

Numerical Modelling of an Adsorption Solar Cooling System

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Abstract—The numerical analysis and performance prediction of a solid adsorption solar refrigerator, using activated carbon/methanol adsorbent/adsorbate pair are presented. The mathematical model is based on the thermodynamics of the adsorption process, and heat and mass transfers within the adsorbent/adsorbate pair.

Keywords—Adsorption solar cooling system, Numerical modelling, performance prediction, Activated carbon-methanol pair.

I. INTRODUCTION

Solar radiation is by far the largest and the most world's abundant, clean and permanent energy source. The amount of solar radiation intercepted by the Earth is much higher than annual global energy use. The energy available from the sun ($82 * 10^{15}$ W) is greater than about 5200 times the global world's need in 2006. In recent years, many promising technologies have been developed to harness the sun's energy. These technologies help in environmental protection, economizing energy, and sustainable development which are the major issues of the world in the 21st century. One of these important technologies is the solar cooling systems that make use of either absorption or adsorption technologies. Due to the environmental problems of chlorofluorocarbons (CFCs) emissions, adsorption cooling technologies are more attractive field of research and development than the conventional vapor compression refrigeration systems. The international and local policies nowadays are directed towards replacing the traditional refrigeration systems with environmentally friendly ones that can be operated by new and renewable energy sources [1]. The solar adsorption cooling systems are good alternative since they operate with environmentally benign refrigerants that are natural, free from CFCs and therefore they have a zero ozone depleting potential (ODP). Furthermore, these refrigerants satisfy the Kyoto protocol on global warming the Vienna Convention for Protection of the Ozone Layer (1985), and Montreal Protocol on Substances Depleting the Ozone Layer (1987).

Adsorption cooling systems are characterized by the simple control, absence of vibration and corrosion problems. The wide range of heat source temperatures (50°C - 600°C), and the low operation and maintenances costs make these systems more attractive [2]. Although the adsorption chiller

systems have these advantages, their drawbacks are the intermittent operation, the requirements of special designs to maintain traditional refrigeration systems, the low specific cooling power (SCP) and the low coefficient of performance (COP) [4]. Besides the poor heat and mass transfer within the adsorbent, the adsorption deterioration of the adsorbent is also vital to the development and applications of the adsorption refrigeration technology [3]. However, enhancement of heat and mass transfer properties in the adsorbent bed, increasing the adsorption properties of the working pairs and a better heat management during the adsorption cycle lead to a more efficient system [2]. The performance of the adsorption cooling system depends mainly on the working pairs used. A good designed system should have the characteristics of large adsorption capacity, large change of adsorption capacity with temperature variation, more flat desorption isotherm. And the refrigerant has a large latent heat per volume, no toxicity, non flammable, no corruption, and good chemical and thermal stability [3]. The most widely used working pairs are activated carbon–methanol, activated carbon fiber–methanol, activated carbon–ammonia, zeolite–water, silica gel–water, calcium chloride–ammonia and composite adsorbent–ammonia. Anyanwu [4,5], have presented a review of the practically realized solid adsorption solar refrigeration cycles. they have classified the cycles according to the adsorbate utilized as: cycles with water as refrigerant, cycles using fluorocarbon as refrigerant, cycles using ammonia as refrigerant and cycles with alcohols as refrigerant. Activated-carbon is the most widely used adsorbent reported in literature due to its extremely high surface area and micro pore volume.

II. PHYSICAL MODEL

The adsorption cooling system likes the basic vapor compression refrigeration machine except that the power compressor is replaced with a thermal compressor or the reactor. The reactor is composed of a type of porous medium that has the ability to adsorb the refrigerant. The working principle of the basic reactor cycle is represented in the Clapeyron diagram, figure (1). The adsorbent-adsorbate cycle consists mainly of four phases; pressurization process at a constant volume (isosteric heating phase), desorption at constant pressure (isobaric heating phase), depressurization at constant volume (isosteric cooling phase), and adsorption at constant pressure (isobaric cooling phase).

At the beginning of the day, state A, the reactor is isolated from both the condenser and the evaporator by valves c and e and is completely charged with the refrigerant. The

Manuscript received November 20, 2012.

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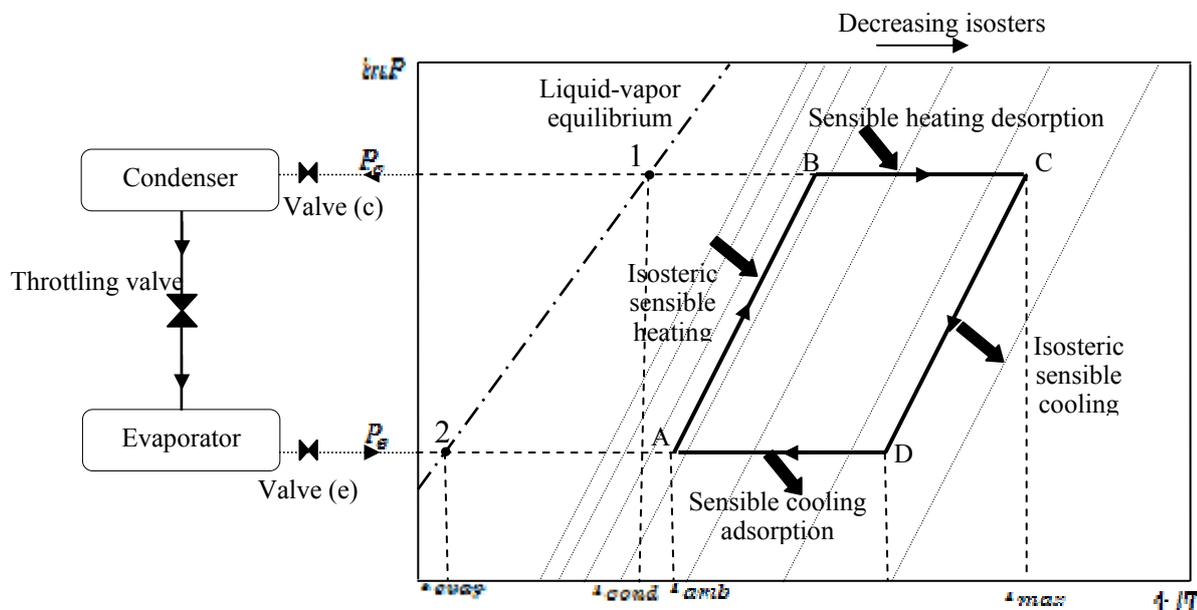


Fig. 1 Clapeyron Diagram for a conventional adsorption cycle

pressure inside the reactor initially equals the evaporator pressure P_{evap} and its temperature is uniform and equals the ambient temperature T_{amb} . When the reactor starts to heat up by the incident solar radiation, both pressure and temperature inside the adsorbent are elevated. This constant concentration

constant volume (isosteric cooling phase), and adsorption at constant pressure (isobaric cooling phase).

At the beginning of the day, state A, the reactor is isolated from both the condenser and the evaporator by valves c and e and is completely charged with the refrigerant. The pressure inside the reactor initially equals the evaporator pressure P_{evap} and its temperature is uniform and equals the ambient temperature T_{amb} . When the reactor starts to heat up by the incident solar radiation, both pressure and temperature inside the adsorbent are elevated. This constant concentration heating phase continues till point B where the pressure reaches a value that equals the condenser pressure P_{cond} which is the saturation pressure corresponding to the condensation temperature T_{cond} . This period is equivalent to the compression in the classic vapor compression refrigeration cycle. At state B, valve c is opened and the adsorbate starts to desorb and flows towards the condenser. During this isobaric heating phase, the reactor discharges the refrigerant, the temperature continues increasing, and the adsorbate concentration continues to decrease as more adsorbate is being freed from the reactor. When the adsorbate temperature reaches the maximum value T_{max} at state C, valve c is closed and the reactor starts the third phase. When the solar flux decreases, the reactor is cooled down at constant volume and the constant lowest isoster till the pressure inside the reactor decreases to the evaporator pressure P_{evap} , point D. The last phase of the reactor cycle starts at the night, point D, when valve e is opened and the refrigerant flows towards the reactor. The adsorption process continues while the reactor is cooled at the constant

evaporator pressure till the higher cycle isoster at point A. The cycle of the machine is intermittent; the cold is produced only during a part of the cycle period (night).

The solar refrigeration system presented in this study has three main components: the solar collector/reactor, figure (2), the condenser and the evaporator. The solar collector/reactor is constituted of a clear plane glass sheet cover; the activated carbon-methanol pair which is contained in the annular space between the two coaxial collector pipes. The inner pipe is perforated in order to ease the flow of methanol into and out from the activated carbon granules and to avoid pressure drops and temperature differences along the collector tube as well. These pipes are integrated in the plane solar collector which its lateral and rear sides are insulated. The inner pipes are connected to a common methanol inlet and outlet headers.

The adsorbent bed is cooled during the adsorption process when the collector glass cover plate is opened by natural convection of air and by radiation from the collector plate and tubes. The condenser pipe is steel and is cooled by natural convection and by radiation.

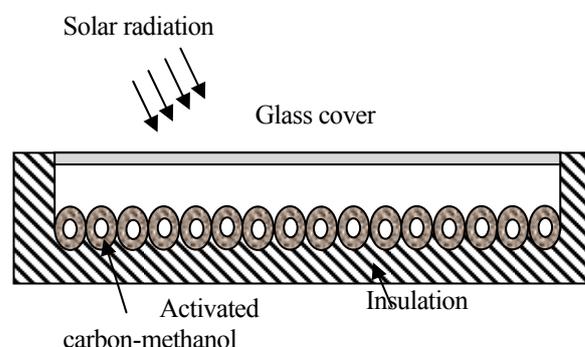


Fig. 2 Schematic of reactor tubular adsorber

III. MATHEMATICAL MODEL

The model simulating the real working of a solar adsorption cooling system takes in account all balances of energy and mass for every element of the machine.

The general equation of heat and mass transfer in the adsorber is given by [6,7]:

$$\frac{\partial}{\partial t}((\rho C)_e T) + \bar{V} \bar{\nabla}(\rho_g C_g T) = \bar{\nabla}(\lambda_e \nabla T) + S \quad (1)$$

where:

$$\lambda_e = \lambda_s(1 - \varepsilon) + \lambda_g(\varepsilon - \alpha) + \lambda_a \alpha \quad (2)$$

$$(\rho C)_e = \rho_s C_s(1 - \varepsilon) + \rho_g C_g(\varepsilon - \alpha) + \rho_a C_a \alpha \quad (3)$$

$$S = \frac{\partial}{\partial t}[(\varepsilon - \alpha)\rho_g] \frac{P}{\rho_g} + \left(\frac{P}{\rho_a} + \Delta H_{ads} \right) \rho_{app} \frac{\partial m_a}{\partial t} \quad (4)$$

$\alpha = m_a \rho_{app} / \rho_a$ is the volume fraction of the adsorbed phase, ε is the total porosity of the activated carbon, ρ_{app} is the apparent density of the activated carbon and ΔH_{ads} is the heat of sorption.

The adsorbed quantity (m_a) is given by the Dubinin-Astakhov model:

$$m_a = w_0 \rho_l(T) \exp \left[-D \left(T \ln \left(\frac{P_s(T)}{P} \right) \right)^n \right] \quad (5)$$

w_0 is the maximum adsorption capacity that depends on the adsorbent/adsorbate pair, n and D are the characteristic parameters. $\rho_l(T)$ is the density of the adsorbate at liquid state; it is given by the following equation:

$$\rho_l(T) = 1066.828531 - 0.942857T \quad (6)$$

$P_s(T)$ is the pressure of saturation; it is given by the following equation:

$$\ln(P_s(T)) = 16.1325 - \frac{4546.856}{T} \quad (\text{Psia}) \quad (7)$$

Assuming that the global solar flux $G(t)$ and the convection heat coefficient with the ambience h_{cv} are left uniformly on the adsorber surface. The total balance of energy in the adsorber is:

$$-\lambda_m \frac{\partial T}{\partial r} \Big|_{r=R_e+ep} = \frac{2}{\pi} a_p G(t) + h_{cv}(T_{amb} - T) + \xi \sigma (T_{amb}^4 - T^4) \quad (8)$$

e_p the thickness of the reactor wall, a_p the absorption coefficient of the adsorber, ξ the emissivity of the adsorber, σ the Stephan Boltzmann, and T_{amb} the ambient temperature.

The associated boundary conditions to the considered problem are:

- Initial condition ($t = 0$), the adsorber is assumed to be at uniform temperature $T(r,0) = T_i$

- Adiabatic condition at $r = R_i$ $\frac{\partial T(r,t)}{\partial r} \Big|_{r=R_i} = 0$

- Continuity of heat flux at the interface adsorber metallic wall ($r = R_e$):

$$-\lambda_e \frac{\partial T(r,t)}{\partial r} \Big|_{r=R_e} = h_w (T_w - T(R_e, t))$$

T_w is the metallic wall temperature and h_w is the heat transfer coefficient at the metallic wall ($h_w = 35 \text{ W/m}^2 \text{ K}$).

The solar performance coefficient (COPs) is defined as the ratio of the cooling power (Q_f) to the incident global irradiance during the whole day (Q_{tot}).

$$COP_s = \frac{Q_f}{Q_{tot}} \quad (9)$$

where:

$$Q_f = \Delta m [L_{ev}(T) - C_l (T_{cond} - T_{ev})]$$

$$\Delta m = m_{a_{max}} - m_{a_{min}}$$

The governing equations are discretized by using the implicit finite volume method. The convergence of the solution method is monitored in terms of the normalized residue of the algebraic equations. The maximum residue allowed for convergence check is set to 10^{-6} .

IV. RESULTS

The presented results have been computed for an annular adsorber of outer / inner radius $R_e / R_i = 0.02 / 0.01 \text{ m}$, and length of 1m. The condenser and evaporator temperatures are assumed to be almost constant during the adsorption cycle. The caption efficiency of the solar collector is 0.75.

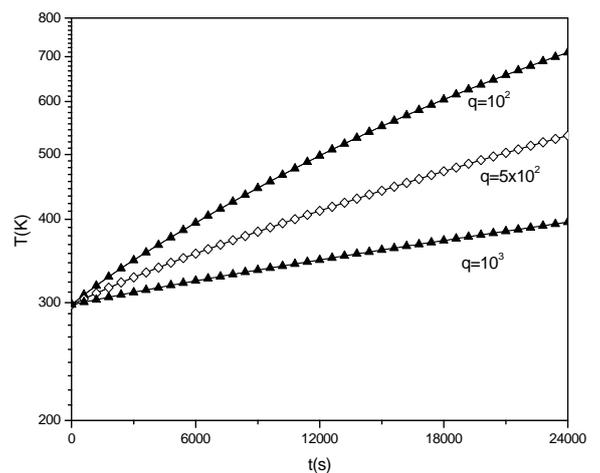


Fig. 3 Adsorption medium temperature as function of time for different values of heat flux

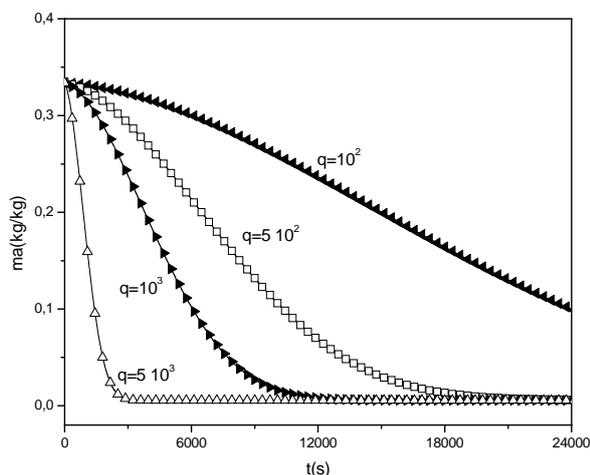


Fig. 4 Adsorption methanol mass as function of time

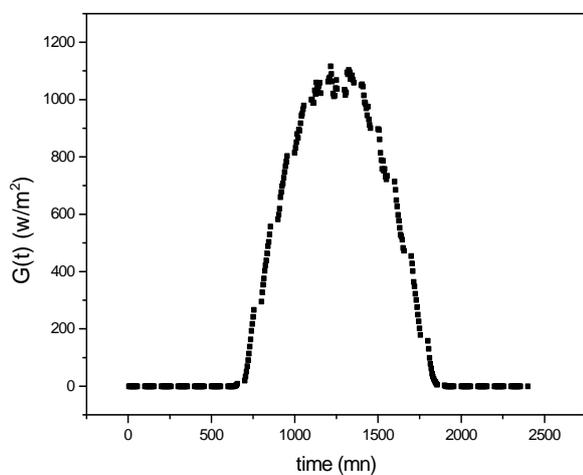


Fig. 5 Diurnal solar flux versus time

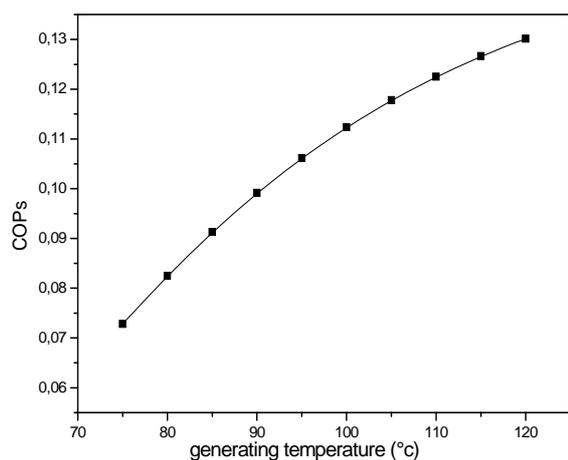


Fig. 6 COPs variations versus generating temperature ($T_{cond}=30^{\circ}C$, $T_{evap}=-5^{\circ}C$)

Figure 3 shows the evolution of the temperature in the adsorption medium, for different values of heat flux. The increase of the temperature as function of time leads to the desorption of the methanol contained in the grains (activated carbon) and from where the reduction of the adsorbed mass

until a constant value (Fig. 4). More the heat flux increases, more the quantity of the desorbed methanol is important.

In this simulation, we have used the solar and climatical data measured in Algiers (Algeria) for clear type day of March. The average global heat flux is presented in figure 5. As it is shown in figure 6, the increase of the generating temperature leads to better solar performances of the system.

V. CONCLUSION

A numerical analysis and solar performance prediction of a solid adsorption solar system using activated carbon/methanol adsorbent/adsorbate pair are undertaken. The modeling of the adsorption cooling system requires the resolution of the equation describing the energy and mass transfer in the tubular adsorber. The solar performances of the system that depend on the incident global irradiance during a whole day depend on the weather conditions.

TABLE I
NOMENCLATURE

Symbol	Quantity	Units
C	specific heat	[J/kgK]
COPs	solar performance coefficient	-
D	characteristic parameter of adsorbent/adsorbate pair	-
G(t)	total solar radiation	[W/m ²]
h	heat transfer coefficient	[W/m ² K]
m _a	adsorbed mass	[kg/kg]
n	characteristic parameter of adsorbent/adsorbate pair	-
P	pressure	[Pa]
P _s	pressure of saturation	[Pa]
Q _{tot}	the incident global irradiance during the whole day	-
r	radial direction	-
R _i	inner radius	[m]
R _e	outer radius	[m]
t	time	[h]
T	temperature	[K]
T _{cond}	condenser temperature	[K]
T _{evap}	evaporator temperature	[K]
T _{gen}	generating temperature	[K]
ΔH _{ads}	heat of sorption	[J/kg]
α	volume fraction of the adsorbed phase	-
ρ	density	[kg/m ³]
λ	thermal conductivity	[W/mK]
ε	porosity	-
subscripts		
a	adsorbed phase	
app	apparent	
e	equivalent	
g	gas	
m	metal	
s	sols	
w	wall	

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