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RESEARCH ARTICLE

INFLUENCE OF OPERATING TEMPERATURES ON THE SOLAR ADSORPTION REFRIGERATION MACHINE USING THE ACTIVATED CARBON-METHANOL PAIR

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Abstract

In this work, we make a detailed analysis of the effects of the operating temperatures (Ta, Te, Tc, and Tg) of our solar adsorption refrigerator using the activated carbon-methanol couple on the thermal coefficient of performance (COPth) and on the quantity of methanol cycled in this machine. The mathematical model used in this part is based on the equation of state of the Dubinin-Astakhov model and the quantities of heat involved during the thermodynamic cycle of the refrigerator. For the validity of our mathematical model, the result of the calculation of the coefficient of performance obtained is compared with the result of Ch. Wassila, who had to work in this field by obtaining very satisfactory results compared to those available in the literature.

Introduction:-

The solar refrigerator of our study consists of four main elements: a sensor-adsorber, a condenser, an evaporator and a cold room.

This machine was dimensioned by making a thermal balance of the sensor, based on data such as temperature, wind speed and solar irradiation of meteorological reports from the region of Thiès, Senegal, place of installation of the machine.

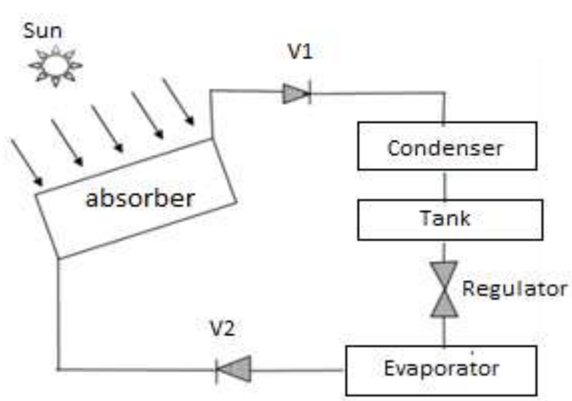

Figure 1:- Solar refrigerator by adsorption.

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The equation for the gas adsorption isotherm on a microporous solid known as the Dubinin-Astakhov equation (D-A) is given by[31]:

$$m(T,P) = w_0 \rho_1(T) \exp\left[-D\left(T.\ln\left(\frac{P_S(T)}{P} \right) \right)^n \right] \quad 1$$

Or;
m: is the concentration (adsorbed mass per unit of adsorbent mass);
w_0: is the maximum adsorption capacity (volume of adsorbate / mass of adsorbent);
ρ_1: is the specific mass of the liquid adsorbate;
D: is the affinity coefficient;
n: is a characteristic parameter of the adsorbent-adsorbate pair.
Ps: saturation pressure of the adsorbate.

Characteristics of sizing equipment:
Meteorological:
So, we have:

- Ambient temperature $\theta_a = 25°C$
- Wind speed $V_v = 2m/s$
- Average daily lighting G=237,5W/m².
- Sky temperature $T_v = 283K$.

Sensor specifications:
The sensor used has the following characteristics:

- emissivity of the absorber $\varepsilon_a = 0.88$
- emissivity of the cover $\varepsilon_c = 0.88$
- transmissivity of the cover (glass slide) $\tau = 85\%$
- cover adsorber $\alpha = 90\%$
- constant by Stephan Boltzmann $\sigma = 5{,}67.10^{-8} W/m^2.K^4$
- Thermal conductivity and thickness of thermal insulation material at the rear of the adsorber (glass wool) $\lambda_{lv} = 0.034 W/m.K$ $e_{lv} = 20cm$.
- Surface temperature of the rear wall of the insulation $\theta_{ar} = 30°C$

The properties of the AC 35 / methanol activated carbon couple:
The physical properties of methanol as a function of temperature are given by:

Latent heat (kJ / kg) as a function of temperature T (K)

$$L(T) = 654{,}23 + 4{,}3956.T - 8{,}5439.10^{-3} T^2 - 1{,}7968.10^{-6} T^3 \quad 2$$

Pressure as a function of temperature T (K):

$$\ln(P) = 8{,}2641 - 0{,}18785T + 7{,}7686.10^{-4} T^2 - 8{,}6669.10^{-7} T^3 \quad 3$$

Specific heat (kJ / kg.K) of methanol as a function of temperature (K)

$$Cp(T) = 2{,}1167 + 0{,}23261T - 5{,}0556E - 02.T^2 + 3{,}9815E - 03.T^3 \quad 4$$

Density (kg / m^3) as a function of temperature (K):

$$\rho(T) = 917{,}35 + 4{,}1898.10^{-3} T - 1{,}4679.10^{-3} T^2 \quad 5$$

Knowledge of the properties of the couple is necessary for the calculation of the amount of heat received or transferred by the AC-35 activated carbon couple. They are presented in the following table:

Table 1:- Values of the constants.

n	D	w_o(l/kg$_{CA}$)	Cp_{AC} (J/kg.K)
2,15	5,02.10^{-7}	0,415	920

Data relating to the adsorber:
We have chosen copper as the construction material for the adsorber. The mass and specific heat of copper are respectively $m_{cu} = 30kg$ and $Cp_{cu} = 0{,}92kJ/kg.K$ [1].

Simplifying assumptions:
We make the following assumptions:
1. We consider that the adsorbed phase is liquid,
2. The adsorbent bed is made up of identical AC-35 activated carbon grains which are distributed uniformly.
3. The physical properties of the liquid, the metal and the adsorbent are constant and homogeneous.
4. The thermal resistance between the metal tube and the adsorbent bed is neglected.
5. The adsorbent bed is homogeneous and isotropic.
6. The porous particles of activated carbon are incompressible

Modeling equations:
Parameters set for the operation of the refrigerator
→ Evaporation temperature / 0 ° C.
→ Hot water temperature / 80 ° C.
→ Condensation temperature / 35 ° C.
→ Ambient temperature / 35 ° C

Energy balance - adsorbent bed
-Equation of conservation of the adsorbent bed
$$\left(\rho_s C_{ps} + \rho_g q C_{pa}\right)\frac{\delta T_s}{\delta t} = \rho_s \Delta H_{ads}\frac{\partial \bar{w}}{\partial t} + \frac{\partial}{\partial z}\left(\lambda e + \frac{\partial T_s}{\partial z}\right) - \frac{2*h_s - m}{d1}(T_s - T_m) \quad 6$$
Equation of energy conservation for the fluid.
$$\rho_f * C_{pf} * \frac{\partial T_f}{\partial t} = -\rho_f * C_{pf} * U_f^b * \frac{\partial T_f}{\partial z} + \lambda_f * \frac{\partial}{\partial z}\left(\frac{\partial T_f}{\partial z}\right) - \frac{2*h_f}{d_f}(T_f - T_m) 7$$

Energy balance - Condenser.
-Equation of energy conservation of the condenser
$$\left(M_m C_{pm}\right)\frac{\delta T_m^c}{\delta t} = -h_m A_{m_{ex(T_m^c - T_c)}} - h_m A_{m_{in(T_m^c - T_{co})}} + \frac{\lambda_m}{V_m}\frac{\partial}{\partial z}\left(\frac{\partial T_m^c}{\partial z^2}\right) 8$$
Energy conservation equation for the fluid.
$$\rho_{co} * C_{pco} * \frac{\partial T_{co}}{\partial t} = -u_{co} * \rho_{co} * C_{pco} * \frac{\partial T_{co}}{\partial z} + \lambda_{co} * \frac{\partial}{\partial z}\left(\frac{\partial T_{co}}{\partial z}\right) - \frac{2*h_{co}}{d_{co}}(T_{co} - T_c) 9$$

Energy balance - Evaporator.
-Equation of energy conservation for the evaporator.
$$\left(M_E C_{pE}\right)\frac{\delta T_E}{\delta t} = -L_E * M_s \frac{\partial q_{ads}^b}{\partial t} + \left(h_f * M_s \frac{\partial q_{des}^b}{\partial t}\right) - (UA)_{ch}(T_E - T_{ch}) 10$$
Equation of energy conservation for the fluid
$$\rho_{ch} * C_{pch} * \frac{\partial T_{ch}}{\partial t} = -u_{ch} * \rho_{ch} * C_{pch} * \frac{\partial T_{ch}}{\partial z} + \lambda_{ch} * \frac{\partial}{\partial z}\left(\frac{\partial T_{ch}}{\partial z}\right) - \frac{2*h_{ch}}{d_{ch}}(T_{ch} - T_E) 11$$

Calculation of COP
The COPth coefficient of performance of the machine for such a cycle takes account of the thermal balances on the adsorber, the condenser and the evaporator is given by:
$$COP_{th} = \frac{Q_f}{Q_c} \quad 12$$
Q_f: is the refrigeration production or the quantity of cold produced on the evaporator (kJ).

Q_c: is the quantity of heat supplied to the absorber (kJ).

Qf expression

The amount of cold produced at the Q_f evaporator is given by:

$$\boldsymbol{Q_f = m_a \Delta m \left[L(T_e) - \int_{T_e}^{T_c} Cp_l(T) dT\right]} \quad 13$$

The first term of this equation represents the heat absorbed for the evaporation of the refrigerant at the evaporation temperature T_e.

The second term represents the sensible heat necessary to bring the condensate from its condensation temperature to that of evaporation T_e.

Or: L(T) et Cp_l represent respectively the latent heat of evaporation and the specific heat of the adsorbate in the liquid state.

m_a : is the mass of the solid adsorbent contained in the adsorber

Δm: is the cyclic mass of the adsorbate, calculated as follows:

$$\boldsymbol{\Delta m = m_{max} - m_{min}} = \text{m}\,(\boldsymbol{T_a, P_e}) - \text{m}\,(\boldsymbol{T_g, P_c}) \quad 14$$

m_{max} is the adsorbed mass corresponding to the adsorption temperature T_a and the evaporation pressure P_e (figure 1), calculated using the Dubinin-Astakhov model

m_{min}: is the adsorbed mass corresponding to the regeneration temperature Tg and the condensation pressure P_c (Figure 2), calculated using the Dubinin-Astakhov model.

Expression Qc

The adsorber receives energy from the hot source, part of which will be used to heat the metal parts of the adsorber, another part used to heat the adsorbent and adsorbate and the rest used for desorption[13].

$$\boldsymbol{Q_c = Q_1 + Q_2 + Q_3 + Q_{des}} \quad 15$$

Q_1, Q_2, et Q_3 are sensitive heats, respectively used for the heating of the adsorbent, the metal parts of the adsorber and the adsorbate.

Q_{des}: is the heat required for desorption corresponding to the mass of the adsorbed desorbed.

For the rest, we accept the hypothesis of incompressibility of liquids and solids, which leads to: Cp=Cv.

Cp: is the specific heat at constant pressure.

Cv: is the specific heat at constant volume.

Sensitive heat of the adsorbent (Q_1)

Q_1: is the heat required to bring the temperature of the solid adsorbent from temperature T_a to temperature. T_g, it is given by[21]:

$$\boldsymbol{Q_1 = m_a \int_{T_a}^{T_g} Cp_2\, dT = m_a Cp_2 (T_g - T_a)} \quad 16$$

m_a : mass of solid adsorbent contained in the adsorber

Cp_2 : specific heat of the adsorbent

maCp_2 :heat capacity of the adsorbent

Sensitive heat of the metal parts(Q_2)

The heat necessary to bring the temperature of the metal parts of the adsorber from T_a to, T_g it is given by[21]:

$$\boldsymbol{Q_2 = m_g \int_{T_a}^{T_g} Cp_w\, dT = m_g Cp_w (T_g - T_a)} \quad 17$$

m_g: mass of metal parts of the adsorber.

Cp_w:specific heat of the metal parts of the adsorber (kJ/kg. °C).

$m_g Cp_w$: heat capacity of the metal parts of the adsorber

Sensitive heat of the adsorbate Q_3

The heat necessary to heat the adsorbate from T_a to T_g, is given by [21]

$$Q_3 : m_a \int_{T_a}^{T_g} m(T)\, Cp_l(T).\text{dT} = m_a m_{max} \int_{T_a}^{T_{c1}} Cp_l(\text{T})\,\text{dT} + m_a \int_{T_{c1}}^{T_g} m(T) Cp_l(\text{T})\,\text{dT} \quad 18$$

m(T): mass adsorbed at temperature Tat condensing pressure P_c is calculated using the Dubinin-Astakhov model.

Desorption heat (Q_{des})

The heat of desorption corresponding to the temperatures T_{c1} and T_g is given by:

$Q_{des} = m_a \int_{m_{min}}^{m_{min}} q_{st} \mathrm{dm}$ 19

Où: q_{st} is the isosteric heat of adsorption

dm :differentiation of the adsorbed mass from equation 7

$$\mathrm{dm} = \mathrm{n}\, DmT^n \left(ln\frac{P_s(T)}{P}\right)^{n-1} \left[d\, ln\, P - \frac{q_{st}}{RT^2} dT\right] \quad 20$$

During the desorption-condensation phase, the pressure is constant and equal to the saturation pressure at the condensation temperature.

So the heat of desorption Q_{des} becomes:

$$Q_{des} = m_a\, \mathrm{n\, D} \int_{T_{c1}}^{T_g} m(T)\, T^n \left(ln\frac{P_s(T)}{P_c}\right)^{n-1} \frac{{q_{st}}^2}{PT^2} \mathrm{dT} \quad 21$$

The total heat supplied to the adsorber Q_C becomes:

$$\mathbf{Q_c = (m_a.Cp_2 + m_g.Cp_w)\,(T_g - T_a) + m_a.m_{max} \int_{T_a}^{T_{c1}} Cp_l(T)dT + m_a \int_{T_{cl}}^{T_g} m(T)Cp_l(T)dT + m_a}\mathrm{n\, D}\int_{\mathbf{T_{c1}}}^{\mathbf{T_g}} \mathbf{m(T)\, T^n \left(ln\frac{P_s(T)}{P_c}\right)^{n-1} \frac{{q_{st}}^2}{PT^2}}\mathrm{dT} \quad 22$$

Où q_{st} is the isosteric heat of adsorption, defined by the following equation:

$$q_{th} = L\,(Tc) + RT\, \ln\left(\frac{P_s(T)}{P_c}\right) + \left[\frac{\alpha RT}{nD}\right]\left[T\ln\left(\frac{P_S(T)}{P_C}\right)\right]^{(1-n)} \quad 23$$

Results and Discussion:-

Model validation:

Figure (2) represents a comparison of the COPth obtained from the proposed model and that given by Wassila. We note that the representative curves of these two models have almost the same appearance with a slight difference between them but acceptable. So from this comparison, we admit that our program works perfectly well.

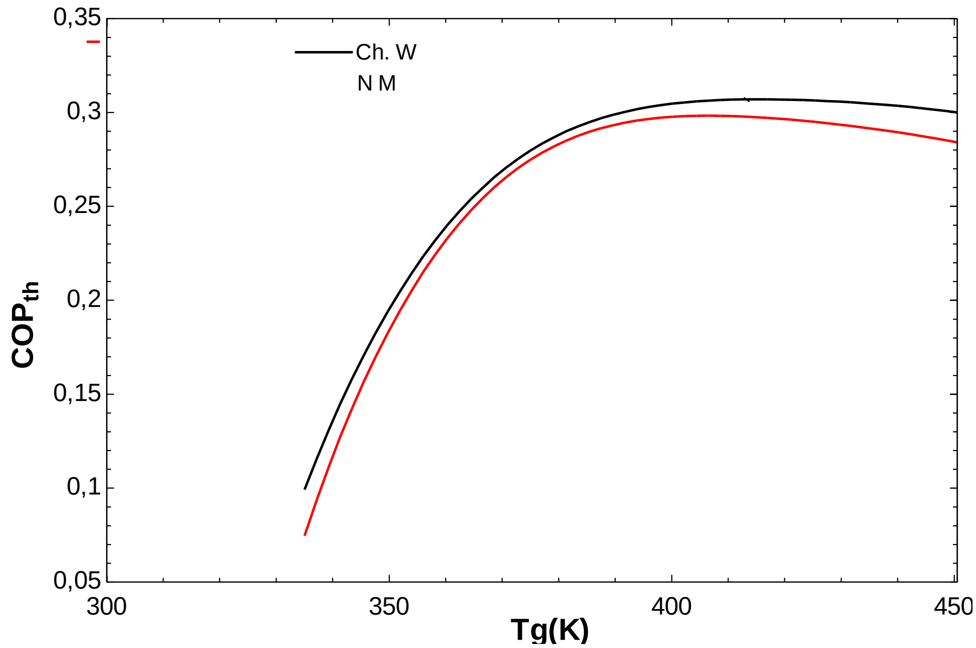

Figure 2:- Variation of COPth as a function of Tg, comparison of models.

Effect of regeneration temperature:

The regeneration temperature is the highest possible temperature reached by the system at the end of the desorption-condensation phase. Thus its effect on the performance of the machine is greater than that of other operating temperatures. Figure (3) gives the variation of the thermal performance coefficient COPth as a function of the regeneration temperature Tg with the adsorption temperature Ta = 298.15 K, the evaporation temperature Te = 272.15 K and the temperature of condensation Tc = 303.15 K. We see that the COPth increases with Tg until an optimum of COPth for Tg between Tg = 406 K and Tg = 421 K. For temperatures higher than Tg = 421 K the COPth decreases. This reduction in COPth shows that the optimal performance of the system is obtained only for a certain value of Tg and the continuation of the heating of the system only serves to increase the temperature of the activated carbon, the temperature of the metal parts of the adsorber and the temperature of the residual methanol.

The regeneration temperature Tg is a design variable which must be optimized. Generally, it is optimized to be able to obtain a large quantity of cycled mass and to avoid the decomposition of the refrigerant [1]. As methanol is the refrigerant, the regeneration temperature is limited to 150 ° C [2], since methanol decomposes beyond this value, which will block the adsorption process where the system stops.

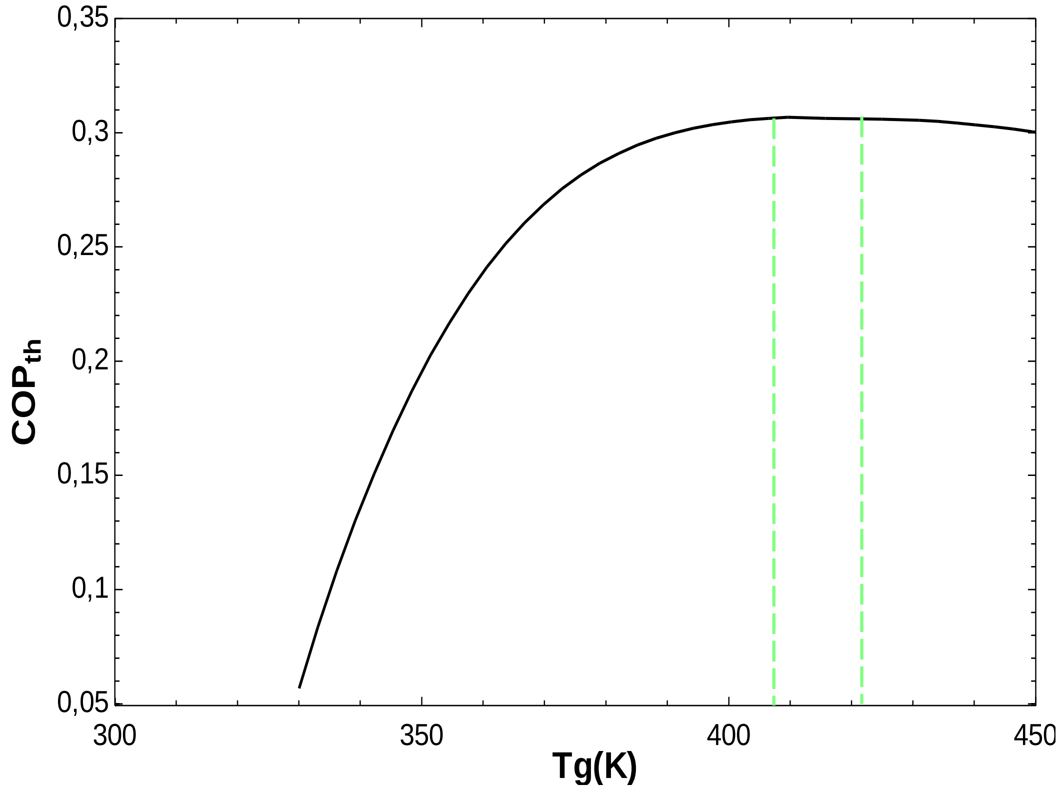

Figure 4:- Variation of COPth as a function of Tg (Ta = 298.15 K; Te = 272.15 K; Tc = 303.15 K).

Effect of adsorption temperature on the coefficient of performance:
Figures 5 and 6 respectively illustrate the variation of COPth and the variation of the cycled mass as a function of Tg and Ta with Tc = 303.15 K and Te = 272.15 K. In these two figures, we clearly see the increase in Ta is accompanied by a decrease in COPth and a decrease in the cycled mass. These results were predictable because, according to the Dubinin-Astakhov model, an increase in Ta leads to a decrease in the maximum adsorbable mass at the start of the refrigeration cycle. Thus, there is a decrease in the mass cycled with Ta hence the decrease COPth. So from these remarks, we suggest to have a better performance of the machine to always try to start the thermodynamic cycle by the lowest possible adsorption temperature so that the mass adsorbed at this temperature is the greatest possible.

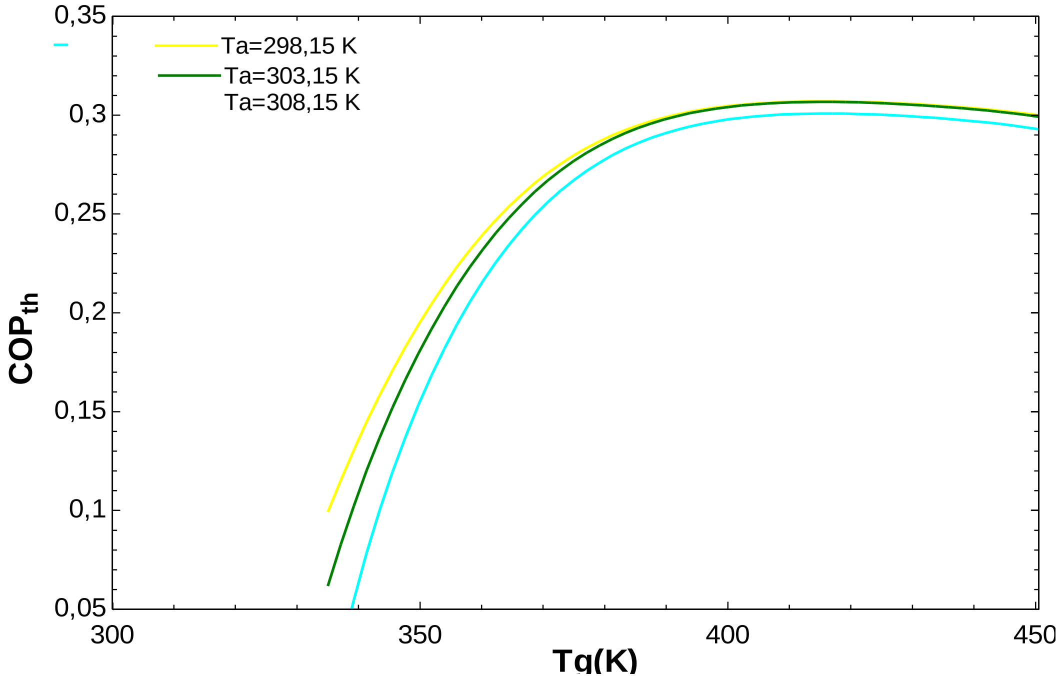

Figure 5:- Variation of COPth as a function of Tg and Ta (Te = 272.15 K; Tc = 303.15K).

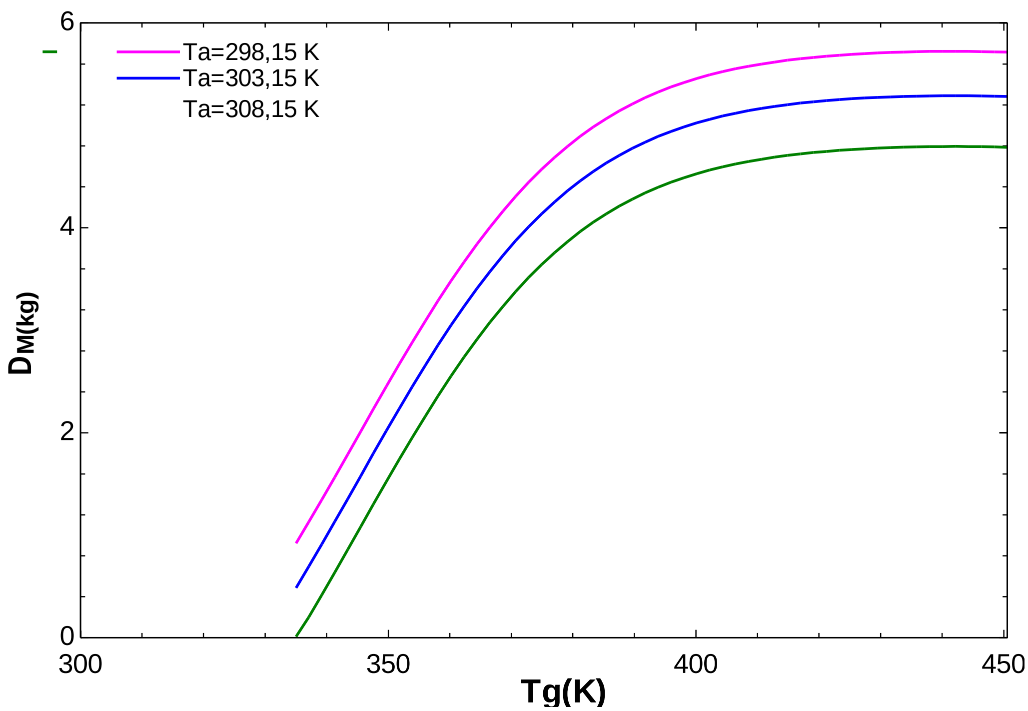

Figure 6:- Variation of the cycled mass as a function of Tg and Ta (Te = 272.15 K; Tc = 303.15 K).

Effect of condensing temperature:

Analysis of figures 7 and 8 shows that the increase in Tc, by setting Ta = 298.15K and Te=272.15 K, and by varying the regeneration temperature Tg causes a decrease in the coefficient of performance of the machine and a decrease in the amount of mass cycled. This can be explained using equation 2, we can see that an increase in Tc leads to an increase in the saturation pressure Ps (Tc) which implies a decrease in the cycled mass given by equation 14. So the cycled mass decreases as well as the COPth of the system

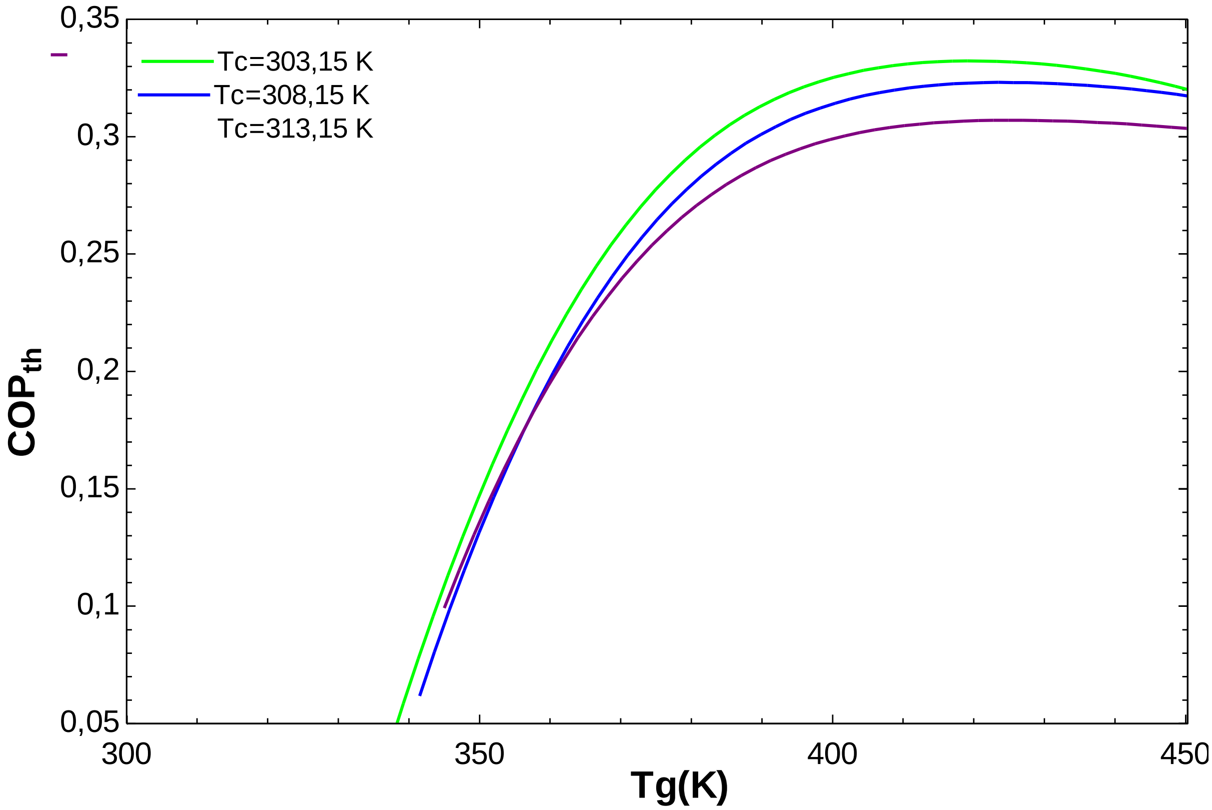

Figure 7:- Variation of COPth as a function of Tg and Tc (Ta = 298.15; Te = 272.15).

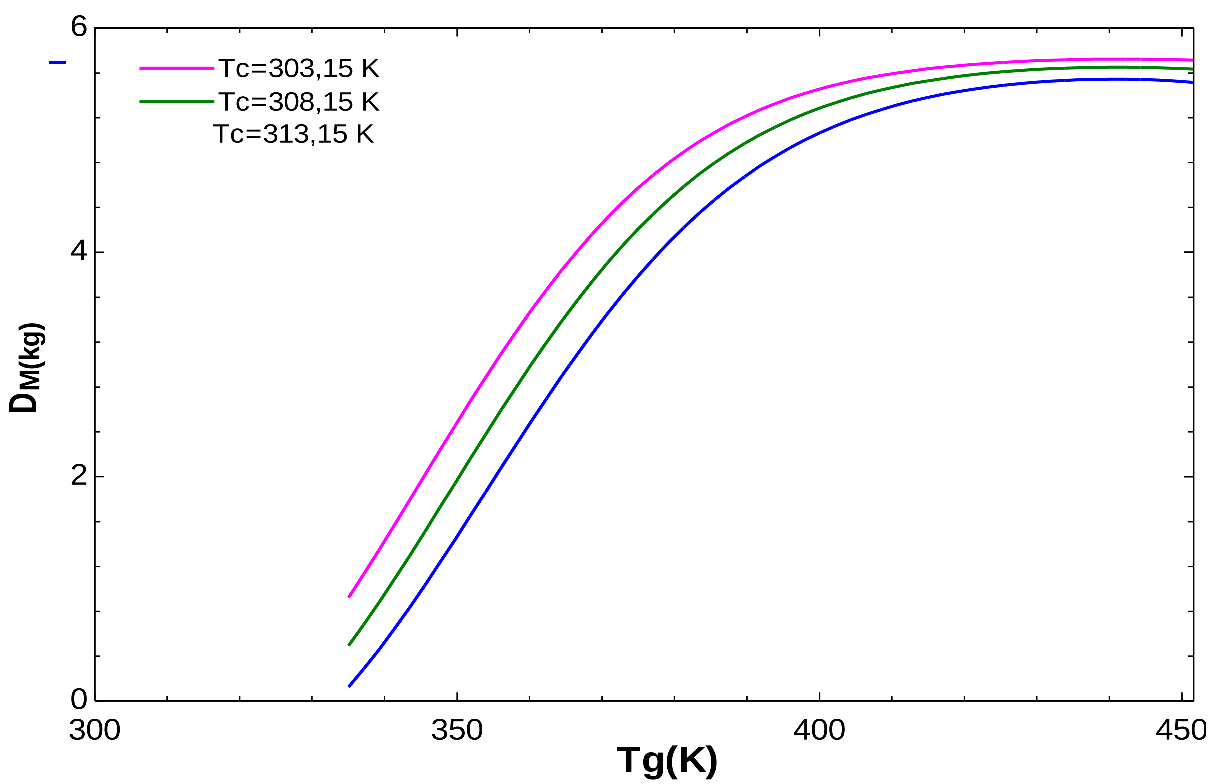

Figure 8:- Variation of the cycled mass as a function of Tg and Tc (Ta = 298.15; Te = 272.15).

Effect of evaporation temperature:
The evaporation temperature is an important parameter which greatly affects the performance of solar adsorption refrigerators. Its effect on the thermal coefficient of performance COPth and on the quantity of methanol cycled is evaluated respectively in figure (9) and in figure (10). On figure (9), we note that the coefficient of performance increases with the evaporation temperature Te. This increase in COPth with the evaporation temperature is explained by the fact that the saturation pressure Ps (Te) of methanol increases with Te which causes an increase in the cyclic mass of methanol illustrated in figure (10).

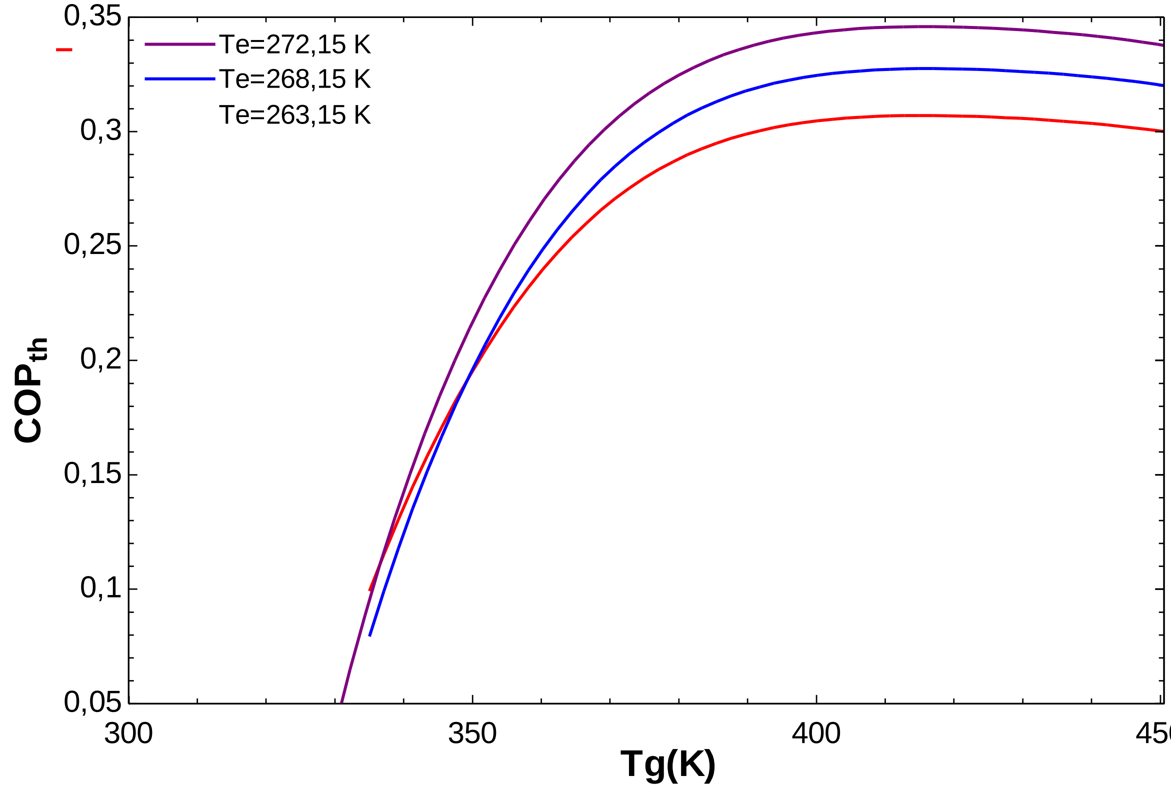

Figure 9:- Variation of COPth as a function of Tg and Te (Ta = 298.15 K; Tc = 303.15 K).

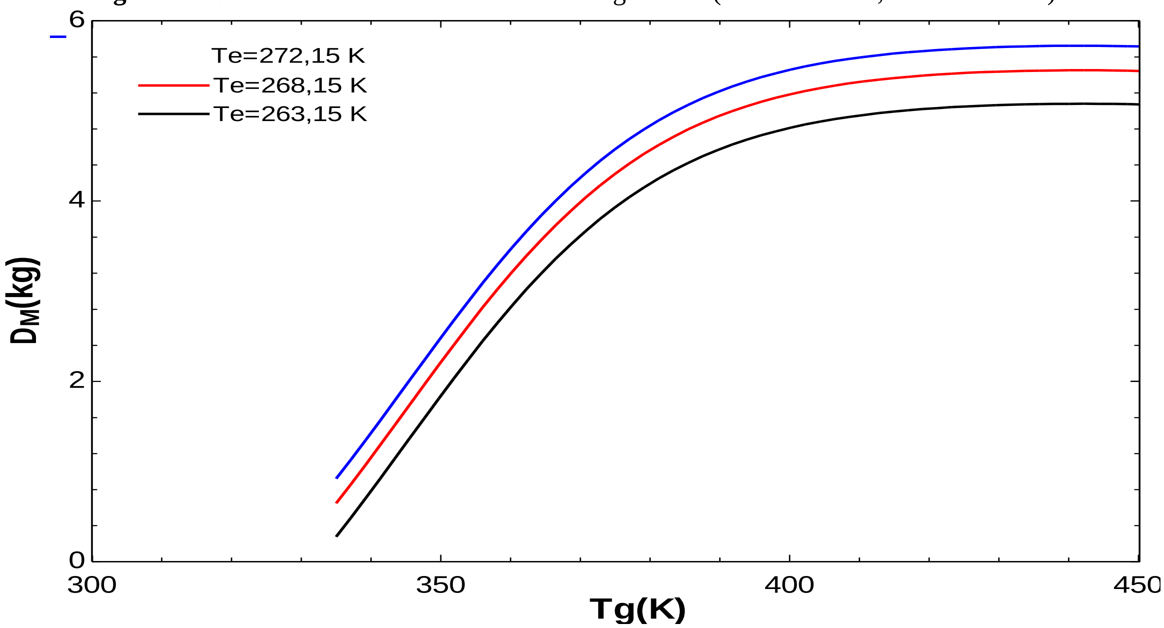

Figure 10:- Variation of the cycled mass as a function of Tg and Ta (Ta = 298.15; Tc=303.15).

Conclusion:-

In this work, the numerical simulation allowed us to clearly see that the operating temperatures of the machine have a very important influence on the performance of the system. So it emerges from this study that the optimization of an adsorption refrigeration machine for better performance inevitably requires mastery and control of the machine's operating temperatures; which is not easy because the evolution of operating temperatures depends on several random factors related to the type of climate in which the experiment is carried out.

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