Parametric Analysis Of Multipurpose Solar Adsorption System- Cooling And Heating

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Abstract- A computer simulation program in visual basic was developed to guide in the design of a multipurpose solar continuous adsorption system and predict its applicability under various operating conditions for specific applications with sufficient accuracy is described. Malaysian activated carbons and methanol are used as the adsorbent-adsorbate pair. The most preferable way to popularize such multipurpose solar system in acceptable efficiency, size and cost is based on using efficient activated carbon and heat-sheet collectors as can be shown in the analysis.

Keywords- solar thermal, adsorption, continuous cycle, multipurpose system, refrigeration-heating, parametric analysis.

I. INTRODUCTION

The research on multi-purpose solar adsorption systems for domestic refrigeration and water heating in last 25 years has been summarized by alghoul et al. (2007) [1]. The proposed dual-purpose solar system presented in this work (shown in Figure 1.1) comprises mainly solar thermal collectors for water heating**,** two storage tanks, each containing an adsorber bed and a condenser. The adsorber beds contain different amount of activated carbon. A receiver, evaporator and icebox. The underlying idea of continuous refrigeration is to produce a flow of methanol from adsorber bed 1 to adsorber bed 2 during the day and from adsorber bed 2 to adsorber bed 1 during the night. Thus the temperatures of the adsorber beds must be regulated to produce the desorption and adsorption processes. In other words, during the day when the temperature of adsorber bed 1 increases causing the methanol to desorb from the activated carbon in adsorber bed 1, the temperature of adsorber bed 2 must be made to decrease in order to cause the adsorption of the methanol by the activated carbon in adsorber bed 2 and vice versa during the night. In practice, this can be carried out using a procedure to control the temperature of the water by closing and opening the flow valves as will be explained in the next section.

In going from adsorber bed 1 to adsorber bed 2 during the day, the methanol will be made to pass through condenser 2, receiver, flow restrictor valve and evaporator respectively. The temperature of condenser 2 is the same adsorber bed 2. Thus, in the day the water in storage tank 2 can be used for domestic hot water.

At sunset, the hot water in storage tank 1 is drained into storage tank 2 via valve number 6 while closing valves number 2, 3, 5 and 7. Gradually the temperature of the water in storage tank 2 increases and adsorber bed 2 eventually undergoes desorption. As the temperature of the water in storage tank 2 increases further, valve number 2 is opened to allow city water to flow causing the temperature of the water in storage tank 1 to decrease. In this manner, adsorber bed 1 can undergo adsorption. During the evening, valve number 4 is always opened so that the hot water from storage tank 1 can be utilized for domestic consumption. However, the decrease in temperature of the water in storage tank 1 is gradual due to the heat recovered from condenser 1 following the desorption process and the sensible and adsorption heat recovered from adsorber bed 1 following the adsorption process.

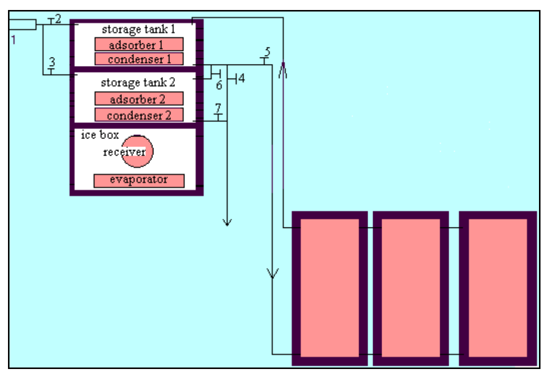

Fig. 1.1: Flow of water in the continuous solar water heating cycle of the dual-purpose system: (1) City water grid. (2, 3) Valves of city water that flows into storage tank 1 and storage tank 2. (4) Valve that controls the flow of hot water from storage tank 1. (5) Return valve of the solar collector flow. (6) Valve connecting storage tank 1 to storage tank 2. (7) Valve that controls the flow of hot water from storage tank 2.

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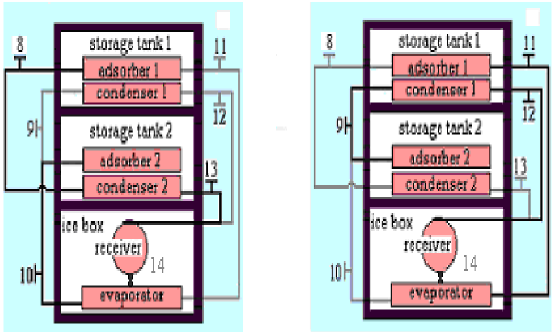

(a) (b)

Fig. 1.2: Flow of methanol (a) during the day (from adsorber bed 1 to adsorber bed 2) and (b) during the night (from adsorber bed 2 to adsorber bed 1), in the continuous adsorption refrigeration cycle of the dual-purpose solar system.

Continuous adsorption refrigeration cycle in the dual-purpose solar system is shown in fig. (1.2 a & b). During the day, the hot adsorber bed 1 will desorb the methanol, which is then collected by condenser 2 and drain into the receiver. The methanol then evaporates through a flow restrictor valve 14 into the evaporator and re-adsorbed in adsorber bed 2. The flow is shown in fig. 1.2(a) as a darkened line. To produce this cycle, valves number 8, 10 and 13 must be opened while the other valves shown in the figure must be closed. During the night the methanol is desorbed from the hot adsorber bed 2 and condensed in condenser 1 before draining into the receiver. It then evaporates through a flow restrictor valve 14 into the evaporator to be adsorbed again by adsorber bed 1. The flow is shown in Fig. 1.2 (b). Valves number 9, 11 and 12 must be opened while the other valves must be closed to allow for this flow. It is seen that both the desorption and adsorption processes take place in the day as well as at night resulting in continuous refrigeration.

The COP of a basic cycle is defined as the ratio between the quantity of heat Q_e drawn from the environment and the quantity of heat that must be supplied to the system,

$$COP=\frac{Q_e}{Q_{1\text{-des}}+Q_{2\text{-des}}} \quad (1)$$

The COP calculated using the above equation is the thermodynamic one, which takes into account the heat balance on the refrigerant and the adsorbent. The real COP of such a cycle takes into account the heat balance on the adsorber bed and on all other components, which also make up the process. Instead the activated carbon is encapsulated in an adsorber bed, which is then heated by hot water. The water temperature is regulated to produce the optimum desorption after it is produced by a high efficiency vacuum solar collector. In this manner there is no danger of the activated carbon disintegrating, as in the case of direct solar heating, since the maximum temperature of the adsorber bed cannot exceed 100°C. The use of two adsorber beds and condensers, alternately heated and cooled by water allows continuous and efficient desorption and adsorption processes to occur. Because the adsorber beds and condensers are immersed in water the heat released by them are not wasted but recovered. The energy efficiency is high with respect to the total solar energy collected. Here are some of the possible design parameters. T_0 = 27.5(°C), $T_{evp}=-5$ (°C), $T_{ice}=0$ (°C), $H_{global-horizontal}$ = 17 (MJ/m^2), Efficiency of solar evacuated tube collector on average summer performance level η_{coll} = 65 (%).

II. PARAMETRIC ANALYSIS

Once the operating conditions, adsorbent-adsorbate properties are specified and the evaluation of the energy equations is completed, performance estimates of the dual-purpose solar continuous adsorption system could be expressed in terms of:

- The coefficient of performance of the refrigeration subsystem cycle which can be written as:

$$COP_{cycle-ice}=\frac{Q_{Netcooling}}{Q_{heat-ads}} \quad (2)$$

- The coefficient of performance of domestic refrigeration in the dual purpose system which can be written as:

$$COP_{dual.system-ice}=\frac{2Q_{Netcooling}}{HA_{coll}} \quad (3)$$

- The coefficient of performance of domestic hot water in the dual purpose system which can be written as:

$$COP_{dual.system-hot.weater}=\frac{Q_{domestic.hot.water-total}}{HA_{coll}} \quad (4)$$

- The coefficient of performance of the dual purpose system can be written as:

$$COP_{dual-system}=\frac{2Q_{Netcooling}+Q_{domestic.hot.water-total}}{HA_{coll}} \quad (5)$$

1. Effect of temperature of hot water as heat source on the performance of the dual system

In this section we will discuss the choice of optimum temperature of hot water and the optimum temperature of the desorption process of the second adsorber bed for the following design conditions:

Activated carbon : $AC-5060$, Mass of ice (produced): M_{ice} =12kg, Temp of evaporator: T_{evp}=-5°C Temp of condenser T_{con} =30°C, and Minimum adsorption

Temp: T_{a2} =30°C. Table (1) summarizes the effect of different temperatures of hot water as heat source and different generating temperatures on the output of the dual-purpose system. From the values shown in Table (1), heating the second adsorber bed to 90^{o}C with hot water at temperatures 98^{o}C or 95^{o}C will require large solar collector area and mass of hot water. The output energy of hot water is also large and over domestic use. There are other combinations of $T_{hot-water}$ and $T_{g2-2nd-adsorber.bed}$ that do not give optimum output. One of the feasible combinations is when $T_{hot-water}$ is at 98^{o}C and $T_{g2-2nd-adsorber.bed}$ is at 85^{o}C. At these design temperatures, a solar collector area of 3.60m^2 is sufficient to raise the temperature of 116kg of hot water to 98^{o}C. The total energy of the domestic hot water produced is 44.69MJ. Other feasible combinations are: $T_{hot-water}$ =98^{o}C, $T_{g2-2nd-adsorber.bed}$ =80^{o}C and $T_{hot-water}$ =95^{o}C, $T_{g2-2nd-adsorber.bed}$ =80^{o}C. It is apparent from the analysis that the difference between the hot water temperature and the generating temperature should be more than 13^{o}C, that is $\Delta T = (T_{hot.water} - T_{g2-2nd-adsorber.bed})$ ≥ 13°C. It is also clear that the mass of hot water and the solar collector area are strongly influenced by the temperature difference between the hot water as the heat source and the desorption temperature of the second adsorber bed.

Table (1): Effect of temperature of hot water as heat source on the performance of the dual system

Second adsorber bed: $T_{g2-2nd-adsorber.bed}$ = 90°C				
$T_{hotwater}$ °C	$Q_{heat-ads}$ (kJ)	M_{hw} (kg)	A_{coll} (m^2)	$Q_{domestic.hot.water-total}$ (kJ)
98	5778	172	5.12	61471
95	5778	276	7.57	88558
Second adsorber bed: $T_{g2-2nd-adsorber.bed}$ = 85°C				
$T_{hotwater}$ °C	$Q_{heat-ads}$ (kJ)	M_{hw} (kg)	A_{coll} (m^2)	$Q_{domestic.hot.water-total}$ (kJ)
98	**6296**	**116**	**3.60**	**44692**
95	6296	150	4.36	53046
90	6296	301	7.63	89249
Second adsorber bed: $T_{g2-2nd-adsorber.bed}$ = 80°C				
$T_{hotwater}$ °C	$Q_{heat-ads}$ (kJ)	M_{hw} (kg)	A_{coll} (m^2)	$Q_{domestic.hot.water-total}$ (kJ)
98	**7210**	**96**	**3.07**	**38725**
95	**7210**	**115**	**3.45**	**42930**
90	7210	172	4.59	55547
85	7210	344	8.02	93397

2. Effect of desorption temperature of the second adsorber bed on the performance of the dual system

Producing specified output of domestic ice at different generating temperature is possible by heating activated carbon to high generating temperature so that the desorbed (released) mass of the methanol will increase. In this way coefficient of performance of the refrigeration cycle will also increase.

Heating more mass of activated carbon at low generating temperature to desorb the same mass of methanol. In this case the coefficient of performance of the refrigeration cycle will decrease. Since hot water temperature as heat source is in the range (98-95°C) is possible by using efficient solar collectors, the temperature of desorption process of the first adsorber bed during day time is designed to be 95°C. To choose the optimum final desorption temperature for the second adsorber bed, for the following design conditions: $AC-5060$ - Methanol, T_{evp} =-5°C, $T_{con} = T_{a2}$ =30°C, $T_{hot-water}$ =98°C M_{ice} =12kg, $T_{g2-1st.adsorber.bed}$ = 95°C, three factors must be studied which affect strongly the dual system; coefficient of performance of the refrigeration cycle, mass of activated carbon and consequently the number of adsorber tubes required at each of these designed desorption temperature.

Table (2): The effect of temperature of the second adsorber bed on the performance of the dual purpose system

$AC-5060$ -Methanol, M_{ice} =**12**kg, T_{evp} =-5°C, $T_{con} = T_{a2}$ =30°C, $T_{g2-1st.adsorber.bed}$ = 95°C, $T_{hot-water}$ =98°C,					
T_{g2} (°C) 2^{nd} $adsorber.bed$	95	90	**85**	80	75
M_{ac} (kg)	25	29	**36**	51	88
m	19	22	**28**	39	68
$COP_{cycle-ice}$	0.467	0.446	**0.413**	0.361	0.269
M_{hw} (kg)	451	172	**116**	96	101
A_{coll} (m^2)	12.56	5.12	**3.60**	3.07	3.21
$Q_{hot.water}$ (kJ) $heat.recovery$	8199	8224	**8741**	9626	12117
$Q_{domestic.hot.water\ total}$ (kJ)	143846	61471	**44692**	38725	40235
$COP_{dual.system-ice}$	0.025	0.059	**0.085**	0.100	0.096
$COP_{dual.system}$	0.674	0.706	**0.730**	0.742	0.738

domestic.hot.weater					
$COP_{dual-system}$	0.699	0.765	**0.815**	0.842	0.834

From the values shown in Table (2), at low desorption temperature (75-80°C); the coefficient of performance of refrigeration cycle is very low. This means that the desorbed methanol is very small, and a big mass of carbon is required to release enough methanol. At high desorption temperature (95-90°C), the coefficient of performance of refrigeration cycle is high, but the mass of hot water is too big for domestic use and also the use of large collector area is not practical and economical. So, the optimum desorption temperature is 85°C from the view point of mass of hot water, collector area, $Q_{domestic.hot.water-total}$, mass of activated carbon, number of adsorber tubes and the coefficient of performance. Also, it is seen that the energy of domestic hot water produced by heat recovery option is reasonably high with the decrease in the desorption temperature of the second adsorber bed. The reason for this is that the increase in the mass of the adsorber bed rejects more sensible heat during cooling process. Finally, we note that for increased mass of activated carbon will result in the use of more adsorber tubes and large water storage tank. The big adsorber bed will increase the size and cost of the system and decrease the coefficient of performance of the adsorption refrigeration cycle.

3. Effect of adsorption-condensation temperature on the performance of the dual system

Producing certain output of domestic ice at different adsorption-condensation temperature can be carried out in two ways: at high temperature of adsorption-condensation, the adsorbed or condensed mass of methanol will decrease, so more activated carbon is required to accommodate the desired mass of methanol. In this case the coefficient of performance of the refrigeration cycle will decrease. At low temperature of adsorption-condensation, the adsorbed or condensed mass of methanol will increase, so less mass of activated carbon can be used to produce the same mass of methanol. In this case the coefficient of performance of the refrigeration cycle will increase. Table (3) illustrates the effect of condensation-adsorption temperature of 35°C on the dual purpose system.

4. Effect of mass of ice on the performance of the dual system

Maximum capacity of the dual system to produce domestic ice is 12 kg during 24 hours. If more ice to be produced (18 or 24 kg ice), the system will be bulky and costly and the hot water produced is too much for domestic use. The only possible way to increase the mass of ice with applicable price, size and volume of domestic hot water is to find another activated carbon with high adsorption capacity and high conductivity.

Table (3): Effect of adsorption-condensation temperature on the performance of the dual

$AC-5060$-Methanol, M_{ice} =**12**kg, $T_{con}=T_{a2}$=**35**°C, T_{evp} =-5°C, $T_{hot-water}$ =98°C, $T_{g2-1st.adsorber.bed}$ = 95°C, $T_{g2-2nd-adsorber.bed}$ =85°C			
	1st adsorber bed	2nd adsorber bed	Dual system
M_{ac} (kg)	43	119	**162**
m	33	92	**125**
$COP_{cycle-ice}$	0.365	0.204	**0.284**
M_{hw} (kg)			**236**
A_{coll} (m^2)			**6.96**
Q (kJ) *Domestic.hot.water total*			**81660**

5. *The ideal cycle of the dual purpose continuous adsorption system*

From the above discussion, ideal operation conditions for the dual system have been determined already: Adsorbent: $AC-5060$ of (W_0 = 0.363, D = 0.00002067, n = 1.599), T_{evp} = -5°C, T_0 =27.5°C, $T_{con}=T_{a2}$ = 30°C, $T_{hot-water}$ = 98°C, $T_{g2-1st.adsorber.bed}$ = 95°C, $T_{g2-2nd-adsorber.bed}$ = 85°C, M_{ice} = 12kg. For the given efficiency of the solar collectors (65%), it is seen that there is acceptable improvement on the efficiency of the hot water production; the reason for this is that there is the utilization of heat recovery from the cooling process to produce hot water besides the direct heating of the water. The efficiency of the dual system is improved significantly from both output of heating and cooling. This means that the system is preferable for heating water and is also practical in terms of size and cost for refrigeration. The actual cost of the dual purpose system using $AC-5060$ to produce 12 kg of ice daily and 45 MJ of domestic hot water is shown in Table (4) where the main cost of the dual system is from the solar collectors and the adsorber tubes.

Table 4: Costing of the dual purpose system by using **Malaysian** activated carbon

Item	**Cost (RM*)**
Evacuated tube collectors	**3600**
Activated carbon	700
Adsorber tubes	**2700**
Water storage tanks (2)	1500

*1USD = 3.4 RM

6. Effect of efficient activated carbon on the dual system

In search of new adsorbent materials, Wang et al. (1997) [3] have reported that, for specially treated ACF, the measured adsorption capacity of methanol is two to three times greater than that of 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. (1986) [4]. Tamaniot-Telto and Critoph (2000) [5] 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. In this section we will discuss the effect of efficient activated carbon on the dual system. As an example here, it is assumed that efficient activated carbon has maximum volume of the adsorption space equal to W_0= 0.6 $m^3 kg_{ac}^{-1}$ which is double that of W_0= 0.363 $m^3 kg_{ac}^{-1}$ of our Malaysian $AC-5060$. From the values shown in Table (5) and Figures (2,3) it is seen that $COP_{cycle-ice}$ is significantly improved (52%) in comparison to the normal activated carbon (44%) because the mass of the required activated carbon is reduced and consequently the number of adsorber tubes is also reduced.

7. Effect of heat-sheet collector on the cost of the dual system

Now, to reduce the cost of the dual system further, solar collectors cost must be reduced. As reported by Alghoul et al. (2005) [6] "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. The actual cost of the dual purpose system using efficient activated carbon and heat sheet collector to produce 12 kg of ice daily and 39 MJ of domestic hot water is shown in Table (6). Also, the cost of the system is reduced significantly and is feasible for the dual purpose system.

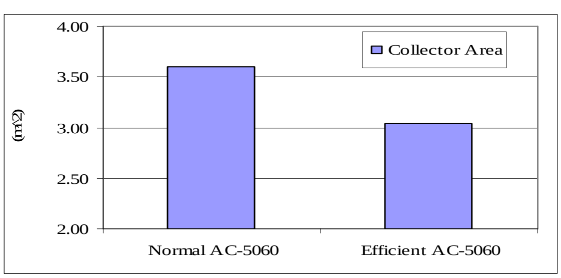

Figure (2): Effect of efficient and normal activated carbon on the area of solar collector.

Table (5): Effect of efficient activated carbon on the performance of the dual system

$AC-5060$ (W_0= 0.6 $m^3 kg_{ac}^{-1}$) – Methanol, T_{evp} = -5°C, T_0 =27.5°C, $T_{con} = T_{a2}$ = 30°C, , $T_{g2-1st.adsorber.bed}$ = 95°C, $T_{g2-2nd-adsorber.bed}$ = 85°C, $T_{hotwater}$= 98°C, M_{ice}= 12kg			
	1st adsorber bed	2nd adsorber bed	Dual system
M_{ac} (kg)	15	22	37
m	12	17	29
$COP_{cycle-ice}$	0.546	0.493	0.52
M_{hw} (kg)			97
$Q_{solar.heat}$ (kJ)			33582
Q (kJ) *Domestic hot water direct solar*			23433
A_{coll} (m²)			3.04
Q (kJ) Domestic.hot.water.total			38575
COP Dual.system.ice			0.101
COP *dual.system domestic. hot.water*			0.745
$COP_{dual-system}$			0.846

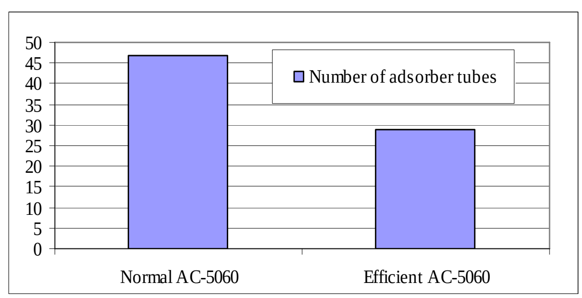

Figure (3): Effect of efficient and normal activated carbon on the number of required adsorber tubes.

Table 6: Costing of the dual purpose system by using efficient activated carbon and heat sheet collector

Item	**Cost (RM*)**
Heat sheet collector	1350
Activated carbon	700
Adsorber tubes	1650

*1USD = 3.4 RM

III. CONCLUSION

A compromise must be made for the optimum design of the dual system. The adsorption system is limited by some constraints that affect the output of domestic refrigeration and hot water such as adsorbent-adsorbate properties, hot water temperature (below boiling temperature), and city water temperature. Condensation-adsorption temperature is a function of city water temperature, and the dual system is limited by the volume of city water. Generating temperature of the adsorber bed is a function of the temperature of hot water and the dual system is limited by the volume of hot water. The maximum generating temperature that can be attained in the dual purpose system is 95°C because it is heated by hot water below boiling temperature. The minimum temperature of adsorption-condensation is 30°C when the system is cooled by city water. The most preferable way to popularize the dual system in acceptable efficiency, size and cost is to use efficient activated carbon and heat-sheet collectors.

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