

Technical Note

Performance of a dual-purpose solar continuous adsorption system

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ABSTRACT

A conceptual design and performance of a dual-purpose solar continuous adsorption system for domestic refrigeration and water heating is described. Malaysian activated carbon and methanol are used as the adsorbent–adsorbate pair. The heat rejected by the adsorber beds and condensers during the cooling process of the refrigeration part is recovered and used to heat water for the purpose of domestic consumption. In a continuous 24-h cycle, 16.9 MJ/day of heat can be recovered for heating of water in the storage tanks. In the single-purpose intermittent solar adsorption system, this heat is wasted. The total energy input to the dual-purpose system during a 24-h operation is 61.2 MJ/day and the total energy output is 50 MJ/day. The latter is made up of 44.7 MJ/day for water heating and 5.3 MJ/day for ice making. The amount of ice that can be produced is 12 kg/day. Using typical value for the efficiency of evacuated tube collector of water heating system of 65%, the following coefficient of performances (COP's) are obtained: 44% for adsorption refrigeration cycle, 73% for dual-purpose solar water heater, 9.1% for dual-purpose solar adsorption refrigeration and 82.1% for dual-purpose of both solar water heater and refrigerator.

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1. Introduction

Storage tank and solar collectors are the main components of any solar water heating system. Since storage tank and solar collectors also form part of a solar adsorption refrigeration system, the later can be modified to include water heating as well. It is hope that in this way the dual-purpose system (refrigeration and water heater) can help reduce the cost, size and perhaps increase the efficiency of the original solar adsorption refrigeration system. In addition to making the solar adsorption system into a water heating system as well, provision can be made to allow such a system to work continuously instead of intermittently. The latter is a property of most solar adsorption refrigeration system.

In the intermittent solar adsorption refrigeration, the adsorption of the adsorbate (e.g. methanol) by the adsorbent (e.g. activated carbon) occurs throughout the night on gradual cooling while the desorption process (the reverse of adsorption) occurs throughout the day on gradual heating. It is the adsorption of the adsorbate that produces the refrigeration effect resulting in the cooling or freezing of the water at the evaporator. Both the heating and cooling of the adsorbent can be brought about using water as the medium. In that way, during the day the water in a storage tank can be heated using

solar collector, causing a rise in the temperature of an adsorber bed (containing the adsorbent) immersed in the water. Besides heating the adsorber bed, the hot water can now be used for domestic purpose, thus, acting as a dual-purpose system. The adsorbate that is desorbed is cooled by a condenser of lower temperature than the adsorber before being returned to the evaporator. In a typical system the heat released by the condenser is usually not recovered. As the evening progresses, the cooled water of the storage tank causes the adsorber to adsorb the adsorbate from the evaporator as a result of a pressure gradient. Heat is then carried away from the evaporator by the adsorbate producing the refrigeration effect. In a 24-h cycle, ice is only produced during the 12-h evening cycle leading to the intermittent nature of the system.

If two storage tanks are installed, each containing a condenser and an adsorber and the temperatures of the water in these tanks are regulated so that the processes of adsorption and desorption occur out of phase, a continuous adsorption refrigeration can be realized. In this paper we describe a conceptual design of such a dual-purpose continuous solar adsorption system. The performance based on a theoretical calculation is presented. Finally, we put forward the estimated cost of production of the system and the payback period.

2. Literature review

Limited designs of solar intermittent adsorption refrigeration have been commercialized (Boubakri et al. [1], Meunier [2], Critoph

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Nomenclature

A_{coll}	area of solar collector (m^2)	M_{hw}	mass of hot water (kg)
C_a	specific heat of adsorber (kJ/kgK)	M_{ice}	mass of ice (kg)
C_{ac}	specific heat of activated carbon (kJ/kgK)	N	payback period (years)
$C_{\text{l,meth}}$	specific heat of liquid methanol (kJ/kgK)	$\eta_{\text{net,eff.heater.refrig}}$	average efficiency of combined conventional heater and refrigerator
$C_{\text{unit.elec}}$	cost of unit electricity (RM/kWh)	$Q_{\text{netcooling}}$	heat to change water at ambient temperature to ice (kJ)
C_w	specific heat of water (kJ/kgK)	$Q_{\text{heat-des}}$	heat desorped by adsorber bed (kJ)
D	discount rate	$Q_{\text{cool-ads}}$	heat adsorbed by adsorber bed (kJ)
G	global solar radiation on horizontal surface at Malaysian location (MJ/m^2)	T_{hw}	temperature of hot water ($^{\circ}\text{C}$)
h (h')	average enthalpy of methanol (kJ/kg)	T_0	ambient temperature ($^{\circ}\text{C}$)
I	inflation rate	T_e	temperature of ice ($^{\circ}\text{C}$)
L_{meth}	latent heat of methanol (kJ/kg)	$T_{\text{hot.water}}$	temperature of hot water ($^{\circ}\text{C}$)
L_{ice}	latent heat of ice (kJ/kg)	X_{conc}	concentrated concentration of methanol per unit mass of activated carbon (kg/kg)
M_a (M'_a)	mass of adsorber (kg)	X_{dil} (X'_{dil})	dilute concentration of methanol per unit mass of activated carbon (kg/kg)
M_{ac} (M'_{ac})	mass of activated carbon (kg)		
M_{meth}	mass of liquid methanol (kg)		

[3], and Tchernev [4]). Although, these designs were technically successful, more research and development are required to make them cost competitive with the conventional or equivalent vapor compression systems.

Continuous solar adsorption refrigeration systems are widely reported because of their higher performance than intermittent ones and for their ability to produce cooling and refrigeration at the same time. Work on the continuous adsorption system have been reported by Douss and Meunier [5], whose cascading cycle consisted of a two adsorber zeolite–water high temperature stage and an intermittent active carbon–methanol low temperature stage. The experimental cooling COP was found to be 1.06 much more than the COP of an intermittent cycle (0.5) and more than the COP of a two adsorber zeolite water cycle 0.75. Saha et al. [6] incorporated a two-stage non-regenerative adsorption chiller in an experimental adsorption heat pump of silica gel–water. The two stage was found to operate effectively with 55°C solar/waste heat in combination with a 30°C coolant temperature. In another study, a heat regenerative adsorption refrigerator using spiral plate heat exchangers as adsorbers and an adsorption heat pump for air conditioning using as adsorbers plate fin heat exchangers or plate fin shell and tube type heat exchangers were developed by Wang et al. [7]. The two systems used activated carbon and methanol as adsorption pair. With a heat source temperature of 100°C , the refrigerator achieved a refrigeration power density of more than 2.6 kg ice per day per kg activated carbon with a COP of 0.13 and the heat pump achieved 150 W/kg activated carbon for air conditioning with a COP of about 0.4. Ben Amar et al. [8] carried out a two dimensional numerical analysis of an adsorptive heat pump system with the temperature wave heat generation. Numerical simulations were performed on two adsorption systems: zeolite–NaX–water and activated carbon AX21–ammonia. The effects of the operating parameters, such as cycle time, permeability and heating temperature, on the COP and the power of cold production were discussed. Critoph [9,10] performed two studies on forced convection adsorption cycle with packed bed heat regeneration. Rather than attempting to heat the bed directly, it was possible to heat the refrigerant gas outside the bed and to circulate it through the bed in order to heat the sorbent. Thermodynamic modeling based on measured heat transfer and porosity data predicted a cycle COP (for a specific carbon) of 0.95 when evaporating at 0°C and condensing at 42°C , and 0.90 when evaporating at 5°C and condensing at 40°C with a generating temperature of 200°C and a modest system regenerator effectiveness of 0.8. In another study, regenerative cycles using two or more refrigerant–adsorbent combinations have been

reported by Douss and Mennier [11]. The simplest one involved two intermittent adsorption cycles operated out of phase such that when one was being heated, the other cooled.

A hybrid adsorption system was reported by Schwarz et al. [12] employing zeolite as the adsorbent and water as the refrigerant. The sensible heat of the adsorber bed and the heat of adsorption were used to heat the water while cooling was achieved using adsorption–evaporation principle. Wang et al. [13] developed a hybrid system of solar-powered water heater and icemaker. The system comprised a solar collector, water tank adsorber/generator, condenser, evaporator, receiver and ice box. The working principle was based on the combination of a solar water heater and an adsorption refrigerator. Wang et al. [14] also developed a combined cycle of heating and adsorption refrigeration. The system consisted of a heater, a water bath and activated carbon–methanol adsorption bed and ice box. This system was also tested with electric heating. The experiments showed the potentials of the application of the solar-powered hybrid water heater and refrigerator. Theoretical simulation was carried out which was found to be in good agreement with the experimental results. A flat plate solar hybrid system with heating and cooling was proposed by Li et al. [15] and an experimental prototype was constructed. With this new hybrid system, both the heat and mass transfer in desorption and adsorption processes were improved effectively. A conventional flat plate solar water heater collector was immersed inside the adsorber bed. The experimental results showed that not only the cooling effect could be obtained, but both the sensible heat of the adsorbent bed and the adsorption heat were recovered effectively to produce hot water for domestic use. The coefficient of performance (COP) of this new flat plate hybrid system reached 0.11 and the heat efficiency was about 0.45. A continuous hybrid solid adsorption–ejector for refrigeration and heating system driven by solar energy was proposed by Zhang and Wang [16]. The thermodynamic theory of this system was constructed, and the performance, simulation and analysis were made under normal working conditions. Zeolite–water–working pair was chosen in view of the good solar energy utilization. From the simulation, the combined hybrid system had a cooling capacity of 0.15 MJ/kg zeolite during daytime and a cooling capacity of 0.34 MJ/kg zeolite in the evening, and could furnish 290 kg hot water at 45°C for domestic use. Furthermore, under the same working conditions, compared with an adsorption system without an ejector with a COP of 0.3, the combined system's COP improved by 10%. In another paper Zhang and Wang [17] reported another design of a continuous solid adsorption refrigeration and heating system driven by solar energy.

The system consisted of a hybrid adsorption bed array, water tank, condenser, evaporator, liquid receiver, throttle valve, valves. Simulation and analysis were conducted under normal working conditions. Some performance parameters of the system were obtained and the effects of water mass in the water tank on the system's $COP_{cooling}$ and $COP_{heating}$ were discussed. The simulation indicated that the system could refrigerate continuously. The working conditions reported were as follows: daily sun-radiation: 21.6 MJ, mean ambient temperature: 29.9 °C, evaporating temperature: 5 °C, heat-collecting coefficient of upper bed: 60% and heat-transfer coefficient between lower bed and ambient α : 2 W/m² K. In the day, a hybrid system of single combined bed could furnish 30 kg of hot water at a temperature of 47.8 °C and had a mean $COP_{cooling}$ of 0.18, a mean $COP_{heating}$ of 0.34. In the evening, the cooling capacity was 0.26 MJ/kg of adsorbent with 1.3 MJ/m² of heat-collecting area. In this paper the performance of a new working cycle of a dual-purpose continuous adsorption system for domestic refrigeration and water heating was also presented.

3. Design of the dual-purpose continuous solar adsorption system

The proposed dual-purpose solar adsorption system consists of

1. Solar thermal collectors for water heating.
2. Two water storage tanks each containing an adsorber bed and a condenser, and are labeled according to the storage tanks they are associated with (see Fig. 4).
3. Receiver, evaporator and ice box.
4. Activated carbon as adsorbent and methanol as adsorbate.

In order to explain the working cycle, reference should be made to the ideal P–T–X diagram of Fig. 1. The diagram is drawn on the first quadrant of the coordinate system and therefore even though the x -axis gives the reciprocal temperature, the understanding is that T increases in the direction of increasing x . The relative concentration of methanol (mass of methanol per mass of activated carbon) is given as X and P_e and P_c are the pressures of the evaporator and condenser, respectively. The path $T_{a2} \rightarrow T_{d1} \rightarrow T_{d2}$ is the desorption cycle when the temperature of the methanol in the absorber bed increases and the pressure reaches saturation. The methanol is then discharged from the absorber and its heat ($Q_{1-des} + Q_{2-des} = Q_c$) only to be released at the condenser. The adsorption path is given by $T_{d2} \rightarrow T_{a1} \rightarrow T_{a2} \rightarrow T_e$. During this cycle the methanol is adsorbed by the adsorbent as its temperature is reduced and the heat ($Q_{1-ads} + Q_{2-ads} = Q_e$) is then taken away from

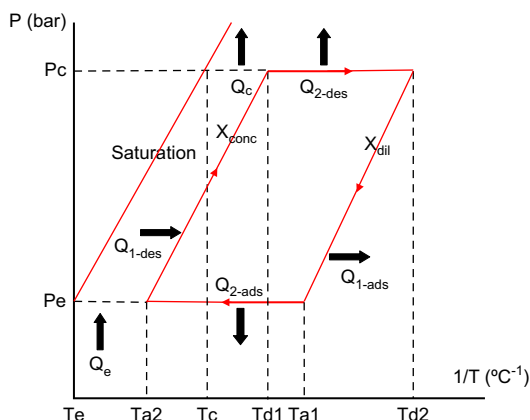


Fig. 1. P–T–X diagram of activated carbon/methanol adsorption system.

the evaporator to be discharged at the adsorber bed. The evaporator is then cooled to a temperature T_e .

In order to produce a continuous working cycle two adsorber beds and two condensers are used. Adsorber bed 1 is connected to condenser 2 and adsorber bed 2 is connected to condenser 1. As shown in Fig. 2, during the day, desorption of the methanol occurs from adsorber bed 1 to the receiver through condenser 2 while adsorption of the methanol occurs from the receiver to the adsorber bed 2 through condenser 1. To affect these cycles, the temperature of the water in storage tank 1 is gradually increased from T_{a2} until T_{d2} while the temperature of the hot water in storage tank 2 (from overnight recovery heat) is rapidly decreased from T_{d2} until T_{a2} through T_c .

In the evening, the roles of the two adsorber bed/condenser systems are reversed. Adsorber bed 2 produces desorption of methanol through condenser 1 into the receiver while adsorber bed 1 adsorbs methanol from the receiver through condenser 2. Thus the temperature of the water in storage tank 2 needs to be increased gradually from T_{a2} until T_{d2} while the temperature of the hot water in storage tank 1 needs to be rapidly reduced from T_{d2} until T_{a2} through T_c (see Fig. 3).

3.1. The heating cycle

In reality the above cycles can be achieved using setups shown in Figs. 4 and 5. Fig. 4 shows the path for regulating the temperature of the water in the two tanks. At sunrise valves 2 and 5 are open and valves 4 and 6 are closed to allow the temperature of the water in storage tank 1, filled by cold water from the main supply 1, to rise gradually as it is being heated by the solar collectors. The flow of cold water into storage tank 1 is stopped by closing valve 2 when the water temperature has reached the set temperature for adsorption. In the morning the temperature of the water in storage tank 2 is high due to the recovery heat from condenser 2 following the adsorption process that occurred overnight. In a typical intermittent system this energy is usually wasted. The temperature of the water in storage tank 2 must rapidly be reduced to allow not only desorption at adsorber bed 1 but also to allow adsorption at adsorber bed 2. This is carried out by allowing cold water 1 to flow into storage tank 2 through valve 3 and at the same time allowing the hot water to be utilized for domestic consumption through valve 7. At the end of these processes, valve 3 is then closed.

In the evening the temperatures of the water in the storage tank 2 must be gradually increased while the temperature of the water in storage tank 1 must be rapidly reduced. This can be done by transferring the hot water from storage tank 1 to storage tank 2 through valve 6 and allowing the hot water to be utilized for domestic use through valve 4. Cold water is also allowed to flow from the main supply 1 into storage tank 1 through valve 2. Valves 3, 5 and 7 must remain closed.

3.2. The cooling cycle

The refrigeration cycle in the dual-purpose solar system is shown in Fig. 5. During daytime the desorbed methanol from adsorber bed 1 is condensed in condenser 2, then evaporates in the receiver/evaporator and re-adsorbed in adsorber bed 2. During the evening, the methanol is desorbed from adsorber bed 2 and condensed in condenser 1, then evaporates in the receiver/evaporator to be adsorbed again in adsorber bed 1.

3.3. Theoretical analysis of the dual system

3.3.1. The heating process

3.3.1.1. Daytime. The desorption process of adsorber bed 1 takes place along the temperature path $T_{a2} \rightarrow T_{d2}$ from morning until the

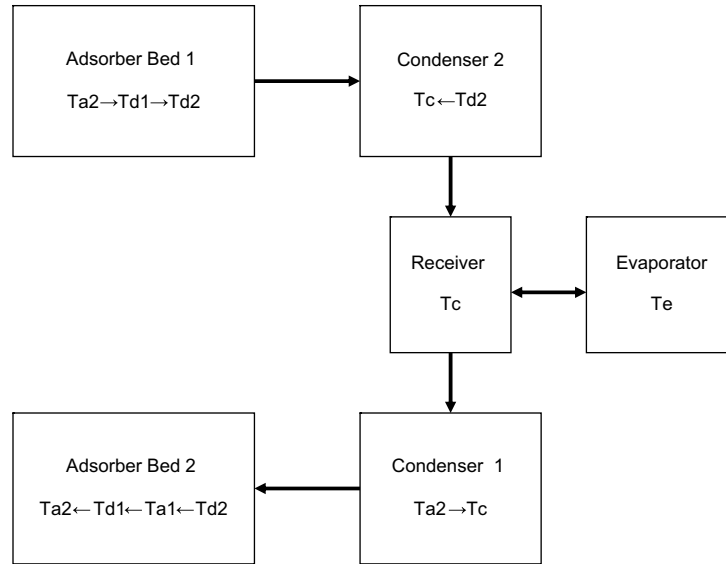


Fig. 2. Temperature cycle of the solar adsorption system during daylight.

end of daylight. The heat is obtained from the water in storage tank 1 heated by the solar collectors. This is given as

$$Q_{\text{heat-des}} = \{M_a C_a + M_{ac} C_{ac}\} (T_{d2} - T_{a2}) + M_{ac} X_{\text{conc}} C_{l,\text{meth}} (T_{d1} - T_{a2}) + M_{ac} (X_{\text{conc}} - X_{\text{dil}}) h + M_{ac} \left(\frac{X_{\text{conc}} + X_{\text{dil}}}{2} \right) C_{l,\text{meth}} (T_{d2} - T_{d1}) \quad (1)$$

where the first term is the sensible heat of the adsorber bed material and activated carbon, the second term is the sensible heat of the concentrated methanol liquid in the activated carbon before the start of the desorption process, the third term is due to the enthalpy of desorption and the fourth term is the average sensible heat of methanol in the activated carbon during the desorption process.

The concentration X , mass of methanol adsorbed per unit mass of activated carbon $\text{kg}_{\text{meth}}/\text{kg}_{\text{ac}}$ can be obtained from the equation of state of the solid–vapor equilibrium given as a functional form

$X = f(P, T)$. The Dubinin–Astakhov (D–A) equation relates concentration, pressure and temperature according to

$$X = \rho_{\text{meth}} W_0 \exp \left\{ -D \left(T \ln \frac{P_s}{P} \right)^n \right\} \quad (2)$$

The enthalpy of desorption (kJ) is given by

$$H_{\text{des}} = \int_{X_{\text{dil}}}^{X_{\text{conc}}} h M_{ac} dX = \int_{T_{d1}}^{T_{d2}} h M_{ac} \frac{dX}{dT} dT \quad (3)$$

where h (kJ/kg) is the average enthalpy calculated by taking the average of the slopes of two extreme isosters of X_{conc} from $(T_{a2} \rightarrow T_{d1})$ and X_{dil} from $(T_{d2} \rightarrow T_{a1})$ using the Clausius–Clapeyron equation which is dependent on X .

The energy equation of solar water heating during daytime can be written as

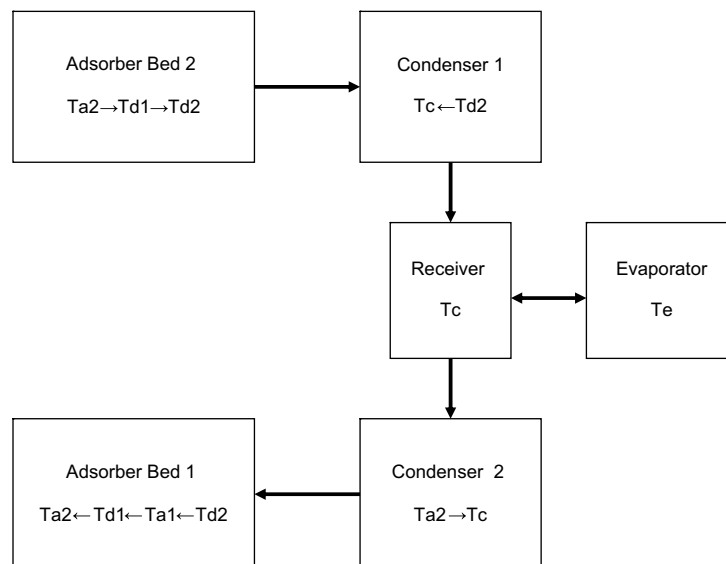


Fig. 3. Temperature cycle of the solar adsorption system during the night.

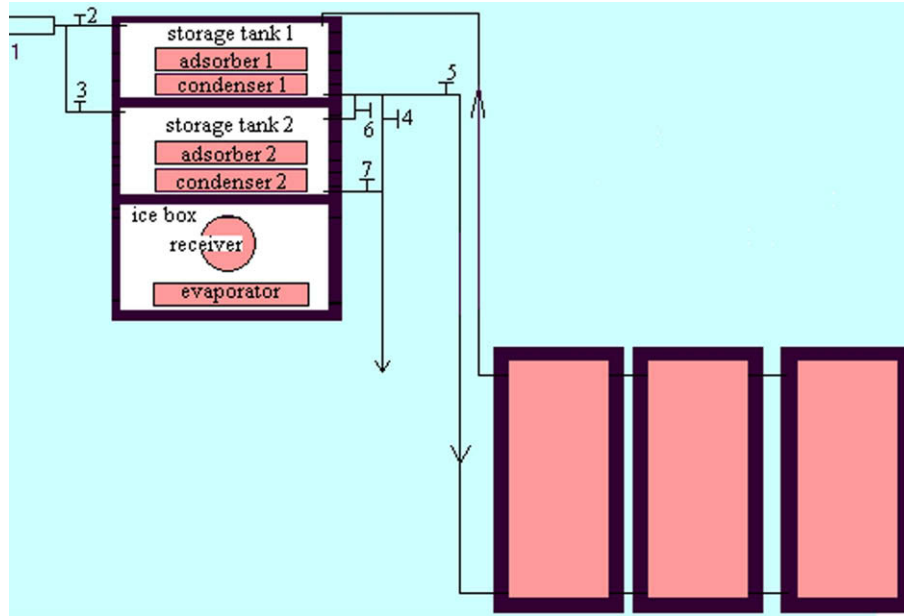


Fig. 4. Solar water heating cycle in the dual-purpose system: (1) cold water supply (2, 3) valves controlling the supply of cold water into storage tanks 1 and 2 (4) valve of domestic hot water from first storage tank (water heated by solar collector and recovered heat). (5) valve controlling the flow of water through the solar collectors (6) valve for hot water flow from storage tank 1 into storage tank 2 and (7) valve controlling the flow of domestic hot water from storage tank 2 during day time.

$$Q_{\text{hot, water}} = M_{\text{hw}} C_w (T_{\text{hw}} - T_0) \quad (4)$$

The energy equation of solar heat is then made up of

$$Q_{\text{solar, heat}} = Q_{\text{hot, water}} + Q_{\text{heat-des}} \quad (5)$$

3.3.1.2. Night time. The water heated to T_{hw} ($^{\circ}\text{C}$) in storage tank 1 is used to heat adsorber bed 2 by draining into storage tank 2. However, it is not that straight forward to raise the temperature of

the adsorber bed in storage tank 2 from $T_{\text{a2}} \rightarrow T_{\text{d2}}$ during the night because the required mass of hot water at T_{hw} ($^{\circ}\text{C}$) is going to be large and this is given by

$$M_{\text{hw}} = \frac{Q_{\text{heat-des}}}{C_w (T_{\text{hw}} - T_{\text{d2}})} \quad (6)$$

To circumvent this problem, a lower generating temperature T'_{d2} of adsorber bed 2 is used. However, in order to desorb the same mass of methanol at a lower generating temperature, bigger mass M' of activated carbon is required for adsorber bed 2. Now the temperature of the adsorber bed 2 is raised from $T_{\text{a2}} \rightarrow T'_{\text{d2}}$ by filling it with hot water from storage tank 1. This hot water can also be used for domestic purposes. The heat of adsorption of adsorber bed 2 is thus given by

$$Q'_{\text{heat-des}} = \{M'_a C_a + M'_{\text{ac}} C_{\text{ac}}\} (T'_{\text{d2}} - T_{\text{a2}}) + M'_{\text{ac}} X_{\text{conc}} C_{\text{l, meth}} (T_{\text{d1}} - T_{\text{a2}}) + M'_{\text{ac}} (X_{\text{conc}} - X'_{\text{dil}}) h' + M_{\text{ac}} \left(\frac{X_{\text{conc}} + X'_{\text{dil}}}{2} \right) C_{\text{l, meth}} (T'_{\text{d2}} - T_{\text{d1}}) \quad (7)$$

3.3.2. The cooling process and heat recovery

3.3.2.1. Day time. During the day, the temperature of the adsorber bed 2 has to be reduced gradually from $T'_{\text{d2}} \rightarrow T_{\text{a2}}$ to cause the adsorption process. This is done by lowering the temperature of the hot water by draining it to the household pipe and topping up storage tank 2 with cold water from the main supply. As the temperature of the water in storage tank 2 is reduced, methanol begins to condense in condenser 2 as a result of desorption at adsorber bed 1. The liquid methanol flows to the evaporator via a flow rate-regulating valve. Evaporation then takes place if the connecting valve with adsorber bed 2 is open and ice is then formed in the refrigeration box.

The energy equation of the adsorption process $T'_{\text{d2}} \rightarrow T_{\text{a2}}$ at adsorber bed 2 resulting in the cooling effect is given by

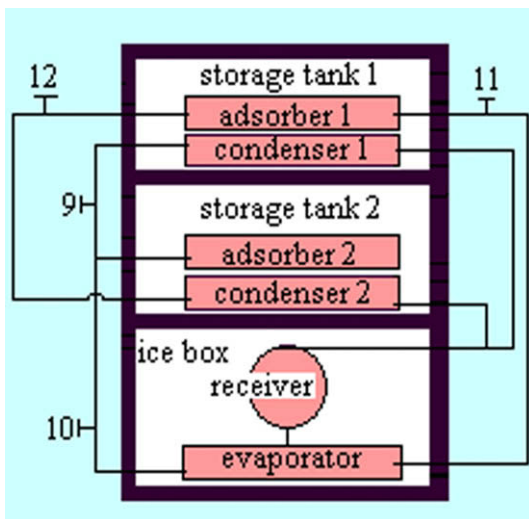


Fig. 5. The refrigeration cycle of the adsorption system: (9) valve controlling the flow of desorbed methanol from adsorber bed 2 during the night (10) valve controlling the flow of cold vapor methanol adsorbed by adsorber bed 2 during daytime (11) valve controlling the flow of cold vapor methanol adsorbed by adsorber bed 1 during the night and (12) valve controlling the flow of desorbed methanol from adsorber bed 1 during the day.

$$Q'_{\text{cool-ads}} = \{M'_a C_a + M'_{ac} C_{ac}\} (T'_{d2} - T_{a2}) + M'_a X_{\text{dil}} C_{l,\text{meth}} (T'_{d2} - T'_{a1}) + M'_a (X_{\text{conc}} - X'_{\text{dil}}) h' + M'_a \left(\frac{X_{\text{conc}} + X'_{\text{dil}}}{2} \right) C_{l,\text{meth}} (T'_{a1} - T_{a2}) \quad (8)$$

3.3.2.2. *Night time.* At sunset, the hot water temperature in storage tank 1 is T_{hw} and this water is then drained from storage tank 1 to storage tank 2. Cold water from the main supply is allowed to flow into storage tank 1 reducing its temperature so that the adsorption process at adsorber bed 1 can be initiated. During the night, the desorbed methanol from adsorber bed 2 is condensed in condenser 1 and flows to the evaporator via a flow rate-regulating valve. Evaporation takes place if the connecting valve with adsorber bed 1 is open.

The energy equation of the adsorption process $T_{d2} \rightarrow T_{a2}$ at adsorber bed 1 resulting in the cooling effect is given by

$$Q_{\text{cool-ads}} = \{M_a C_a + M_{ac} C_{ac}\} (T_{d2} - T_{a2}) + M_{ac} X_{\text{dil}} C_{l,\text{meth}} (T_{d2} - T_{a1}) + M_{ac} (X_{\text{conc}} - X_{\text{dil}}) h + M_{ac} \left(\frac{X_{\text{conc}} + X_{\text{dil}}}{2} \right) C_{l,\text{meth}} (T_{a1} - T_{a2}) \quad (9)$$

The heat rejected by the condenser is given as

$$Q_{\text{con}} = M_{\text{meth}} C_{l,\text{meth}} (T_{d2} - T_c) + M_{\text{meth}} L_{\text{meth}} \quad (10)$$

The heat rejected from the adsorber beds ($Q_{\text{cool-ads}}$ and $Q'_{\text{cool-ads}}$) and the condensers (Q_{con}) during the cooling process is recovered and utilized as domestic hot water. Thus within 24 h the heat recovered is given as,

$$Q_{\text{hot.water-heat.recovery}} = Q_{\text{cool-ads}} + Q'_{\text{cool-ads}} + 2Q_{\text{con}} \quad (11)$$

Including the heat recovered, the total amount of heat given to the hot water during the 24 h operation is

$$Q_{\text{domestic.hot.water-total}} = M_{hw} C_w (T'_{d2} - T_0) + Q_{\text{hot.water-heat.recovery}} \quad (12)$$

In order to produce M_{ice} of ice, the heat energy that is extracted is

$$Q_{\text{netcooling}} = M_{\text{ice}} (L_{\text{ice}} + C_w (T_0 - T_e)) \quad (13)$$

The energy from solar heating is given as

$$Q_{\text{solar.heat}} = \eta G A_{\text{coll}} \quad (14)$$

where η is the solar collector efficiency given as

$$\eta(X) = 0.717 - 1.52X - 0.085GX^2 \quad (15)$$

with

$$X = \frac{T_m - T_a}{G} \quad (16)$$

where T_m is the average inlet and exit temperature of collector, T_a is the ambient temperature, and G is the insolation level.

For evacuated tube solar collector η is found to be in the range (0.62–0.84) as reported by Alghoul et al. [18].

3.4. Performance estimates

From the above equations the following performance indexes can be obtained.

- The coefficient of performance of the refrigeration subsystem single cycle,

$$\text{COP}_{\text{cycle-ice}} = \frac{Q_{\text{netcooling}}}{Q_{\text{heat-des}}} \quad (17)$$

- The coefficient of performance of the refrigeration cycle in the dual-purpose system,

$$\text{COP}_{\text{dual.system-ice}} = \frac{2Q_{\text{netcooling}}}{G A_{\text{coll}}} \quad (18)$$

- The coefficient of performance of domestic hot water in the dual-purpose system,

$$\text{COP}_{\text{dual.system-hot.water}} = \frac{Q_{\text{domestic.hot.water-total}}}{G A_{\text{coll}}} \quad (19)$$

- The coefficient of performance of the dual-purpose system,

$$\text{COP}_{\text{dual-system}} = \frac{2Q_{\text{netcooling}} + Q_{\text{domestic.hot.water-total}}}{G A_{\text{coll}}} \quad (20)$$

4. Results and discussions

The granular activated carbon used as adsorbent is a Malaysian type AC-5060 with $W_0 = 0.363$, $D = 0.00002067$, $n = 1.599$. W_0 is the maximum adsorption volume of the activated carbon. D is the function of the adsorbent microstructure and n describes the surface heterogeneity. The material properties used in the dual solar system are shown in Appendix.

In order to choose the optimum parameters of the design, a compromise must be made in the choice of the temperature and volume of hot water for the domestic hot water and refrigeration, volume of cold water for the cooling process (heat recovery process), efficiency, size, cost, and collectors' area. Table 1 shows the ideal cycle inputs and outputs of the dual-purpose system. Assuming an efficiency of about 65% for the solar collectors, it is seen that there is an acceptable improvement on the coefficient of performance of the hot water production; the reason being that there is utilization of the heat recovered from the cooling process besides the direct heating of the water. Also, the performance of the dual system has significantly improved in terms of heating and cooling. This means that the system is conducive for water heating and is also attractive with respect to size and cost for refrigeration.

5. Costing of the dual-purpose system

Based on the parameters of the ideal cycle the actual cost of the dual-purpose system using Malaysian activated carbon AC-5060 and methanol to produce 12 kg of ice daily and 45 MJ of domestic hot water is shown in Table 2. It is obvious that the main cost of the dual system is from the solar collectors and the adsorber tubes.

6. Payback period

In order to calculate the payback period, a few assumptions have to be made. Firstly, the solar adsorption system is assumed to be maintenance free for at least 10 years. Secondly, let us assume the payback period to be n when the cost of using the solar adsorption system will become equal to the cost of using a conventional water heater and a refrigerator. To work out the present worth of the electricity that is to be used for n years into the future to run the water heater and refrigerator, the discount d and

Table 1
The ideal cycle of the dual-purpose system

Adsorbent: activated carbon (AC-5060)			
Adsorbate: methanol			
$T_e = -5\text{ }^\circ\text{C}$, $T_0 = 27.5\text{ }^\circ\text{C}$, $T_c = T_{a2} = 30\text{ }^\circ\text{C}$, $T_{\text{hot,water}} = 98\text{ }^\circ\text{C}$, $M_{\text{ice}} = 12\text{ kg}$			
$T_{d2-1\text{st.adsorber.bed}} = 95\text{ }^\circ\text{C}$, $T_{d2-2\text{nd.adsorber.bed}} = 85\text{ }^\circ\text{C}$			
$G = 17\text{ MJ/m}^2$			
$A_{\text{coll}} = 3.6\text{ m}^2$			
Parameter	1st Adsorber bed	2nd Adsorber bed	Dual system
T_{a1}	68.6	68.6	
T_{d1}	53	44.2	
$X_{\text{conc}} (\%)$	0.166	0.166	
$X_{\text{dil}} (\%)$	0.082	0.11	
$M_{\text{ac}} (\text{kg})$	25	36	61
$M_a (\text{kg})$	37	55	92
m (No. of adsorber tubes)	19	28	47
$Q_{\text{sensible,heat,des}} (\text{kJ})$	3065	3934	6999
$H_{\text{des}} (\text{kJ})$	2963	2881	5844
$Q_{\text{heat,des}} (\text{kJ})$	6028	6815	12 843
$Q_{\text{con}} (\text{kJ})$	2815	2815	5630
$\text{COP}_{\text{cycle,ice}}$	0.467	0.413	0.440
$M_{\text{hw}} (\text{kg})$			116
$GA_{\text{coll}} (\text{kJ})$			61 200
$Q_{\text{solar-heat}} (\text{kJ})$			39 159
$Q_{\text{domestic.hot.water-direct solar}} (\text{kJ})$			27 849
$Q_{\text{hot.water,heat.recovery}} (\text{kJ})$	8199	8741	16 940
$Q_{\text{domestic.hot.water-total}} (\text{kJ})$			44 789
$\text{COP}_{\text{dual system-ice}}$			0.091
$\text{COP}_{\text{dual system-domestic.hot.water}}$			0.730
$\text{COP}_{\text{dual system}}$			0.821

inflation rates i have to be factored in. These rates are required in the expression for the cumulative present worth which is given as

$$P_a = \frac{1 - x^n}{1 - x} \quad (21)$$

where x is

$$x = \frac{1 + i}{1 + d} \quad (22)$$

If C_{elec} is the cost per day of the amount of electricity consumed to provide $Q_{\text{domestic.hot.water-total}}$ and $Q_{\text{netcooling}}$ per day, the present worth PW of electricity cost per annum is

$$\text{PW} = 365P_a C_{\text{elec}} \quad (23)$$

In evaluating Eq. (23) the unit electricity cost is assumed to be constant over the payback period of n years.

Thus the electricity cost per day is

$$C_{\text{elec}} = \frac{(Q_{\text{domestic.hot.water-total}} + Q_{\text{netcooling}}) C_{\text{unit,elec}}}{3600(\text{kJ/kWh}) \eta_{\text{net,eff.heater.refrig}}} \quad (24)$$

Table 2
Costing of the dual-purpose system using Malaysian activated carbon

Item	Cost (RM ^a)
Evacuated tube collectors	3600
Activated carbon	700
Adsorber tubes	2700
Water storage tank	1500
Evaporator-copper tubes	75
Condenser-copper tubes	150
Ice box	300
Piping and fitting	200
Total	9225

^a 1 USD = 3.2RM.

Table 3
Parameters used in the calculation of the payback period

Parameter	Remarks
Inflation rate i (%)	3
Discount rate d (%)	10
x	0.9364
$\eta_{\text{net,eff.heater.refrig}}$ (%)	80
$C_{\text{unit,elec}}$ (RM)	0.27
$Q_{\text{domestic.hot.water-total}} + Q_{\text{netcooling}}$ (kJ)	50 419
Daily electricity consumption (kWh)	17.5
Cost of electricity per annum (RM)	1725.28
Cost of water heater (RM)	400
Cost of refrigerator (RM)	800
Cost of solar adsorption system (RM)	9225
Payback period n (years)	5.3

With reasonable values of the parameters given in Table 3, the payback period is worked to be 5.3 years.

Even though the payback period of 5.3 years is reasonable, the system can be improved further to make it more attractive economically and technically. One way is to reduce the number of adsorber tubes of the adsorber bed. However, reducing the number of adsorber tubes will cause a reduction in the mass of the adsorbent. Thus searching for new adsorbent materials is essential. Wang et al. [19] have reported that, for specially treated activated carbon fiber ACF, the measured adsorption capacity of the methanol is two to three times greater than that of the normal activated carbon, and the estimated adsorption time is only about 1/5 to 1/10 of that of normal activated carbon used by Meunier et al. [20]. In such a case the system is suitable to be used in temperate countries where the strength of radiation is low and the length of daylight is variable.

Tamariot-Telto and Critoph [21] investigated the thermo physical properties of two types of monolithic activated carbons with an intention to design and fabricate a high performance generator for sorption refrigeration systems and heat pumps using ammonia as refrigerant. It was found that, reduction in volume from granular bed to monolithic bed was up to 50%, which could lead to a substantial economic gain.

To reduce the cost of the dual system further, solar collectors cost must be reduced. As reported by Alghoul et al. [18] "heat sheets" take advantage of a heat pipe effect to construct solar collectors of carbon steel in which the collector sheet itself is a flat plate version. In addition to its high thermal conductivity the heat sheet has the further advantage that its conductivity is only in one direction, so energy can be transported from the collector sheet to the water tubes but not vice versa.

The positive contribution of a heat sheet solar collector on the dual system will be highlighted in our future publication Alghoul et al [22] in which we include numerical data regarding performance and cost of the heat sheet solar thermal collector besides the cost of the dual system using activated carbon fiber and solar heat sheet collector.

7. Conclusion

A dual-purpose solar adsorption refrigerator and water heater is presented. The system uses activated carbon as adsorber and methanol as adsorbate. Two adsorber beds and condensers are used. Other components include a receiver, an evaporator and a ice box. Each combination of adsorber bed/condenser is immersed in water contained in a storage tank. Adsorber bed 1 is coupled to condenser 2, receiver, evaporator and adsorber bed 2, while adsorber bed 2 is coupled to condenser 1, receiver, evaporator and adsorber bed 1. The water in storage tank 1 is heated using solar collectors to a maximum temperature of 98 °C and the heat is regulated using flow valves. The temperature of the water is

regulated in order to cause the adsorption and desorption processes. In the day desorption occurs in adsorber bed 1 at a generating temperature of 95 °C while at the same time adsorption occurs in adsorber bed 2 at a temperature of 30 °C. In the evening desorption occurs in adsorber bed 2 at a lower generating temperature of 85 °C while at the same time adsorption occurs in adsorber bed 1 at a temperature of 30 °C. Thus the ice can be produced continuously. The amount of activated carbon used in adsorber bed 2 is about 35% more than that used in adsorber 1. This is to allow a lower terminating temperature of 85 °C for the desorption process in adsorber bed 2, making it suitable to be heated using hot water from storage tank 1. The total amount of hot water available for domestic used is 116 kg/day and the amount of ice produced is 12 kg/day.

Because the heat produced by the adsorber beds and condensers are recovered the coefficients of performance of this system is maximized. In a typical solar adsorption refrigerator, this heat is wasted. The coefficients of performances calculated are given as follows: $COP_{cycle-ice} = 0.44$, $COP_{dual-system-ice} = 0.091$, $COP_{dual-system-domestic-hot-water} = 0.73$, $COP_{dual-system} = 0.821$. The cost of the system is estimated to be RM9225 with a payback period of 5.3 years using reasonable values of the economic and technical parameters. The system performance and the cycle time can be improved further by using better quality adsorbent such as activated carbon fiber and high efficiency solar collectors such as heat sheets. Such a system is suitable to be used in temperate climate where the strength of radiation is low and the length of daylight is variable.

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Appendix

Properties of materials used in the dual solar system

Materials properties	Remarks
Specific volume of ice at 0 °C: $C_{v,ice}$ (m ³ /kg)	0.001091
Average specific heat of activated carbon: C_{ac} (kJ/kgK)	0.70
Specific heat of water: C_w (kJ/kgK)	4.19
Specific heat of copper: C_{copper} (kJ/kgK)	0.39
Average specific heat of liquid methanol: C_{meth} (kJ/kgK)	2.65
Gas constant: R (kJ/kg/mol/K)	8.3219
Molecular weight of the methanol: M (kg/mol)	32.04
Latent heat of methanol: L_{meth} (kJ/kg)	1200
Latent heat of ice: L_{ice} (kJ/kg)	333
Price of one kilogram of Malaysian activated carbon in Ringgit Malaysia (RM).	10
Bulk density of activated carbon ρ_{ac} (kg/m ³)	760
Density of ice at 0 °C: ρ_{ice} (kg/m ³)	917
Length of adsorber tube: $l_{ads-tubes}$ (m)	1
Outside diameter of adsorber copper tube: $O.D_{ads-tube}$ (m)	0.0508
Inside diameter of adsorber copper tube: $I.D_{ads-tube}$ (m)	0.0483
Outside surface area of adsorber copper tube: $O.S.A_{ads-tube}$ (m ² /m)	0.1596
Weight of one meter adsorber copper tube: $w_{ads-tube}$ (kg/m)	1.7321
Price of one meter copper adsorber tube in Ringgit Malaysia (RM)	50
Outside diameter of condenser, evaporator, and perforated copper tube: $O.D_{con, evp, perforated-tube}$ (m)	0.0127

(continued on next page)

Appendix (continued)

Materials properties	Remarks
Inside diameter of condenser, evaporator, and perforated copper tube: $I.D_{con, evp, perforated-tube}$ (m)	0.0112776
Outside surface area of condenser, evaporator, and perforated copper tube: $O.S.A_{con, evp, perforated-tube}$ (m ² /m)	0.0399
Weight of one meter copper tube used for condenser, evaporator, and methanol mass transfer: $w_{con, evp, perforated-tube}$ (kg/m)	0.24
Price of one meter copper tube used for condenser, evaporator, and perforated copper tube in Ringgit Malaysia (RM).	7
Price of one meter square of solar flat plate collector in Ringgit Malaysia (RM)	500
Price of one meter square of evacuated tube collector in Ringgit Malaysia (RM)	1000
Pressure of methanol at condenser temperature: P_{con} (bar)	0.215
Pressure of methanol at evaporator temperature: P_{evp} (bar)	0.029
Global solar radiation on horizontal surface at Malaysian location: G (MJ/m ²)	17

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