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INFLUENCE OF EVAPORATOR MASS TRANSFER COEFFICIENT ON THE EFFICIENCY OF SILICA GEL/WATER SOLAR ADSORPTION REFRIGERATORS

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ABSTRACT

The objective of this study is to determine the influence of the mass transfer coefficient k of the evaporator on the performance of an adsorption solar refrigerator operating with silica gel/water couple. Indeed, this intrinsic parameter of the evaporator, related to its geometry and thermo-physical parameters, plays a very important role in the cold production process. This study shows that for a higher value of k, the temperatures of the refrigerant and the adsorbent are lower, proof that cooling is more efficient. In addition, the COP is higher and the refrigerant fraction in the adsorbent is larger, reflecting the fact that a large amount of refrigerant could be evaporated and thus the cooling is better. Also, the parameter k directly depends on the characteristic length of the evaporator and the difference in mass concentration of the refrigerant in the evaporator and the adsorbent.

KEYWORDS: Cooling, evaporator, mass transfer factor, adsorption.

1. INTRODUCTION

The solar sorption cooler full of many advantages. It is autonomous, robust and above all, ecological [1],[2]. However, as its reduced performance did not allow it to be competitive in the market [3]. The insulation problems, intermittently [4] and very low cooling power [1] are among other shortcomings observed in this type of refrigerator. It is therefore important to determine the factors influencing the cooling process. Several studies were conducted in this direction. For example, we study the influence of certain parameters such as operating temperature, the properties of the adsorbent torque / adsorbate [5],[6] the influence of the choice of the couple [7] and also the adsorption cycle [3],[8] the performance of the refrigerator. In this paper, we study the influence of the mass transfer coefficient of the evaporator performance. This parameter is very important in the evaporator process and plays a critical role in the cooling capacity of the refrigerator. The aim of the present work is to provide an evaporator model to obtain a better yield.

2. MATERIALS AND METHODS

2.1. Materials

2.1.1. Refrigerator Overview

The following figures show photographic images of the refrigerator operating torque silicagel water on which is carried the study. In Figure 1, we have a view inside of the refrigerator with the evaporator at the bottom pistol-shaped. As in Figure 2, it brings close the cylindrical condenser. The white color represents the insulating block portion of the refrigerator.

Figure 1 : Photo of the evaporator and the chest

Figure 2 : Photo condenser

2.1.2. Presentation of measurement tools

In this section, we make case for measuring devices used in the various experiments with photographic illustrations.

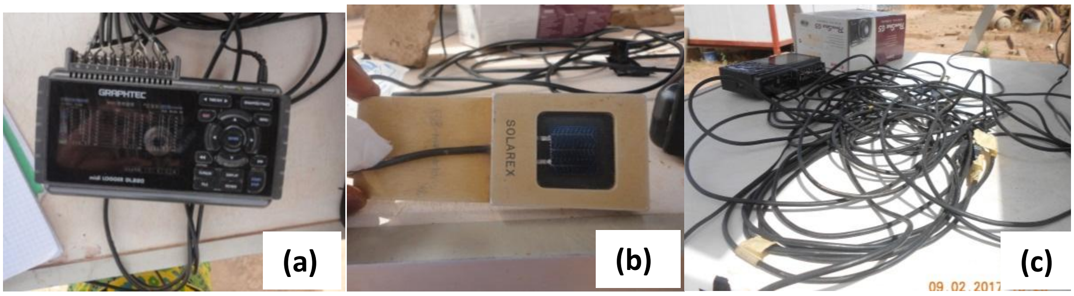

Figure 3: Measuring apparatus: (a) the data logger; (b) the solarimeter; (c) thermocouples

Figure (a) shows the data logger which an automatic device, programmable, which records individual measured values and series of measurements of certain physical quantities such as temperature, pressure, relative humidity.

Figure (b) shows the radiometer to measure the intensity of solar radiation.

Figure (c) shows the thermocouples which are cables used for the temperature measurement at given points.

2.2. Methods

2.2.1. Adsorption phenomenon

Adsorption translated fixing the molecules of a gas or a liquid to the surface of a solid. This reaction is endothermic and exists in two forms: one is physical adsorption or physical adsorption and chemical adsorption or chemisorption. This phenomenon is used by the solar refrigerators adsorption to allow regeneration of the adsorbent torque/adsorbate in the sensor. In effect, the vapors initially desorbed adsorbate at the sensor are reabsorbed after condensation and evaporation in the refrigerating cycle. There are many physical models to describe this phenomenon scientifically. We will speak about some of them in the next point.

2.2.2. Adsorption model

a. Polanyi model

This theory, also called filling theory micropore volume, stipulates that the space in the vicinity of the interface adsorbent/adsorbate is as a succession of equipotential surfaces each limiting a volume W_i occupied by the liquid adsorbed molecules. W_i is given by the following formula:

$$W_i = \beta * f(A_i)$$

With$A_i = RT * ln\left(\frac{P_S}{P}\right)$

$T: adsorption\ temperature.$

$\beta: coefficient\ of\ affinity\ independent\ of\ T\ and\ taking\ into\ account\ the\ nature\ of\ the\ adsorbent$

$P: equilibrium\ pressure\ in\ the\ vicinity\ of\ the\ adsorbent\ surface\ at\ temperature\ T.$

$P_S: saturation\ pressure\ of\ the\ adsorbate\ in\ the\ gas\ phase\ at\ temperature\ T.$

$T: perfect\ gas\ constant.$

A_i: *Polanyi adsorption potential.*

b. Dubinin model

This model is inspired by Polanyi model. In this model, the adsorption potential of Polanyi is interpreted in equation (E-III) as a change in the free energy corresponding to the isothermal-reversible transfer of one mole of adsorbate from the liquid state to the adsorbed state.

$$\mathbf{A_i = -\Delta G = RT * \ln\left(\frac{P_s}{P}\right)} \qquad \textbf{(i)}$$

Also, from experimental data, Dubinin et al[5] were able to demonstrate that the volume W_i is a Gaussian function of the adsorption potential and is expressed as follows:

$$\boldsymbol{W_i = W_o \exp\left[-K\left(\frac{A_i}{\beta}\right)^2\right]} \qquad \textbf{(ii)}$$

By substituting the expression of A_i in (E-III), we obtains:

$$\boldsymbol{W_i = W_o \exp\left[-D\left(T * \ln\left(\frac{P_s}{P}\right)\right)^2\right]} \qquad \textbf{(iii)}$$

- $D = \frac{KR^2}{\beta^2}$ *a characteristic coefficient of the adsorbent/adsorbate pair.*
- W_i *the volume occupied by the adsorbed phase.*
- W_0 *the maximum adsorbable volume.*

The adsorbed mass is given by the formula:

$$\boldsymbol{m = \rho_l(T) * W_i = \rho_l(T) * W_o \exp\left[-D\left(T * \ln\left(\frac{P_s}{P}\right)\right)^2\right]} \qquad \textbf{(iv)}$$

With $\rho(T)$ *the density of the adsorbate in the liquid state*

C. Adsorption kinetics in the case of torque silicagel water

According to Walid al SOTEHI and [9], The concentration of water in the silica gel at thermodynamic equilibrium is given by the relationship Boelman:

$$\boldsymbol{X^* = 0.346\left(\frac{P_s(T_e)}{P_s(T_s)}\right)^{\frac{1}{1.6}}} \qquad \textbf{(v)}$$

$P_s(T)$ can be estimated from the relationship Freundlich [9]:

$$P_s(T) = 0.0000888(\mathrm{T}-273.15)^3 - 0.0013802(\mathrm{T}-273.15)^2 + 0.0857427(\mathrm{T}-273.15) + 0.470937$$

The equation governing the mass transfer kinetics is written as[9]:

$$\boldsymbol{\frac{\partial X}{\partial t} = k_s a_v (X^* - X)} \qquad \textbf{(vi)}$$

- $k_s a_v = \frac{FoD_s}{R_p}$ *the effective transfer coefficient inside the pores of silicagel.*
- $D_s = D_{s0} e^{-\frac{E_a}{RT}}$ *effective diffusivity.*

with:

$D_s = 2.54 * 10^{-4} m^2.s^{-1}, R_P = 1.7 * 10^{-4} m, E_a = 4.2 * 10^4 J.mol^{-1}, F_0 = 15$

$R = 8{,}314\, J.mol^{-1}.K^{-1}$

2.2.3. Heat of adsorption

The adsorption heat can be estimated from the following formula [9];

$$\boldsymbol{Q_{ads} = m_s \Delta H_{ads} \frac{\partial X}{\partial t}} \qquad \textbf{(vii)}$$

2.2.4. Evaporation

a. Definition

Evaporation is a gradual transition from a body of the liquid to the gaseous state. This phenomenon is endothermic and absorb a very high heat amount in surrounding environment. In the adsorption refrigerators, the heat required to evaporate the refrigerant is drawn from the enclosure to be cooled thus creating cooling.

b. Method of calculating the mass transfer coefficient

In analogy to the heat transfer, the mass flow is given by the formula (viii) [10]:

$$\boldsymbol{J_0 = kS * \Delta C = kS * (C_{m0} - C_\infty)} \qquad \textbf{(viii)}$$

The computation of k in natural convection is done using the following correlations Ranz and Marshall [11]:

$$Sh = 2 + 0.6 * Gr_m^{\frac{1}{4}} * Sc^{\frac{1}{3}} pour Gr_m < 10^8 \quad \text{(ix)}$$

With $\begin{cases} Gr_m = \frac{g \times \beta^* \times \Delta C \times L^3}{\nu_a^2} \\ Sc = \frac{\nu_a}{DF_a} \end{cases}$

- β^* *is the mass expansion coefficient of air* $\beta^* = \frac{1}{\rho_a}\left(\frac{\partial \rho_a}{\partial C}\right)_{T,P}$
- ΔC *represents the difference in concentration of water vapor between the adsorbent and evaporator*
- DF_a *is the mass diffusivity of the air*

The coefficient k is given by the following relationship:

$$Sh = \frac{k * L}{DF_a} \text{ (x)}$$

2.2.5. Transfers equations

- **Heat balance at the evaporator**

$$m_r Cp_r \frac{\partial T_r}{\partial t} = -[L_v - Cp_r(T_c - T_r)] * \left[\frac{kS}{R * T_{eq}}\left(P_{v,sat-eau} - P_{v,ads}\right)\right] \text{(xi)}$$

- **Heat balance at the adsorber**

$$(m_s Cp_s + m_s X Cp_r)\frac{\partial T_s}{\partial t} = m_s \Delta H_{ads}\frac{\partial X}{\partial t} + m_s Cp_r (T_r - T_s)\frac{\partial X}{\partial t} \text{ (xii)}$$

- **Relationship between the mass content of refrigerant and the transfer coefficient**

$$m_s \frac{\partial X}{\partial t} = \frac{kS}{R * T_{eq}}\left(P_{v,sat-eau} - P_{v,ads}\right) \text{ (xiii)}$$

3. RESULTS AND DISCUSSION

Recall the formulas of various physical quantities which can be observed the influence of the transfer coefficient.

- Coefficient of performance (COP) [9],[12]:

$$COP = \frac{Q_{ev}}{Q_{gen}} = \dot{m}_r \times \frac{Cp_r \Delta T_r}{Q_{gen}} = \frac{kS\left(P_{v,sat-eau} - P_{v,ads}\right)}{R * T_{eq}} \times \frac{Cp_r \Delta T_r}{Q_{gen}} \text{(xiv)}$$

- Specific Cooling Power (SCP)[9]:

$$SCP = \frac{Q_{ev}}{m_{ads}} = \dot{m}_r \times \frac{Cp_r \Delta T_r}{m_{ads}} = \frac{kS\left(P_{v,sat-eau} - P_{v,ads}\right)}{R * T_{eq}} \times \frac{Cp_r \Delta T_r}{m_{ads}} \quad \text{(xv)}$$

The data used in the simulation program are:

$$S = 0.2585\, m^2 \,;\, m_s = 60\, kg \,;\, m_r = 35\, kg \,;\, Cp_r = 4180\, J.kg^{-1}.K^{-1} \,;$$
$$Cp_s = 924\, J.kg^{-1}.K^{-1} \,;\, T_c = 298\, K \,;\, Q_{gen} = 10\, W \,;\, R = 8.316\, J.mol^{-1}.K^{-1}$$
$$\nu_{ads} = 15.6 * 10^{-6} m^2.s^{-1};\; DF_a = 2.42 * 10^{-5} m^2.s^{-1};\; g = 9.8\, m.s^{-2};\; \beta^* = 3.661 * 10^{-3} K^{-1}$$

3.1. Influence of k on the refrigerant temperature

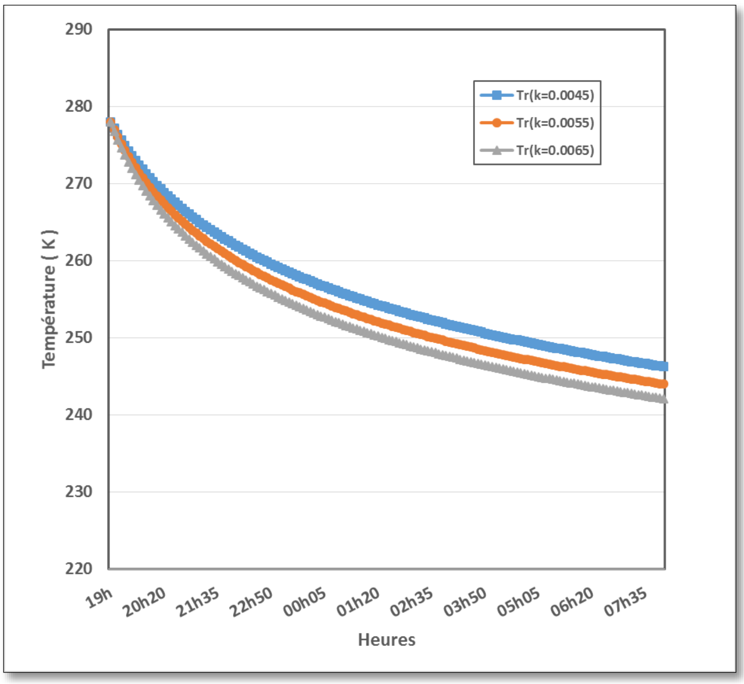

Figure 4: influence of k on the refrigerant temperature

Figure 4 shows changes in the coolant temperature during the evaporation for different values of k phase. We are seeing a greater value of k promotes cooling the refrigerant. This is due to the fact that more than k, the greater has been a significant amount of refrigerant which passes from the liquid state to the vapor state by drawing the latent heat in the refrigerant.

3.2. Influence of k on the temperature of the adsorbent

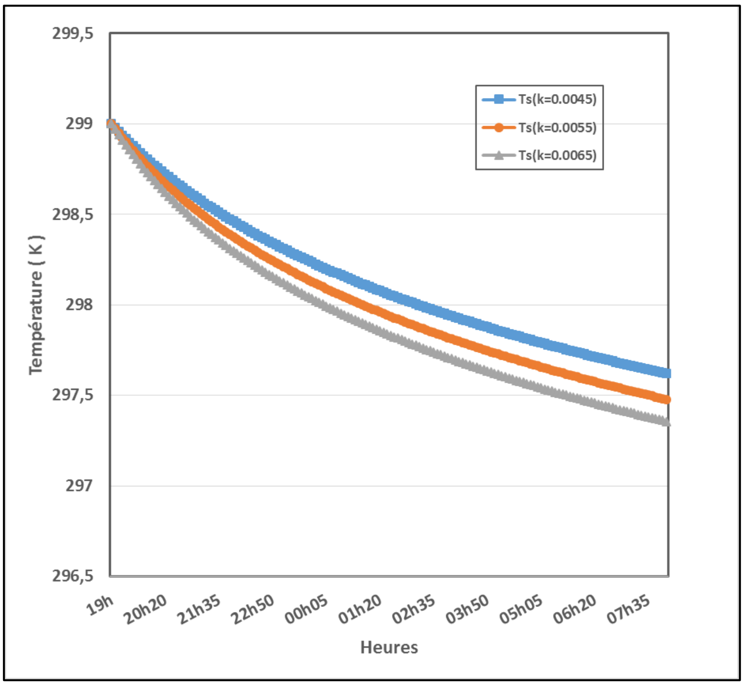

Figure 5 : influence of k on the temperature of the adsorbent

Figure 5 shows the evolution of the temperature of the adsorbent during the evaporation for different values of k phase. As in ***Figure 4***, we see a decrease in the temperature of the adsorbent (silicagel) to a larger value of k. This is quite logical. Indeed, when the mass transfer coefficient is high, the refrigerant vapors leaving the surface of the refrigerant have a lower temperature and contribute to lowering the temperature of the adsorbent since they will be re-adsorbed by the latter.

3.3. Influence of k on the mass fraction of refrigerant

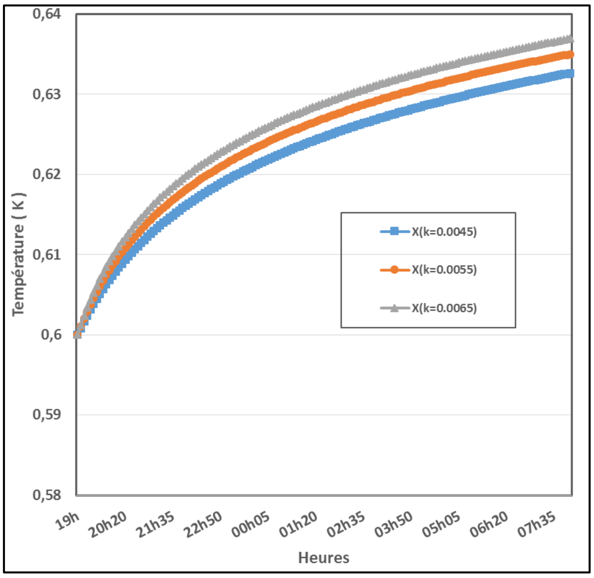

Figure 6 : influence of k on the mass fraction of the refrigerant

Figure 6 shows the evolution of the mass as during the evaporation for different values of k phase. We observe an increase of X to a larger value of k. This is quite logical. Indeed, when the mass transfer coefficient is high, the refrigerant vapors reaching the adsorbent surface are more important which will result therefore to increase the concentration of refrigerant vapor into the adsorbent.

3.4. Influence of k on the coefficient of performance (COP)

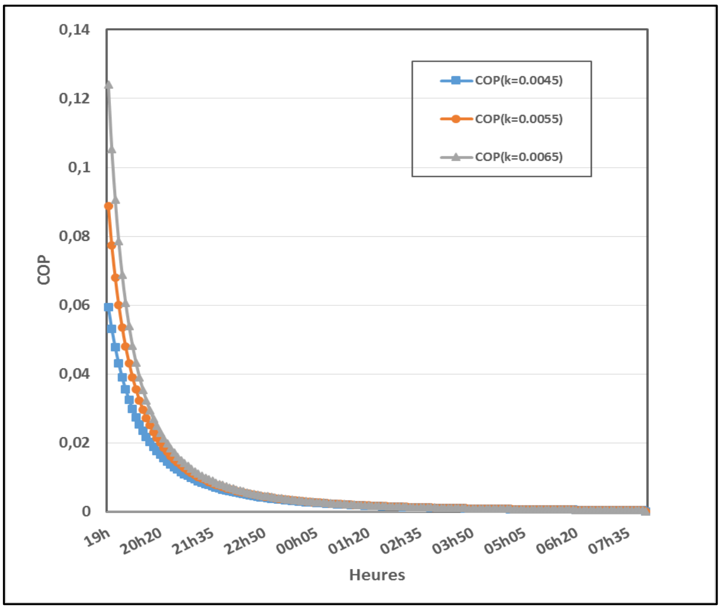

Figure 7 : influence of k on the coefficient of performance (COP)

Figure 7 shows the evolution of the coefficient of performance during the evaporation for different values of k phase. A phase sudden decrease is observed between 19h and 20:30 and a slight decrease of the curve after 20:30 until the end of evaporation. So this shows that the COP decreases gradually as one approaches the end of evaporation. We can explain this by the fact that during the adsorption phase, the adsorbent tends to saturate, which reduces the volume of refrigerant adsorbable hence a decline in its ability to adsorb negatively influencing thus the performance of the refrigerator during this period. As for the influence of k, we can see a greater value of k provides relatively high COP.

3.5. Influence of k on the specific cooling power (SCP)

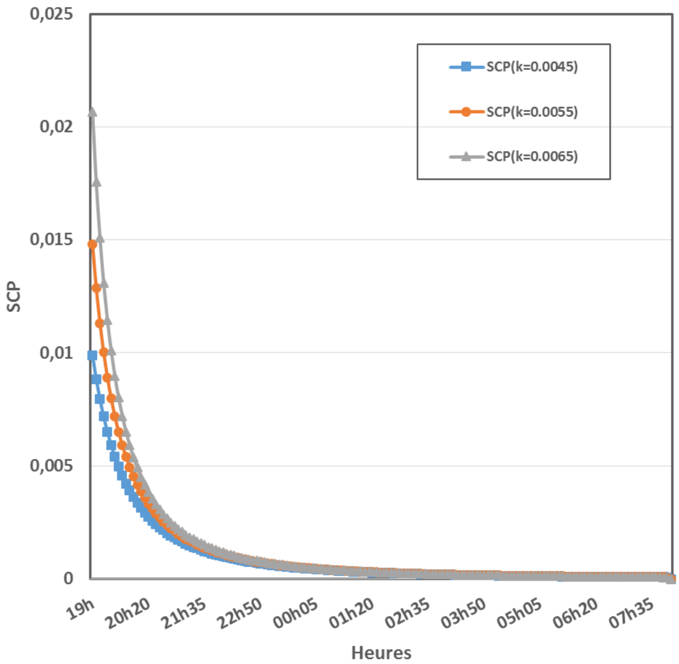

Figure 8 : influence of k on the specific cooling power (SCP)

Figure 8 shows the evolution of the power of specific cooling during the evaporation for different values of k phase. As in Figure 4, we observe practically the same gaits and also find a large enough mass transfer coefficient thus promotes cooling.

3.6. Influence of the characteristic length L on k

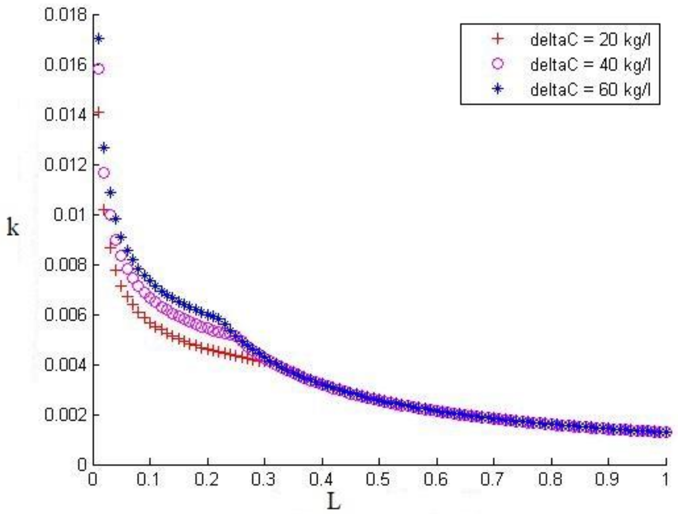

Figure 9 : Influence of the characteristic length L on k

The above graph shows the evolution of the mass transfer coefficient as a function of the characteristic dimension (L) for different values of ΔC. One can observe that k decreases and as L increases. Moreover, we note that for L < 0. 3m, we have large values of k where the value of ΔC is greater. As against the curves merge

for values of L> 0.3m. This provides that for values of L greater than 0.3m, ΔC has no more influence on the coefficient k.

3.7. Influence of k on ΔC

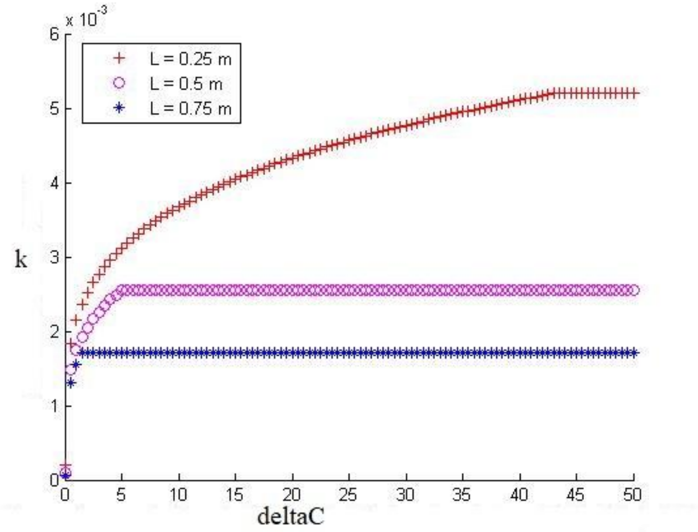

Figure 10 : Influence of k on delta (ΔC)

Figure 10 shows influence of ΔC on the transfer coefficient for different values of L. The three curves each comprise two phases; a growth phase and a phase invariance. The growth stage reflects the fact that the increase of ΔC is therefore favorable to the coefficient k. This can be explained by the fact that over the concentration difference, the greater the number of water molecules that switch to the gas phase will be. Furthermore, we note that for smaller values of L we have larger values of k, confirming the result before. The second phase corresponds to the invariance stage reflects the fact that from a certain value of ΔC, the increase has no effect.

4. CONCLUSION

This study allows us to understand more fully the behavior of the solar sorption cooler. Indeed, it highlights the role of a very important parameter in the operation of the refrigerator. This is the mass transfer coefficient.

This parameter affects several properties of the refrigerator such that the temperature of the adsorbent, the refrigerant, the mass fraction of the refrigerant in the adsorbent, the coefficient of performance (COP), the specific cooling power (SCP). Thus, larger values of k increase the performance of the refrigerator.

Furthermore, it should be noted that parameters such as the characteristic dimension (L) of the evaporator so that the concentration difference between the air at the surface of the coolant and the air above (ΔC) influence the mass transfer coefficient k.

5. ACKNOWLEDGEMENTS

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