International Journal of Science and Research (IJSR)
ISSN: 2319-7064
ResearchGate Impact Factor (2018): 0.28 | SJIF (2019): 7.583

Modeling and Simulation of Adsorption Refrigeration System Using Low-Grade Thermal Energy

Dr. Ajoy Kumar[1], Kumar Abhinandan[2]

[1]Vice-Principal, St. John College of Engineering & Management, University of Mumbai, India

[2]UG Student, Mechanical Engineering, National Institute of Technology, Patna, India

Abstract: ***Adsorption refrigeration systems are among the promising thermally driven systems that can improve the effectiveness of utilizing low-grade thermal energy resources such as waste heat or solar energy. The refrigerants used in these systems are environmentally friendly like water, ammonia, methanol, etc. Though, adsorption systems are the capable alternative for conventional vapor compression refrigeration systems, to date they were not been commercialized for small scale. High initial cost and weight, coefficient of performance and specific cooling power are the major issues to divest the adsorption system from commercialization. This study evaluates the effect of operating and design parameters on the performance of the adsorption refrigeration system. To evaluate the performance of the system, mathematical modeling has been proposed, developed and used to simulate at different operating and geometrical parameters of the adsorption system. Simulation carried out by using the current model has a maximum of 2 % of average error compared with original results obtained from the literature.***

Keywords: Waste heat, Environment pollution, Adsorption refrigeration system, solar energy

1. Introduction

In the last few decades, the demand for air conditioning and refrigeration increasing gradually to a large extent. But, traditional air conditioning systems employ refrigerants that could cause harm to the ozone layer and also responsible for global warming. With the stringent environmental requirements, conventional refrigeration methods have been hard-pressed in facing this challenge.

As a result, there is a strong need for alternative cooling technology that uses sustainable and renewable energy supply. The proper technology should be environmentally benign and provide reasonable performance so that it can be comparable with a commonly used vapor compression cooling system [4], [5]. Around 80 % of the energy on the earth comes from fossil fuels. Hence, the awareness of the decrease in fossil fuel resources, remote area problems, and environmental issues lead to development toward new technology. Use of abundantly available energies like solar, wind, biomass, hydropower, geothermal energies, and even thermal waste from various processes can be effectively utilized for fulfilling the demand of energy [1-3]. For such a reason, Vapor absorption and vapor adsorption technologies have been gained attention as a novel technology to the alternate conventional cooling system which utilizes low-grade thermal energy. Low-grade thermal energy such as solar energy, exhaust from the I.C. engine has been easily available. In the vapor absorption system, the compressor is replaced by the compressor which absorbs the refrigerant by using liquid material. Absorption is the process in which liquid or gaseous particles get absorbed in liquid or solid material. Because of the liquid usage, the system is unable to perform in some applications like automobiles, fish boats, etc. However, the performance of the system is low compared to the conventional system. In the vapor adsorption system, the solid material is used in the compressor. Adsorption is a surface phenomenon occurs at the surface of the adsorbent material due to the forces of attraction between refrigerant particle and adsorbent material. This process can create the film of refrigerant over adsorbent material. Generally, the adsorption process occurs in the compressor named as adsorber. Adsorption systems can minimize drawback of vapor absorption system application in automobile, fish boat, etc. But, eventually, some technical and performance drawbacks are identical in both of the systems which can cause a lack of commercialization. Low coefficient of performance, low specific cooling capacity, poor heat, and mass transfer leads to higher initial cost, weight and bulky system [6],[7]. From the past two decades, solid sorption systems in some ways seem a more promising choice. They can efficiently use solar energy or exhaust from I.C.engine as a primary energy source. However, these systems are energy saving compared to the conventional cooling systems which have simpler control, no vibration, no pollution, no noise, less operational and maintenance cost. Adsorption system contains less moving parts leads to less complexity.

Many industries have been utilizing current technology in their plants, but adsorption systems were not commercialized for small scale applications to date.

In the current study, performance improvement parameters, different working pair characteristics, adsorption isotherm models and design parameters have been analyzed theoretically and simulated using Microsoft excel programming for the adsorption refrigeration system. A theoretical model has been developed to analyse system parameters and compared with experimental results.

1.1 Absorption refrigeration system

The vapor absorption refrigeration system mainly consists of the expansion valve, condenser, evaporator, and compressor. The schematic diagram of a basic vapor absorption system is shown in Fig.1.

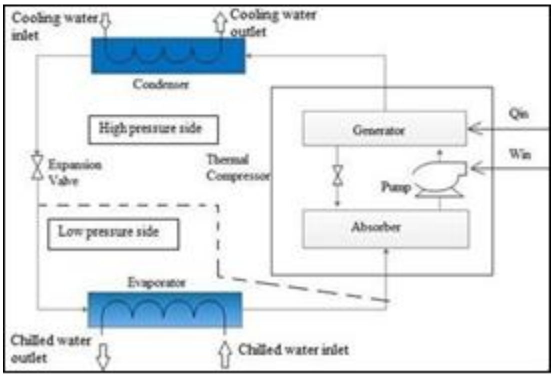

Figure1: Schematic diagram of vapor absorption refrigeration system

A compressor is the combination of absorber and generator. In vapor absorption refrigeration system liquid refrigerant and liquid absorbent are used. In vapor absorption refrigeration system heat is utilized as input. The generator is heated by using the heat source. When the generator is heated the refrigerant is separated from the liquid absorbent and is compressed in the generator. Due to the compression, pressure, and temperature of the refrigerant increases. The compressed refrigerant is passed through the condenser where the heat of the refrigerant is rejected to the surrounding and phase change of the refrigerant occurs. During the process, the temperature of the refrigerant will decrease but the pressure is still high. The liquid refrigerant is passed through the expansion valve to reduce its pressure to the evaporator. In the evaporator, due to the absorption of external heat from the refrigerating space refrigerant gets vaporized. Again the absorber from the generator is sent back to the absorber to absorb refrigerant coming out of the evaporator and this way cycle is repeated [8]. The selection of condenser and evaporator is decided from the refrigerant's saturation pressure and temperature, which is used in the system. Absorber design will be dependent on the condensation pressure of the refrigerant and the capacity for which the whole system is decided to design. The refrigerants used in the system should have high latent heat. The most commonly used refrigerant in this system is ammonia.

The energy performance of the absorption system is evaluated by the coefficient of performance(COP), defined as the ratio of the cooling capacity obtained at the evaporator to the heat input to the generator and work input to pump.

2. Adsorption refrigeration system

Basic components of the adsorption refrigeration system are adsorber, condenser, and evaporator. Intermittent adsorption refrigeration cycle consists of one adsorber bed. The heat from the external source has been supplied to the adsorber bed as input to the system. The schematic diagram of the basic intermittent adsorption system is represented in Fig.2.

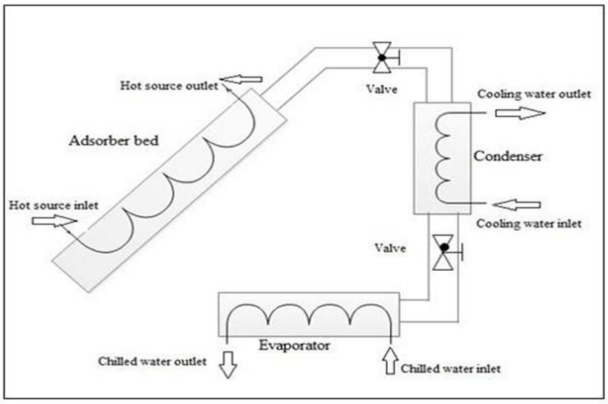

Figure 2: Schematic diagram of the vapor adsorption refrigeration system

Initially, the vapor refrigerant from the evaporator gets adsorbed at the surface of the adsorbent material in adsorber bed at low pressure and temperature. External heat source has been provided to the system as input. Hence, the temperature and pressure of the adsorber bed increases. As a result, adsorbed refrigerant from the surface of adsorbent material gets desorbed. Desorbed refrigerant is transferred to the condenser attached next to the adsorber bed when the pressure of disrober bed equals to the condenser pressure. In the condenser, the heat of the refrigerant is rejected to the surrounding and phase change of refrigerant occurs. Due to the rejection of heat, the temperature of the refrigerant is reduced but the pressure is still high. Hence, the refrigerant in the liquid state is passed through expansion value for reducing the pressure to the evaporator. In the evaporator, refrigerant gets vaporized due to the absorption of heat from the refrigerated space/liquid, as a result, the refrigeration effect is obtained. During the process, the temperature of the desorber bed is still high but for adsorption phenomenon, pressure and temperature of adsorber bed should be minimum. Hence, to attain temperature difference, the further cooling effect could not be provided. Hence it is called the intermittent adsorption cycle. When the temperature of the desorber bed is reduced to the evaporator temperature, the next cycle is carried out [5]. The selection of the desorber can be carried out by taking consideration of the saturation pressure of the refrigerant used in the system for specific cooling load capacity. Another important element is the refrigerant. Ideally, the chosen refrigerant should have a vapor pressure slightly higher than atmospheric at the evaporation temperature. Also, the vapor pressure at the condensing temperature should not be excessively high to minimize the size and strength of the system components. Technically, the refrigerant should have high latent heat and good thermal stability. The refrigerants commonly considered in the adsorption system are water, ethanol, methanol, ammonia, carbon dioxide. The performance of the adsorption system is evaluated by the coefficient of performance (COP) defined as, the ratio of refrigerating effect obtained at evaporator Q_{evap} to the input heat provided to the desorber be Q_{in}.

3. Research Objective

This paper concentrates mainly on the study of mathematical modeling of the adsorption system, which can be further useful for theoretical analysis. Till date studies were carried out experimentally to analyse the system performance but it also leads to high cost. By developing such a minimum cost of a theoretical model, which can predict the performance of the real system can minimize the costing problems. A theoretical model is also aimed to develop the performance improvement parameters and study the effect of their presence on the overall performance of the system. The theoretical model can be useful for analysing the performance of small scale adsorption systems that could be developed for commercialization.

Research objectives for the current study are presented as follows:

1) To develop mathematical modeling for the calculation of behaviour of real adsorption system.
2) To perform a simulation with variation in working pairs, types of heat source, different temperature and to examine the temperature profile of adsorbent bed concerning time.
3) To study the effect of cycle time and adsorbent mass (kg) on the performance of the adsorption refrigeration system.
4) To obtain the relationship between adsorbent bed thickness and overall heat transfer coefficient.

4. Problem definition

An adsorption refrigeration system has been attracted to researchers due to environmental friendliness and an alternative source for electrical energy. Besides, that low coefficient of performance and large size are other reasons. Due to less effectiveness, this system has not been commercialized for small scale requirements. It is needed for improving the performance value and attention towards the size and weight of the system for commercialization.

5. Thermodynamic cycle

A basic adsorption refrigeration system shown in Fig.3, consists of an adsorber bed, condenser, evaporator, disorder bed, and expansion valve.

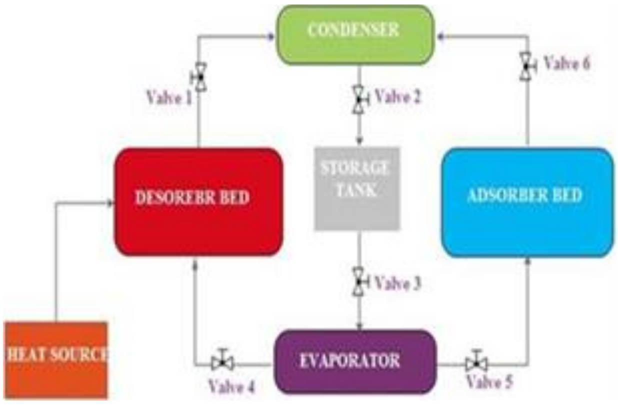

Figure 3: Thermodynamic cycle of the adsorption refrigeration cycle

An idealized basic cycle [5] shown in Fig.4, normally includes four basic processes namely isosteric heating, isobaric desorption-condensation, isosteric cooling, and isobaric evaporation and adsorption.

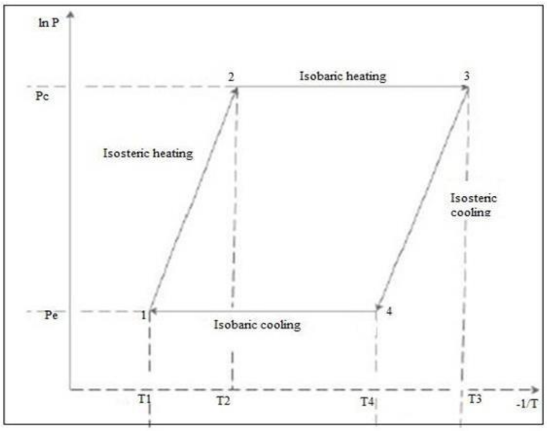

Figure 4: Schematic diagram of the continuous adsorption refrigeration system

1) ***Isosteric heating (1-2):***
Initially, all the valves are closed. The desorber bed is heated up using an external heat source that can be derived from solar energy or exhaust of the I.C. engine. During this process, the temperature rises from T_1 to$T_2$and the pressure of the refrigerant rises from P_e to P_c due to the desorption of refrigerant in the desorber bed at a constant temperature. It needs to be emphasized here that $P_e$and P_c have been determined by evaporating temperature and condensing temperature [5].

2) Isobaric desorption condensation (2-3):
The adsorbent inside the bed is continuously heated until the temperature reaches the maximum desorption temperature T_2 and pressure equal to the condensation pressure (P_c) of the refrigerant. The pressure in the desorber bed and condenser is nearly equal at the same point in time. Then, the valve between desorber and condenser is opened and desorbed refrigerant flows from desorber to condenser at constant pressure. The refrigerant in the condenser is cooled by the secondary fluid used in the heat exchanger. The pressure of the condenser has been fixed to the saturation pressure of the refrigerant used for the system. Some of the latent heat is rejected during the process and the phase change process of the refrigerant is carried out [5].

3) Isosteric cooling (3-4):
When the phase change of the refrigerant is carried out in the condenser then some amount of heat is rejected in the atmosphere and the temperature of the refrigerant keeps on decreasing. At the same time, the pressure of the refrigerant is high. Hence, to reduce the pressure and maintaining it to the evaporator pressure (P_e), the refrigerant passes through the expansion valve by opening the valve between condenser and evaporator. The refrigerant is vaporized at very low pressure by taking latent heat from the secondary fluid used in the evaporator. During the process, the temperature is decreased from T_3 toT_4 and pressure is reduced up to P_c to P_e [5].

4) Isobaric evaporation and adsorption (4-1):

During this step, the valve between the adsorber bed and evaporator is opened. The refrigerant in the evaporator passes through the valve to an adsorber bed which is maintained at low pressure. Due to the low-pressure adsorption process has been carried out at the surface of the adsorbent material. Adsorption is an exothermic reaction which leads to the production of adsorption heat in the adsorber. The heat is known as the heat of adsorption. This heat is removed by using secondary fluid in adsorber bed and the temperature of the adsorber is reduced to T_1 [5].

6. Operating range of working pair

Table 1 represents various working pairs suitable for a specific input heat source in the adsorption refrigeration system. An input heat source may be solar energy or exhaust of I.C.engine. The most commonly used working pair is silica gel- Water, which is applicable for a very small range of temperatures. Activated carbon-ammonia is suitable for higher input heat sources application which is generally input heat from exhausts [1].

Table 1: Operating range for different type of working pairs

No.	Working pair	Temperature range(^{0}C)
1	Silica gel- Water	50 - 85
2	Activated carbon- Methanol	80 - 100
3	Calcium chloride- ammonia	120 - 150
4	Activated carbon - ammonia	Temperature above 150
5	Zeolite- Water	Temperature above 200
6	Metal hydride- Hydrogen	-100 - 500
7	Activated carbonEthanol	Temperature above 120

7. Methodology

Figure 5 shows the flow chart (graphical representation) of the procedure used for simulation. Microsoft excel environment has been used to carry out programming in Macros. The program starts with the initialization of:

1) Constants used in the equation
2) Variables used for the system.
3) Estimated initial values of various differential parameters.

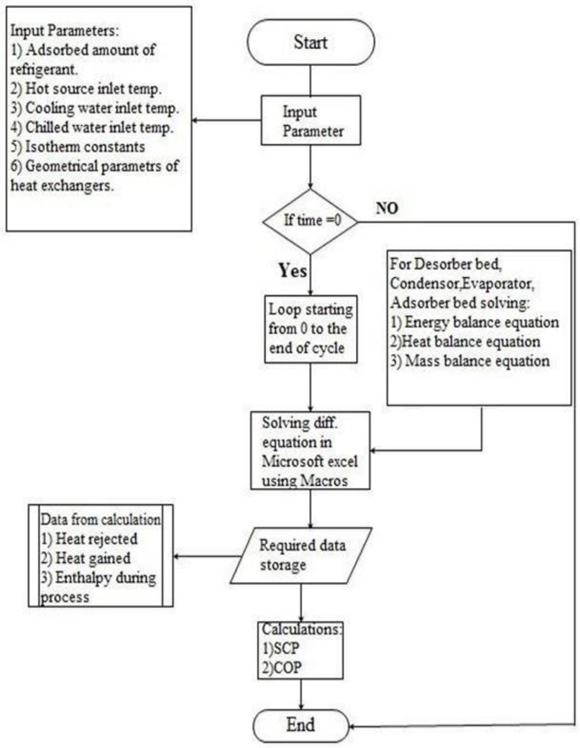

Figure 5: Flow chart of the methodology for simulation of the adsorption system

8. Results and Discussion

The results of the simulation have been carried out for evaluating the performance and relationship between the four-bed adsorption refrigeration systems [10]. Likewise, performance evaluation of the adsorption system developed for a 1 kW of the cooling system is also shown [9]. Jribi et.al. [10], (2014), presented a study on simulation of MaxorbIII-CO2 four-bed based adsorption cooling system. Adsorber/desorber bed temperature profile, the effect of the cycle time of performance of the system, the effect of hot source inlet temperature on system performance has been deeply studied through simulation during the study. During the adsorption/desorption process flow of refrigerant through beds has been studied using simulation [10]. Tiwari [9] carried out experimentation on a 1 kW cooling capacity adsorption refrigeration system for truck cabin cooling purposes. A developed theoretical model is validated using the experimental results of this system by comparing system performance of both simulated and experimental values.

The simulation model developed in the Microsoft excel environment has been used to evaluate the performance of simulation carried out in literature [10]. The system is simulated for Maxorb III-CO_2 based four-bed adsorption system.

Figure 6 shows the amount of adsorbed refrigerant at the surface of adsorbent material with variation in pressure at a constant temperature.

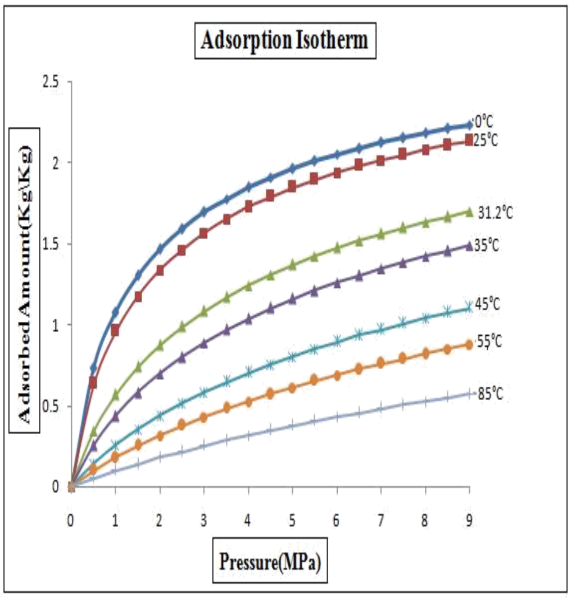

Figure 6: Graphical representation of adsorption isotherm

The nature of the obtained curve is concave. To analyze the behavior of refrigerant, simulation is carried out for different constant temperatures as shown in the graph. According to the graph, it seems that the adsorption capacity of the refrigerant at lower temperatures (at 0^{0}C) is high. Likewise, the adsorption capacity of the refrigerant at a higher temperature (at 85^{0}C) is low. After some points the isotherm curve becomes linear. In that condition, adsorbent material has reached its saturation level. Beyond that point, no further adsorption of refrigerant has been carried out.

8.1 Effect of cycle time on specific cooling capacity

Figure 7 shows the graph of the effect of the adsorption/desorption cycle time on the cooling capacity of the system.

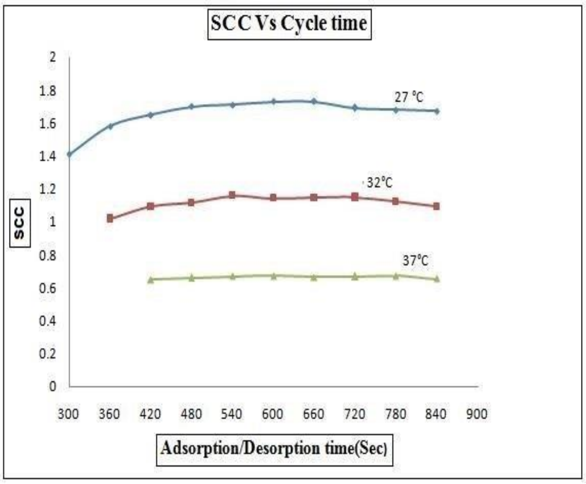

Figure 7: Effect of adsorption/desorption time on specific cooling capacity

Three different simulations have been carried out by changing the cooling water inlet temperature to analyze its effect on the cooling capacity. As, the time of cycle increases, specific cooling capacity (SCC) also increases but after a certain time it keeps on decreasing. The amount of refrigerant coming out of the condenser changes its phase from liquid to vapor by absorbing the heat from an external source (i.e. water, air). The vapor form of refrigerant is transferred to an adsorber bed which is connected to the evaporator section to carry out the adsorption process. Hence, at certain conditions cooling capacity is maximum. The optimum value of cooling capacity obtained for 27^{0}C, 32 ^{0}C, 37 ^{0}C cooling water inlet temperatures are 600 ^{0}C, 540 ^{0}C and 720 ^{0}C respectively.

8.2 Effect of hot source inlet temperature on cooling capacity

Figure 8 shows the graph of the effect of adsorption/ desorption time on the coefficient of performance (COP) of the system. As shown in the graph, COP value increases as the adsorption/desorption cycle time increases.

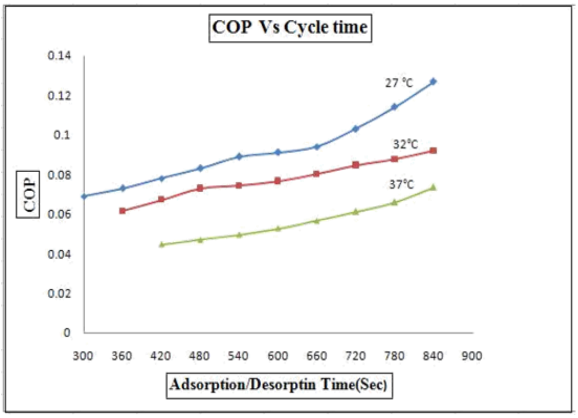

Figure 8: Effect of adsorption/desorption time on the coefficient of performance

The system is simulated for three different conditions by changing the cooling water inlet temperature. As the temperature of input heat source increases the cooling capacity also increases due to a higher desorption rate of refrigerant from the adsorbent material in desorber bed. As a result, the COP of the system increases.

Figure 9 shows the graph of the effect of hot source inlet temperature on the cooling capacity. The cooling capacity increases linearly with an increase in hot source inlet temperature.

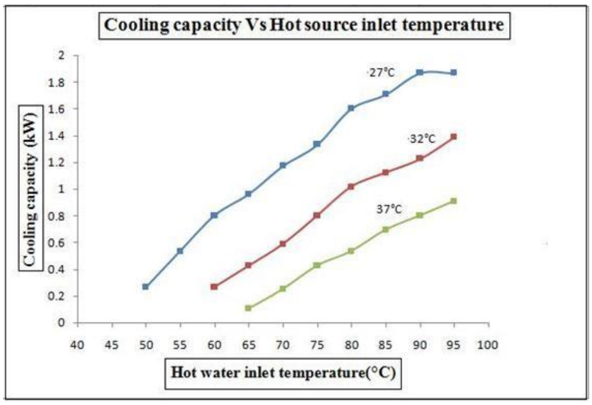

Figure 9: Effect of hot source inlet temperature on cooling capacity

Increased heating source temperature enhances the chiller's cooling capacity (due to enhancing desorption rate) that generates the adsorbed refrigerant before the adsorption/evaporation mode. Three simulations are carried out for 27^0C, 32^0C, and 37^0C as cooling water inlet temperature.

As shown in Fig.9, it is noteworthy to mention that the increase in cooling water inlet temperature reduces the cooling capacity of the system. For 27^0C temperature of cooling water, cooling capacity values are higher than 32^0C and 37^0C temperature. At optimum desorption pressure of 7.1MPa at hot source inlet temperature optimum value of cooling capacity obtained for 27^0C, 32^0C and 37^0C are 1.845 kW, 1.25 kW and 0.8 kW respectively.

Figure 10 shows the graph of the effect of hot source inlet temperature on the COP. COP increases up to the temperature of 90^0C and after that decreases.

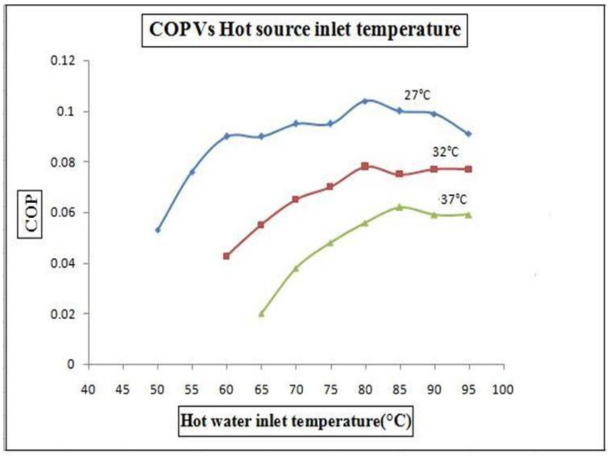

Figure 10: Effect of hot source inlet temperature on the coefficient of performance (COP)

Three simulations have been carried out for 27^0C, 32^0C, 37^0C of cooling water inlet temperatures. Curve gets decreased due to heat consumed by the desorber bed using the hot source, becomes higher compared to the cooling capacity generated in the evaporator section at a certain point.

Figure 11 shows the temperature profile of the adsorber/desorber for three complete cycles. The graph also shows the hot source inlet temperature. When a desorber bed is subjected to heat from an external source, the refrigerant starts to desorb from the surface of adsorbent material.

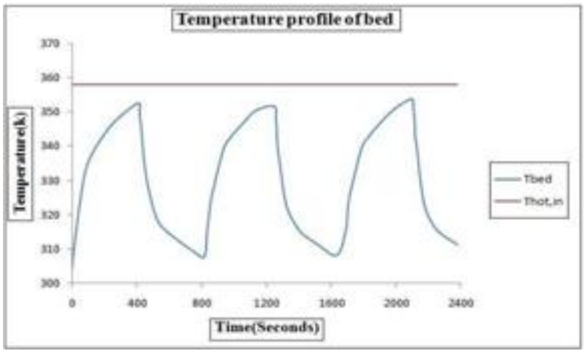

Figure 11: Temperature profile of adsorber/desorber bed for complete three cycles

Rate of desorption of refrigerant increases as the input heat source temperature increases along with pressure inside bed up to the saturation pressure of refrigerant used in the system. Then, the refrigerant is passed to the condenser by opening the valve connected between desorber and condenser. For a continuous cycle, the hightemperature bed needs to be cooled and to get adsorbed in stipulated cycle time. Hence, the temperature of the bed decreases by circulating secondary fluid (water) through it. While another bed performs as desorber to run the system. The optimum value of COP obtained from simulation for MAXORB III-CO***2*** pair is 0.1 at a hot source inlet temperature of 85^0C, cooling water inlet temperature 270C and chilled water inlet temperature of 150C. Optimum evaporator temperature for the system is ranging between 2-5 0C and condensation temperature of 31.5 0C. The optimum pressure obtained for the system is 7.3MPa.

9. Conclusion and Future Scope

Adsorption refrigeration systems in such ways have been considered as an ideal replacement for conventional vapor compression refrigeration machines due to its energy-saving and environmental friendliness. They can efficiently use solar energy, exhaust from I.C.engine or waste heat generated from any source. Also, the adsorption system can use environmentally friendly refrigerants such as ammonia, water, methanol, ethanol instead of chlorofluorocarbon, so that ozone layer depletion and global warming could be reduced.

Current research work has been carried out for activated carbon-ammonia and MaxorbIII-CO_2 based adsorption refrigeration system. A simulation model is developed in Microsoft Excel using the Macros environment. Current research findings are represented as follows:

The adsorption system performance using new refrigerant CO_2 was studied with MAXORB III which is an advanced form of activated carbon that has a maximum pore size. Adsorption isotherm was studied at different pressure and temperature shows drastic change at maximum pressure. Adsorption process stops after achieving a saturation level of adsorbent material. Both adsorption isotherm models are selected to study the nature of adsorption at the surface of adsorbent material. Both adsorption models are built up by taking consideration of heterogeneity between adsorbent material and refrigerant at adsorber. Other models do not consider the heterogeneity parameter. By considering the heterogeneity parameter, the nature of the adsorption of refrigerant is studied more accurately compared to other isotherm models.

COP obtained for MAXORB III-CO_2 based four-bed system is 0.1. The performance of the adsorption system was poor due to the lower latent heat of CO_2. Hence, CO_2 is not a practical commercialization of the adsorption system. The decrease in cycle time increases the performance of the system because the rate of desorption/adsorption is high.

Cooling water temperature should be minimum for obtaining better performance of the system.

Evaporation temperature should be maximum for the evaporation process which will directly affect the system performance and cycle time.

Parameters affecting system performance are hot source inlet temperature, Overall heat transfer conductance, Adsorption/desorption cycle time, Number of beds and thickness of bed cooling water temperature.

The maximum COP obtained from simulation for validation of experimentation is ranging between 0.4-0.45 for activated carbon-ammonia based two-bed adsorption refrigeration system. The validation result with original results from literature and experimentation has percentage error ranging between 0.5 to 2%.

The performance of the system can be increased by adding metal additives in unconsolidated adsorbents.

Copper and aluminium chips would be preferable.

The maximum thickness of the adsorbent bed should be ranging between 3-5 mm.

The maximum use of adsorbent material could decrease the performance of the system. The overall heat transfer coefficient is uniform along the adsorbent bed.

10. Future Work

The current study presented a simulation model on an excel environment which is near about cost-free. The simulation model is easy to operate and install. It can be considered a strong foundation for future work. The following work has been suggested for future work:

1) The simulation model can be tested for different working pairs such as silica gel-water, AC- methanol, AC ethanol,
2) Zeolite-Water etc. simulation model can be further used for different hot source inlet temperature of various range.
3) The effect of the different mass flow rates of hot source inlet temperature, cooling water, chilled water on system performance and cycle time.
4) The effect of various condensation and evaporation temperature on system performance.
5) The simulation model can be used for further analysis of the thickness of adsorbent material in adsorber bed. The effect of various thicknesses on specific cooling capacity and coefficient of performance can be analyzed.

References

[1] Choudhary.B, Saha.B.B, Chatterjee P.K and Sarkar.J.P, 2013.An overview of development in adsorption refrigeration systems towards a sustainable way of cooling.Applied Energy, Vol.104, 554-567.
[2] Saha.B.B, Thu.K, Chakraborty.A and Kb.K.C. 2009. Most energy-efficient approach of desalination and cooling. Cooling India, Vol.5 (2), 70-76.
[3] Askalany.A, Saha.B.B, Kariya.K, Ismail.I.M, Salem.M, Ali.H.H, and Morsy.M.G. , 2012.Hybrid adsorption cooling system- An overview. Renewable and sustainable energy, Vol.16, 5787-5801.
[4] Fernandes.M.S, Brites.GJVN, Costa.J.J, Gasper.A.R, Costa.V.A.F. 2014. Review and future trends of solar refrigeration systems. Renewable and sustainable energy. Vol.39, 102-123.
[5] Demir.H, Mobedi.M, Serma.U, .2008. A review on adsorption heat pump: Problem and solution. Renewable and energy review Vol. 12, 2381-2403.
[6] Ziegler.F.2002.State of art in sorption heat pumping and cooling technologies International journal of refrigeration, Vol.102, 554-567.
[7] Dabrowaski.A.2001. Adsorption from theory to practice. Advances in colloid and interface science, Vol.93pp 135-224.
[8] Jones.W.P. 2001. Air conditioning engineering. Fifth Edition, Elsevier Butterworth-Heinemann publication.
[9] Harish Tiwari. 2012. Design and development of air cooling system for the cabin of a truck by using heat from engine exhaust. Ph.D. Dissertation, University of Pune.
[10] Jribi S, Saha B. B, Koyama S, Bentaher H,.2014.Modeling and simulation of activated carbon-CO_2 four- bed based adsorption cooling system. Energy conversion and management, Vol.78, 958-991.

Author Profile

Dr. Ajoy Kumar completed his Bachelors and Masters in Mechanical Engineering at B.I.T.Sindri and Ph.D. from University of Ranchi. He has 28 years of academic experience. He is currently working at St. John College of Engineering and Management, Palghar, University of Mumbai, India.

Kumar Abhinandan-UG Student, Mechanical Engineering, National Institute of Technology, Patna, India