Bioenergy-driven Green Cooling System for Different Climate Conditions: Minimum, Maximum, and Optimum Desorption Temperature

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Abstract: In recent years, adsorption technology-based cooling systems are being increasingly examined as a sustainable technological alternative for fulfilling the fast-growing cooling demands due to their potential to employ low-grade heat energy and environmentally benign working fluid. The present study is an attempt to evaluate the cooling assessment of a single-stage adsorption cooling system coupled with a bioenergy heating unit. The maximal, minimal, and optimal limits of heat source temperature are evaluated for two different climate conditions. The Dubinin-Astakhov isotherm model is adopted to analyze the adsorption uptake of ethanol refrigerant over biomass-derived activated carbon sorbents. The MATLAB R2021b platform is used to numerically investigate the effects of various operating parameters such as evaporator temperature, ambient temperature, and regeneration temperatures on the coefficient of performance, cooling power, and mass of adsorbent to combustion fuel ratio. The optimal regeneration temperature for WPT AC is found to be lesser (92 °C) than that of M AC (94 °C) at ambient temperature of 32 °C. Moreover, the theoretical results demonstrate that both adsorbents with ethanol as refrigerant require an equal amount of minimal and maximal regeneration temperature of corresponding to ambient temperature of 38 °C. Overall, the methodology described in the present work is quite valuable for designing and implementing the bioenergy-powered green cooling system.

Key words: Bioenergy, adsorption cooling, optimum desorption temperature, biomass-derived activated carbon, ethanol

1. Introduction

In the past few decades, the mechanical compression-based refrigeration cycle has dominated in HVAC sector (Heating Ventilation, and Air Conditioning) due to its reliability and compactness. However, it has mainly two drawbacks: (i) high-grade energy consumption, and (ii) the usage of traditional refrigerants with a large potential for environmental harm. Although, zero ODP (ozone depletion potential) refrigerants like R-134a and R-22 are now in use, they have a considerable global warming potential (GWP) [1]. The above-mentioned issues are addressed by heat-operated refrigeration and airconditioning cycle such as the adsorption cooling cycle [2]. It has several advantages such as the ability to work on ultra-low-temperature low-grade heat energy sources [3], the usage of ozoenvironmental-friendly working pairs, no moving parts, and peak power demand reduction. Despite these advantages, the traditional adsorption-based cooling system (ACS) performs poorly due to its intermittent and complex operation, and poor adsorption capacity of adsorbent material as well as the design of the sorption reactor [4].

In order to improve the thermal performance of ACS, various strategies including multi-stage, multi-beds, heat recovery, mass recovery, highly porous adsorbents, composite adsorbents, extended surface heat exchangers, finned tube adsorbers, and micro-scaled thermal compressors are employed. The activated carbon (AC) prepared by waste biomass shows good potential to work as an adsorbent in ACS [5]. As biomass is an abundantly available, low-cost, and carbon-neutral material, scientists and researchers are making their efforts in the direction of agro-residue-derived activated carbon and its composite for various sustainable energy applications.

Recently, several research attempts [6–8] have been made toward the usage of AC as an adsorbent for adsorption heat transformation applications. According to the available literature, the biomass-derived highly porous AC sorbents are significantly more effective in terms of adsorption capabilities and surface area, but to the best knowledge of authors, there is almost no numerical investigation reported so far to calculate the minimal, maximal, and optimal regeneration temperature for bioenergy powered single stage ACS. Therefore, it is necessary to calculate the maximum, minimum, and optimum limits of regeneration temperature for bioenergy-powered green cooling systems. Additionally, the present work aims to study the effects of various operational parameters on cooling performance and estimation of a new parameter i.e., the ratio of the mass of adsorbent to the mass of combustion fuel, which interlinks the bioenergy heating unit with a cooling system.

2. Bioenergy-Powered Adsorption Cooling System

The schematic of a green cooling system coupled with a bioenergy heating unit is shown in Fig. 1. It consists of two circuits: (i) a refrigerant circuit and (ii) a heating circuit. The refrigerant circuit includes a thermal compressor (a unit of adsorber and desorber), condenser, throttling valve, and evaporator; however, the heating circuit is having heat storage tank coupled with a bioenergy-based heating device developed by Tyagi *et al.* [9]. The combustion of agro-residue waste solid biofuels takes place in a biomass combustion device, where the hot fluid i. e. water heated up and then transports thermal energy to the sorption reactor or thermal compressor for regeneration of the adsorbent bed [10]. The thermal compressor consists of two highly porous activated carbons derived from waste biomass as adsorbents for the adsorption and desorption of ethanol vapor which is circulating in the refrigerant circuit as an adsorbate. The required fitting parameters such as maximum uptake, activation energy, and index parameter in equilibrium uptake model for both adsorbents are tabulated in Table 1.

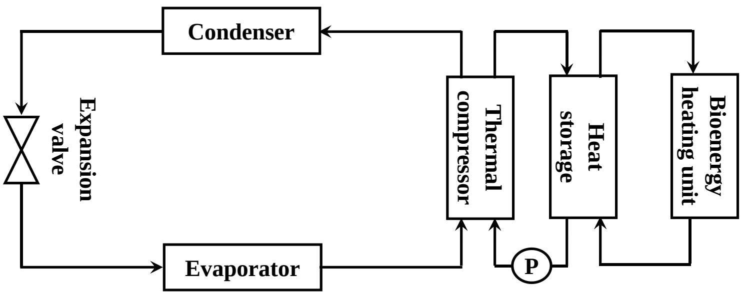

Fig. 1. Bioenergy coupled green cooling system.

3. Mathematical Modeling

The theoretical modeling for a steady-state single-stage double-bed adsorption cooling system is discussed in detail [11]. To couple the bioenergy-based heating unit with a cooling system, a mathematical expression is presented.

3.1. Equilibrium uptake model

The equilibrium adsorption uptake value is calculated by Dubinin-Astakhov (D–A) model along with the Antoine equation at a specified pressure and temperature conditions.

$$W = W_o \cdot \exp[-\{((R \cdot T)/E) \cdot \ln (P_s/P)\}^n] \quad (1)$$

where W, W_o, P, R, T, E, P_s, and n represent the equilibrium adsorption uptake (kg/kg), the maximum adsorption uptake (kg/kg), equilibrium pressure (kPa), gas constant (kJ/kg-K), temperature (K), activation energy (kJ/kg), saturation pressure (kPa), and index parameter, respectively.

3.2. Isosteric heat of adsorption

The following expression can be used to calculate the isosteric heat of adsorption, which is the amount of thermal energy released during the landing of refrigerant over the porous surface of the adsorbent.

$$-Q_{st} = R \cdot T^2 \cdot (dP_s/dT) + E \cdot \{-\ln (W/W_o)\}^{(1/n)} \quad (2)$$

3.3. Cooling power assessment

The thermodynamic performance analysis of the adsorption refrigeration cycle is carried out in terms of cooling power (CP), given in the following Eq. (3).

$$CP = m_{ref} \cdot dh_{evap} \quad (3)$$

The mass flow rate of adsorbate (m_{ref}) can be calculated as:

$$m_{ref} = m_{ad\text{-}ref}/t_{ads} = (m_{ad} \cdot \Delta W)/ (2 \cdot t_{ads}) \quad (4)$$

where, the change in adsorption uptake is represented by $\Delta W=W_{max}-W_{min}$. The $m_{ad\text{-}ref}$, m_{ad}, dh_{evap}, and t_{ads} represent mass of adsorbed refrigerant, the mass of adsorbent, the latent heat of vaporization, and the adsorption time, respectively.

3.4. Estimation of COP

The coefficient of performance (COP) can be estimated by the following expression,

$$COP = (CP \cdot t_{ads})/Q_{h,in} \quad (5)$$

The heat input $Q_{h,in}$ is the summation of heat required by the metallic cover, refrigerant or adsorbate, adsorbent, and heat of adsorption.

$$Q_{h,in} = Q_{mc} + Q_{ref} + Q_{ad} + Q_{st} \quad (6)$$

The heat required by the metallic cover (Q_{mc}),

$$Q_{mc} = m_{mc} \cdot c_{p\_mc} \cdot (T_{des} - T_{ads}) \quad (7)$$

The heat required by adsorbate (Q_{ref}),

$$Q_{ref} = m_{ad\text{-}ref} \cdot c_{p\_ref} \cdot (T_{des} - T_{ads}) \quad (8)$$

The heat required by adsorbent (Q_{ad}),

$$Q_{ad} = m_{ad} \cdot c_{p\_ad} \cdot (T_{des} - T_{ads}) \quad (9)$$

where, T_{ads}, T_{des}, m_{mc}, m_{ad}, c_{p_mc}, and c_{p_ad} represent the adsorption temperature, desorption temperature, mass of metal cover, the mass of adsorbent, specific heat of metal cover, and specific heat of adsorbent, respectively.

3.5. Mass of adsorbent to combustion fuel

The mass of adsorbent material to combustion fuel is considered a new performance index for bioenergy-powered ACS [12], and can be estimated using:

$$m_{ad}/m_{cf} = Q_{use}/Q_{h,in} \quad (10)$$

where, $Q_{use} = \eta_{b\_device} \cdot m_{cf} \cdot LHV_{cf}$

The efficiency of a bioenergy device (η_{b_device}) i.e., a small-scale gasifier or combustion device, and the low heating value of combustion fuel (LHV_{cf}) are given in published literature [13]. The fitting parameters based on the D-A isotherm model for both highly porous adsorbents derived from waste biomass material are given in Table 1.

Table 1. Fitting parameters for D-A isotherms

Adsorbent	Fitting parameters		
	W_o (kg/kg)	E (kJ/kg)	n (-)
WPT AC	1.90	91.55	1.43
M AC	1.65	105.91	1.62

4. Discussion of results

In order to study the maximal, minimal, and optimal limits of desorption temperature, a steady-state thermodynamic performance analysis is carried out for the temperature range of 60 to 200 °C. A detailed comparative investigation has been presented based on CP, COP, and mad/mcf in the sub-sections.

4.1. Evaluation of ΔW

The effects of ambient temperature and desorption temperature on the difference between maximum uptake and minimum uptake are shown in Fig. 2. Initially, the changes in uptake shoot up with an increase in desorption temperature up to approximately 110 °C due to the dramatic reduction in the minimum uptake while maximum uptake remains constant irrespective to the desorption temperature. Afterward, the change in uptake keeps increasing at a slow pace, and the graph flatter beyond the desorption temperature of 140 °C for both the adsorbents as well as the ambient temperatures. Here in, it can be seen that the difference in uptake is more at a low value of ambient temperature for both the adsorbents. This is because of the difference between the amount of the vapor adsorbed and desorbed at low- and high-pressure conditions. The change in adsorption uptake can be utilized as a criterion to estimate the maximum temperature for the regeneration temperature. Herein, it can be seen that after a certain value of change in uptake (near to the flattening of the graph), no further significant enhancement has been found in the ΔW. Therefore, the theoretical maximum regeneration temperature is identified when the percentage difference between the two consecutive measurements of ΔW is negligible (less than ± 0.5%). However, the experimental value of maximum regeneration temperature can be estimated by the degradation of refrigerant into some other non-useful compounds as suggested by Mahesh and Kaushik [14]. In the case of WPT AC at $T_{des,max}$, the ΔW is estimated as 0.5377 kg/kg at T_{amb} of 38 °C and 0.7298 kg/kg at T_{amb} of 32 °C, respectively. On the other hand, the ΔW at $T_{des,max}$ for M AC is estimated as 0.5872 kg/kg at T_{amb} of 38 °C and 0.7770 kg/kg at T_{amb} of 32 °C, respectively.

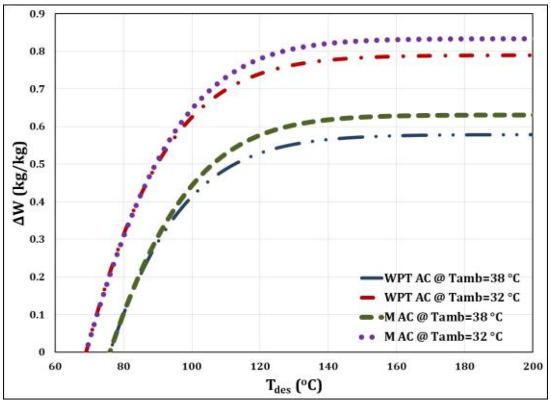

Fig. 2. Effect of ambient temperature on the change in uptake.

4.2. Variation in heat input

It shows how much thermal or heat energy is required to desorb the liquid molecules of refrigerant from the porous surface of the adsorbent. As per Eq. (6), heat input is the summation of thermal energy required by the metallic cover, refrigerant or adsorbate, adsorbent, and heat of adsorption. From Fig. 3, the heat input increases with an increase in desorption temperature whereas it is found to be higher at low ambient temperature conditions. To compare the heat input requirement by both adsorbents, the M AC requires more heat to desorb the adsorbate molecules at fix temperature of desorption. The WPT AC offers a low desorption temperature requirement at a constant value of heat input. This is because of the higher specific heat of the M AC. The lower heat input helps in the higher performance of the cooling system.

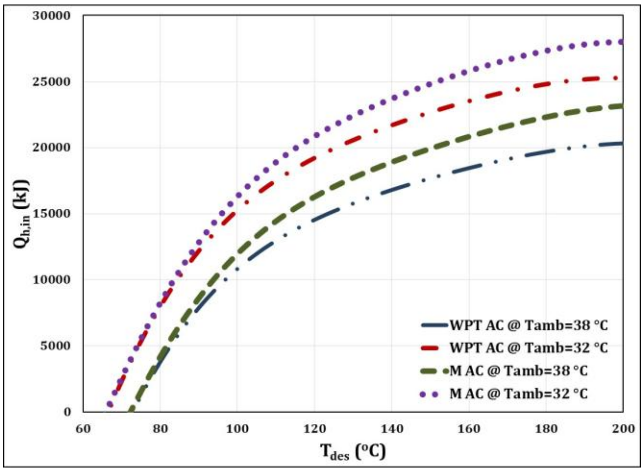

Fig. 3. Heat addition at different ambient temperatures.

4.3. Comparison based on cooling power

Cooling power (CP) is the measure of the size of a refrigeration system. It is a function of the mass flow rate of the refrigerant, thermophysical property of the refrigerant and adsorbent, latent heat of vaporization, time of adsorption, and change in uptake. CP shows a similar trend of the curve as a change in adsorption uptake is having. In this analysis, the minimum CP is utilized as the criterion for minimal desorption temperature. It means the intersection point of the CP curve at the desorption temperature axis gives the lowest temperature required for the regeneration of the adsorbent bed [15]. This shows that there is a throughput from the thermal compressor at this temperature. Therefore, according to this criterion, the adsorption cooling system working at low ambient temperature conditions requires a lesser minimum regeneration temperature. Herein, the minimal regeneration temperature is the same for both the adsorbents i. e. WPT AC and M AC as shown in Fig. 4. The CP value at optimum desorption temperature is calculated as 14.67 ton at T_{amb} of 38 °C and 19.34 ton at T_{amb} of 32 °C, respectively, for WPT AC. In the case of M AC, the CP values at optimal desorption temperature are calculated as 16.49 ton at T_{amb} of 38 °C and 20.79 ton at T_{amb} of 32 °C, respectively.

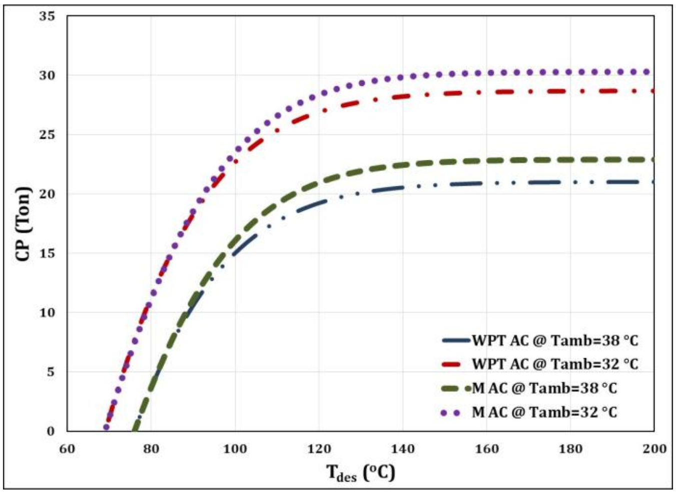

Fig. 4. Cooling power corresponds to desorption temperature.

4.4. Comparison based on COP

The coefficient of performance (COP) of a system shows the effectiveness of the cooling system. It can be seen from Fig. 5 that there is a peak in the COP curve which indicates the optimum value of temperature for the regeneration of the adsorbent bed. As the desorption temperature increases, the COP increases drastically up to a certain value of temperature, later on, it starts decreasing at a slow pace. Therefore, COP is utilized as a criterion to identify the optimal value for regeneration temperature. Similar to the CP, COP is found to be higher at low ambient temperatures. Moreover, the WPT AC shows a comparatively high value of COP than that of the M AC. The maximum COP is found to be 0.48 for WPT AC and 0.47 for M AC, respectively at T_{amb} of 38 °C. Moreover, the maximum COP at T_{amb} of 32 °C is found to be 0.52 for WPT AC and 0.50 for M AC, respectively.

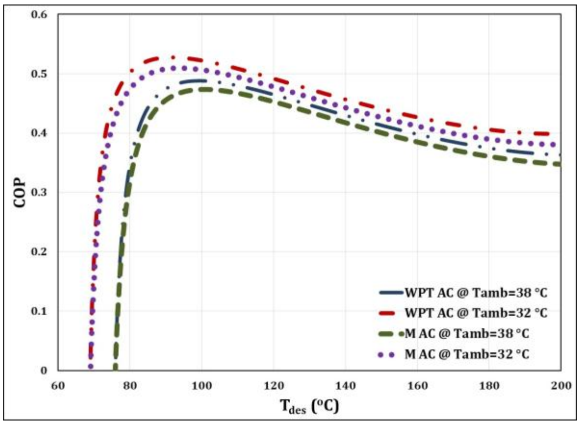

Fig. 5. COP corresponds to desorption temperature.

4.5. Comparison based on the mass of adsorbent to combustion fuel

In order to theoretically link the heating unit which is driven by a bioenergy system, the ratio between the mass of adsorbent to the mass of combustion fuel is considered as the important parameter. The minimum value of this ratio is an indicator to select the best adsorbent material at particular operating conditions. It can be seen that the ratio between the mass of adsorbent to the mass of combustion fuel drastically decreases with an increase in desorption temperature. At constant ambient temperature, M AC requires less mass of adsorbent per kg of fuel combustion. At a constant value of mad/mcf, the system at a low ambient temperature can give a throughput than that of the system at a higher ambient temperature, as shown in Fig. 6. At $T_{des,opt}$, the values of mad/mcf are found to be 7.39 kg/kg at T_{amb} of 38 °C and 7.28 kg/kg T_{amb} of 32 °C for WPT AC. Moreover, in the case of M AC at the maximum COP, it is found to be 7.08 kg/kg at T_{amb} of 38 °C and 7.02 kg/kg T_{amb} of 32 °C, respectively.

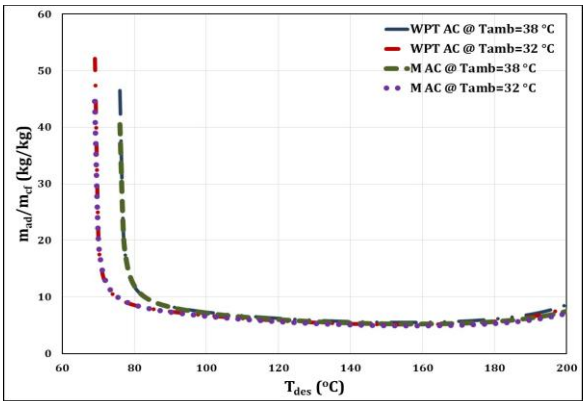

Fig. 6. Mass of adsorbent to combustion fuel corresponding to desorption temperature.

4.6. Comparison based on maximum, minimum, and optimum regeneration temperature

A comparative investigation for WPT AC and M AC adsorbents with ethanol refrigerant is carried out on the basis of minimal, maximal, and optimal values of desorption temperature at two different ambient conditions, as shown in Table 2. The minimum and optimal regeneration temperatures are calculated at the non-zero value of CP and greatest COP, respectively. On the other hand, the maximal COP is estimated when the percentage difference between the two consecutive data points of ΔW is negligible (less than ± 0.5%). It is estimated that both adsorbents with ethanol refrigerant require an equal amount of minimum regeneration temperature at both ambient temperatures. Unlike T_{amb} of 38 °C, WPT AC-ethanol can withstand a higher regeneration temperature than that of the M AC-ethanol pair at Treg of 32 °C. In the case of the optimal desorption temperature, M AC-ethanol needs a little high regeneration temperature than that of the WPT AC-ethanol pair for both ambient conditions. However, the WPT AC-ethanol pair shows higher COP than that of the M AC-ethanol pair at $T_{reg,min}$, and vice versa for the CP. As far as the minimal mad/mcf is concerned, the M AC-ethanol working pair requires less amount of adsorbent material per kg of combustion fuel for both temperatures of ambient.

Table 2. Maximal, minimal, and optimal desorption temperature

Adsorbent	Tads (℃) @ Tamb = 32 ℃			Tads (℃) @ Tamb = 38 ℃		
	Min.	Max.	Opt.	Min.	Max.	Opt.
WPT AC	69	119	92	76	123	99
M AC	69	117	94	76	123	101

5. Concluding Remarks

In the present study, an estimation of the minimal, maximal, and optimal limits of regeneration temperature for a single-stage bioenergy-powered ACS having two highly porous ACs has been conducted on the basis of cooling power, change in uptake, and COP, respectively. In order to interlink the bioenergy heating unit with the cooling system, the ratio of the mass of adsorbent to the mass of combustion fuel is considered as another performance index. The theoretical examination of the bioenergy-powered ACS can lead to the following inferences:

- The minimal Treg corresponding to the small throughput of the thermal compressor is found to be the same for both ACs irrespective of ambient temperatures.
- The peak in the COP curve denotes the optimal temperature for the regeneration of the adsorbent bed for both pairs.
- The values of optimum T_{reg} for WPT AC are found to be 92 °C (COP_{max} = 0.52, CP_{opt} = 19.34 ton, $(m_{ad}/m_{cf})_{opt}$ = 7.32 kg/kg) and 99 °C (COP_{max} = 0.48, CP_{opt} = 14.67 ton, $(m_{ad}/m_{cf})_{opt}$ = 7.39 kg/kg) at T_{amb} of 32 °C and 38 °C, respectively.
- At theoretical $T_{reg,max}$, the values of COP and m_{ad}/m_{cf} are found to be lesser than that of the $T_{reg,opt}$. However, it is the reverse for CP.
- In the case of M AC, COP_{max}, CP_{opt}, and $(m_{ad}/m_{cf})_{opt}$ are estimated as 0.5, 20.79 ton, 7.02 kg/kg (at T_{amb} = 32 °C), and 0.47, 16.49 ton, 7.08 kg/kg (at T_{amb} = 38 °C) corresponding to $T_{reg,opt}$ of 94 °C and 101 °C, respectively.
- As far as the minimal mad/mcf is concerned, the M AC-ethanol working pair requires less amount of adsorbent material per kg of combustion fuel for both temperatures of ambient.
- In contrast to the WPT AC-ethanol pair, the M AC-ethanol pair uses less heat to desorb the adsorbate molecules at a fixed desorption temperature.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Author Contributions

P. R. Chauhan: Conceptualization, Investigation, Methodology, Software, Data curation, Formal analysis, Writing - original draft, Writing - re-view & editing. S. K. Tyagi: Conceptualization, Writing - re-view & editing, Supervision.

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