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The Mechanism of Adsorbents Adsorption Affinity in Relation to Geometric Parameters

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Abstract. In the process of incorporating adsorption with thermal desalination, adsorbents are important because they increase the water vapour uptake rate, and this yield more desalinated water over a short period when adsorbents chosen properly. The key parameters in the selection of adsorbents for adsorption desalination (AD) cycle are thermo-physical properties, surface characteristics and water vapour uptake capacity. Three types of adsorbents (Silica gel, zeolite and activated alumina) compared to find which adsorbent can be used as the adsorbent-refrigerant pair, by looking at their adsorption affinity in relation to geometric parameters. The silica gel found to be the suitable adsorbent as it adsorbs 12% higher than zeolite and 18.9% higher than Al_2O_3 at equilibrium. All adsorbents were at 90% and above in average percent desorption throughout the optimal time cycle of 1200s.

1. Introduction

Global energy demand is quickly rising, particularly in emerging market nations, because of population and economic growth, contributing to water crises [1]. The increasing demand brings new problems on the available energy and freshwater resources. Despite all these obstacles, it created great opportunities for researchers to innovate new reliable technologies that will not consume much energy as compared to the one used before. The goal is to raise living standards, provide access to modern energy infrastructure, and protect the global environment by using the same energy for water purification process [2].

As an alternative way to solve water shortage, the manufacturing sector and academic associations have embarked on exploring the ocean. Throughout that research process, the desalination was found to be the solution of the worldwide water crises. The need for desalination research is influenced by several factors, including water quality, kind of energy source, location for feed consumption, and brine outflow. Nonetheless, just three applied sciences, reverse osmosis (RO), multi-stage flashing (MSF), and multi-effect distillation (MED), dominated the desalination industry, with a combined production of about 94% of total capability [3].

The essential signal for selecting a desalination technique is genuine energy usage, regardless of whether the power is in the high-grade structure, such as electricity, steam, or low-grade, such as low-temperature waste heat or renewable energy. When choosing a desalination technology, some critical constraints, such as the intensity of feed water quality, strategic planning for power and water demand, and the diversity of energy sources, outweigh the energy efficiency factor. According to [3], a work-driven computer conducts desalination very accurately in theory because there is much less irreversibility involved.

In addition, it should be noted that high-grade strength in the form of electrical energy is required to complete the task. A pie chart of water distribution on the planet is shown below. It reveals that

seawater (saline) makes up 97% of the water while freshwater makes up just 3% [4][5]. Groundwater, icecaps and glaciers, surface water, and other elements account for 3% of the total. The primary freshwater reserves are icecaps and glaciers, although this water is inconveniently located in certain regions. The main source of fresh water is shallow groundwater, which is used for a variety of purposes [6].
However, while rivers and lakes are the most widely used water resources, they only contain a finite amount of water, necessitating the purification of saline water to fulfil the world's growing water demand [5]. Numerous elements are guiding the now reported and on-going worldwide water problems. Global energy consumption is quickly rising, particularly in developing market nations, because of population and economic expansion, contributing to water shortages. According to the pie graphic shown in fig.1.1 seawater makes up the largest amount of water on the planet's surface; hence, desalination might be a solution to water insufficiency.
There are several desalination processes available, including reverse osmosis, thermal desalination, and ion exchange. This method produces high-quality water and can offer drinking water in regions where natural drinking water is scarce. The major drawback of these systems is that they are environmentally unfriendly, ecologically unfavourable. Its construction and maintenance are prohibitively expensive because of the enormous energy requirements of its functioning. This led numerous scholars to work on a desalination project. Many researchers were inspired to work on a desalination project because of these challenges [5].

Water distribution on earth

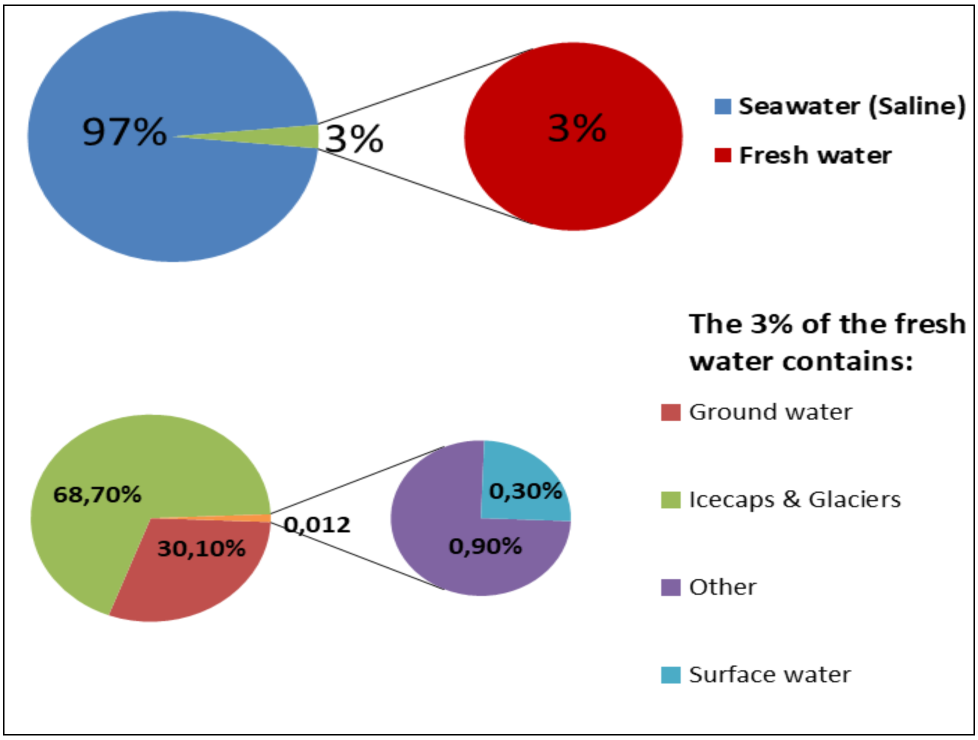

Figure 1.1: Water distribution on earth [6]

Several research under conducted with the goal of lowering the energy consumption required for this device's operation. This involves the integration of the solar system as well as other techniques for increasing system efficiency. Finding sufficient energy sources to meet the world's rising demand is one of society's most pressing issues. Sorption cooling, which is driven by low-degree heat and produces cooling power, is gaining appeal as an energy conversion technology [7]. The sorption phenomenon arises when thermal and adsorption desalination are incorporated with the goal of creating energy-efficient desalination systems [8].

1.1. Sorption Phenomenon

Sorption technology is a method that combines adsorption and desorption. Sorbents are the fundamental distinctions between two types of technology. Generally, liquid phase absorbents, and granular or lightweight adsorbents are used. One of the performance enhancing strategies for the thermal desalination device is the adsorption/desorption cycle. It benefits from a wide spectrum of adsorbents for a wide range of temperatures applied to various heat sources, typically between 50°C and 400°C. Furthermore, the characteristics of strong adsorbents make it more viable under high vibration circumstances.

This method takes use of the adsorption-desorption cycle to boost the vapour adsorption rate [8]. It is a modest desalination technology that requires just reduced waste heat, which is abundantly accessible from renewable energy sources or power plant exhaust [9]. The Adsorption Desalination (AD) cycle generates two beneficial outcomes with only one heat source: high-quality drinking water and cooling. Adsorbents are the most important part of the adsorption/desorption process, and there are many different types of them in the market. Each adsorbent's performance is determined by the factory's characteristics.

This suggests that the production of adsorbents varies depending on the producer, which is why this research is being carried out [10]. The content is fundamentally related to the advancement of adsorption cooling development within the field of working pairs of adsorptions, productivity of heat and mass transfer, and cooling cycle of adsorption, etc. Many Chillers, such as silica gel-water adsorption, have been successfully marketed on the market because of advancements in adsorption refrigeration technology. The following are more detailed summaries of the adsorption cooling system progression:

- ❖ Working pairs of adsorptions and their processes
- ❖ Adsorption cooling system structure
- ❖ Heat enhancement and mass transfer of the adsorption surface and,
- ❖ Thermal characteristics of various advanced renewable cycles.

The working pair of adsorptions is a critical component of the refrigeration adsorption and heat pump system. Thermal characteristics of the working pair have a major impact on the system's efficiency coefficient, velocity rise in adsorbed temperature, and initial expenditure. For efficient cooling efficiency, the appropriate adsorption working pairs are chosen based on the heat source temperatures, and the appropriate adsorption cooling cycles are chosen based on the real needs. The nature and characteristics of the method varies for various pairings employed in adsorption cooling[11].

There are two functioning methods for adsorption refrigeration. The first process is adsorption and cooling. The adsorption heat in this system releases cooling water or air into the heat sink, and the pressure within the adsorbed drops to a level lower than the pressure of evaporation. Under the pressure gap, the coolant evaporates and is absorbed by the adsorbent, and the evaporation process produces the cooling output. The next step is desorption and condensation mechanisms. This cycle's low-grade heat drives the endothermic desorption process.

Universally, the term adsorption refers to enrichment of one or more of the components in the region between two bulk phases (interface layer or adsorption space). Adsorption and desorption are often used to indicate the direction from which they approached the equilibrium state. Hysteresis of adsorption occurs when the adsorbed quantity is not brought to the same level by the approach of adsorption to the specified equilibrium pressure. The reaction, at constant temperature, between the amount adsorbed and the equilibrium pressure, is known as the adsorption isotherm [12].

1.2. Adsorption isotherms

The adsorption isotherm is the equilibrium of adsorption at a constant adsorbent temperature [11]. Adsorption isotherms are one of the several useful methods for understanding the process of adsorption and for quantitative evaluation of the partition or distribution of interest solutes at equilibrium between the solid and fluid phases involved. Adsorption isotherms refer to a set of measurements of adsorption performed at a given temperature and whose effects are plotted as a relationship between adsorbed and non-adsorbed quantities [13][11]. The table below shows the mathematical adsorption isotherm models.

Table 1-1: Mathematical adsorption model used to calculate geometric parameters and the equations are taken from [11].

Isotherm	Nonlinear form	Linear form
Langmuir	$q_e = \frac{Q_o b C_e}{1 + bC_e}$	$\frac{C_e}{q_e} = \frac{1}{bQ_o} + \frac{C_e}{q_o}$
Toth	$q_e = \frac{K_T C_e}{(a + C_e)^{\frac{1}{t}}}$	$logq_e = logC_e - \frac{1}{t}ln(a_T + C_e)$
Dubinin-Astakhov (D-A)	$q^* = q^0 \times exp\left\{-\left[\frac{RT}{E} \times in\frac{P_o}{P}\right]^n\right\}$	
BET	$q_e = \frac{q_s C_{BET} C_e}{(C_s - C_e)\left[1 + (C_{BET} - 1)\frac{C_e}{C_s}\right]}$	$\frac{C_e}{q_e(C_s - C_e)} = \frac{1}{q_s C_{BET}} + \frac{C_{BET} - 1}{q_s C_{BET}} \frac{C_e}{C_s}$
Freundlich	$q_e = K_f \times C_e^{\frac{1}{n}}$	$logq_e = logK_f - \frac{1}{n}logC_e$

Adsorption isotherms are utilized in the assessment of surface characteristics such as adsorbent affinity and adsorption capacity to develop effective adsorption systems. This aids in the development of effective adsorption systems. The structure of these isotherms retains much knowledge about the essence of the phase of adsorption. Adsorption often used to extract contaminants by allowing adsorbents like activated alumina, molecular sieve zeolite or silica gel connected to them. Adsorbents are porous solids that tie in their surface liquid or gaseous molecules[14][5].

The adsorption process mostly includes what referred to as a fixed bed adsorber, where a substance like air passes through a solid adsorbent bed. The adsorbent is normally used to draw the undesirable particles in the air as the moisture evaporates. But in this case are used as an intermediate phase in adsorption desalination to reduce the energy consumption and speed up the process. It helps to improve efficiency by placing various layers of these beds [11]. In addition, the adsorbents are used in desalting, and they can continue adsorbing until they get into saturation phase [11]. The saturation phase of each adsorbent differs from one to another.

This means that some other adsorbents have high adsorption affinity than other and that is explained more in [15]. In the process of adsorption desalination, it is important to use an adsorbent that has the high affinity to adsorb, hence the selection of geometric parameters is import [16]. One of the most essential jobs for adsorption technology users is choosing an adsorbent for a certain application. In theory, an adsorbent may be chosen based on a variety of variables such as adsorption capacity and selectivity, adsorbate uptake kinetics, compatibility with operating conditions, and, of course, cost [17].

The characteristics of the solid surface influence adsorption. Gases and vapours adsorb on solids having a highly developed surface. Therefore, selection or synthesis of adsorbents for a target adsorbate molecule is based on the adsorption isotherm. Geometric parameters that are of interest are the pore size diameter, surface area, the affinity to adsorb the vapour, distance between the fin and the material of the fin and the pipe. These geometric parameters will be compared using three different types of adsorbents in a gravimetric method to see which adsorbent that has the higher affinity.

The adsorbents used; activated alumina, silica gel and molecular sieve zeolites. It has been shown that surface properties such as surface chemistry and pore size distribution (PSD) of adsorbents play a significant role in the adsorption process hence the study is conducted. The adsorbent pore size distribution (PSD) specifies the fraction of its structure which a molecule of given size and shape can access. The size of the adsorbents relative to the pore size of the adsorbents is important in controlling the adsorptive mechanism of competition for a given size pore. Below there is a table showing the adsorbents granules dimensions.

Table 1-2: Adsorbent granules dimensions

Properties	Zeolite (3A)	Silica gel	Activated alumna
Size	3-5 mm	3-5 mm	2-5mm
Shape	Spherical	Beads	Spherical
Qualified Ratio of Particle size (%)	94	97	92
Bulk density G/L	760	767	750
Moisture (%)	<2	1.43	1.5

The overarching goal in designing adsorption chillers that use different type of adsorbent as the adsorbent-adsorbate pair is to leverage low-temperature waste-heat sources from industry. This research aims to find the adsorbent with good geometric parameters that can adsorb and desorb using desorption conditions. The three adsorbents used (silica gel, zeolite, and molecular sieve zeolite) compared through adsorption cycle and the one extract more adsorbate means it has high affinity to adsorb. Adsorption isotherms are utilized in the assessment of surface characteristics such as the adsorbent's affinity and adsorption capacity to build effective adsorption systems.

2. Material and System Design

The gravimetric method used in finding the geometric parameters by capturing the efficient water vapour uptake, and it was used to determine the optimum cycle time for the given AD cycle under the given operational conditions. The system consists primarily of three chambers, an experimental setup designed and built: adsorbent chamber, dosing chamber (absorber) and evaporator. A series of valves and tubes connected in the chamber. The evaporator used as a vapour source and connected to the dosing chamber. Each chamber, connected to a water circulator to regulate the temperature of the chamber, is placed within an individual water shower.

There are two working processes for refrigeration by adsorption. The first step is that of cooling and adsorption. In this system, the adsorption heat releases cooling water or air into the heat sink and the pressure within the adsorber decreases to a level below the pressure of evaporation. The coolant is evaporated and adsorbed by the adsorbent under the pressure gap, and the evaporation process provides the cooling output. Second, the mechanism of desorption and condensation. The low-grade heat triggers the endothermic process of desorption during this period. In the condenser, the desorbed refrigerant vapour condensed and cooled through the heat sink.

Vacuum pump utilized for departure reason. A warming tape mounted on the associating cylinders to control the solid shapes temperature. A reading rag pressure sensor is used. A variety of thermocouple sensors are connected to the temperature determined at various positions in the test ring. Temperature sensors and pressure transmitters, connected to a form of data logger, record the data every second. The isotherms and kinetics of the different adsorbents used measured in a certain range of temperature. The test-rig kinetics of sorption design shown in fig. 2.1 with dotted line on the schematic lay out, and it is the important part of the system.

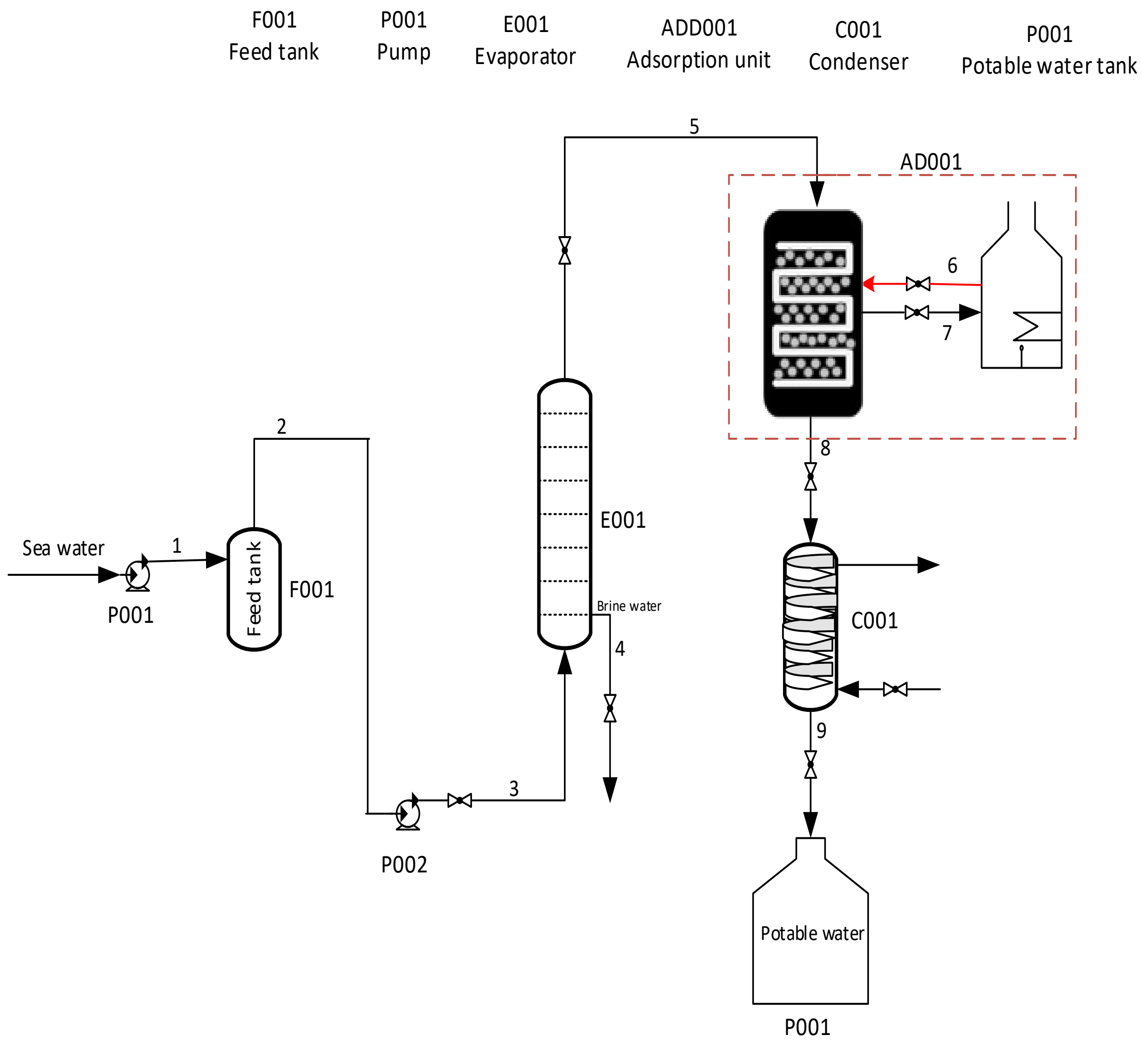

Figure 2.1: Schematic diagram of the experimental set-up

3. Procedure

The adsorbent dried up in an oven, cooled to the initial temperature of the isobaric adsorption and then weighed. The evaporator is filled with water and heated up until is boiling. The adsorbents placed on the heat exchanger and the heat exchanger is under vacuum. The coil connected to the heat exchanger from cooling refrigerator cools the adsorbent until they meet the saturation stage and become hydrophilic. The load cell weighs each step and recorded to the data logger. Once the adsorbent is saturated, the steam released from the evaporator and adsorbed by adsorbents for a certain amount of time. The regenerated water release from the water bath to the heat exchanger and adsorbents become hydrophobic and reject the steam. After desorption the vapour moves to the condenser and the condensate (Fresh water) collected.

4. Results and Discussion

The three distinct adsorbents, activated alumna, silica gel-water and zeolite-water, were examined in a single bed adsorption system. The system has been thermodynamically simulated for three adsorbents using adsorption equilibrium isotherms to test which adsorbent has a high affinity to adsorb the vapour [18][19]. The difference in weight of the silica gel between its saturated condition and the final desorbed state regarding temperature and time is measured using a moisture balancing approach. Adsorption, as is well known, is dependent on the characteristics of the solid surface and the solvent medium [19].

Gases and vapours adsorb on solids with a highly developed surface (silica gel in this case). Moisture balancing studies and representative plots for the three types of adsorbents, namely silica gel, activated alumina, and zeolite, are presented in fig. 3.2. The behaviour of water vapour desorption rates has been discovered to be time and temperature dependent. The graph of the percentage desorption obtained over time is shown in Fig. 3.1. It further shows the mass adsorbed as a function of time for three distinct adsorbents. Silica gel has the highest moisture adsorption capability from 300s to 1200s as shown in fig.3.1.

The results reveal that the silica gel-water pair has greater adsorption properties suitable for this adsorption chiller. Whereas the zeolite-water pair requires a higher temperature heat source for a stable desorption process and that will consume more energy. The activated alumina has a smaller surface-area-to-weight ratio and displays more variation in the amount adsorbed as a function of relative humidity variations [15]. Activated alumina is mostly utilized in heatless regenerative dehumidifying equipment because of its adsorption properties [15]. According to the results on fig. 3.1 the silica gel outperforms the zeolite and activated alumina during adsorption cycle.

In fig. 3.2 it is observed that the cycle of 1200s is sufficient to achieve 90% regeneration for all three investigated adsorbents. All adsorbents in fig.3.1 they rapidly increase until they reach 1200s that are where they starting to move slowly as they are approaching the equilibrium phase. It is stated in literature that in high-temperature regeneration and in less than 20°C evaporation temperature, synthetic zeolite has a superior adsorption performance [5]. The silica gel has shown to be more successful due to its ability to be regenerated at temperatures as high as 82°C, whereas molecular sieves can be regenerated at 550°C.

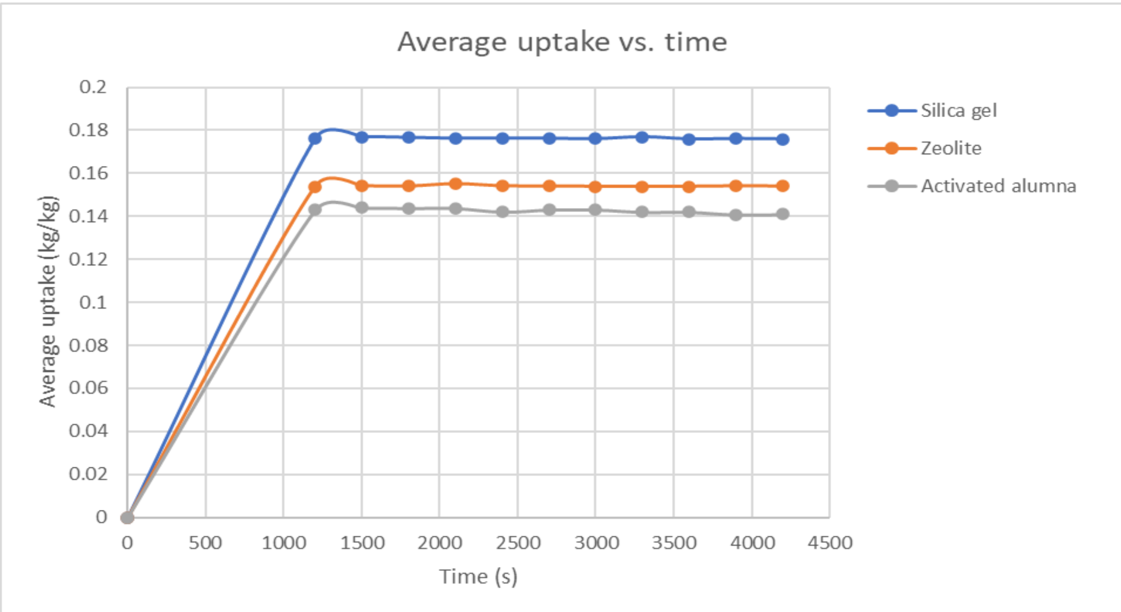

Fig. 3.1: Comparison of adsorbent in adsorption cycle

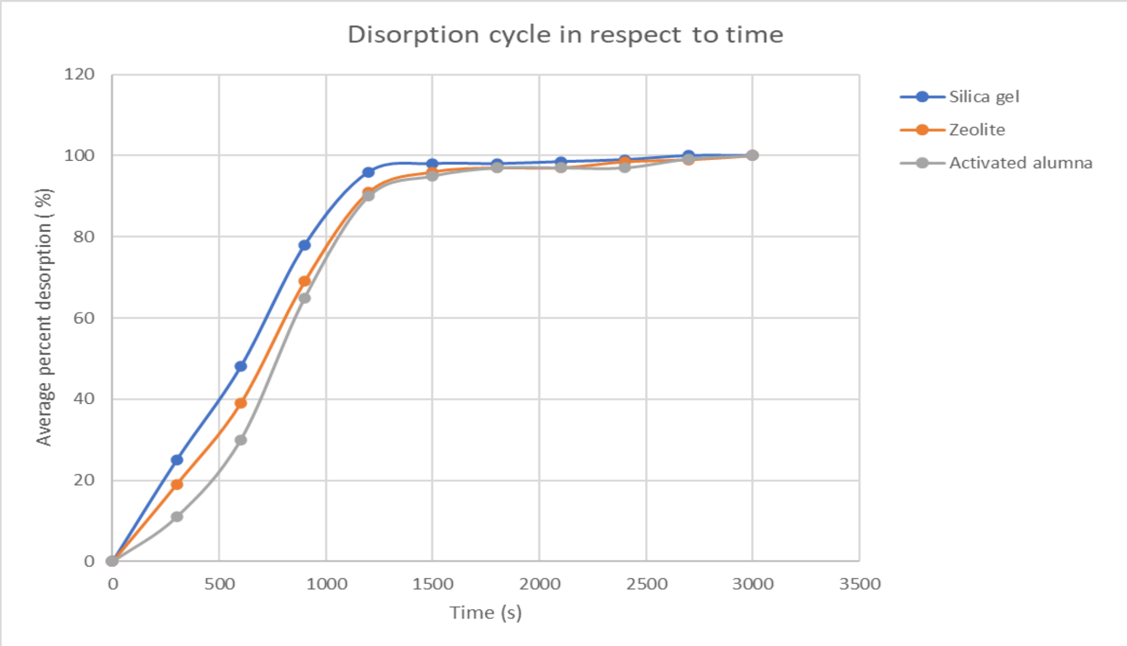

Fig. 3.2: The graph of average desorption cycle with respect to time

5. Conclusion

The adsorption desalination system is a newly developed thermal desalination system that requires low-temperature input for desalination to take place. For this system to remain utilizing the low energy, an adsorbent that can easily desorb vapour at a low temperature is needed [20][15]. The main purpose of this research is to conduct a study that uses the geometric parameters of adsorbents to find the adsorbent with the high affinity while operating with low regeneration temperature. A gravimetric analysis is used to conduct this study and premeditated under the following kinetics conditions evaporator; T= 10°C, condenser T= 30°C, and desorption at T= 75°C.

To study each adsorbent's adsorption affinity, the regeneration temperature and desorption rate were monitored concurrently using gravimetric method. The tested adsorbent range between 2-5mm for activated alumina and 3-5mm for silica gel and zeolite. The volume intake of water vapour cycle explored in relation to time. The silica gel adsorbs 12% vapour higher than zeolite and 18.9% vapour to Al_2O_3 at equilibrium (1200s). Through the results provided in this study, it can be concluded that the silica gel is the suitable adsorbent for adsorption chiller as it outperformed the other two adsorbents when they were compared based on adsorption chiller's conditions.

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