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Heat Recovery Based Thermodynamic Analysis of Adsorption Refrigeration

Verma A.*, Sachdeva G.
National Institute of Technology Kurukshetra, Haryana, India
*corresponding author

Abstract: The increasing entropy of the universe is a fundamental driver accelerating the rise in Earth's temperature, thereby significantly intensifying the global demand for cooling technologies. Heat-driven adsorption refrigeration systems have emerged as a promising solution, effectively utilizing low-grade thermal energy to meet this growing demand. This study presents a numerical analysis of a two-bed adsorption refrigeration system employing 208C activated carbon and monolithic carbon composite as adsorbents, with R32 serving as the adsorbate. The performance of the system was evaluated in terms of the Coefficient of Performance (COP), considering variations in condenser pressure, evaporator pressure, and maximum desorption temperature across different adsorbent–adsorbate pairs. The results indicate that the monolithic carbon composite–R32 pair exhibits a superior COP compared to the 208C–R32 combination. To further enhance system efficiency, a novel heat recovery-based adsorption refrigeration cycle was developed, wherein the heat rejected during the cooling and adsorption processes is effectively reutilized for the heating phase. The monolithic carbon composite–R32 pair achieved the highest COP within the heat recovery-based cycle, demonstrating its strong potential for application in efficient, sustainable cooling systems.

Keywords: COP, adsorption, desorption, activated carbon.

Introduction

As industrialization increases, entropy generation also rises, leading to a temperature increase on Earth [1]. Consequently, there is a significant surge in the demand for cooling. The conventional vapor compression refrigeration system utilizes high-grade energy, such as mechanical power or electricity, to operate. Additionally, the use of refrigerants like CFC, HFC, and HCFC contributes to ozone layer depletion [2].

To address these issues, researchers are actively working on solid sorption refrigeration using composite adsorbent. The significance of adsorption refrigeration has grown tremendously because it utilizes low-grade energy, specifically waste heat, for its operation and low-cost composite adsorbent. Moreover, it employs environmentally friendly refrigerants like ammonia, methanol, and water. Adsorption refrigeration and air-conditioning technology involve negligible moving parts, resulting in the absence of noise and vibrations. Numerous combinations of adsorbates and adsorbent composites exhibit broad working temperature ranges, spanning from 50 to 420°C. For instance, activated carbon paired with NH_3 or CH_3OH, as well as zeolite-water and silica gel-water combinations are among the available options. These pairings offer versatility across a wide temperature spectrum.

Several investigations [3] have explored the utilization of low-grade energy sources, such as industrial waste heat or solar heat, within the field of adsorption technology for various applications, including desalination or the generation of cooling and refrigeration effects. A notable illustration is the study conducted by Wang et al. [4], where they developed an adsorption air conditioner for a locomotive driver cabin. This system, powered by exhaust gases with temperatures ranging from 350°C to 450°C, exhibited a cooling power of 5 kW and a COP of 0.25. Operating with an exhaust temperature of 450°C, cooling air temperature of 40°C, and chilled water temperature of 10°C, the setup achieved a cycle time of 1060 seconds. Additionally, Zejli et al. [5] proposed a theoretical model for a multi-effect desalination system employing adsorption heat pump technology with zeolite composite as the solid vapor adsorbent. Despite these advancements, it is crucial to recognize that several researchers have observed that the simple adsorption refrigeration cycle often yields low COP values, typically ranging from 0.1 to 0.6.

Researchers have actively tackled the challenge of improving the COP in adsorption refrigeration systems [6], acknowledging its historically low values by using various adsorbent composites. A noteworthy contribution by Akahira et al. [7] involved the exploration of a two-bed adsorption refrigeration cycle utilizing silica gel and activated carbon composites. They incorporated mass recovery to leverage pressure differentials and enhance refrigerant mass circulation, specifically with the silica gel-water pair. The study concluded that the mass recovery-based cycle, particularly when supplied with hot and cooling water, outperformed the basic cycle in terms of both Cooling Capacity (CC) and COP. Expanding on this work, Wang et al. [8] demonstrated various adsorption refrigeration cycles with adsorbent composites, including continuous heat recovery, mass recovery, thermal wave, convective thermal wave, cascade multi-effect, and hybrid heating and cooling cycles. In another innovative approach, Sapienza et al. [9] introduced an adsorptive chiller based on three hybrid adsorbers, conducting their initial testing campaign under real HVAC operating conditions.

In a different avenue, Krzywanski et al. [10] analyzed a tri-bed twin-evaporators-based adsorption chiller model using genetic algorithms (GA) and artificial neural networks (ANN) to optimize cooling capacity. However, it's worth noting that the operational complexity of the different adsorbent composites with tri-bed twin-evaporator adsorption chiller increased. Additionally, Saha et al. [11] designed a dual-mode silica gel–water-based adsorption chiller that effectively utilizes waste heat (40°C to 95°C). This dual-mode system showcases versatility in adapting to different heat sources for improved efficiency.

After the 1973 oil crisis, researchers [12], [13], initiated a quest for alternative energy sources, with a particular emphasis on renewable energy to meet global energy demands by using various adsorbent composites[14], [15], [16] . Solar energy emerged as a favored option, especially for refrigeration and cooling applications, where Vapor Compression Refrigeration Systems (VCRS) could potentially be replaced by solar-operated adsorption refrigeration systems, thereby reducing reliance on electricity. Berdja et al. [14] explored solar adsorption refrigeration in the Algerian climate using ANSYS for temperature distribution analysis over the adsorption plate. Their analysis extended to different components of solar adsorption systems, including the adsorption plate and the evaporative chamber, with considerations for various arrangements and adsorbent composites. Anyanwu et al. [17] contributed to the field by establishing a thermodynamic design procedure for solar adsorption refrigeration, and conducting performance analyses with different adsorbent composite and adsorbate pairs.

An adsorption-based air-conditioner has been designed and fabricated [18] utilizing a silica gel-water working pair. In their experimental investigation, they observed significant cost benefits and proposed the residential application of the adsorption-based air-conditioner for cooling and heating. The application of compound parabolic concentrators in conducting comparative experiments within adsorption refrigeration systems has been explored [19]. To enhance system performance across various operating modes, they implemented an improved mass transfer method. With enhanced mass transfer a solar adsorption refrigeration prototype has been developed [20] which concluded an average enhancement of 35.9% in refrigeration capacity with adsorbent composites.

The effectiveness significantly hinges on the careful selection of adsorbent composite [21] and adsorbate pairs during the design phase, necessitating thorough research [22], [23], [24]. In an investigation conducted by Ahmed et al. [25], various adsorbate pairs used in solar adsorption systems were explored, revealing that Silica gel and chlorides with water exhibited the highest Coefficient of Performance (COP), while zeolite with water demonstrated inferior performance under similar conditions. Additionally, Zhang et al. [26] reviewed novel adsorbent-absorbate working pairs for adsorption refrigeration, assessing their impact on performance parameters such as COP and specific cooling power. Essential properties of adsorbent-adsorbate pairs influencing performance include the adsorbent's particle size, composites, micropore size, total porosity, and stability. Li et al. In summarizing the above research on adsorbent-adsorbate properties, it is evident that further research is imperative to meet the growing demands for enhanced adsorption refrigeration performance.

1. **Working principle**

1.1 Basic Intermittent Cycle

The basic cycle consists of essential components, including an adsorber bed, an evaporator, a condenser, an expansion device, various valves, and heating and cooling systems, as depicted in Figure 1. The adsorption refrigeration process comprises four stages: sensible heating, desorption and condensation, sensible cooling, and adsorption and evaporation.

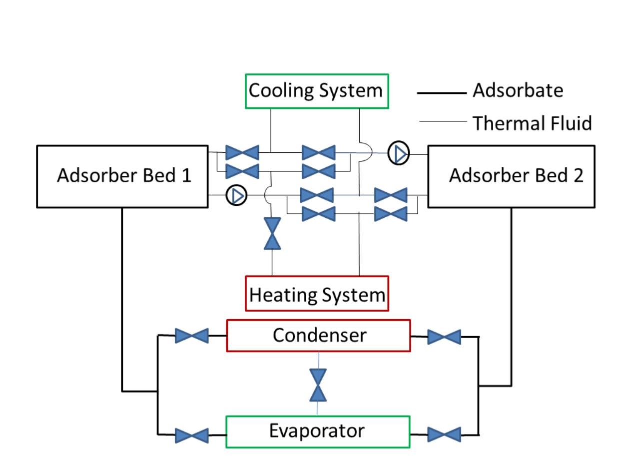

Fig. 1. - Heat recovery-based adsorption refrigeration system. The thick line represents the flow of adsorbate, while the thin represents the flow of thermal fluid.

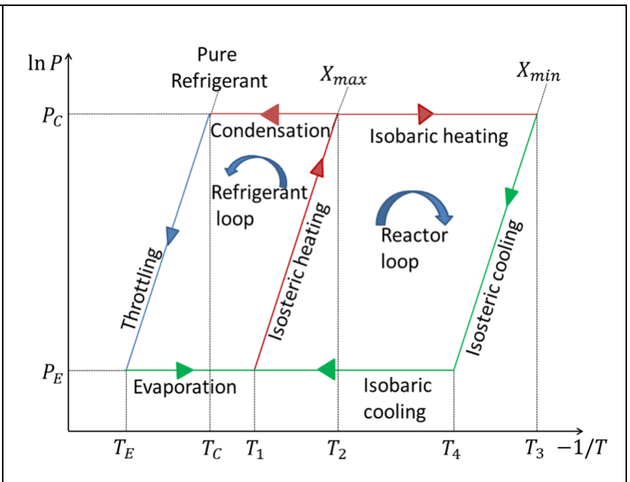

Fig. 2. - Clapeyron diagram of adsorption refrigeration cycle.

During the sensible heating process, the concentration of refrigerant within the adsorber bed remains constant (isosteric), while the temperature increases from T_1 to T_2, and the pressure reaches P_c. After sensible heating, the desorption process initiates, and the adsorbate enters the condenser at P_c. Throughout desorption, the temperature of the bed rises from T_2 to T_3. Upon completing the desorption process, the cooling and depressurization of the adsorber bed commence, resulting in a temperature reduction fromT_3 to T_4. As the adsorber bed reaches T_4 and the pressure aligns with P_e, the adsorption process begins, during which the temperature decreases from T_4 to T_1.

This paper analyzed the thermodynamic performance of the basic and heat recovery type adsorption refrigeration cycle. Four performance parameters; T_1, T_3, P_e and P_c were used to obtain the COP relation for comparing different adsorbent-adsorbate pairs at different operating conditions.

1.2 Continuous Cycle

The intermittent nature of the basic single-bed adsorption refrigeration cycle stems from the alternating occurrence of adsorption and desorption processes. To ensure continuous production of the refrigeration effect, a minimum of two adsorber beds is required [Ojha et al. [13]].

1.3 Regenerative Cycle

After the completion of the desorption of refrigerant from the bed there will be a lot of heat in the bed, a substantial amount of heat remains within the bed. This residual heat presents an opportunity for utilization in heating applications during the subsequent bed heating phase. To boost the efficiency of the adsorption refrigeration cycle, optimizing the harnessing of this released heat is essential. By incorporating this rejected heat into the sensible heating process, we can effectively reduce the overall demand for external heat input, thereby enhancing the overall performance of the cycle.

2 Mathematical modeling

2.1 Adsorption Equilibrium

The adsorption of the adsorbate in the adsorption bed has been estimated through the D-A (Dubinin-Astakhov) equation:

$$x = x_o \ \exp\left[-K\left\{\frac{T}{Tsat} - 1\right\}^n\right] \tag{1}$$

The latent heat of sorption has been calculated for any temperature and pressure using Eq. (2), where R represents the gas constant:

$$\frac{d}{dT}\left(\ln P\right) = \frac{h}{RT^2} \tag{2}$$

2.2 Heat Equation for Sensible Heating

The heat required for heating the bed and the adsorbed refrigerant from evaporator pressure to condenser pressure has been calculated using Eq. (3). Eq. (4) delineates the relationship between the mass of the adsorbed refrigerant and the maximum concentration, along with the mass of the activated carbon:

$$\left(Q_h\right) = \int_{T_1}^{T_2} C_{v,ac(T)} m_{ac} dT + \int_{T_1}^{T_2} C_{va(T)} m_a dT \tag{3}$$

$$m_a = x_{conc} m_{ac} \tag{4}$$

2.3 Desorption Heat

The heat required for desorption, necessary to release the refrigerant from the bed at a constant condenser pressure, has been calculated using Eq. (5). Subsequently, the desorbed refrigerant enters the condenser, where the refrigerant undergoes the condensation process:

$$Q_g = \int_{T_2}^{T_3} C_{pac(T)} m_{ac} dT + \int_{T_2}^{T_3} C_{pa(T)} m_a dT + \int_{T_2}^{T_3} m_a h_a \frac{\partial x\left(T, T_c\right)}{\partial T} dT \tag{5}$$

2.4 Cooling of Adsorber bed

The cooling heat for the adsorber bed after the desorption phase is computed by Eq. (6), which is taken from the cooling effect generated by the system. During this stage, the pressure within the adsorber bed decreases from the condenser P_c to P_e, while the temperature concurrently drops from T_3 to the T_4:

$$Q_c = \int_{T_4}^{T_3} C_{pac(T)} m_{ac} dT + x_{dil} \int_{T_4}^{T_3} C_{va(T)} m_{ac} dT \tag{6}$$

2.5 Adsorption Heat

The adsorption of the refrigerant from its gaseous phase onto the surface of the adsorbent composite occurs in the liquid form, necessitating the rejection of latent heat from the adsorber bed and has been calculated using Eq. (7):

$$Q_{ad} = \int_{T_4}^{T_1} C_{p,ac(T)} m_{ac} dT + \int_{T_4}^{T_1} m_a h_a \frac{\partial x(T,T_e)}{\partial T} dT + \int_{T_4}^{T_1} C_{p,a(T)} m_a dT - \int_{T_4}^{T_1} C_{p,ag(T)} m_{ac} \Delta x d(T - T_e) \quad (7)$$

The second term in Eq. (7) accounts for adsorption heat, while the last term has been included to accommodate any cooling effect generated by the refrigerant. After the refrigerant undergoes condensation in the condenser, a combination of liquid and vapor refrigerant is present as it expands from P_c to P_e . As a result, the cooling needed for the vapor refrigerant is calculated using Eq. (8):

$$Q_{co} = \int_{Te}^{Tc} C_{v,f(T)} (x_{conc} - x_{dil}) m_{ac} dT \quad (8)$$

The refrigeration effect produced by the system has been calculated using Eq. (9). The latent heat of evaporation has been determined at the evaporator pressure corresponding to the respective refrigerant:

2.6 System Performance Equations

$$Q_{ref} = L_e (x_{conc} - x_{dil}) m_{ac} \quad (9)$$

The system's performance, expressed as the COP), is established through Eq. (10):

$$COP = \frac{Q_{ref} - Q_c - Q_{ad} - Q_{co}}{Q_g + Q_h} \quad (10)$$

2.7 Equations for Heat Recovery

The fraction of heat rejected during the adsorption process and cooling of the bed has been utilized for the heating process, thereby reducing the amount of heat required for a sensible heating process:

$$Q_r = e(Q_{ad} + Q_c) \quad (11)$$

The recovered heat has been calculated using Eq. (11), where 'e' represents the effectiveness of the regenerator and has been assumed to be 0.8 in this investigation:

$$COP_r = \frac{Q_{ref} - Q_c - Q_{ad} - Q_{co}}{Q_g + Q_h + Q_r} \quad (12)$$

The performance of the heat recovery-based cycle has been evaluated using Eq. (12).

Table 1. D-A equation's parameter for adsorbent-adsorbate pairs

Activated Carbon	Refrigerant	x_0	K	n
208C	R32	0.476	2.4634	1.3880
Monolithic	R32	0.461	2.6729	1.3326

3 Results and discussion

3.1 Variation of P_e and P_c

From Fig. 3 it is clear that as the condenser pressure increases the heat requirement for the desorption of the refrigerant increases hence the COP decreases while with the increase in evaporator pressure (P_e), as shown in Fig. 4, the COP increases for both the basic and heat recovery-based cycles increases because the heat requirement for the desorption process decreases.

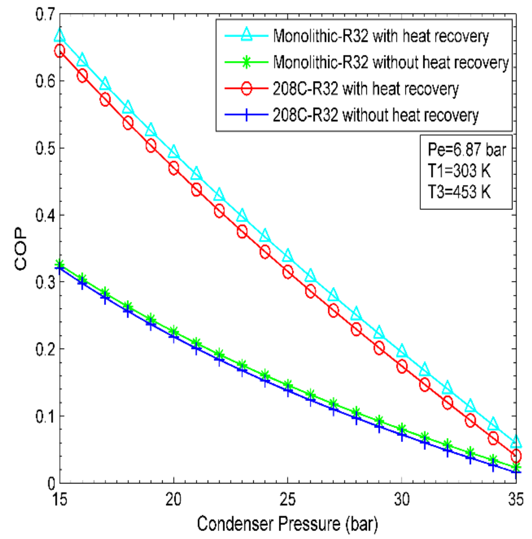

Fig. 3. - COP for R32 with P_c

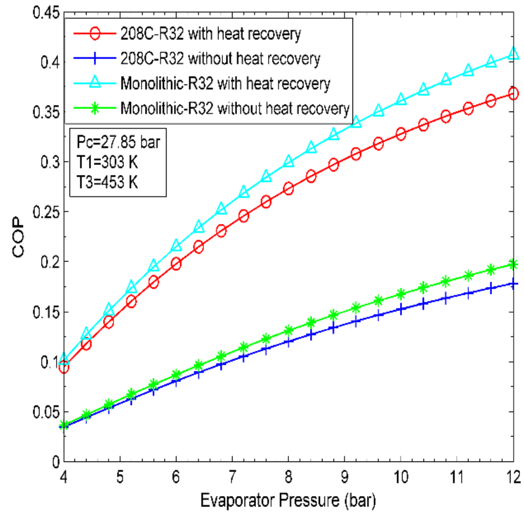

Fig. 4. - COP for R32 with P_e

As the desorption temperature increasing the desorption of the refrigerant from the adsorber bed increases but after a certain time the desorption rate from the bed decreases because the concentration of adsorbate on the bed decreases and at the same time the heat input decreases so it results in the decrease the COP of the system (Fig. 5).

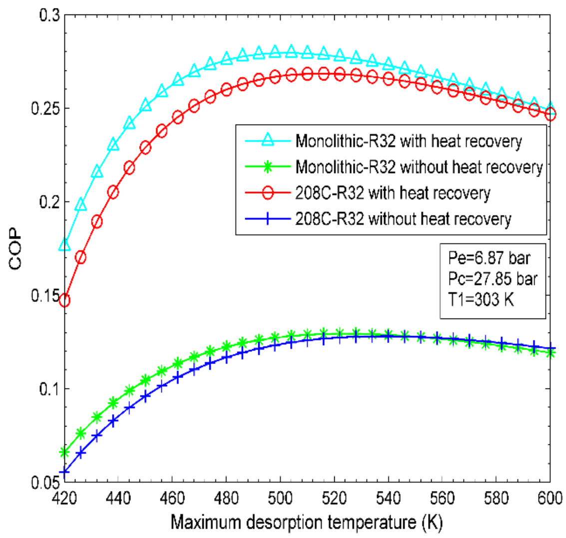

Fig. 5. - COP for R32 with maximum desorption temperature

The specific heat capacities, enthalpy and characteristic gas constant are given in Table 2 for the calculation of the different heat equations.

Table 2. Thermo-physical properties

Property name	R32	Activated Carbon
$C_p\left(kJ/kgK\right)$	2.27	$0.175+2.245\times10^{-3}\times T$
$C_v\left(kJ/kgK\right)$	0.93	$0.175+2.245\times10^{-3}\times T$
$C_p\left(gas\right)\left(kJ/kgK\right)$	1.2	-
$C_{v,a,avg}\left(kJ/kgK\right)$	0.99	-
$h_{fg,eva}\left(kJ/kgK\right)$	323.16	-
$R\left(kJ/kgK\right)$	0.16	-

Conclusions

A thermodynamic model has been methodically created and examined for both basic and heat recovery-based adsorption refrigeration cycles, considering diverse combinations of adsorbates and adsorbent composites. The study involves the systematic tuning of essential operating parameters such as evaporator pressure, condenser pressure, and maximum desorption temperature. From the analysis, it has been analyzed that COP decreases with an increase in the condenser pressure and increases with an increase in the evaporator pressure. By increasing maximum desorption temperature the COP first increases and then decreases. From the above analysis, it has been also analyzed that reducing the size of the system adsorbent composite plays an important role in adsorbing the adsorbate.

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Nomenclature

$C_{p,}$	Specific heat of adsorbate at constant pressure [J/kg K]	Q_{ref}	Condensation energy [J]
$C_{p,}$	Specific heat of activated carbon at constant pressure [J/kg K]	R	Gas constant for adsorbate [J/molK]
$C_{p,}$	Specific heat of adsorbate gas at constant pressure [J/kg K]	T_1	Minimum adsorption temperature [K]
$C_{v,}$	Specific heat of activated carbon at constant volume [J/kg K]	T_2	Minimum desorption temperature [K]
C_{vl}	Specific heat of saturated liquid adsorbate at constant volume [J/kg K]	T_3	Maximum desorption temperature [K]
H	Heat of adsorption	T_4	Maximum adsorption temperature [K]
H_{f}	Latent heat of vaporization [J/kg]	e	Effectiveness of regenerator
K	Dubinin coefficient	T_c	Condensation temperature [K]
m_a	Mass of adsorbed adsorbate [kg]	T_{sat}	Saturation temperature [K]
m_a	Mass of activated carbon [kg]	x_0	Saturation concentration of adsorbate [kg/kg]
n	Coefficient in D-A equation	x_{conc}	Maximum conc. of adsorbed adsorbate [kg/kg]
P_c	Condensing pressure [Pa]	x_{dil}	Adsorbate conc. after desorption [kg/kg]
Q_g	Desorption energy [J]	Δx	Amount of desorbed adsorbate

References

[1] Tiratsoo J. Incidentand TPI detection: A new solution? Glob Pipeline Mon 2009;5:1–29. https://doi.org/10.1029/2010RG000345.

[2] Savitha DC, Ranjith PK, Talawar B, Rana Pratap Reddy N. Refrigerants for sustainable environment–a literature review. Int J Sustain Energy 2022;41:235–56. https://doi.org/10.1080/14786451.2021.1928129.

[3] El-Sharkawy II, Abdelmeguid H, Saha BB. Towards an optimal performance of adsorption chillers: Reallocation of adsorption/desorption cycle times. Int J Heat Mass Transf 2013;63:171–82. https://doi.org/10.1016/j.ijheatmasstransfer.2013.03.076.

[4] Wang DC, Xia ZZ, Wu JY. Design and performance prediction of a novel zeolite-water adsorption air conditioner. Energy Convers Manag 2006;47:590–610. https://doi.org/10.1016/j.enconman.2005.05.011.

[5] Zejli D, Benchrifa R, Bennouna A, Bouhelal OK. A solar adsorption desalination device: First simulation results. Desalination 2004;168:127–35. https://doi.org/10.1016/j.desal.2004.06.178.

[6] Li XH, Hou XH, Zhang X, Yuan ZX. A review on development of adsorption cooling - Novel beds and advanced cycles. Energy Convers Manag 2015;94:221–32. https://doi.org/10.1016/j.enconman.2015.01.076.

[7] Akahira A, Alam KCA, Hamamoto Y, Akisawa A, Kashiwagi T. Mass recovery adsorption refrigeration cycle - Improving cooling capicity. Int J Refrig 2004;27:225–34. https://doi.org/10.1016/j.ijrefrig.2003.10.004.

[8] Wang X, Chakarborty A, Ng KC, Saha BB. How heat and mass recovery strategies impact the performance of adsorption desalination plant: Theory and experiments. Heat Transf Eng 2007;28:147–53. https://doi.org/10.1080/01457630601023625.

[9] Sapienza A, Gullì G, Calabrese L, Palomba V, Frazzica A, Brancato V, et al. An innovative adsorptive chiller prototype based on 3 hybrid coated/granular adsorbers. Appl Energy 2016;179:929–38. https://doi.org/10.1016/j.apenergy.2016.07.056.

[10] Krzywanski J, Grabowska K, Herman F, Pyrka P, Sosnowski M, Prauzner T, et al. Optimization of a three-bed adsorption chiller by genetic algorithms and neural networks. Energy Convers Manag 2017;153:313–22. https://doi.org/10.1016/j.enconman.2017.09.069.

[11] Saha BB, Koyama S, Kashiwagi T, Akisawa A, Ng KC, Chua HT. Waste heat driven dual-mode, multi-stage, multi-bed regenerative adsorption system. Int J Refrig 2003;26:749–57. https://doi.org/10.1016/S0140-7007(03)00074-4.

[12] Dusane BM, Ghuge C. A Review On Solar Adsorption Refrigeration System // IOSR J Eng WwwIosrjenOrg ISSN 2016;06:1–07.

[13] Khattab NM. A novel solar-powered adsorption refrigeration module. Appl Therm Eng 2004;24:2747–60. https://doi.org/10.1016/j.applthermaleng.2004.04.001.

[14] Berdja M, Abbad B, Yahi F, Bouzefour F, Ouali M. Design and realization of a solar adsorption refrigeration machine powered by solar energy //Energy Procedia 2014;48:1226–35. https://doi.org/10.1016/j.egypro.2014.02.139.

[15] Sumathy K, Yeung KH, Yong L. Technology development in the solar adsorption refrigeration systems. Prog Energy Combust Sci 2003;29:301–27. https://doi.org/10.1016/S0360-1285(03)00028-5.

[16] Louajari M, Mimet A, Ouammi A. Study of the effect of finned tube adsorber on the performance of solar driven adsorption cooling machine using activated carbon-ammonia pair. Appl Energy 2011;88:690–8. https://doi.org/10.1016/j.apenergy.2010.08.032.

[17] Anyanwu EE, Ogueke N V. Thermodynamic design procedure for solid adsorption solar refrigerator. Renew Energy 2005;30:81–96. https://doi.org/10.1016/j.renene.2004.05.005.

[18] Pan Q, Peng J, Wang H, Sun H, Wang R. Experimental investigation of an adsorption air-conditioner using silica gel-water working pair. Sol Energy 2019;185:64–71. https://doi.org/10.1016/j.solener.2019.04.054.

[19] Zhao C, Wang Y, Li M, Zhao W, Li X, Yu Q, et al. Impact of three different enhancing mass transfer operating characteristics on a solar adsorption refrigeration system with compound parabolic concentrator. Renew Energy 2020;152:1354–66. https://doi.org/10.1016/j.renene.2020.01.110.

[20] Wang Y, Li M, Ji X, Yu Q, Li G, Ma X. Experimental study of the effect of enhanced mass transfer on the performance improvement of a solar-driven adsorption refrigeration system. Appl Energy 2018;224:417–25. https://doi.org/10.1016/j.apenergy.2018.05.017.

[21] Younes MM, El-Sharkawy II, Kabeel AE, Saha BB. A review on adsorbent-adsorbate pairs for cooling applications. Appl Therm Eng 2017;114:394–414. https://doi.org/10.1016/j.applthermaleng.2016.11.138.

[22] Askalany AA, Salem M, Ismail IM, Ali AHH, Morsy MG. A review on adsorption cooling systems with adsorbent carbon. Renew Sustain Energy Rev 2012;16:493–500. https://doi.org/10.1016/j.rser.2011.08.013.

[23] Thu K, Chakraborty A, Saha BB, Ng KC. Thermo-physical properties of silica gel for adsorption desalination cycle. Appl Therm Eng 2013;50:1596–602. https://doi.org/10.1016/j.applthermaleng.2011.09.038.

[24] Ismail A Bin, Li A, Thu K, Ng KC, Chun W. Pressurized adsorption cooling cycles driven by solar/waste heat. Appl Therm Eng 2014;67:106–13. https://doi.org/10.1016/j.applthermaleng.2014.02.063.

[25] Ahmed MS, Shehata AABDE, Abd A, Shehata E-K. A review: future of the adsorption working pairs in cooling 2007.
[26] Zhang X, Wang F, Lei X, Wang Y, Zhang Q, Wu X, et al. Influential factors and optimization analysis of adsorption refrigeration system performance. AIP Adv 2020;10. https://doi.org/10.1063/5.0026131.

Information of the authors

Verma Ashok, m.tech, research scholar, Department of Mechanical Engineering, NIT Kurukshetra
e-mail: ashok_61900050@nitkkr.ac.in

Sachdeva Gulshan, PhD, assistant professor, Department of Mechanical Engineering, NIT Kurukshetra
e-mail: gulshansachdeva@nitkkr.ac.in