Experimental Assessment of a Continuously Operating Solar Vapour Adsorption Cooling System Operated with Composite adsorbent/ethanol as working pair

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ABSTRACT: Adsorption cooling is a tried-and-true efficient heat conversion technology that can substantially reduce pollution while increasing energy efficiency. The conventional singlebed adsorption system for cooling purposes has a low efficiency because it is prone to intermittent cooling. Moreover, the adsorbent-adsorbate pair of typical adsorption system for cooling contributes significantly to its inefficiency. This study suggests a novel composite adsorbent that is synthesized by activated carbon as the parent element, with expanded natural graphite powder and metal-organic framework as secondary elements. In the composite, polyvinylpyrrolidone is the binder. The design, development, and performance study of the cooling system operated with activated carbon-ethanol as well as the composite adsorbentethanol has been examined. For experimental purposes, a two-bed adsorption system has been designed, operating with solar energy and a chilling capacity of 600 W. The performance of the cooling system using the newly suggested working pair has been experimentally evaluated. It is found that the coefficient of performance (COP) of the system is 0.54 at a desorption temperature of 88°C. It has been observed that the COP of the cooling system increases by 20.69% compared to the adsorption system that utilizes activated carbon-ethanol. The introduction of the composite adsorbent-adsorbate operating pair could greatly enhance the performance of adsorption cooling systems.

Keywords: adsorbate, adsorbent, cooling, energy, solar

Abbreviations

AC	Activated carbon
AB	Adsorbent Bed
CFC	Chlorofluorocarbon
COP	Coefficient of Performance
СР	Cooling power
V	Valve
EG	Expanded graphite
GI	Galvanised iron
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
MOF	Metal organic frame work
РСМ	Phase Change Material
PVP	Polyvinylpyrolidone
SAC	Two-bed solar adsorption cooling
SCP	Specific cooling power
SGP	Silica gel powder

Nomenclature

А	area [m ²]
Ap	aperture [m]
В	mirror reflectivity [-]
С	specific heat [J.kg ⁻¹ .K ⁻¹]
D	Structural constant [-]
Di	diameter [m]
D_0	receiver outer diameter [m]
М	mass [kg]
Р	pressure [Pa]
Qcp	cooling power [W]
Т	temperature [K]
t	time [s]
U	overall heat transfer coefficient [Wm ⁻² .K ⁻¹]
~ . ~	

Greek Symbols

ρ	density [kg.m ⁻³]
η	efficiency [%]

Subscripts

ac	activated carbon
ads	adsorption
amb	ambient
b	bed
chil	chiller
со	collector
cold	cold water
com	composite
con	condenser
cons	constant
CW	cooling water
eva	evaporator
hw	hot water
wa	water in the evaporator

1. Introduction

International attention has been increasing in the last few decades towards the potential effects of energy shortages, global warming, and ozone depletion. Traditional refrigeration systems emit CO₂ and other greenhouse gases such as CFCs and HFCs, which are key factors in ozone layer depletion, and they also require mechanical energy to operate. Due to the energy crisis and sustainability issues associated with the usage of CFCs and HFCs, the adsorption refrigeration system has received significant attention in this area since the 1970s [1]. The adsorption refrigeration technology has a bright future in the challenge against conventional vapor compression refrigeration systems. Vapour adsorption refrigeration systems are superior to conventional refrigeration systems due to their simpler controls, minimal vibration, and low running costs, especially when operated by waste heat or solar energy. The real attraction of the adsorption cooling system lies in its use of an adsorbent that aligns with both the Kyoto Protocol regarding the global warming potential as well as the Montreal Protocol concerning the depletion of the ozone layer [2-4]. These systems are ideal for utilizing solar or waste heat energy, as they can be powered by low-temperature energy resources. Because of these advantages, many researchers have investigated thermally driven adsorption-based desalination and cooling systems, to address cooling and freshwater demands over the years [5]. Additionally, it has been observed that adsorption-based systems can produce desalinated water and cooling using heat sources at 50°C [6, 7]. These characteristics have motivated numerous researchers to investigate the systems both theoretically and experimentally in an effort to enhance the performance. Recently, the introduction of artificial intelligence for optimizing adsorption cooling systems and improving heat transfer conditions in the adsorbent bed has proven effective in increasing system efficiency [8–10].

In the case of adsorption system, the choice of the adsorbent/adsorbate pair is a crucial parameter that affects the performance of the systems. Currently, common operating pairs used in sorption cooling systems include zeolite/water, silica gel/water, activated carbon/ammonia, activated carbon/methanol, and others. These pairs have been chosen for their favourable adsorption characteristics. One key disadvantage of this type of system is its low performance, resulting from the adsorbate's low adsorption uptake by the adsorbent [11]. To overcome these disadvantages, improvements can be made to the adsorption/desorption capacity, surface properties, thermal conductivity, and heat/mass transfer properties of the working pair. These improvements can be achieved by consolidating the adsorbent or creating a composite

adsorbent. Thus, selecting a new composite adsorbent/refrigerant working pair for the vapour adsorption cooling system becomes a viable option for enhancing system performance.

The section describes the efforts being made to improve the effectiveness of the vapour adsorption cooling system through a new working pair by modelling as well as experimentation. In recent years, numerous theoretical and experimental studies on solar adsorption cooling (SAC) systems have been published. Simulation tools are used to determine the ideal operating conditions for the two-bed vapour adsorption cooling system in order to achieve the best performance. In 2007, Saha et al. [12] established a simulation model to evaluate the influence of operating parameters on the performance of the system. The simulation study demonstrates the effects of hot/cold water temperature of the adsorption bed, hot/cold water flow rates, and adsorption-desorption duration on the performance of the system. The findings of this work highlight the importance of operating temperatures in determining system performance. Fong et al. [13] utilized the simulation-optimization method to study the ideal SAC system parameters. The TRANSYS framework has been employed for the system optimization. Through the simulation-optimization process, optimized designs of the adsorption cooling system were identified, resulting in primary energy consumptions approximately 7.1% lower than those determined by standard design practices. In 2020, Sztekler et al.[14], mentioned the potential integration of the adsorption cooling system and gas turbine. The maximum cooling capacity attained by the simulation model has been 1.070 kW with water as the refrigerant. In addition to detailed transient analysis of the system, the appropriate selection of operating pairs also plays a vital part in improving the system performance. Popular working pair used for the system include activated carbon/ammonia, activated carbon/methanol, and silica gel-water. However, toward the end of the twentieth century, the working pair of activated carbon fiber/ethanol and activated carbon fiber/methanol is developed.

In 2003, Wang *et al.* [15] performed research on a specifically processed activated carbon-methanol and proved that the solid bed with activated carbon had higher methanol adsorption capacity than granular activated carbon and also required less time to adsorb. Guilleminot *et al.* [16] reported a COP of 0.12 for the SAC system that uses activated carbon-methanol as operating pair. Alelyani et al. [17] developed a adsorption refrigerator, which is operated with a solar collector. Here, the cooling capacity obtained by the system has been 223 kJ and the solar COP is 0.15. In 2022, Bujok et al. [18] conducted a series of experiments by

combining an adsorption system with a solar collector. The testing processes were conducted on specific days in July and August. The COP and cooling capacity attained by the system has been 0.531 - 0.692 and 5.16 - 8.71 kW, respectively. Tso et al. [19] synthesised composite adsorbent using activated carbon, CaCl₂, and silica gel. This newly developed adsorbent performs better than the parent material (activated carbon) by 933%, being able to absorb 0.23 g of water for one gram of adsorbent at 900 Pa. Here, chemical adsorbent CaCl₂ upgrades the system's performance because the change in enthalpy of hydration for CaCl₂ is significantly greater than the heat of water adsorption on solid adsorbents. Wang et al. [20] introduced a consolidated adsorbent made of CaCl₂ and expanded graphite powder for an adsorption cooling system for making ice in fishing boats. The consolidated adsorbent is found to be effective for the system because of its high thermal conductivity when compared with the CaCl₂. The thermal conductivity of this newly developed adsorbent is 6.5-9.8 Wm⁻¹K⁻¹, which is 32 times more than that of CaCl₂. Saha et al. [21] investigated the ability of low-grade ethanol to adsorb onto the metal-organic framework like MIL-101Cr both theoretically and experimentally. The adsorbent is an appropriate choice for the vapour adsorption cooling system because it can absorb 1.1 kgkg⁻¹ of ethanol at 300^oC.

Vapour adsorption cooling technology offers a promising substitute for conventional cooling systems, which consume a lot of electrical energy and exacerbate problems like resource depletion and degradation of the environment. According to the literature, the combination of activated carbon and ethanol is particularly effective for adsorption cooling systems. However, conventional single-bed adsorption cooling systems face challenges like intermittent cooling, which can be addressed by using multi-bed adsorption systems. Additionally, the low heat transfer characteristics of the conventional adsorbent-adsorbate pair in standard adsorption cooling systems significantly impact their efficiency. This limitation can be mitigated by selecting suitable composite adsorbents.

The innovative aspect of the proposed work lies in the development of a new consolidated adsorbent using activated carbon as the base material, which offers enhanced adsorption capacity for ethanol and improved thermal properties. This approach leads to a substantial enhancement in the sorption processes and overall system performance. Based on the research investigation presented in Part 1 of this work [22], which outlined specific directions for creating a novel composite adsorbent and published its characteristics, the goal of Part 2 is to establish an experimental setup for a two-bed adsorption cooling system

operating with activated carbon/ethanol and composite adsorbent/ethanol as working pairs. This paper also focusses on the experimental procedures and provides a comparative analysis of the system performance when operating with the two working pairs.

2.Two bed adsorption cooling system

The main components of the adsorption cooling system are two adsorbent beds (either a desorber or an adsorber, depending on the mode of operation), a condenser chamber, an expansion valve, an evaporator unit, and a parabolic concentrator. Here, the sorbent beds are filled with adsorbent material that is efficient in desorbing or adsorbing the vapour adsorbate or refrigerant while on the desorption or adsorption process. The valves in the system helps to regulate the flow of refrigerant as shown in Fig. 1. The adsorption of refrigerant during the adsorption process is an energy releasing process; therefore, a continuous cooling of the adsorbent bed is required to eliminate the excess heat produced in the sorption bed [23]. When desorption occurs, an external heating source may be used to warm the desorption bed.

Initially, the adsorbent bed 1 (AB1) is heated by flowing hot water through it while all the valves are fully closed (V1, V2, V3, and V4). When AB1 reaches the condenser pressure, the valves V1 and V2 open and the refrigerant vapour is transferred from AB1 to AB2. The adsorption of AB2 ceases when the maximum adsorbate from AB1 is desorbed. The vapour refrigerant condenses during the flow of vapour adsorbent from AB1 to AB2 through the common condenser.

The liquid refrigerant is now introduced into the evaporator unit through the expansion valve after the refrigerant pressure is decreased from the condenser pressure to the evaporator pressure. The refrigerant vaporizes in the evaporator by absorbing the latent heat of the cooling medium. The vapor adsorbate is subsequently supplied to AB2 to complete one cycle of operation. By circulating cooling water through AB2 during the adsorption process, its temperature can be decreased. During the subsequent cycle, the valves V3/V4 are fully opened while the other valves V1/V2 remain in closed position.

3. Design of SAC system

The section details the steps involved in the design of different components of the SAC system - condenser, adsorbent bed, evaporator, storage tank, and collector.

3.1 Design of components of the SAC system

The evaporator is a cylindrical tank in which a copper tube of 3/8-inch size, is spirally wound inside it. The SAC system is designed to cool the 18 kg of water from 30 $^{\circ}$ C to 5 $^{\circ}$ C in 1 hr. This spiral coil is completely covered with water which is to be cooled. The ethanol flows through the pipe and is vapourised by capturing latent heat from the space to be cooled [24]. The cooling effect of the system is given by the Eq. (1),

$$Q = M_{wa}C_p \left(T_{wf} - T_{wi}\right) \tag{1}$$

The refrigeration capacity of the system is estimated to be 600 W. For internal flow (lowpressure vapour ethanol coming from the expansion valve flowing through the copper tube of the evaporator) and fully developed flow constant heat flux, Nu = 4.26 [25].

The total area of the coil has been calculated by

$$Q = UA(LMTD) \tag{2}$$

Then the overall length of the coil is 12 m

The condenser unit used in the system is tank and coiled type. The desorbed ethanol is flowing through the copper tube where it condenses by transferring the latent heat of vapourisation to the water filled in the condenser for cooling purposes. The required length of the coil is 13 m.

As the adsorbent bed is the crucial component of the system, the total performance of the system is strongly dependent on its physical features. A bed of adsorbent must have enhanced heat and mass transmission capabilities. The bed is stuffed with granular absorbents. Metallic mesh is stretched across the heat exchangers to prevent adsorbent spillage while allowing ethanol vapour to permeate. During the process of adsorption/desorption, the adsorbent material is heated/cooled by transferring hot/cold water via the copper tubes of heat exchangers [26].

Volume of ethanol –	Mass of ethanol	(3)
	Density of ethanol	(3)

The adsorption rate of ethanol in the selected activated carbon has been experimentally determined as 0.369 kg kg⁻¹.

Total mass of activated carbon for each bed =
$$\frac{\text{Mass of ethanol evaporated}}{\text{Concentration ratio}}$$

Volume of activated carbon = $\frac{\text{Mass of activated carbon}}{\text{Density of activated carbon}}$ (4)

Total volume of adsorbent bed = Volume of ethanol + Volume of activated carbon (5)

Thus, by fixing the length and diameter as 36 cm and 28 cm, respectively, the adsorbent bed has been constructed and Table 1 gives the design dimensions of the various components of the SAC system.

3.2 Design of Parabolic Solar Collector

The solar collector for the system is made up of a parabolic concentrator, supporting structure for the collector, a receiver, and a reflecting surface. The following section details the design procedure of the parabolic solar collector. The parabolic trough collector for the SAC system has been designed based on the performance (COP) of the cooling system and is given as:

$$COP = \frac{\text{Refrigerating effect}}{\text{Heat input}}$$
(6)

Here, COP of the adsorption cooling system is 0.68 [2] and the refrigerating effect is 600 W.

Heat input =
$$\frac{\text{Refrigerating effect}}{\text{COP}}$$
 (7)

The efficiency of the parabolic concentrator is given as the ratio of the output power of the parabolic concentrator to the input power of it and is given by Eq. (8)

$$\eta_{PTC} = \frac{\text{Heat output}_{PTC}}{\text{Heat input}_{PTC}}$$
(8)

Now, the area of the parabolic trough collector is calculated by [21]

$$A_p = \frac{Q_{PTC}}{I}$$
(9)

The common accessible reflective stainless-steel sheets are used to create a pilot troughreceiver unit. The stainless steel sheet measuring 2.5 m x 1.3 m is used as the reflecting surface. The parabolic trough collector is designed based on a simple parabolic equation. The cross section of the parabolic collector has been located as shown in Fig. 2 and is obtained by using the geometric equation shown in Eq. (16). The sheet is then curved into a parabolic trough module with a 3 m² aperture area, so that 2.5 m length and 1.2 m aperture width. Now, the parabolic equation in Cartesian coordinate is given by the Eq. (10) [27,28]

$$x^2 = 4fy \tag{10}$$

The height of the parabola with respect to focal length and aperture can be obtained by rearranging Eq. (10).

$$\left(\frac{A_p}{2}\right)^2 = 4fh \tag{11}$$

$$h = \frac{A_p^2}{16f}$$
(12)

The rim angle is given by the Eq. (13)

$$\tan\frac{\Psi}{2} = \frac{A_p}{4f} \tag{13}$$

The geometrical concentration ratio C_G can be calculated as the ratio of the aperture area of the collector A_p to the receiver surface area A_r

$$C_G = \frac{A_P}{A_r}$$
(14)

The focal point of the present model is chosen at the aperture line, meaning that the collector height h is same as focal length 'f 'with rim angle Ψ is 90⁰. Table 2 gives the geometrical parameters of the designed parabolic trough model for the present study.

4. Performance indicators of SAC system

Three metrics are used to define the performance of the given SAC system namely: (a) coefficient of performance (COP), (b) cooling power (CP), and (c) specific cooling power (SCP). The amount of heat absorbed by adsorbent bed,

$$Q_{in} = hot water mass flow rate x C_p x (T_{in} - T_{out}) x t$$

$$= m_{hw} x C_p x (T_{in} - T_{out}) x t$$
(15)

Refrigerating effect $(Q_{eva}) = Mass \text{ of water in the evaporator } xC_p x(T_{eva, final} - T_{eva, initial})$ = $M_{wa} xC_p x(T_{eva, final} - T_{eva, initial})$ (16)

(a) The Coefficient of performance (COP): The COP of the system is defined as how well the input energy is transferred into beneficial cooling effect (Q_{eva}).

$$COP = \frac{Q_{eva}}{Q_{in}} \tag{17}$$

(b) Cooling power (CP): The cooling power is primarily used to determine the performance of the cooling system and may be written as:

$$Cooling \ power(CP) = \frac{Q_{eva}}{Operating \ time \ in \sec}$$
(18)

(c) Specific cooling power (SCP): The specific cooling power (SCP) is to assess the performance of the adsorption cooling system under different sizes and is defined as the ratio cooling capacity of the system to the unit mass of adsorbent present in the adsorbent bed.

Specific cooling power
$$(SCP) = \frac{CP}{m_{ac}}$$
 (19)

5. Selection of working pair for the experimental work

The efficiency of the SAC system not only dependent on the design parameter of the adsorbent bed but also on the choice of working/operating pair. Therefore, the judicious selection of the operating pair improves system performance. The operating pairs used in the SAC have their advantages and disadvantages. This section considers the proper selection of common working pairs for the present study. The selection of working pair for the composite adsorbents is also detailed in this section.

5.1 Activated carbon (AC)-ethanol

The choice of adsorbate for the adsorption cooling system many depends on the size of the molecules in the adsorbent bed, significant latent heat of vapourization, high thermal conductivity, non-toxic, non-corrosive, and environmentally friendly properties. The ideal adsorbates for adsorption cooling systems are thought to be water, ammonia, and methanol. Ammonia is extremely toxic, whereas water cannot be used for applications below 0^oC. In the presence of copper, methanol dissociates above 120^oC and is extremely flammable and toxic. A better environmentally friendly refrigerant with better adsorption/desorption properties must therefore be thoroughly investigated [29].

Among natural refrigerants/adsorbates such as ammonia, water, and methanol, ethanol is interesting to be applied due to its friendly environmental effect on global warming and ozone depletion potentials. Ethanol is a flammable, colourless liquid with a faint odour. It burns with a blue flame that is smokeless and sometimes difficult to see in daylight. Moreover, ethanol has a boiling point of 78.24°C, and good adsorption properties with activated carbon make this working pair more attractive for the SAC system. In most cases, the solar adsorption cooling systems are operating below 100°C making the said operating pair for solar adsorption refrigeration systems nowadays. Activated carbon is a good option for the adsorbate in the adsorption cooling system due to its low cost and ease of availability. According to ASHRAE, the American Society of Heating, Refrigeration, and Air-Conditioning Engineers, the refrigerant ethanol belongs to the A2L group and is more desirable as the operating pair for the SAC system due to its lower flammability, nontoxic nature, ability to operate below 0°C, and high affinity for ethanol vapour towards activated carbon [30].

The frequently employed adsorbents nowadays are silica gel, zeolite, and activated carbon. When natural zeolite is the adsorbent, the system needs a large quantity because at operating temperature the desorption quality of the vapour refrigerant from the adsorbent is very less. However, it is used for solar cooling applications because of its non-linear pressure dependence. But the silica gel and activated carbon shows linear pressure-dependent isotherms. Here the silica gel meets the above criteria of deterioration phenomenon of the adsorption capacities and aging causes to rethink using the silica gel as the adsorbent. The excellent porous and large surface properties of activated carbon make it a popular adsorbent for the SAC system. Since activated carbon is a physical adsorbent, less heat is needed to desorb the

adsorbate from its vapour phase. Moreover, it is a good option for the SAC system due to its inexpensive price and ease of accessibility. The adsorption and desorption capacities of activated carbon are good compared to ordinary carbon and the strong affinity of activated carbon towards ethanol vapour makes it chosen as the adsorbent-refrigerant pair for the initial study of the research work. Ethanol and activated carbon have the following properties:

Adsorbate: Ethanol

- i. Good adsorption rate with activated carbon.
- ii. High latent heat of vaporization.
- iii. Low freezing point $(-114^{\circ}C)$
- iv. Zero ODP and low GWP
- v. It can be quickly removed from the surface with a low-grade heat source.

Adsorbent: Activated carbon

- i. Ease of availability.
- ii. Large surface area.
- iii. Extremely high pore size and pore volume.
- iv. Stable and inert to alcoholic agents.
- v. High adsorption capacity.

5.2 Selection of component materials for composite adsorbent

The consolidated or composite adsorbent is an integration of two or three different adsorbents with the appropriate quantity of binder. The presence of component materials in the proper ratio will improve the thermal as well as the physical properties, which also leads to an increase in the efficiency of the SAC system. The improvement in the heat transmission of the adsorbent materials employed in the adsorbent bed is the most effective way of enhancement of the performance of the SAC systems. One of the best method to enhance heat transfer in adsorber/desorber reactors has been to use consolidated or composite adsorbents. The composite adsorbent is superior to the parent adsorbents in terms of surface features, thermophysical characteristics, and adsorption rate, which enhances the physical and surface properties of the parent adsorbents, the composite adsorbent has better surface volume, thermal as well as physical properties, and higher adsorption rate than single adsorbents. This helps to improve the surface as well as physical characteristics of parent adsorbate and improves the performance of the SAC system. The poor thermal conductivity of activated carbon and the low performance of the system helps to look for new component materials to create a composite adsorbent for the proposed SAC system with activated carbon as the parent adsorbent. Thus, the defects of the parent material can be overcome by forming a composite by adding Metal-organic framework (MOF) MIL-53Al, Expanded Graphite Powder (EGP) and Polyvinyl Pyrrolidone (PVP) as the additives. The property of the different materials selected for the composite preparation is detailed in Table 3.

The metal organic frame work -MIL-53(Al) is one of the components of the consolidated adsorbent and are linked together by 1,4-benzenedicarboxylate ligands to form an infinite trans chain. This MOF has a framework of one-dimensional channels in the shape of a diamond, which aids in the adsorption of tiny molecules into the structure. MIL-53 (Al) exhibits remarkable stability and resilience against hydrolysis in both neutral and acidic conditions. It has been established that MIL-53 (Al) is one of the more desirable MOFs for having excellent structural stability in aqueous solutions. The choice of this MOF as a component material for the AC in this composite production is also influenced by its substantial pore volume, outstanding chemical stability, excellent thermal conductivity, and good surface area [31, 32]. Moreover, thermal conductivity of the parent adsorbent can also be enhanced by the addition of EGP [33]. The composite preparation utilises PVP as a binder. It is because PVP has better thermal conductivity than other types of binders [34]. Table 4 lists the physical properties of the additive materials, and Table 5 outlines the BET surface area and pore volume of the base material and the additive materials used to make the consolidated adsorbents for the current study.

The Indo-German Carbon Ltd in Kochin, Kerala, India supplied the granular activated carbon (AC) used in this study. It has a BET surface area that varies from 900 to 1150 m²g⁻¹, a mesh size of 12, with an density of 0.69 gcm⁻³ (grade VP E122). The secondary adsorbents used for the composite preparation are MIL-53Al metal-organic framework (MOF), silica gel, and expanded graphite powder (EGP). Akshar Chem LTd, Gujarat, India provides EGP with a mesh size of 20–60 and a purity of 99.5%. QTrade Link, Mehsana, Gujarat, India, provided the SGP, having a size of 50-80 mesh, a density of 0.60-0.90 gcm⁻³, and a surface area (BET) of 350 m²g⁻¹. The MOF of type MIL-53Al with a density of 0.40 gcm⁻³ and a BET surface area of 1500 m²g⁻¹ has been supplied by Intelligent Materials Ltd., Punjab, India.

Polyvinylpyrolidone (PVP), which is produced by Bangalore Fine Chem. in Karnataka, India, is uses as the binder for the composite preparation. Siddha Chemicals, Pune, India, provided the ethanol used as the adsorbate, which has a purity of 99.5%.

6. Experimental Procedure

The procedure for carrying out experiment is described in detail here. Initially, the experiment is conducted on a two-bed SAC system using activated carbon-ethanol as the working pair and finally with proposed composite adsorbent-ethanol as the working pair for comparison. The prime aim of this investigation is to determine the effect of evaporator and hot water temperatures on system efficiency. Figure 3 depicted the experimental setup of the adsorption cooling system operated with a solar collector. In this experiment, the system is energized by hot water from the solar collector. If the temperature of the circulating hot water from the parabolic collector is completely inadequate to operate the system, then a supplementary heating source is used. The vacuum condition is ensured with a vacuum pump, and once the desired vacuum conditions are achieved, the system is ready for charging the refrigerant. The adsorbent bed (AB1) has now been charged with a sufficient quantity of ethanol. The following are the steps involved in the experimental study:

- Initially, hot water temperature from the heating source, say 80°C, is allowed to flow through H1 into the adsorbent bed AB1 for heating; during this process, all valves V1, V2, V3, and V4 are fully closed.
- The refrigerant which is in vapour form leaves from the evaporator are adsorbed by AB2 through the valve V4. The condenser temperature, evaporator temperature, and pressure of the system are recorded.
- iii. The temperature of AB2 increases due to the adsorption of the vapour refrigerant. As a result, maximum cooling water circulation is ensured via the bed AB2 to bring the bed temperature to the same as the atmospheric temperature.
- iv. This completes one cycle, and during the next cycle, the V1 and V4 are in closed position, and the entire process is revised to achieve continuous operation.
- v. Where the solar intensity is low, supplementary heating of hot water is provided to release the trapped refrigerant from the adsorbent bed.

- vi. A number of observations are performed with different hot water temperatures by maintaining the evaporator temperature constant to examine the influence of hot water on the performance of the SAC system. It is mostly used to determine the impact of hot water temperature on SAC system performance.
- vii. Similarly, the influence of evaporator temperature on system performance can be determined by repeating the procedure for different initial temperatures of the evaporator.

7. Uncertainty analysis

Experiments may include errors and uncertainties due to a variety of reasons, including the choice of instrument, setup and surroundings, calibration, test design, and observations. An accurate technique for determining uncertainty entails precisely defining the uncertainties in a range of original experimental measurements. These measurements are subsequently used to derive the intended outcome of the experiments. In the current investigation, measurements are made of the adsorbent mass, time, and the fluid temperature of the operating system. The Q_{eva} , Q_{in} , and COP of the SAC system are all functions of several parameters. The Table 6 provides overall uncertainty of the calculated parameters [22].

$$\delta Q_{eva} = \sqrt{\left(\frac{\partial Q_{eva}}{\partial M_{wa}} \delta dM_{wa}\right)^2 + \left(\frac{\partial Q_{eva}}{\partial C_p} \delta C_p\right)^2 + \left(\frac{\partial Q_{eva}}{\partial \Delta T} \delta d\Delta T\right)^2}$$
(20)

$$\frac{\partial Q_{eva}}{\partial M_{wa}} = C_p \,\Delta T \tag{21}$$

$$\frac{\partial Q_{eva}}{\partial \Delta T} = M_{wa} C_p \tag{22}$$

$$\delta Q_{in} = \sqrt{\left(\frac{\partial Q_{in}}{\partial m_{hw}} \delta d m_{hw}\right)^2 + \left(\frac{\partial Q_{in}}{\partial C_p} \delta C_p\right)^2 + \left(\frac{\partial Q_{in}}{\partial \Delta T} \delta d \Delta T\right)^2 + \left(\frac{\partial Q_{in}}{\partial t} \delta t\right)^2}$$
(23)

$$\frac{\partial Q_{in}}{\partial m_{hw}} = C_p \,\Delta T \,t \tag{24}$$

$$\frac{\partial Q_{in}}{\partial \Delta T} = m_{hw} C_p t \tag{25}$$

$$\delta COP = \sqrt{\left(\frac{\partial COP}{\partial Q_{eva}} \delta dQ_{eva}\right)^2 + \left(\frac{\partial COP}{\partial Q_{in}} \delta Q_{in}\right)^2}$$
(26)

$$\frac{\partial COP}{\partial Q_{eva}} = \frac{1}{Q_{in}}$$
(27)

$$\frac{\partial COP}{\partial Q_{in}} = \frac{-Q_{eva}}{Q_{in}^2}$$
(28)

8. Results and Discussion

The performance of the system is assessed experimentally under the meteorological circumstances of the TKM College of Engineering, Kollam. Activated carbon and ethanol is utilized as the working pair in the experimental investigation. The experiments are performed between January and December of 2023. The hot water collected from the parabolic concentrator is then directed to the adsorbent bed. Here, both the hot water temperature and the evaporator inlet water temperature have a substantial effect on the performance of the SAC system, including the refrigeration effect, COP, and SCP, which is working with activated carbon/ethanol as the operating pair.

8.1 Solar intensity and the atmospheric temperature with time

The solar intensity and atmospheric temperature data are collected for the whole year, and their variations with time on a warm day are presented in Figs. 4 and 5, respectively. Additionally, Fig.6 displays the receiver outlet fluid temperature variation over time on the warm day. The experimental results show that the maximum solar intensity obtained is 1229 Wm⁻² and the average solar intensity of about 950 Wm⁻² for most of the day has been obtained. The availability of this high-intensity solar radiation gives a high temperature to the receiver fluid. This high-temperature receiver fluid is utilised as the heating source of the SAC system for the present investigations.

8.2 Impact of hot water temperature on the COP of the system

The hot water received from the solar collector is utilised as the generating or heat source of the SAC system. Consequently, the hot water utilised in the experiment has a maximum temperature range of about 88°C to 90°C. Figure 7 illustrates the impact of hot water temperature on COP under simulation and experiment conditions using composite adsorbent B- ethanol as the working pair. The experimental profile displays a similar pattern, demonstrating a good agreement with the simulation data. Figure 7 indicates that both in simulation and experimental studies, the COP of the system is increased with rise in hot water temperature. The reason for this is that, as the temperature of the hot water rises, more refrigerant mass is being ejected from the adsorbent bed, improving the refrigerating effect than the energy input to the system. This will boost the COP of the SAC system.

Moreover, the results of the simulation mostly reflect the fluctuation in system performance under various operating conditions. However, the experimental output are still somewhat inferior to the simulation results in terms of specific values, mostly for the following causes: (i) In the experimental scenario, there has been a heat loss to the surroundings. (ii) several system processes have not been carried out during the experiment under perfect circumstances. (iii) the specific heat capacity used for the simulation is stable, but it fluctuates significantly with temperature in the experiment. The maximum COPs obtained from experimental studies are 0.54, and 0.46, respectively. This is because the system is simulated in ideal conditions with no energy loss to the environment. In comparison to the parent working pair, the COP of the SAC system operating with consolidated adsorbent shows a better result since it is having superior surface properties, outstanding thermal conductivity, and a significant adsorption/desorption capacity towards the adsorbate.

8.3 Impact of hot water temperature on the refrigerating effect and SCP of the system

The figure 8 depicts the influence of the hot water temperature or desorption temperature of the adsorption cooling system, which is crucial to the refrigerating effect. The refrigerating effect acquired through simulation has significantly risen, while the refrigerating effect obtained through experiment for composite adsorbent-ethanol as working pair is increased from 341 kJ to 1618 kJ. The findings in both situations illustrate the same pattern: as the hot water or the desorption temperature of the SAC system rises, the refrigerating effect

also rises sharply. This is because greater driving temperatures result in a rise in the amount of desorbed refrigerant, which in turn causes the increase in the refrigerating effect of the system. As the hot water temperature rises, there is an increasing discrepancy between the simulation and experiment output which if due to an increase in heat transfer losses during operation. The impact of hot water temperature on the specific cooling power of the cycle is shown in Fig. 9. The SCP is significantly influenced by the temperature of the hot water. As the hot water temperature rises, the SCP of the system also increases. This is because a higher hot water temperature results in more refrigerant desorption, which enhances the refrigerating effect. Additionally, this action leads to an improvement in the efficiency of the refrigerating effect of the system. When compared to the SAC system operated with AC-ethanol, the composite B-ethanol working pair in the SAC system shows better performance.

8.4 Influence of evaporator water temperature (inlet) on the performance of the system

The influence of inlet evaporator water temperature on the COP, refrigerating effect, and specific cooling power is shown in Figs. 10 and 11. The increase in temperature of the inlet evaporator water from 22^oC to 30^oC leads to increases in COP and refrigerating effect. This is due to an increase in the inlet evaporator water temperature, which causes more refrigerant to evaporate from the evaporator, increasing the refrigerating effect and hence raising the system's COP. In addition to that, the lower evaporator temperature more energy input is needed for the evaporation of refrigerant from the evaporator and causes a large cycle time to finish the operation of the SAC system, which also causes to decline the performance of the system. The SCP also depends upon the refrigerating effect, so the same effect can be observed as depicted in Fig.11.

8.5 Influence of mass flow rate of hot water on the performance of the system

The influence of the mass flow rate of the hot water on the performance of the system is shown in Figs. 12 and 13, when the system functioning with composite adsorbent-ethanol as working pair. The increase in the inlet hot water mass flow rate causes more refrigerant to be evaporate from the adsorbent matrix. This aids in improving the COP and refrigerating effect of the system. Furthermore, the same effect for the specific cooling effect can be depicted in Fig. 13. Due to the low heat input to the system reduces the rate of the desorption process. However, a suitable hot water mass flow rate of 0.028 kgs⁻¹ is preferred for the present investigation. This is because the decrease in the COP of the system is marginal after the specified mass flow rate. This is due to the higher flow rate of inlet hot water resulting in large energy lost to the atmosphere, and the higher mass flow requires extra pump work which lowers the system performance.

9. Evaluation of current work with works reported in literature

An evaluation of the present work and works reported in the literature is shown in Table 6. In comparison to Wang et al. [15], the COP of the system obtained in the current research study is approximately 77.78% higher. The superior thermal conductivity and adsorption capacity of composite adsorbents lead to enhance in the rate of adsorption of adsorbate. This property also accelerates the desorption/adsorption of refrigerant and boost the refrigeration effect of the system. The performance outcome of the study of Tso *et al* [19] is also presented in the Table 7.

10.Conclusion

The present work introduces composite B-ethanol as a new operating pair for the twobed adsorption cooling system operated with solar energy. The composite B comprises MIL-53(Al), EGP, PVP, and activated carbon as parent material in the appropriate proportion by weight. Thus, the relevant conclusions drawn from the research work have been summarised as follows:

- a) The energy equation has been used to design the evaporator, condenser, adsorbent bed, energy storage tank, and solar collector of the SAC system.
- b) The highest COP achieved from the experimental study is 0.54 at a desorption temperature of 88°C operating with composite B - ethanol as working pair
- c) The system achieves SCP of 21.13 Wkg⁻¹ at the maximum desorption temperature of 88°C operating with composite B ethanol as the working pair, which is 35.02 % higher than the SCP of the system with activated carbon-ethanol as the working pair
- d) The increase in temperature of the inlet evaporator water leads to the increases in COP and refrigerating effect

e) The increase in the inlet mass flow rate of hot water media causes more refrigerant to be desorbed from the adsorbent matrix and improves the COP and refrigerating effect of the system

The implementation of a composite adsorbent-adsorbate pair has the potential to enhance the efficiency of adsorption cooling systems. In remote locations where solar energy is available, the proposed system provides cooling water as well as it can be used to preserve food and medicine. Future research paths will examine composite interactions with new additives with metal oxides in order to enhance the thermophysical and porous characteristics of parent adsorbent. The work will also concentrate on developing a hybrid system for both desalination and atmospheric water generation. This system will employ an adsorption cooling mechanism utilizing a newly developed composite adsorbent designed for refrigerant water. In addition to that integrating the system with PCM [35] also helps to improves operating time as well as the system performance.

Declaration of competing interest

The authors state that they have no financial conflicts of interest or personal relationships that may have influenced the research presented in this paper.

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Figure 12. Influence of hot water mass flow rate on COP and refrigerating effect with composite B-ethanol as working pair



Figure 13. Influence of hot water mass flow rate on SCP with composite B-ethanol as working pair

Components	Material	Dimension	
	Copper tube	Length: 12 m	
Evenerator		Diameter: 3/8 inch (9.53 mm)	
Evaporator	Stainless steel	Diameter: 26 cm	
(Double walled: puff	(Inner round chamber)	Height: 38 cm	
ilisulated)	GI Sheet	Suitable dimensions for	
	(Outer cubic chamber)	covering inner vessel and	
	(Outer euble chamber)	insulation are used	
	Coppor tubo	Length: 10 m	
Adsorption Bed (2 Nos.)	Copper tube	Diameter: 3/8 inch (9.53 mm)	
	Stainless steel	Length: 36 cm	
	(Cylindrical chamber)	Diameter: 28 cm	
	Common tubo	Length: 13 m	
Condenser	Copper tube	Diameter: 3/8 inch (9.53 mm)	
	GI Sheet	Length: 38 cm	
	(Cubic chamber)	Height: 38 cm	

Table 1. Design dimensions of various components of the SAC system

 Table 2. Geometrical parameters of the designed parabolic trough model

Parameter	Numerical Value
L	2.5 m
A_p	1.2 m
f	0.3 m
C_G	31.84 [-]
D_0	0.03 m

Table 3. Property	of selected	material for	composite	adsorbent	preparation	[22]
1 2			1		1 1	

Sl. No.	Material	Property
1	Expanded graphite powder [EGP]	Porosity is very high
		Density is very low
		Good thermal conductivity
2	Metal organic framework [MOF]	High specific surface area
	MIL-53Al	Pore volume is large.
		High chemical stability
3	Polyvinyl Pyrrolidone [PVP]	Better heat conductivity over other
	(Binder)	types of binders

Table 4. Physical parameters of additive materials [22]

Material	Thermal conductivity (Wm ⁻¹ K ⁻¹)	Density (kgm ⁻³)	Specific heat capacity (kJkg ⁻¹ K ⁻¹)	Thermal diffusivity (mm ² sec ⁻¹)
Expanded Graphite	1.25	2260	0.79	0.7
MIL-53 Al	0.46	400	0.96	1.2
PVP (Binder)	1500	1200	-	-

Table 5. BET surface area and pore volume of the base material and the additive materialsused to make the consolidated adsorbents for the current study [22]

Base material	BET surface area [m²g⁻¹]	Pore volume [cm ³ g ⁻¹]
Activated carbon	1050 ± 25	0.62
Expanded graphite powder	37 <u>±</u> 2	0.04
MIL-53 Al	1830 ± 29	0.74
PVP	146 ± 3	0.12
Composite B	1597±26	0.93

Description	Total uncertainty [%]
Cooling effect	±0.73%
Heat input to the system	±2.54%
СОР	±2.67%

Table 6. Overall uncertainty in different parameters

Table 7. Comparison with the different working

Working pair	Work	Type of work	COP [-]
Composite adsorbent-ethanol	(Present work)	Experiment	0.54
AC-ethanol	(Present work)	Experiment	0.46
Composite AC-water	Tso et al. [19]	Simulation	0.45
Activated carbon-methanol	Wang et al. [15]	Experiment	0.12

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