A REVIEW ON ADSORPTION CHILLING SYSTEMS AND VIABLE FUTURE FOCUS IN REFRIGERATION

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Abstract: - The adsorption refrigeration system has gained significant insight in recent years as it has paved an important way of utilizing low-grade thermal energy and eco-friendly refrigerant efficiently. However, it is yet to be commercially viable due to its low Coefficient of Performance (COP) and specific cooling power (SCP) in comparison to the traditional chilling technologies. This paper reviews various validation in incorporating different strategies to maximize the performance and cooling power of the system, out of which, prominent stages include-waste heat recovery, mass recovery, multi-bed, multi-stage, and revamp functionality.

This study acknowledges different parameters and allied substitution, for instance, low evaporative temperature, low generative temperature functioning can be controlled by infusing the mass recovery technique. Furthermore, other variables like appropriate cycle time and switching time are discussed to attain optimum performance of the system as it is regarded that the adsorption chiller greatly relies on the functionality of the system. Besides, to the above-stated variables, an adsorbent material is employed and this assures a considerably desirable performance.

This study further extended in briefing the economic criterion, increasing the power to mass ratio, and also improving the knowledge regarding the potential performance of the system in the long run when the energy-driven is either solar or waste heat energy source.

Keywords: Adsorption, COP, Waste Heat recovery, Refrigeration

1. Introduction

This paper comprises of the discussion on the Adsorption chilling technology. Firstly, a glimpse idea of conventional refrigeration technology is discussed. Secondly, the need for an alternative cooling system is explained. Later, an introduction to the adsorption mechanism and a brief analogy between the two chilling systems is discussed. Other performance criteria and future scope to the technology in combination with sensors is broadly explained.

VAPOR COMPRESSION REFRIGERATION CYCLE (VCR CYCLE)

The most commonly used refrigeration cycle is the VCR cycle and regarded as the conventional refrigeration cycle. There are mainly four processes involved in this cycle. Initially, the evaporator absorbs the heat from the surroundings at a certain pressure and temperature and the refrigerant is heated up to saturated vapor line, therefore increasing temperature and the refrigerant undergoes a reversible adiabatic process under compression with the help of the compressor, thereby the pressure of the refrigerant increases and attains a superheated state. A constant pressure process takes place after de-superheating of refrigerant in vapor state in the condenser chamber, where all the heat absorbed is emitted out and a saturated liquid refrigerant enters the throttle section which neither produces nor consumes work, and hence pressure decreases in this isenthalpic process. After this process, the temperature is attained which is lesser than the initial temperature of the surrounding, and the refrigerant goes back to the evaporator and the cycle continues. This cycle provides the necessary refrigeration effect. [1]
NEED FOR AN ALTERNATIVE COOLING SYSTEM

The traditional VCR cycle uses high-grade energy and environmentally hazardous refrigerant. According to the U.S Energy Information Administration (EIA), as in 2019, electricity use for cooling the interior of buildings by the U.S. residential and commercial sectors was about 380 billion kilowatt-hours (kWh), which was equal to about 10% of total U.S. electricity consumption in that year. Similarly, for a country like India, which constitutes about 17.7% of the world population, as of 2020, consumption of electricity is increasing exponentially over the years.

The air quality index (AQI) in most of the cities in India, is close to 400 which is a severe condition and the impact of cooling systems catering to air pollution is significant. So, there is a top-priority requirement for an alternative solution. The adsorption cooling technology proves to be an efficient way to overcome all the difficulties caused due to the conventional systems by the use of low-grade energy and waste heat recovery process.

Adsorption mechanism is a surface phenomenon in which the accumulation of molecular species occurs at surface- rather than the bulk of solid. The adsorbent solids are present in their finely divided state having large surface area and thus acts as good adsorbent and this property increases with an increase in surface area per unit mass of adsorbent at a given temperature and pressure. During this process of adsorption, the residual forces on the surface of the adsorbent get balanced by adsorbing the adsorbate, thereby decreasing its surface energy, which reflects as an exothermic reaction. This heat generated is called enthalpy of adsorption, which causes a significant increase in the temperature of the eco-friendly refrigerant (generally water), therefore eliminating the use of a compressor in the system; and thus, abating the use of electricity to a large extent. The adsorption chamber acts as a thermal compressor which operates on heat [1].

Adsorption cycle which works on two separate phases- the adsorption phase and the desorption phase. In the adsorption phase, at low pressure, water in the evaporator evaporates, then water in its vapor form moves up to the adsorber and is adsorbed by the adsorbents, thereby increasing the pressure in the adsorber bed. When this attained pressure is more than the condenser pressure, naturally the refrigerant moves to the condenser. In the desorption phase, waste heat or the low-grade energy desorbs the adsorbed water vapor and moves to the condenser to liquefy and reject heat (considered as the waste heat) which later will be used again in the cycle, and then transfers water in liquid form back to the evaporator via the throttle valve and the cycle continues. Most processes are analogous to the traditional process of chilling, except for using the waste heat and adsorber-desorber instead of a compressor, which proves to be effective in the reuse of heat, hence saving a significant amount of thermal energy and power consumption to a large extent respectively [2,3]. Figure 3 depicts the adsorption mechanism and is evident in heat rejection and heat recovery from the figure.
2. Stages and Performance Parameters

This cycle has its demerits in having a low coefficient of performance and specific cooling power. Researchers are continuously working to combat this by infusing different stages and varying different performance criteria. A generic depiction of the cycles and performance variations are presented below. [3]

A. Heat Recovery

The objective of this cycle is to recover the heat energy by the virtue of temperature difference between the absorber and desorber during the switching between the evaporation and condensation process. The energy in the bed with higher temperature passing to absorber is transferred directly to the bed with lower temperature while passing to the desorber, also increasing the pressure while passing through absorber to condenser and decreases pressure (depressurization) while desorption. The cooling water flows into the hot absorber and is heated up, hence the heated water passes to cold desorber, thereby pre-heating it. Then, the cooling water returns and the hot water bypasses the system so that there is no external thermal energy required during this process. This entire heat recovery takes place in the adsorption bed. [1] [3]

B. Mass Recovery

The technique of mass recovery proves to be very effective in increasing the cooling capacity of the chilling system, which is the main objective of any cooling system, thereby increases the Coefficient of Performance (COP). It is seen from the heat recovery process that an increase in temperature pressurizes the refrigerant and attains a higher pressure than the inlet condenser pressure and vice-versa occurs during the desorption process (cooling of the bed), where the adsorbers are not directly connected to the evaporator and condenser. But, in the mass recovery process, fractional pressure change occurs even without any temperature increase or decrease in the bed. Here, adsorber and desorber may be connected and mass of the refrigerant circulates in the bed under pressure drop of either adsorber or desorber. This naturally occurs during the switching process and this pressure drop continuously makes the refrigerant circulate, hence mass is recovered [2,4].

With the equation of specific heat formula:

\[ Q = mC_p\Delta T \]

The cooling capacity of the system increases, as the mass is continuously present in the bed and heat transfer occurs with a greater percentage than earlier without mass circulation. In the equation, \( Q \) is the heat energy in Joules(J), \( m \) is mass of the refrigerant in kilograms(kg), \( C_p \) is the specific heat capacity in Joules/kilograms
Kelvin (J/kg-K), ΔT is the temperature difference between adsorber and desorber in Kelvin (K). This stage is very effective in places where heat recovery techniques cannot be used due to environmental conditions. [2] [4]

C. Multi-stage Process

This technique is generally incorporated when the basic source of the system comes from solar energy radiation. When there is a variation in climatic conditions, and the source of energy naturally falls short, a multi-stage setup can be used accordingly. Here, the entire setup is made in such a way that the process occurs at two different stages simultaneously. The requirement of two pairs of adsorbent beds with the usual evaporator and condenser is essential and hence this process undergoes the thermodynamic states of the adsorption system – pre-heating, desorption, pre-cooling, and adsorption. It is experimentally proven that this system functions effectively even at a waste heat temperature of 55°C. A combined stage technique increases efficiency by about 20% where the culmination of two identical processes is brought together to function. [1]

D. Multi-bed Process

Out of all the above techniques, the technique of multi-bed increases efficiency and performance rapidly. They have major benefits in maximizing the cooling capacity, improving the quality of instantaneous cooling, etc. From the previously tested experiments and research, it is observed that a multi-bed adsorption chiller reduced the fluctuations in the chilled water outlet, which thereby increased the waste heat recovery efficiency at a greater rate. A combination of a multi-bed adsorber chiller system with infusing the waste-heat recovery technique will increase the system performance exponentially [1,4].

Moreover, other techniques like thermal, cascade cycle, and cycle time can also be parameterized and can be found better performing cycles and techniques by various experiments. However, even though these techniques are efficient in their form, they need to be used at the appropriate conditions of the surrounding. It is also important to always compare the conventional form of chilling systems with adsorption systems whenever a new technique is incorporated to check the performance, so that a better understanding of various factors like Coefficient of Performance (COP), specific cooling power (SCP), economics and cost involved and not leaving behind, the environmental impact it can cause to the society needs to be considered.

3. Working Pairs

Working pairs are the most important factor when we introduce a completely new form of chilling system. Analogous to the refrigerant used in the conventional system, where we parametrize properties like low boiling and melting point, high latent heat of evaporation, less viscous and low specific volume, high thermal conductivity, non-toxic, non-flammable, non-explosive, non-corrosive, easy maintenance, and handling capability, it is advisable to parametrize properties relatively in adsorption chilling systems like high adsorption capacity, a large change of adsorption capacity with small variation in temperature, good compatibility with the refrigerant etc. It is merely impossible to attain all the mentioned properties. Thus, we can use a few common working pairs. The following gives a brief discussion on the working pairs used with their merits and demerits.

A. Activated carbon-methanol systems

Activated-carbon methanol systems prove to be the best user working pairs in adsorption systems due to their large adsorption capacity, which means the affinity of the pair is high with the adsorber bed, high evaporating of latent heat of methanol. The highest COP is achieved with this working pair. On the other side, the functionality of this working pair, though proves to have higher performance is restricted to a working temperature of less than 120°C due to the chemical reaction that can take place between the working pair as the activated carbon helps and speeds up the reaction of methanol to form dimethyl ether at a temperature of about 150°C. Methanol has a high toxic property which makes the pair not suitable to use and also activated carbon does not form a metallic bond and can only covalently bond, thermal conductivity
is poor. These properties deficit the use in the chilling systems, as they go against the criteria we have parametrized. [1] [2]

B. Activated carbon-ammonia systems

In the conventional refrigeration systems, we use ammonia to a greater extent, but when activated carbon is paired with ammonia, a desorption pressure of about 1.6MPa is attained, hence a higher-pressure bearing capacity system needs to be designed. Due to this high pressure, it enhances the mass transfer of the working pair and shortens the response time between the switching of the adsorption-desorption process. However, it is still a far thought on using this pair due to the irritant smell of ammonia gas, toxicity, and corrosive properties. Disregarding the chemical and environmental properties, this pair is very well efficient in other thermodynamic and physical properties. So, we must work on eliminating, rather reduce the unsuitable chemical properties for better performance [1].

C. Silica gel-water systems

In the introduction to the adsorption system, silica is one of the firstly regraded adsorbent material. When this adsorbent is paired with environment-friendly water, it is assumed to be the best working pair. But this assumption is disproved, as this pair is a low-temperature working pair that can be driven by about 75°C heat source. Under low pressure, water uptake in silica gel is very little and requires a high evaporative temperature. [1] [4]

D. Calcium chloride- ammonia systems

In chemical adsorption systems, this pair is commonly used due to the large adsorption capacity of calcium chloride. As discussed earlier, ammonia as a commonly used refrigerant has a low boiling point property. However, the other factors of expansion, decomposition, deterioration, and corrosion in the calcium chloride-ammonia adsorption system make it ill-suited for commercial use in more applications, rather it is restricted to very few applications based on specific individual property of the pairs, [1][3]

Similar pairs and more working pairs are introduced, experimented, and tested for performance. However, specific applications require different working pairs and as engineers and scientists, we must make a decision based on the usage with high efficiency and considering the environmental variables.

4. Future Scope of Adsorption Chilling Technology

Researchers and scientists are continuously working towards the betterment of society. In the field of refrigeration and air-conditioning, it is of prime importance to have a better performing system with greater COP and SCP, not disregarding the economics and environmental hazards, as it has become a necessity to have such cooling systems in most, the developed and developing nations across the globe after rapid urbanization of majority of the parts in the world. The methodology to work on these adsorption systems needs to always be compared with traditional refrigeration technology, to study the merits and demerits of both systems and design and develop a generalized, and almost close to an ideal working cycle with maximum efficiency and performance, also not contributing harmful effluents to the atmosphere.

Specifically, in the field of adsorption technology, different variants are being tried out by researchers, like using different working pairs, which have adsorbent properties and combining them with fin-like structures made of materials with high thermal conductivity, so that heat transfer increases, and therefore cooling capacity also increases proportionally. Recently, researchers have observed that different orientations or arrangements [7] of the adsorbents also cater to differences in performance. Altogether, the culmination of all the stated and other new parameters needs to be considered while designing such systems.

CFD (Computational Fluid Dynamics) analysis needs to be done appropriately with high resolution meshing for accurate results for all variants in materials, orientation, working pairs, etc. Shortly, there are areas on
simulating the flow analysis using non-meshing techniques with higher accuracy than the current FEM techniques involved, which also can be incorporated undoubtedly to our adsorption systems.

On the other hand, after industrialization, the world is marching forward towards new technologies in artificial intelligence, machine learning [5], neural networking, etc. These techniques also can be embedded into refrigeration [6] systems, as explained below:

For instance, in our case of adsorption technology, performance depends greatly on various factors, like operating time, operating conditions, switching time between adsorber, and desorber. Initially, we can develop a machine learning algorithm based on supervised learning, where it works on input-output methodology. The following table can give us a better understanding of how it can be performed.

| Temperature of surrounding (°C) | Technique to be used |
|---------------------------------|----------------------|
| < 50°C (less solar radiation)   | Multi-stage system   |
| <85°C (low evaporative temperature) | Mass recovery technique |
| >120°C (high evaporative temperature) | Waste heat recovery technique |

Table 1 Input output algorithm of temperature and techniques to be used

In the above table, a temperature sensor measures the surrounding temperature(input) and generates an output of which technique to be used in developing the system. This is the first stage. The values given in the table may vary with the properties of working pairs.

Similarly, another sensor can detect the maximum temperature of adsorber and desorber that is attained between the switching process and can, therefore, compute the switching time and check for maximum efficiency trial with various trial and error datasets collected as shown in the table below.

| Maximum temperature of adsorber (°C) | Maximum temperature of desorber (°C) | Time taken In seconds |
|--------------------------------------|--------------------------------------|----------------------|
| 250                                  | 238.9                                | 10.0                 |
| 253.4                                | 236.1                                | 8.4                  |
| 255.3                                | 231.9                                | 7.1                  |
| 252.9                                | 235.6                                | 8.5                  |

Table 2. Switching time between adsorber and desorber

Two sensors can be embedded into the system, one at adsorber and one at desorber and by measuring the temperature difference between the two and estimating the time taken for switching between adsorber and desorber, we can compute the response time, again with various variables like material, refrigerants, etc. and hence we can plot a graph and check for least switching time between different pairs and beds, and can estimate
maximize efficiency. The tables are for illustration purposes only on how future technology can be enabled into adsorption systems. It just gives the idea to work on systems and is not the generated data.

5. Conclusion

This paper reviews the adsorption technology that is currently a point of research in the field of refrigeration and air-conditioning. For any new system to be viable to use, a reference system needs to stand as the fulcrum to compare and estimate results. In that notion, the traditional VCR system was discussed on its working and the thermodynamic cycle. We also got a brief idea of the need for adsorption systems, acting as an alternative and the adsorption mechanism was established broadly. Then, various performance parameters that enable us to provide a better efficient system were discussed on waste heat recovery, mass recovery, multistage and multi-bed systems. Various working pairs also were discussed with their merits and demerits. Conclusively, the paper summarizes on how modern techniques like AI and Machine learning [5] can be incorporated in adsorption systems [6] for better future of the society in making convenient and quick analysis without harming the nature and live in a sustainable environment

References

[1] D.C.Wang Y. H.Liab D.Lia Y. Z.Xiab J. P. Zhanga, “A review on adsorption refrigeration technology and adsorption deterioration in physical adsorption system”, Elsevier, https://doi.org/10.1016/j.rser.2009.08.001
[2] Amir Sharafian, Seyyed Mahdi Nemati Mehr, Poovanna Cheppudira Thimmaiah, Wendell Huttema, Majid Bahrami, “Effects of adsorbent mass and number of adsorber beds on the performance of a waste heat-driven adsorption cooling system for vehicle air conditioning applications”, Elsevier, https://doi.org/10.1016/j.energy.2016.06.099
[3] Ali Alahmerab, Salman Ajiba, Xiaolin Wange, “ Comprehensive strategies for performance improvement of adsorption air conditioning systems: A review”, Elsevier, https://doi.org/10.1016/j.rser.2018.10.004
[4] M.Z.I.Khanal, B.B.Sahab, K.C.A.Alimc, A.Akisawa, T.Kashiwagia, “ Study on solar/waste heat driven multi- bed adsorption chiller with mass recovery”, Elsevier, https://doi.org/10.1016/j.renene.2006.02.003
[5] A. Santana, Y. Fukuyama, K. Murakami and T. Matsui, “Machine learning application for refrigeration showcase fault discrimination,” 2016 IEEE Region 10 Conference (TENCON), Singapore, 2016, pp. 10-13, doi: 10.1109/TENCON.2016.7847948.
[6] Guo-liang Ding, “Recent developments in simulation techniques for vapour-compression refrigeration systems”, International Journal of Refrigeration, Volume 30, Issue 7,2007, ISSN 0140-7007, https://doi.org/10.1016/j.ijrefrig.2007.02.001.
[6] Sourav Mitra, Seung Taek Oh, Bidyut Baran Saha, Pradip Dutt & Kandadai Srinivasan,” Simulation Study of The Adsorption Dynamics of Cylindrical Silica Gel Particles” vol 46, Heat Transfer Research.
