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Impacts of desiccant liquid properties on the membrane based heat exchanger performance

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***Abstract*— The membrane based heat exchanger is a new proposition of clean air conditioning technologies in which is investigated in this paper. The air and desiccant liquid are used inside membrane based heat exchanger. In order to evaluate the impacts of desiccant liquid properties on the heat and mass transfer distributions, a two-dimensional model including the momentum, heat and mass transport equations is solved by CFD code. Significant parameters such as inlet velocity, temperature and water content of desiccant liquid are mentioned. The results show that the increasing of desiccant liquid velocity minimizes the heat and mass transfer rates between the air and desiccant liquid channels. A high inlet desiccant liquid temperature leads to a large (small water content) specific humidity ratio values in the outlet air (desiccant liquid) channel. In addition, the inlet water content of desiccant liquid has a strong effect on the outlet humidity and water content distributions when it becomes higher. Also, this investigation takes into account the effect of desiccant liquid proprieties which also have a strong effect on the sensible, latent and total effectiveness of studied exchanger.**

***Keywords*— Membrane based heat exchanger; desiccant liquid; effectiveness.**

I. Introduction

Energy recovery technologies can be classified into two categories; the sensible heat exchangers in which recover only the sensible heat with a great effectiveness, problem of maintenance, and price; the second category is the total heat exchangers. Total heat exchangers or membrane based heat exchangers are a new category of recovery equipments in which use a porous membrane. They can recover both heat and moisture with a high effectiveness [1-3].

These membrane based technologies are affected by various operating and geometric parameters such as the fluids nature, membrane properties, inlet parameters values, etc.

Firstly, the specifications of porous membranes are their proprieties which are permeable only to the vapour and used in dehumidification and recovery processes. Several studies specify to built and improve new membranes with high performance. Zhang et al [4] fabricated a novel vapour permeable composite membrane in which used polyethersulfone (PES) coated into a dense polyvinyl alcohol (PVA). The uses of lithium chloride (LiCl) salt like an additive to the PVA solution is to facility and improve the moisture permeation. The LiCl concentration has a great effect of in the water vapour permeability of the hydrophilic polymer membrane. X.R. Zhang et al [5] are used the same approach to prepare a cellulose acetate (CA) membrane. The process involves a cheap raw material of CA, an environmental friendly solvent acetic acid, and additive de-ionized water. The composite membrane is formed by coating solvent acetic acid and additive de-ionized water casting solution onto the CA support membrane. Studies found that the approach is successful in making membranes for heat and moisture recovery with high moisture permeability. The approach provides an environmental friendly yet economical solution for preparing membranes for heat and moisture recovery.

Secondly, many prove that the membrane based heat exchanger performance may be related to the operating and geometric conditions. Zhang et al [6-8] investigated and tested the different flow arrangements (co-current, counter flow, and cross flow) for membrane based heat exchangers. Nusselt and Sherwood numbers are calculated for the three flow arrangements. They concluded that the flow arrangements has an effect on the heat and mass transfer rates between the fresh and exhaust channels of membrane based heat exchangers. Also, they constructed and investigated a quasi-counter flow parallel heat exchanger. An experimentally and detailed mathematical modelling are carried which the momentum, heat and mass transport equations are solved in the different regions of the quasi-counter membrane based heat exchanger. They found that quasi-counter flow geometry has a great effectiveness then the other membrane based heat exchangers [9].

However, recent studies specify that the desiccant liquid air membrane energy exchanger which used two different fluids. The performance of these exchangers may be related to the desiccant liquid proprieties. In literature, several materials have been investigated such as Magnesium Chloride ($MgCl_2$) [10], Lithium Chloride (LiCl) [11], and Lithium Bromide (LiBr) [12].

In order to compare a novel flow arrangement configuration and to evaluate their effects on the desiccant liquid air membrane energy exchanger performance, Vali et al. [13] developed a numerical model and they found that with the same membrane area the counter-cross-flow arrangement is better than pure counter-flow and lower than pure cross-flow.

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Abdsalem et al. [14] proposed a novel desiccant liquid air membrane energy exchanger designs in order to enhance the cooling capacity and control the fluids temperature. They found that the sensible cooling capacity, moisture removal rate, and total effectiveness of the studied exchanger are enhanced respectively by up to 140%, 54%, and 39% by compared to a normal normal desiccant liquid air membrane energy exchanger with the same design parameters.

It is obvious that the choice of desiccant liquid properties is one of the most important parameters influencing on heat exchanger performances. In this study, a membrane based heat exchanger is numerically investigated. The desiccant liquid impacts on heat and mass distributions are evaluated. Also, their impacts on the sensible, latent and total effectiveness are established. The aims of this paper are to show the effects of one component from many other parameters which have an impact on the total heat exchanger performance.

II. Mathematical Formulation

A. Description of Membrane based heat exchanger

A schematic description of membrane based heat exchanger is shown in Fig. 1. This system operated with two different fluids in which the desiccant liquid flows in the first channel which is separated by a porous membrane from the adjacent air channel. In this investigation, the air streams were hot and humid; however the desiccant solution is characterized by cool and concentrated properties. So, the heat and moisture are usually transferred from the hot and humid air to the cool and concentrated desiccant solution through the porous membrane. The two fluids flow inside the total het exchanger in counter-current flow arrangement.

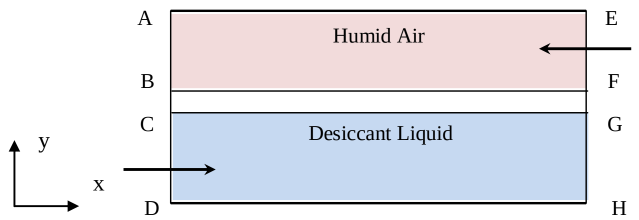

Fig. 1. Schematic description of the studied exchanger.

A numerical model is carried at different conditions, which consist of the air channel, the desiccant liquid channel, and the porous membrane. Therefore, the governing equations established as shown in Fig. 1. In addition, the following assumptions are made:

- The regime inside air and desiccant liquid channels is steady and laminar (Re < 2300).
- The membrane is permeable only to water vapor.
- The membrane properties are not dependent of the fluids proprieties.
- Desiccant solution crystallization and air stream condensation are neglected.
- The heat and moisture transfer between the two fluid channels only normal direction to the membrane.

B. Governing Equations

It can be observed that the problem is modeled in the x-y plane. Therefore, the governing equations including the air channel, desiccant liquid channel and porous membrane are written in Cartesian coordinates as follows.

1) Air channel

The momentum conservation:

$$\frac{\partial u_a}{\partial x_a}+\frac{\partial v_a}{\partial y_a}=0 \qquad (1)$$

where u_a and v_a are respectively the air velocities in the x_a and y_a directions.

Conservation of momentum equations:

$$u_a\frac{\partial u_a}{\partial x_a}+v_a\frac{\partial u_a}{\partial y_a}=-\frac{1}{\rho_a}\frac{\partial p_a}{\partial x_a}+\nu_a\left[\frac{\partial^2 u_a}{\partial x_a^2}+\frac{\partial^2 u_a}{\partial y_a^2}\right] \qquad (2)$$

$$u_a\frac{\partial v_a}{\partial x_a}+v_a\frac{\partial v_a}{\partial y_a}=-\frac{1}{\rho_a}\frac{\partial p_a}{\partial x_a}+\nu_a\left[\frac{\partial^2 v_a}{\partial x_a^2}+\frac{\partial^2 v_a}{\partial y_a^2}\right] \qquad (3)$$

where ρ_a represents the air density (kg.m^{-3}).

Heat and mass transfer equations:

$$u_a\frac{\partial T_a}{\partial x_a}+v_a\frac{\partial T_a}{\partial y_a}=\alpha_a\left[\frac{\partial^2 T_a}{\partial x_a^2}+\frac{\partial^2 T_a}{\partial y_a^2}\right] \qquad (4)$$

$$u_a\frac{\partial W_a}{\partial x_a}+v_a\frac{\partial W_a}{\partial y_a}=D_{va}\left[\frac{\partial^2 W_a}{\partial x_a^2}+\frac{\partial^2 W_a}{\partial y_a^2}\right] \qquad (5)$$

where α_a denotes the thermal diffusivity of air. D_v and W_a represent respectively the water vapor diffusivity and the air specific humidity.

2) Desiccant liquid channel

The momentum conservation:

$$\frac{\partial u_l}{\partial x_l}+\frac{\partial v_l}{\partial y_l}=0 \qquad (6)$$

where u_l and v_l are respectively the desiccant liquid velocities in the x_l and y_l directions.

Conservation of momentum equations:

$$u_l\frac{\partial u_l}{\partial x_l}+v_l\frac{\partial u_l}{\partial y_l}=-\frac{1}{\rho_l}\frac{\partial p_l}{\partial x_l}+\nu_l\left[\frac{\partial^2 u_l}{\partial x_l^2}+\frac{\partial^2 u_l}{\partial y_l^2}\right] \qquad (7)$$

$$u_l\frac{\partial v_l}{\partial x_l}+v_l\frac{\partial v_l}{\partial y_l}=-\frac{1}{\rho_l}\frac{\partial p_l}{\partial x_l}+\nu_l\left[\frac{\partial^2 v_l}{\partial x_l^2}+\frac{\partial^2 v_l}{\partial y_l^2}\right] \qquad (8)$$

where ρ_l is the desiccant liquid density (kg.m^{-3}).

Heat and mass transfer equations:

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$$u_l \frac{\partial T_l}{\partial x_l} + v_l \frac{\partial T_l}{\partial y_l} = \alpha_l \left[\frac{\partial^2 T_l}{\partial x_l^2} + \frac{\partial^2 T_l}{\partial y_l^2} \right] \quad (9)$$

$$u_l \frac{\partial W_l}{\partial x_l} + v_l \frac{\partial W_l}{\partial y_l} = D_l \left[\frac{\partial^2 W_l}{\partial x_l^2} + \frac{\partial^2 W_l}{\partial y_l^2} \right] \quad (10)$$

where α_l and D_l denote respectively the thermal and mass diffusivities of desiccant liquid.
In the previous equations, W_a and W_l represent respectively the air humidity and desiccant liquid water-to-salt mass ratios. They are indicated the moisture/water content of both air and desiccant liquid flows as defined.

$$W_a = \frac{\text{mass} - \text{of} - \text{water}}{\text{mass} - \text{of} - \text{dry} - \text{air}} \quad (11)$$

$$W_l = \frac{\text{mass} - \text{of} - \text{water}}{\text{mass} - \text{of} - \text{salt}} \quad (12)$$

In addition, the properties of desiccant liquid has mostly a strong impact in water content Wl which known also by liquid humidity ratio as defined.

$$W_l = 0.62198 \frac{p_{v,eq}}{P - p_{v,eq}} \quad (13)$$

where P denotes the total pressure however, $p_{v,eq}$ represents the partial pressure of water vapor under equilibrium condition at the solution-membrane interface.

3) Membrane

Due to the geometric and physical proprieties of the membrane (small thickness, thermal conductivity …), the mass and heat transfer rates in the x-direction are negligible. Therefore, the heat and mass transfer equations in the two interfaces of a porous membrane can writhen as.

$$\frac{\partial^2 T_m}{\partial y^2} = 0 \;;\quad \frac{\partial^2 W_m}{\partial y^2} = 0 \quad (14)$$

C. Numerical approach

The governing equations shown in the previous section are solved by using the Successive Over Relaxation method (SOR) with Chebyshev acceleration one for each control-volume [15, 16]. Conde correlations [17] are used for the desiccant liquid properties, which is chloride lithium (LiCl) in this study. This numerical model should satisfy the conservation of the developed equations which depict the heat and mass transfer situation. In addition, the convergence criteria are assured.

The boundary conditions are shown in above figure (Fig. 1), in which:

- AB :

$$x_a = 0 \;;\; 0 \le y_a \le H_a \;;\; \frac{\partial T_a}{\partial x_a} = 0 \;;\; \frac{\partial W_a}{\partial x_a} = 0$$

- BC

$$x_m = 0 \;;\; 0 \le y_m \le H_m \;;\; \frac{\partial T_m}{\partial x_m} = 0 \;;\; \frac{\partial W_m}{\partial x_m} = 0$$

- CD:

$$x_l = 0 \;;\; 0 \le y_l \le H_l \;;\; u_l = u_{l,0} \;;$$
$$v_l = 0 \;;\; T_l = T_{l,i} \;;\; W_l = W_{l,i}$$

- DH

$$y_l = 0 \;;\; 0 \le x_l \le L_l \;;\; v_l = 0 \;;$$
$$\frac{\partial T_l}{\partial x_l} = 0 \;;\; \frac{\partial W_l}{\partial x_l} = 0 \;;\; \frac{\partial u_l}{\partial x_l} = 0$$

- FG :

$$x_m = L_m \;;\; 0 \le y_m \le H_m \;;$$
$$\frac{\partial T_m}{\partial x_m} = 0 \;;\; \frac{\partial W_m}{\partial x_m} = 0$$

- AE :

$$y_a = H_a \;;\; 0 \le x_a \le L_a \;;\; v_a = 0 \;;$$
$$\frac{\partial T_a}{\partial x_a} = 0 \;;\; \frac{\partial W_a}{\partial x_a} = 0 \;;\; \frac{\partial u_a}{\partial x_a} = 0$$

- EF :

$$x_a = L_a \;;\; 0 \le y_a \le H_a \;;\; u_a = u_{a,0} \;;$$
$$v_a = 0 \;;\; T_a = T_{a,i} \;;\; W_a = W_{a,i}$$

- GH :

$$x_l = 0 \;;\; 0 \le y_l \le H_l \;;$$
$$\frac{\partial T_l}{\partial x_l} = 0 \;;\; \frac{\partial W_l}{\partial x_l} = 0$$

- BF

$$y_a^m = H_a^m \;;\; 0 \le x_m \le L_m \;;$$
$$T_a^m = T_{a,\text{int}} \;;\; W_a = W_{a,\text{int}}$$

- CG :

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$$y_s^m = H_s^m \quad ; \quad 0 \le x_m \le L_m \quad ; \quad T_s^m = T_{s,\text{int}} \quad ;$$

$$W_l^m = W_{a,\text{int}}^m = f\left[P_v\left(T_{s,\text{int}}, W_{l,\text{int}}\right)\right] \text{ où}$$

$$\begin{cases} W_{a,\text{int}}^m = \dfrac{0.62185\, P_{s,\text{int}}}{P_{atm} - P_{s,\text{int}}} \\ W_{a,\text{int}}^m = \dfrac{M_v\, P_{s,\text{int}}}{M_a\, (P_{atm} - P_{s,\text{int}}) + M_v\, P_{s,\text{int}}} \end{cases}$$

$P_v\left(T_{s,\text{int}}, W_{l,\text{int}}\right)$ is calculated by Conde correlation.

In order to evaluate the performance of the desiccant liquid air membrane energy exchanger, the sensible and latent effectiveness can be calculated by Eqs. (15) and (16).

$$\varepsilon_s = \frac{(\dot{m}_a c_{pa})\left(T_{a,in} - T_{a,out}\right)}{\left(\min(\dot{m}_a c_{pa}, \dot{m}_l c_{pl})\right)\left(T_{a,in} - T_{l,in}\right)} \tag{15}$$

$$\varepsilon_l = \frac{(\dot{m}_a c_{pa})\left(W_{a,in} - W_{a,out}\right)}{\left(\min(\dot{m}_a c_{pa}, \dot{m}_l c_{pl})\right)\left(W_{a,in} - W_{l,in}\right)} \tag{16}$$

Therefore, the total effectiveness can be expressed as:

$$\varepsilon_{tot} = \frac{(\dot{m}_a c_{pa})\left(H_{a,in} - H_{a,out}\right)}{\left(\min(\dot{m}_a c_{pa}, \dot{m}_l c_{pl})\right)\left(H_{a,in} - H_{l,in}\right)} \tag{17}$$

III. Results and Discussion

In order to examine the numerical model, this investigation carried out under inlet operating conditions: inlet air temperature 35°C, inlet humidity ratio 20g.kg^{-1}, and inlet velocity 1 m.s^{-1}.

A. *Inlet velocity impact*

Firstly, the inlet the desiccant liquid temperature is 25°C and water content of desiccant liquid flow is 70%. However, inlet desiccant liquid velocity varies from 0.05 to 0.5 m.s^{-1}. Fig. 2 illustrates the variations of outlet air and desiccant liquid temperatures for various inlet desiccant liquid velocities. The outlet temperature values for both air and desiccant liquid sides decrease slowly when the inlet desiccant liquid velocity varies from 0.05 to 0.5 m.s-1. We can remark that the variation of desiccant liquid velocity causes a weak effect on the heat transfer rate between air and desiccant liquid sides which decreases by 0.16 °C at the outlet air side, and decreases by 0.66 °C at the outlet desiccant liquid side.

Table 1 shows the influence the variation of outlet air humidity ratio and the water content of desiccant liquid for inlet desiccant liquid velocities. By varying the inlet desiccant liquid velocity from 0.05 to 0.5 m.s-1, the outlet air humidity ratio weakly decreases by 0.27 g.kg-1 in addition, the water content of desiccant liquid decreases by 9.29% at the outlet desiccant liquid side.

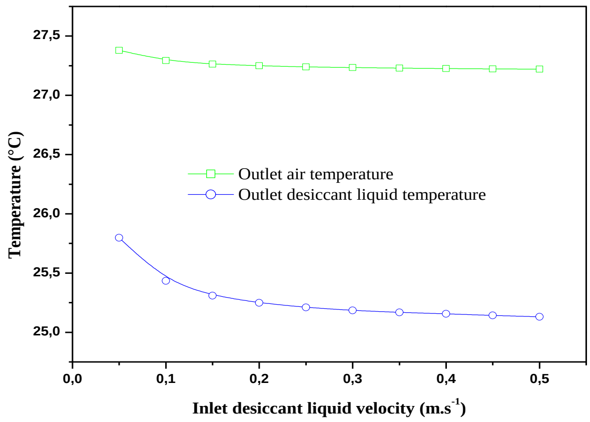

Fig. 2. Outlet temperature variations of air and desiccant liquid.

TABLE I. Outlet air humidity ratio and water content of desiccant liquid.

Inlet desiccant liquid velocity (m.s^{-1})	***Outlet air humidity ratio (g.kg^{-1})***	***Water content (%)***
0.05	15.57	81.15
0.10	15.48	75.11
0.15	15.44	74.11
0.20	15.40	73.21
0.25	15.38	72.67
0.30	15.35	72.30
0.35	15.33	72.04
0.40	15.32	71.87
0.45	15.31	71.86
0.50	15.30	71.85

The sensible, latent and total effectiveness are shown in Fig. 3. As seen, when the inlet desiccant liquid velocity increases from 0.05 to 0.5 m.s^{-1}, the sensible effectiveness decreases by 4% however, the latent effectiveness increases by 2.3%. It is concluded from these results that the desiccant liquid velocity has a weak effect on the mass and heat transfer rates in the desiccant liquid membrane energy exchanger who decreases tiny under high fluid flow velocities.

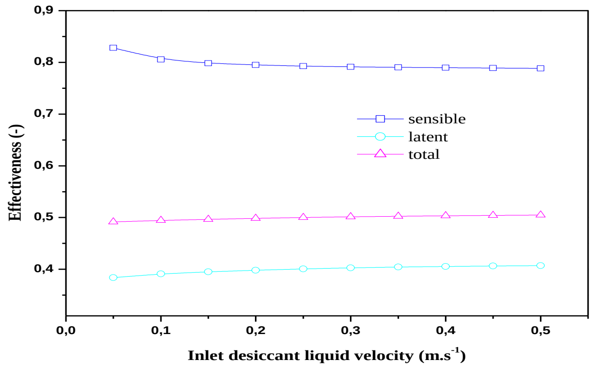

Fig. 3. Sensible, latent and total effectiveness.

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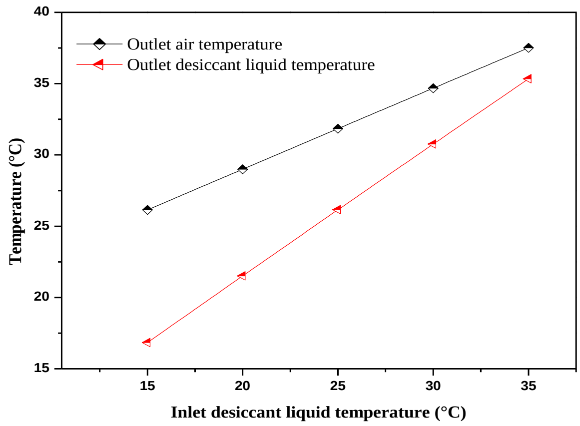
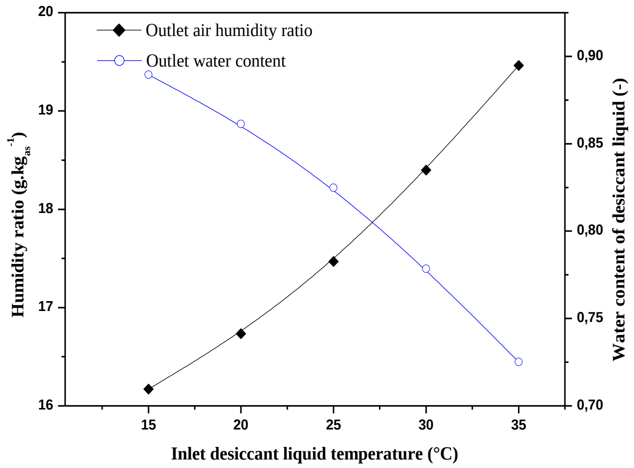
B. *Inlet temperature impact*

Secondly, the inlet the desiccant liquid temperature varies from 15 to 35°C, however the water content of desiccant liquid flow is 70% and the inlet desiccant liquid velocity fixed at 0.05 $m.s^{-1}$.

Fig. 4a shows the outlet air and desiccant liquid temperatures increase respectively by 11°C and 18.5°C, when desiccant liquid temperature increases from 15 to 35°C. This signifies that the heat transfer rate in the studied exchanger improves under low desiccant liquid temperatures. Further, Fig. 4b shows the outlet water content of desiccant liquid decreases from 88.94 to 72.51%, while the humidity ratio values outlet air channel increase from 16.17 to 19.46 $g.kg^{-1}$ when the inlet desiccant liquid temperature values vary from 15 to 35°C. It can be explained that the desiccant liquid have a strong affinity to absorb the water vapor under low desiccant liquid temperature values in which can leads to a better mass transfer. Therefore, it can be confirmed by the decreasing of sensible, latent and total effectiveness when the inlet temperature values of desiccant liquid increase from 15 to 35°C as shown in Fig. 5.



a



b

Fig. 4. a. outlet temperature variations and b. outlet air humidity ratio and water content of desiccant liquid.

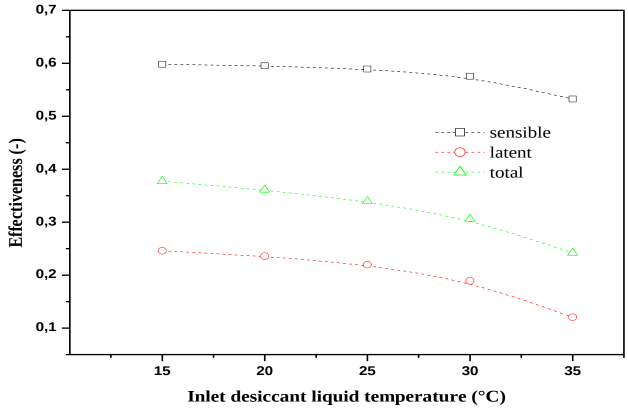


Fig. 5. Sensible, latent and total effectiveness.

C. *Inlet water content of desiccant liquid impact*

Finally, the inlet the desiccant liquid temperature kept at 25°C and water content of desiccant liquid flow varies from 60% to 90%. However, inlet desiccant liquid velocity is 0.05$m.s^{-1}$.

Fig. 6a illustrates the outlet temperature values of air and desiccant liquid for inlet water content of desiccant liquid from 60% to 90%. It can be seen that the outlet temperature values of two fluids (air, desiccant liquid) are not affected by the inlet water content variation of desiccant liquid. Their values maintained respectively at 29.7°C and 26°C, when the inlet water content value increases from 60 to 90%. However, Fig. 6b shows the outlet values of air humidity ratio and water content of desiccant liquid. By changing the inlet water content value from 60% to 90%, the outlet water content of desiccant liquid increases by 25%. Also, the outlet air humidity ratio increases gradually and, finally tends to become stable. It can be concluded that the desiccant liquid begins to absorb or desorb efficiently under an optimal values which are between 65% and 75% of inlet water content, then it enters in a stable phase or saturation phase.

The sensible, latent and total effectiveness of desiccant liquid air membrane energy exchanger under various inlet water content values of desiccant liquid are shown in Fig. 7. The latent and total effectiveness increase gradually to finish at constant values 25.45% and 34.34%.However, the sensible effectiveness maintains stable for different inlet water content values due to the stability of air and desiccant liquid temperatures at outlet channels.

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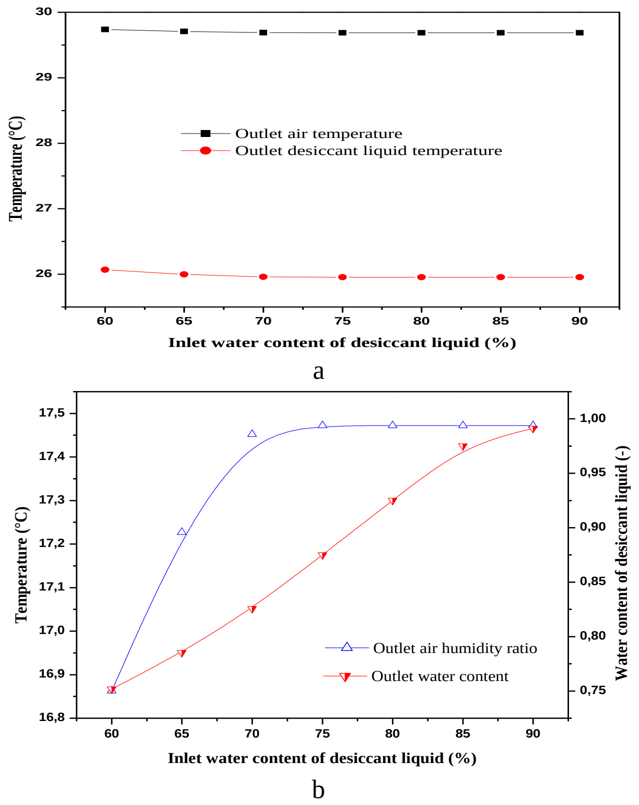

Fig. 6. a. outlet temperature variations and b. outlet air humidity ratio and water content of desiccant liquid.

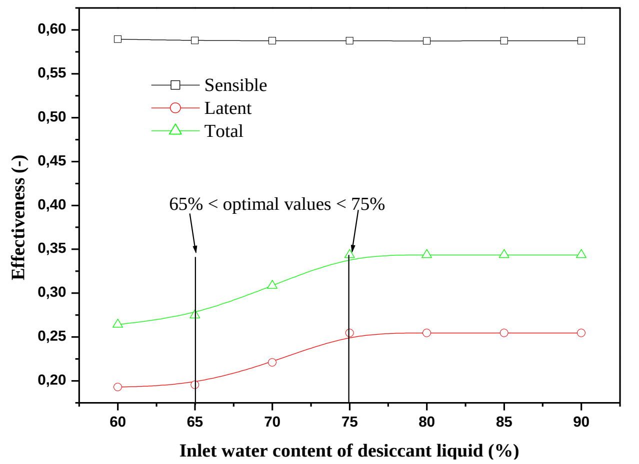

Fig. 7. Sensible, latent and total effectiveness.

IV. Conclusions

As concluded, the desiccant liquid properties causes a strong effect on the heat and mass transfer rate in the desiccant liquid air membrane energy exchanger which enhances under the inlet optimal values. Generally, the operating conditions have usually impacts on the exchanger's performance. These above results confirm the efficiency of the desiccant liquid air membrane energy exchanger and provide a solution to improve the heat and mass transfer rates in the membrane based technologies

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