 'charge boost' Köl et al. [26] came to conclusion of increasing the energy density even further and reducing charging temperature by repeating the ‘charge boost’ several times.

Li et al. [27] experimentally investigated dual-mode thermochemical sorption energy system using for seasonal solar thermal energy storage. Sorption working par has been expanded graphite/strontium chloride-ammonia (SrCl₂-NH₃). Mentioned system has two working modes (direct heating supply and temperature-lift heating supply) during discharging phase to provide useful output heat for end user according to different ambient temperatures in winter. When the output heat does not satisfies users’ demand temperature-lift is performed where the heat released by the low-temperature unit is used to supply the evaporation heat and elevate the working pressure of high-temperature unit.

Investigation on novel modular sorption thermal cell by Jiang et al. [28] presents flexible unit which could supply cold and heat separately to end user or combined. Modular sorption thermal cell consists of sorption reactor, condenser and evaporator in one tank where sorption reactor and liquid tank are physically separated with insulation layer and are connected through the channel with the valve. Investigated cell could be connected to sorption battery for scaling applications, which reveals great potentials for solar energy utilization.

The aim of this work is to present sorption thermal storage tank with silica gel HX13 which can be used for long-term thermal energy storage. Parts of thermal storage, experimental results of adsorption and desorption, i.e. temperatures, heat fluxes and heat are presented and explained in the paper.

2. THEORETICAL ANALYSIS

Closed sorption system has been used in the research. This system utilises water as the adsorbate what is shown in Figure 1. During the process of desorption, the adsorbent is saturated and heated through the heat exchanger. Surface-bound adsorbate is evaporated from the adsorbent and the heat is transferred from the condenser. Desorption mode stops when the adsorbent is dried out (depends on the amount of input heat in the adsorber), i.e. adsorbate is condensed in the condenser, or when the adsorbent and adsorbate are separated.

During the process of adsorption, the adsorption heat has to be discharged from the adsorber and evaporation heat supplied into the evaporator. If this is not possible, sorption process reaches thermodynamic
equilibrium and the flow of water vapour is stopped. When the adsorbent is saturated with water vapour, the process ends and the tank is discharged. The tank needs to be recharged again (desorption) in order to continue the process. Circular process of adsorption storage shown in Figure 2 is the same as a circular process of a heat pump, except in this case during the process of adsorption and desorption the time break occurs. This break is the time when the storage heat is not needed.

The adsorbed mass of the fluid (adsorbate) varies between a minimum (line C-D) and the maximum value (line A-B). Adsorption takes place (between points D-A) at the evaporation pressure $p_e$ and desorption (between points B-C) at the condensation pressure $p_c$ [4]. This four-step cycle consists of:

i. Heat storage in the tank begins with isosteric heating of the adsorbent (humidity is constant) through the heat exchanger. The valve that separates the tank from the evaporator/condenser is closed. The temperature and pressure in the adsorber are increasing along the line between points A and B until the temperature $T_{des1}$ is reached. At this temperature, pressure is equal to the pressure of condensation of the adsorbed adsorbate (point B) [30].

ii. At point B the valve between the condenser and the adsorber is opened. Adsorbent is heated (the line between the points B-C) until the adsorbate is evaporated from the adsorbent, which then becomes dry. Maximum available temperature $T_{des2}$ is reached. Meanwhile condenser is cooled to maintain the pressure of condensation $p_c$. Heat generated by the condensation $Q_c$ is discarded into the environment as a waste heat. That has an influence on the temperature of condensation $T_c$, which must be kept as low as possible in order to make optimal desorption. At maximum attained temperature $T_{des2}$ the level of saturation of the adsorbent with adsorbate is the lowest ($x_{min}$), therefore the cycle is stopped with closing the valve between condenser and adsorber. When the valve is closed - and the adsorbate and adsorbent are separated - the tank is charged. Thus the stored heat can be used without heat losses, even after a longer period [30].

iii. Depending on heat storage duration and ambient temperature, the temperature of the heat storage falls. Temperature drop and consequently the pressure drop are shown with isostera – line

Figure 1: Working principle of a closed-cycle desorption/adsorption heat storage [29].

Figure 2: p-T-x diagram of thermochemical storage cycle [30].
between points C and D. The temperature may drop to $T_{ads}$ or even lower [30].

iv. Discharging begins with the valve opening, which separates the evaporator from the adsorber. Before that a higher-pressure level in the evaporator than in the adsorber is established, because of the added heat. Heat can be provided from a variety of sources (solar, earth etc.). Liquid is evaporated at a pressure $p_e$ and temperature $T_e$. The valve opens; adsorbate is re-adsorbed in the adsorbent. Adsorption heat is released (line D-A). Generated heat is called useful heat and can be transferred or used in the heating system through the heat exchanger in the adsorber [19].

3. MASS AND ENERGY BALANCE OF ADSORPTION HEAT STORAGE

Schematic mass balance of sorption heat storage system is presented in Figure 3, where adsorber container is presented on the left side of the figure and the evaporator/condenser container on the right side. In the desorption mode, the mass flow of the water vapor ($m_{vapor}$) is transferred from the adsorber to the condenser. In the adsorption mode, water vapor is transferred in the opposite direction from the evaporator to the adsorber. The condensate is evaporated and bonded with the adsorber [29].

![Figure 3: Mass balance of adsorption heat storage [29].](image)

Due to the mass transfer certain properties in the control volume (dashed line) changes as follows:

- the mass of water in the condenser/evaporator ($\Delta m$),
- saturation of the adsorber ($\Delta x$).

Figure 4 schematically shows the energy balance, where some of the processes occurs only during the adsorption and some of them only during desorption mode. The adsorber is heated with the heat source ($Q_{des}$). This heat is transferred through the heat exchanger to the adsorbent where it is used to separate molecules of water from adsorbent and for evaporation. Water vapour entering the evaporator/condenser contains internal energy ($u_v$) and evaporation heat ($Q_E$) that was needed to desorb the water from the silica gel. Water vapour is than condensed in the condenser. Its internal energy is discharged (i) through the heat exchanger as condensation heat ($Q_C$), which could be used to preheat the sanitary water. Part of discharged condensation heat (ii) transfers through the tank walls into surroundings and presents heat losses ($Q_{Loss}$).

![Figure 4: Energy balance of adsorption heat storage [29].](image)

The energy balance based on Figure 4 can be written as

$$Q_{Des} + Q_E - Q_{Ads} - Q_C - Q_{Loss} = 0$$  \hspace{1cm} (1)

4. PRINCIPLE OF THE OPERATION

The heat produced by the solar collector is stored in the adsorption heat storage and is later used for space heating of the house. The system is designed in a way so that can be connected to a heating cycle during winter or the solar cycle during summer. Sorption system is cyclical, what means that in the summer time tank is being charged and in the winter time tank is being discharged. The scheme of closed system for
residential house heating with the adsorption storage tank and the main parts of this system is shown in the Figure 5.

The scheme on Figure 5 shows the solar collector, the adsorption heat reservoir, the heating system and the low temperature source of energy. Some elements operates only in the summer time and others only in the winter time. When it is sunny and warm and the level of solar radiation is highest (up to 900 W/m\(^2\)), the water passing through the solar collector heats up. Solar collector used for heating buildings and sanitary hot water is medium-temperature system and is converting solar radiation into heat. This system works in the range from 45 to 120 °C [31]. Heated water comes from the solar collector and is directed into the sorption tank to the adsorber, wherein the adsorbent saturated.

The water releases the heat through the heat exchanger and dries the adsorbent. Water returning from the heat exchanger is cooled and returned back to the collector. Described circle is called the primary circuit. In the secondary circuit adsorbate is separated from the adsorbent due to heating. Adsorbate evaporates to the evaporator/condenser where it condensates. If the released heat during condensation is at sufficiently high temperature level it can be used for example to preheat domestic hot water. Condensate, which is collected in the evaporator/condenser, is separated from the adsorbent with the valve (depending on the design). Once the adsorbent is dried, the phase of charging the storage ends. Usually, the discharge phase begins when the temperature of surroundings is sufficiently low and the building heating is required. Water is then directed with the valve to the winter circuit where are also the primary and the secondary circuit. Water in the primary circuit in the evaporator/condenser is evaporated with heat from the solar collector.

During the cold weather, as often in winter, the collector does not get sufficient energy and additional energy source is needed which acts as a reserve. These can be electric heaters or heat pumps, which heats water that is directed into the evaporator/condenser where heat through the heat exchanger evaporates the condensate (sorbate). Cooled water from the evaporator/condenser returns to the solar energy collector or to the additional energy source. In the secondary circuit, the valve between the adsorber and the evaporator/condenser is opened and water vapour is bound to the adsorbent what causes chemical reaction and the consequence is released heat. Released adsorption heat warms up water in the heat exchanger, and heated water is directed to the water heating system (i.e. radiators, floor heating). Adsorption heat can be used until the adsorbent is saturated with adsorbate to a certain degree. The tank is discharged when the adsorbent is saturated and the switch to the next container take place (depending on the system model).

5. EXPERIMENTAL STUDY

The idea and inspiration for the tank design came from the sketch of the tank that has been published in the report of the European project MODESTORE (Modular High Energy Density Sorption Heat Storage) [4]. This is the second generation of the storage tank, which differs from the first mainly in the fact that the adsorber and the evaporator/condenser are in a single container. The sorption thermal storage tank is shown in Figure 6.
Adsorbent material was in the form of poly-dispersed system composed of granules in diameter from 1 to 5mm (Figure 7). Chemical name is sodium alumino-silicate adsorbent with chemical formula Na₂O Al₂O₃ * 2SiO₂. The colour of the adsorbent is greyish white, the bulk density of 20,2 kg/m³ and the molecular weight of 365 kg/kmol.

On the left side of the Figure 8 the front view of the evaporator/condenser is shown and on the right side of the Figure 8 the interior of the tank with electric heater is shown. On the Figure 9 heat exchanger with metal mesh basket (Figure 9 – left side) and hole for water supply (Figure 9 – right side) is shown Figure 9.

In investigated experiment the behaviour of the adsorption tank (Figure 10) during the charging and discharging was observed.
Figure 11: Heat exchanger and the measuring instruments.

Figure 11 presents the experimental set up during the adsorption/desorption process where the measurements of inlet and outlet water temperature, the adsorbent temperature and water temperature took place. Temperature sensors were placed on particular locations (no. 1, 2, 3, 4) and connected to the data acquisition device Agilent 34970 (9), where measured temperatures were further processed with the personal computer (10). Absolute adsorption working pressure was found to be between 20 and 60 mbar, what means that first it was necessary to vacuumize the heat exchanger. In order to establish the required pressure condition in the reservoir, vacuum pump (6) and manometer (5) were used. Water was pumped from the reservoir and water coming from the heat exchanger (11) was directed into drains. The water container (7) was placed on the weight scale (8), which enabled precise measuring of quantity of inlet water in the evaporator. For the process of desorption, instantaneous water heater (12) was installed in order to enable hot water.

At the time of charging and discharging of the tank, Agilent 34970 was collecting the following parameters:

- time – used PC internal clock,
- inlet water temperature (1) in the heat exchanger (11),
- outlet water temperature (2) from the heat exchanger (11),
- the temperature (3) in the evaporator/condenser and
- the temperature in the adsorber or the temperature of the adsorbent (4).

The temperature was measured with NiCr-Ni (Type K) thermocouples, which were calibrated by standard procedure. Uncertainty of temperature measurement was found 0.4%. Mass flow rate was determined by weighing water in a given time interval and was found to be 5.124 kg/h. The uncertainty of the mass flow was 1.2%. By the heat flux calculation the temperature dependent specific heat $c(T)$ was considered. The combined relative uncertainty of the adsorption heat flux was found to be 1.8%.

6. RESULTS AND DISCUSSION

6.1. Adsorption

In pursuit of the measurement of the adsorption phase (discharging the tank), it was necessary to dry out the tank interior first. Afterwards the 5700 g of dry silica gel-HX13 was put into the adsorbent metal mesh basket. After the tank was properly assembled and sealed, vacuum pump sucked air from the tank to 20 mbar of absolute pressure. Mass flow of water through the heat exchanger was set to 5124 g/h at temperature of 22 °C. Basic demonstration scheme of mentioned phase is shown in Figure 12. Agilent 34970 started with measurements of temperatures in duration of 24 h.

As it is seen in Figure 13, when the valve for releasing water opened, water in tank evaporated and was adsorbed on the surface of the adsorbent. As a consequence of the adsorption the temperature of the adsorbent has rapidly (after 3 min and 15 s) risen up to 50 °C and soon reached maximum at 54.9 °C.

After increased temperature in the adsorption process the temperature of the adsorbent was gradually
decreasing as seen in Figure 13, probably due to the degree of saturation of the adsorbent. The temperature of the adsorbent reached a common point with the temperature of the water flowing from the heat exchanger after about three hours. The situation after this point was maintained until the end of the measurement. The temperature of the adsorbent dropped to 23.14 °C, what means that water vapour was still adsorbed on the adsorbent, but in very small quantities. The difference between the inlet of water into the heat exchanger, and the adsorbent after 24 h was 1.3 °C.

As seen from Figure 13 the temperature of the water, which was entering the heat exchanger was practically constant throughout the measurement. The temperature of the water leaving the heat exchanger was, as expected, gradually increased, primarily as a result of adsorption heat, which was transferred through the pipe of the heat exchanger. Maximum temperature 43.1 °C was achieved after 22 min and 45 s. Due to the temperature drop of the adsorbent, the amount of heat transferred was lower than at the beginning. Therefore the water temperature at the exit from the heat exchanger was lower. The downward trend curve is maintained until the end of the measurement.

From the curve, which shows the temperature of the water in the evaporator on the Figure 13, it can be seen that the temperature of the water very quickly fell to 8.35 °C which is the minimum. Soon after this bending point occurs, the temperature quickly rises to 14.53 °C and then to the end of measurements varies between 13 °C and 15 °C. The rapid temperature drop in the beginning was probably due to intensive evaporation. When the water is evaporated at such low temperature, its inner energy is used and that lowers the water temperature in the evaporator. Due to establishing a steady state in the container after intensive evaporation of the water, bending occurs. At a temperature of 14.53 °C this variation was stabilized and varied with the difference of 2 °C until the end of the measurement.

Using the obtained data and Eq. (2)

\[ Q_i = m_i \cdot c_{p,i} \cdot \Delta T_i \]  

the instantaneous heat flow is shown in Figure 14.

Figure 14 shows that heat flux increased proportionally with the increase of temperature of the water leaving the heat exchanger. The maximum heat flux 123.2 W was reached at the maximum temperature difference (ΔT) between the water inlet (T_{ex,i}) and outlet (T_{ex,o}) of the heat exchanger. After this point, the heat flux started to fall until the end of the measurement. At the end of the measurement heat flux 0 W should be obtained, but because of temperature settings which
shuted-off after 24 h, the temperature difference between the inlet and outlet of the water in the heat exchanger was still showing some minimal $\Delta T$. The average heat flow was found to be 121.8 kW.

$$Q_i = Q_i \Delta t$$  \hspace{1cm} (3)

The total heat from the tank represents the sum of $Q_i$ according to Eq. (4) for the observed time steps, where final time step is $n=5760$.

$$Q_{\text{total}} = \sum^n_i Q_i$$  \hspace{1cm} (4)

The resulting total heat as a function of time is shown in Figure 15. As can be seen from the gradient $\frac{dQ}{dt}$ the most of the heat was obtained at the beginning. After about 1.5 hour the gradient started to decrease gradually. In a 24 hours period the tank managed to transfer the total heat of 1.83 MJ or 0.508 kWh. The specific heat/volume is according to volume of the heat exchanger (0.0104 m$^3$) equal to 48.88 kWh/m$^3$.

According to work of Stritih et al. [5] testing the ability of energy storage in latent and sensible heat exchanger (at an initial temperature difference of 40 °C between the inlet and the outlet of the storage tank) showed the following results:

- paraffin latent heat storage - 63 kWh/m3 and
- water sensible heat storage - 52 kWh/m3.

The adsorption heat storage thus fall into the category of the water sensible heat storage, but is nevertheless a little bit better, also according to investigation of Yu et al. [7] where the following results with silica can be found; (i) type SG-127B = 24.85 kWh/m$^3$ and (ii) type SG-LE32 = 14.89 kWh/m$^3$.

There are several factors that we must take into consideration. One of the most influential factor is ability of adsorber to adsorb water vapour. Adsorption heat decrease exponentially with the degree of saturation of the adsorbent and therefore is lower. Adsorbent, which was used probably was not developed for heat storage purposes. In order to achieve better results of adsorption mode another adsorber developed in the last three years with higher adsorption properties should be used.
heating was turned off. The temperature of the heat sink should be the same as the inlet, but was not because the temperature sensors have not been calibrated to such high temperatures and therefore exhibits certain error. Rapid fall of the inlet temperature was caused with late valve closing. Afterwards temperatures got closer to temperature of surroundings. The adsorber and adsorbent temperature were increasing quite rapidly and reached maximum at the 85 °C. This temperature was maintained until the heating was stopped (after 4 hours) and then slowly dropping to the ambient temperature. Adsorbent was cooled down much slower than water in the heat exchanger, probably because the adsorbent was in vacuum, which served as an insulator. After the desorption mode, the adsorption mode should start again, but the pressure in the tank increased from the initial 20 mbar to the 100 mbar of absolute pressure.

The results of desorption was evaluated by weighing of removed water (adsorbat) from the adsorbent. The tank drained 4758 g of water. The mass of dry adsorbent and water mass were known, so the difference was 1150 g of water in the adsorbent. Summing these two masses gives 5908 g of water in the tank after both (two) modes. This result should be matched with the mass of water, which has been added at the start of the measurement (6032 g), but it does not. The mass difference of 124 g probably remained in the tank bottom walls. The temperature during both weighing was the same (21.5 °C). The mass difference was 2%, which is acceptable. From the measured data it is now possible to determine the level of moisture in the adsorbent. Assuming that the adsorbent was completely dry at the beginning, results show that the adsorbent contained about 20.18% moisture after the desorption, what means that minimal or almost no adsorbed water vapour was desorbed in the desorption. This probably happened because during the process of desorption, walls of the tank should be cooled in order to carry out intensive condensation. The results would be even better if the water in condenser was cooled.

Another very important feature is the fact that vacuum and adsorbent inside the tank are both insulators. Heat transfer from the heat exchanger to the adsorbent was most likely due to attenuation only at the junction and elsewhere was already negligible, therefore the water was evaporated from a small part of the adsorbent only. Much better results can be achieved by a slightly different design of the heat exchanger, where the emphasis would be right at the interfaces of the heat exchanger and the adsorbent.

7. CONCLUSIONS

For efficient utilization of solar heat energy, compact and cost effective seasonal thermal storage systems are essential. One of the options is to use sorption heat storage principle.

Heat storage tank with silica gel HX-13 as adsorbent has been designed. There were a lot of challenges with the under-pressure in the tank, which were successfully exceeded, but it should be noted that in the implementation of further attempts the sealing must be performed with vacuum sealing techniques to keep vacuum in the tank for several days.

However, it should be noted that the results of the adsorption mode would be better if the metal mesh...
basket would be totally covered with the adsorbent. Because of the absence of the adsorbent, the other two tubes of heat exchanger were uncovered and during the adsorption mode the water vapour was raised above the basket where the tubes were uncovered, and cooled water in them. As a result, the temperature of water at the exit from the heat exchanger was lower, with maximum of 43.1 °C and was than dropping until the end of the measurement to approximately 25 °C. Consequently the resulting heat generated from the heat storage was lower.

In the investigation presented in the present paper it was demonstrated that the adsorption heat storage tank actually works in practice. In the period of 24 h the heat from the heat exchanger was 1.83 MJ. In addition the storage tank has one outstanding characteristic, which is that heat can remain stored in the tank as long as adsorbent and adsorbate are separated, what is a huge advantage over sensible and latent heat storage.

NOMENCLATURE

- \( c_p \) specific heat (J/kgK)
- \( \Delta m \) mass change (kg)
- \( m \) mass flow (kg/s)
- \( m_{\text{vapor}} \) vapor mass flow (kg/s)
- \( p_c \) condensation pressure (Pa)
- \( p_e \) evaporation pressure (Pa)
- \( Q_{\text{Ads}} \) adsorption heat (J)
- \( Q_{\text{Des}} \) desorption heat (J)
- \( Q_c \) condensation heat (J)
- \( Q_e \) evaporation heat (J)
- \( Q_i \) heat of individual point (J)
- \( Q_{\text{loss}} \) heat loss (J)
- \( Q_{\text{Total}} \) total heat from heat exchanger (J)
- \( \dot{Q} \) heat flux (W)
- \( \dot{Q}_i \) heat flux of individual point (W)
- \( T_{\text{Ads}} \) temperature at the beginning of adsorption (K)
- \( T_{\text{Des}} \) temperature at the end of desorption (K)
- \( T_{\text{Des1}} \) temperature at the beginning of desorption (K)
- \( T_{\text{Des2}} \) temperature at the end of desorption (K)
- \( \Delta t \) time interval (s)
- \( \Delta T \) change in temperature (K)
- \( U_p \) internal energy of vapor (J)
- \( x_{\text{min}} \) minimal saturation (kg Adsorbate/kg Adsorbent)
- \( \Delta x \) saturation change (kg Adsorbate/kg Adsorbent)
- \( WH \) water heater

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