Comparative analysis of Silica-gel/Water and Zeolite/water Pair on adsorption Refrigeration System

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Abstract. The current work presents a comparative investigation on the execution of closed cycle adsorption refrigeration systems with Zeolite as adsorbent and water as adsorbed in one system and silica-gel as adsorbent and water as adsorbate in another system. In the present analysis, the effect of variation of the regeneration temperature on the coefficient of performance (COP) along with specific cooling power (SCP) for both the pairs has been studied and compared. From the analysis, it was found that specific cooling power (SCP) and coefficient of performance (COP) for Zeolite/water pair are better at a lower range of regeneration temperature while it is not that good for silica-gel/water pair. Both the pairs perform well at higher regeneration temperature. This being a theoretical study the results may vary practically.

1. Introduction
As there are many applications where transport refrigeration is required like milk, ice-cream, medicines, and agro-products transportation, so in the present work compatibility to run a refrigeration system with the exhaust gases of the automobile has been investigated along with the comparison of two working pair i.e. Silica-gel/Water and Zeolite/water which has not been reported yet. Sorption system is one of the ways to utilize heat energy instead of work for refrigeration. But the disadvantage is that there are comparatively more equipment in a sorption system than in the vapor compression system. Another disadvantage is the corrosion problem in the evaporator. In addition to this, the debris resulting from the corrosion fouls the narrow opening in the system. Since the refrigerants used in the vapor-compression system are not eco-friendly, technologies like sorption refrigeration are currently gaining importance. Sorption refrigeration systems can be classified as absorption and adsorption refrigeration system. As these systems are for the most part kept running by low-grade energy like the sun-powered energy, squander warmth of engines and so on, so in this regard adsorption refrigeration system is better as it requires less heat input sources as compared to absorption systems.

Chua et al [1] and Boelman et al [2] presented the thermodynamic analysis of an adsorption system. Detailed performance analysis of the adsorption system has also been reported by Chua et al [3] which basically focuses on entropy generation analysis of a two-bed silica gel water adsorption chiller also natural zeolite-water pair adsorption unit was concreted and its thermodynamic comparison with adsorption system was done by Tchernev et al [4]. Zhu et al [5] calculated refrigeration capacity of waste heat driven adsorption chiller in a diesel engine powered fishing boat on temperature variation of zeolite adsorbent bed there are multiple possibilities describe the performance of sorption systems. The most commonly used criterion is the coefficient is the coefficient of amplification (COA) for heat generation which can be determined by calculating or measuring the exchanged heat flows in the heat exchanger of sorption system however these coefficients do not take into account temperatures of
exchanged heat. Klein et al [7] described a new approach for evaluation and comparison of sorption systems with the proposed method it is possible to analyze the adsorption/desorption phenomenon for ideal systems. Sakoda et al [8] established a first step model which demonstrated the effect of regeneration temperature on the performance of the adsorption system. Adsorption equilibrium was fully described by Chihara et al [9] for a silica-gel/water pair. A novel zeolite-water adsorption air condition system has been established by Wang et al [10]. In that system heat and mass transfer of the adsorber has been taken into account to improve the performance of the cooling system.

Based on the previous work done by various peoples this paper presents a theoretical analysis of silica-gel/water and zeolite/water adsorption systems. Also, a comparative study has been performed the heat source for regeneration being the diesel engine’s exhaust gases.

2. Basic Adsorption Refrigeration Cycle

The basic adsorption refrigeration cycle as shown in figure 1 is a combination of four thermodynamics processes in which two are isosteric and two are isobaric as represented in Clapeyron diagram the first process starts at point 1 it is an isosteric process which means the concentration of adsorbate in the adsorbent \( q_{\text{max}} \) remains constant and the adsorber bed is heated by circulating the hot water, the temperature of adsorber bed increases up to \( T_2 \) which is the limiting desorption temperature and the pressure increases up to condenser pressure \( P_c \) there is no desorption of refrigerant during this process.

The second process which is an isobaric process starts from point 2 in this process the temperature of adsorber bed is continuously increased up to regeneration temperature \( T_3 \) and simultaneously the desorbed adsorbate goes into the condenser and its vapor condensed in the condenser and collected in a receiver. After this process, the concentration of adsorbate in the adsorbent reached a minimum level \( q_{\text{min}} \). The third process which is again an isosteric process starts from point 3, in this process the adsorber bed is cooled by circulating the cold water and the temperature and pressure decreases up to \( T_4 \) and to the evaporator pressure \( P_{\text{ev}} \) respectively. After that the adsorber bed is associated with the evaporator and the last isobaric process is started from point 4 in this process the adsorber bed is again cooled up to point 1 and both the adsorption and evaporation occurs simultaneously and the adsorbate concentration again reached to \( q_{\text{max}} \) during this process the cold is produced and this is the complete basic refrigeration cycle.

![Figure 1. Basic Adsorption Refrigeration Cycle](image-url)
3. Description of system
The system for silica gel-water and zeolite-water pair adsorption refrigeration driven by exhaust heat (loss of exhaust gases and cooling water loss) of the internal combustion engine depicted in figure 2 since, during adsorption period, no cooling effect is produced so two adsorber beds are proposed to be used. In both, the system silica-gel/zeolite is used as adsorbent whereas water is used as a refrigerant. The system is driven by the exhaust gas and hot water coming out of the engine in the way that hot water is heated by the exhaust gas and becomes hotter and this is more heated hot water is used as the heat source for the refrigeration system. During the first phase of the process (i.e. when valves V1 and V4 are closed and V3 and V2 are opened) there is desorption from adsorber-I and adsorption from adsorber-II. Similarly, during the second phase of the process (i.e. when valves V1 and V4 are opened and V3 and V2 are closed), there is desorption from adsorber-II and adsorption in adsorber-I, and the cycle repeats.

Figure 2. Adsorption refrigeration system driven by exhaust heat of I.C. engine

Thus using two adsorbers, the systems may approach continuous refrigeration. The cycle repeats itself in a way similar to the vapor compression system, during desorption water releases at the pressure of condenser (i.e. $P_{\text{cond}}$) in the same way as in compression system. Then water vapor is condensed at a temperature $T_{\text{cond}}$ in the condenser where heat is rejected to the atmosphere (which is at $T_a$) and it cools down. After that it is passed through a throttle valve, thus reducing the pressure up to $P_e$. This low pressure and low temperature make water to evaporate at $T_e$ by extracting heat from desired space.

A set of experiments was performed to evaluate waste heat by a C. I. Engine of 5 HP, single cylinder, water-cooled having 553cc swept volume. This experiment was performed at different loading conditions at a constant speed of 1500 rpm. Figure 3 clearly shows that more than 50% of energy is wasted which can be utilized to run the adsorption refrigeration system. With the help of this heat input (i.e. by both exhaust & cooling water), different values of mass flow of refrigerant and the capacity of the refrigeration system at different condenser temperature and evaporator temperature were obtained.
4. Methodology
The adsorption equilibrium equation for the adsorber bed as shown in figure 2 is described by Chihara et al [9]

\[ q^* = k \left( \frac{P}{P_s} \right)^n \]  

(1)

Where \( q^* \) is the amount adsorbed in equilibrium at pressure \( P \), \( P_s \) is the saturation vapor pressure of the adsorbent and, \( k \) & \( n \) is constants.

Again the value of \( k \) can be defined as

\[ k = \rho^* \left( \frac{\varepsilon_p}{\rho_p} \right) \]  

(2)

Where \( \rho^* \) is the density of adsorbate in the adsorption phase, \( \varepsilon_p \) is the pore fraction in a particle, \( \rho_p \) is the density of the particle.

By using equation (1), water per kg of silica-gel released from the adsorber bed i.e. \( \Delta q \) as described by Sakoda et al [8]

\[ \Delta q = K \left[ \left( \frac{P_s(T_{ev})}{P_s(T_a)} \right)^{\frac{T}{T_a}} - \left( \frac{P_s(T_{cond})}{P_s(T_{reg})} \right)^{\frac{T}{T_a}} \right] \]  

(3)

So using equation (1) for silica-gel/water pair governing equations [8] are

\[ q^* = 0.34 \left( \frac{P}{P_s} \right)^{\frac{1}{6}} \]  

(4)

\[ \frac{dq}{dt} = k \cdot a \cdot \Delta q \]  

(5)
Where

\[ k_s a_p = \frac{15D_{ae}}{r_p^2} \exp\left(\frac{-E_a}{RT}\right) \]  

(6)

And the governing equation for Zeolite/water pair [10] is

\[ \frac{dq}{dt} = 0.019 \exp\left(\frac{-906}{T}\right) \Delta q \]  

(7)

\[ q^* = 0.331 \exp\left[-2.99\left(\frac{T}{T_s} - 1\right)^2\right] \]  

(8)

Specific cooling power is given by the equation

\[ SCP = M_{ad} \frac{dq}{dt} \Delta h_{ev} \]  

(9)

\[ Q_{in} = M_{ad} \frac{dq}{dt} [h_{out} - h_{in} + \Delta h_{des}] \]  

(10)

The coefficient of performance is given by

\[ COP = \frac{SCP}{Q_{in}} \]  

(11)

### 5. Results and Discussion

The thermal compressor works between two pressures limits i.e. evaporator pressure and condenser pressure. By using equation (3) a thermal cycle can be drawn for both the working pairs as shown in figure 4 and 5 for silica-gel/water and zeolite/water respectively. With the help of these figures, one can obtain the \( \Delta q \) (kg/kg of adsorbent) for different ambient temperatures and regeneration temperatures. By using above equation from (1) to (11), SCP and COP values have been calculated for different values of regeneration temperature (i.e. \( T_{reg} \)) and results are shown by figure 6 and figure 7. Generation temperature (i.e. \( T_{gen} \)) is varying from 330K (which is the minimum temperature required to generate the pairs 333K for zeolite/water and 335K for silica-gel/water pair) to 400K. Both pairs are used to produce same evaporator temperature (i.e. 280K) for ambient condition 310K assumed.

![Figure 4. Variation of \( q^* \) with Regeneration Temperature](image-url)
Figure 5. Variation of $q^*$ with Regeneration Temperature

Figure 6 and Figure 7 shows that both SCP and COP values for the entire range of generation temperature are found higher for silica-gel/water pair. But at higher temperature i.e. around 400K, values of SCP and COP for zeolite/water are very much comparable with silica-gel/water pair.

Figure 6. Variation of SCP with Regeneration Temperature
6. Conclusion
An approach for comparison of silica-gel/water pair and zeolite/water pair system has been described in this paper. After evaluation, it is found that the performance of zeolite/water pair is better at low generation temperature (up to 345K) and at high regeneration temperature silica-gel/water pair is better at 400K regeneration temperature the SCP for silica-gel/water pair is 20% more and the COP is 15% more than the zeolite/water pair. Also, both pair is found good and can be used to run solely by engine exhaust at full load on the engine. But at partial load on the engine, generation temperature is low enough to run the system, as at low generation temperature both pairs performance is very poor. However, it is advisable to hybrid this system with other low-grade energy systems.

7. References
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