Heat and mass transfer in partially blocked membrane based heat exchanger

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Abstract—***Membrane Based Heat Exchangers or total heat exchangers are a new technologies to recovery both heat and moisture quantities from hot humid to cold dry air streams. The traditional design of these technologies is the parallel plate membrane based heat exchanger. In this paper, a novel geometric design of the membrane based heat exchanger is proposed. A metal blocks along the channels are inserted, in which their effects on the temperature and humidity ratio distributions are investigated. A two-dimensional numerical model including the momentum, heat and mass transport equations in both fresh and exhaust air streams are established. Therefore, this study provides a solution to improve the heat and mass transfer mechanisms and enhance the membrane based heat exchanger efficiency.***

Keywords—total heat exchanger; partial blocks; membrane.

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 (MBHEs) are a new category of recovery equipments in which use a hydrophilic membrane. They can recover both heat and moisture with a high effectiveness [1-3].

The specifications of hydrophilic membranes are their proprieties which are permeable only to the vapor 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 vapor 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 vapor 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.

However 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 modeling 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].

It is obvious that the choice of flow arrangements is one of the most important parameters influencing on heat exchanger performances. However, their study focused on the operating

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parameters more than the geometric ones. In this study, a partially blocked membrane based heat exchanger is investigated. Heat and mass transfer in the exchanger is numerically modeled. The blocks impacts on the heat and mass distributions are established. The aims of this study are to present a new channels design and illustrate their impacts on the total heat exchanger performance.

II. MATHEMATICAL FORMULATION

The partially blocked (PB) membrane based heat exchanger is shown in Fig.1. It consists three principal components such as hot humid air channel, cool dry air channel, and hydrophilic membrane in which the moisture transferred from hot humid to cold dry air streams. In the present paper, the solid layer is designed with a small square obstacle.

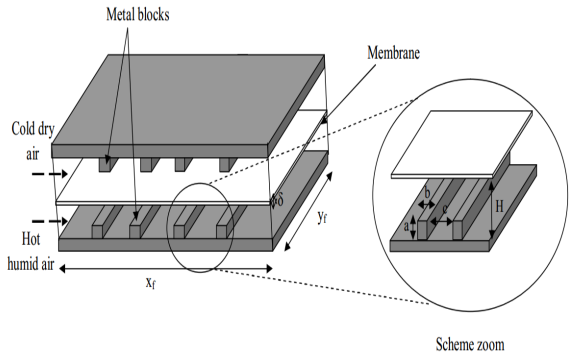

Fig. 1. Schematic description of membrane based heat exchanger.

Several geometric and operating parameters are required to solve the system numerical equations which are specified in Tables 1.

TABLE I. SPECIFICTIONS OF MEMBRANE BASED HEAT EXCAHNGER.

Parameters	***Values***	***Unit***
x_f	185	mm
y_f	185	mm
H	4	mm
δ	100	μm
λ_m	0.13	$W.m^{-1}.K^{-1}$
D_m	$8\ 10^{-6}$	$m^2.s^{-1}$

The inlet operating conditions of air temperature and humidity ratio are respectively 35°C and 0.020 $kg.kg^{-1}$ for fresh air and 25°C and 0.010 $kg.kg^{-1}$ for exhaust air. In order to model this physical problem which includes the mass, momentum, energy, and water vapor concentration equations, a two dimensional model of the co current MBHE system are presented. All equations are developed in dimensionless form as shown below.

The continuity equation:

$$\frac{\partial u^*}{\partial x^*}+\frac{\partial u^*}{\partial y^*}=0 \tag{1}$$

Where u and v are the velocities ($m.s^{-1}$) in x and y directions, respectively.

Conservation of momentum equations in x and y coordinates:

$$u^*\frac{\partial u^*}{\partial x^*}+v^*\frac{\partial u^*}{\partial y^*}=-\frac{\partial p^*}{\partial x^*}+\frac{1}{Re}\left[\frac{\partial^2 u^*}{\partial x^{*2}}+\frac{\partial^2 u^*}{\partial y^{*2}}\right] \tag{2}$$

$$u^*\frac{\partial v^*}{\partial x^*}+v^*\frac{\partial v^*}{\partial y^*}=-\frac{\partial p^*}{\partial x^*}+\frac{1}{Re}\left[\frac{\partial^2 v^*}{\partial x^{*2}}+\frac{\partial^2 v^*}{\partial y^{*2}}\right] \tag{3}$$

In steady state, heat transfer through the MBHE is modeled using the energy equation applied to incompressible fluid with constant physical properties:

$$u^*\frac{\partial \theta}{\partial x^*}+v^*\frac{\partial \theta}{\partial y^*}=\frac{1}{Pr.Re}\left[\frac{\partial^2 \theta}{\partial x^{*2}}+\frac{\partial^2 \theta}{\partial y^{*2}}\right] \tag{5}$$

During heat exchanger process, moisture is transferred through membrane by diffusion. Based on the above assumption, the vapor water transport is governed by the following equation:

$$u^*\frac{\partial \xi}{\partial x^*}+v^*\frac{\partial \xi}{\partial y^*}=\frac{1}{Sc.Re}\left[\frac{\partial^2 \xi}{\partial x^{*2}}+\frac{\partial^2 \xi}{\partial y^{*2}}\right] \tag{7}$$

We introduce the dimensionless numbers which are defined by the following expressions as,

$$Re=\frac{u_0 H}{\nu}\ ;\ \ Pr=\frac{\nu}{\alpha}\ ;\ Sc=\frac{\nu}{D_v} \tag{4}$$

Where D_v represents the vapor diffusivity in the vapor-air mixture ($m^2.s^{-1}$). α is thermal diffusivity of air ($m^2.s^{-1}$). ν is the cinematic viscosity ($m^2.s^{-1}$).

The dimensionless Cartesian coordinates and velocities are calculated as

$$x^*=\frac{x}{H}\ ;y^*=\frac{y}{H}\ ;u^*=\frac{u}{u_0}\ ;v^*=\frac{v}{u_0} \tag{9}$$

Thus, using the above equations for replacing the pressure term in Eq. (10), we obtain:

$$p^*=\frac{p}{\rho_a u_0{}^2} \tag{10}$$

Where ρ_a and u_0 represent the air density ($kg.m^{-3}$) and the mean velocity value ($m.s^{-1}$), respectively.

The dimensionless temperature and humidity ratio are defined by

$$\theta=\frac{T-T_{ei}}{T_{fi}-T_{ei}} \tag{11}$$

$$\xi=\frac{\omega-\omega_{ei}}{\omega_{fi}-\omega_{ei}} \tag{12}$$

Where T is the temperature (K) and ω is the humidity ratio ($kg_{vapor}.kg^{-1}{}_{dry\ air}$).

Further, the Sherwood number is correlated with Nusselt, Prandlt and Schmidt numbers as follow [6, 9]:

$$Sh = Nu.\left(\frac{Sc}{Pr}\right)^{-1/3} \tag{13}$$

Due to the small membrane thickness, heat and mass water vapor transfer in other directions are considered negligible.

So, heat and mass transfer through membrane can be simplified to one dimensional equation:

$$\frac{\partial^2 \theta_m}{\partial y^{*2}} = 0 \; ; \frac{\partial^2 \xi_m}{\partial y^{*2}} = 0 \qquad (14)$$

III. Numerical Approach

The systems of equations introduced in the present paper are coupled and nonlinear. The equations are solved by using the Successive Over Relaxation Method (SOR) [10]. The solution was considered converged when the relative error between the new and the old values of the considered variable become less than 10^{-5}. First, the velocity and pressure are solved in all domains. Then, we solve the heat equation. And finally, we solve the vapor water equation. This process is repeated up to the residuals achieve the desired values.

IV. Results and Discussion

Numerous studies are focused to improve the heat and transfer mechanisms in the MBHE by developing the global design of the heat exchanger, modifying the hydrophobic membrane proprieties, and choosing the best flow arrangements. However, there are many studies carried out to investigate only the flow effects around obstacles which have many influence on the flow proprieties. Therefore, the use of obstacle in the MBHEs is our novelty idea to study their impacts on the mass and heat transfers through the hydrophobic membrane and on the MBHE efficiency.

A. Validation results

To validate our numerical model, we compare our results with Zhang experimental data of similar MBHE under the same operating and geometric conditions.

Fig. 2 shows the outlet air temperature results for the co-current flow arrangement and under various air velocities. By varying the air flow velocity from 0.5 to $2.5 m.s^{-1}$, both numerical and experimental temperature values, in the fresh air side, are increased by 1.5°C. In contrast, in the exhaust air side, the outlet air temperature is reduced by 1.7 °C. This indicates that the heat transfer efficiency in the MBHE decreases under high air flow velocities [6].

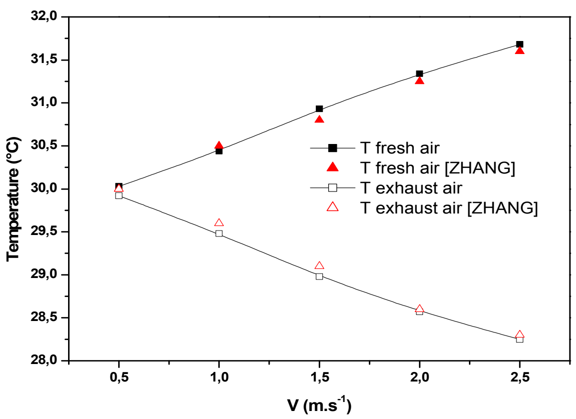

Fig. 2. Comparison between numerical and experimental temperature values.

Further, the numerical and measured experimental results of the air relative humidity are shown in Fig. 3. The air relative humidity varies from 56.4% to 58% and from 55.5% to 53% in the fresh and exhaust air sides, respectively. The effects of air flow velocities on the air relative humidity values can be explained by the dependence correlation between the air temperature and relative humidity.

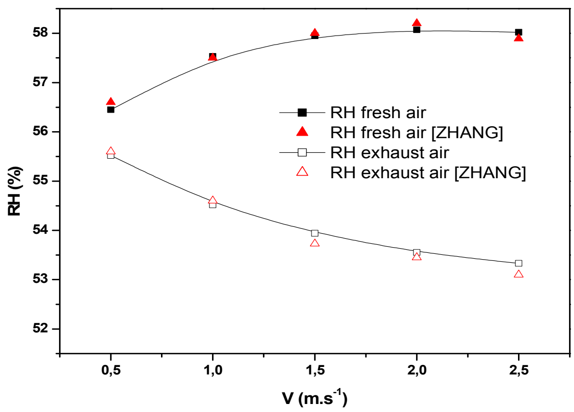

Fig. 3. Comparison between numerical and experimental humidity values.

In the previous Fig. 2 and Fig. 3, the solid lines with square points represent the numerical fresh and exhaust air values and the discrete triangle points are the experimental fresh and exhaust air values. We can explain the small error between our numerical results and Zhang experimental data by the measurement difficulties due to the small dimension of the MBHE design such as the channel heights which are about a few millimeters. The difference percentages between the numerical model results and the experimental measurements are lower than 1.5%. Therefore, acceptable conformity is found between the numerical and experimental results under various air velocity values.

This conformity signifies that our numerical model is successful to resolve the heat and mass transfer equations and to investigate their effectiveness on the MBHEs. Hence, we have applied this model to the MBHE geometric optimization by changing the continuous gas channels by partially blocked geometry.

B. Numerical results

Fig. 4 and Fig. 5 describe respectively the dimensionless temperature and humidity ratio distributions in the fresh and exhaust air channels for both normal (NOR) and PB geometries, on the membrane surfaces and for co-current flow arrangement in the PB MBHE. As depicted in these figures, the temperature and humidity ratio distributions in air channels and membrane surfaces begin with different boundary conditions. However, the outlet values leave with a small difference between the PB and normal geometries. The PB dimensionless values are lower (higher) by 10% than the normal geometry values in the outlet fresh (exhaust) air sides. As indicated, the heat and mass flux in the fresh and exhaust air channels vary symmetrically with various MBHE geometries as indicated in Fig. 4 and Fig. 5.

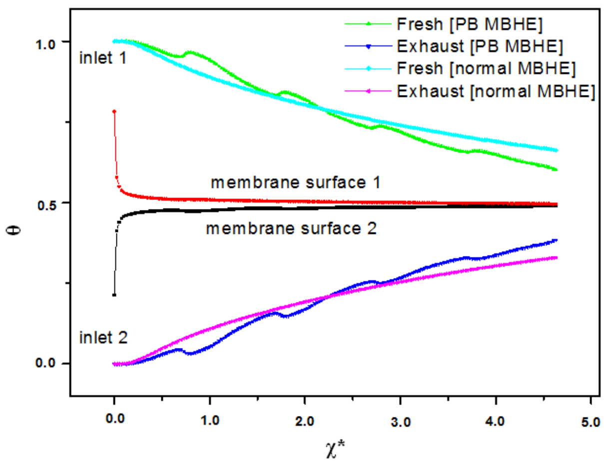

Fig. 4. Dimensionless temperature distributions in channels of normal and partially blocked geometries membrane based heat exchanger.

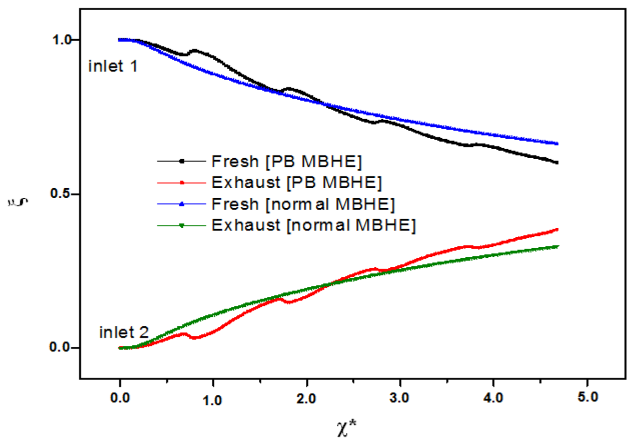

Fig. 5. Dimensionless humidity ratio distrubitions in channels of normal and partially blocked geometries membrane based heat exchanger.

The air variations are due to the heat and mass transfer between both fresh and exhaust sides. These variations between the normal and PB geometry results can be explained by the effect of the designed square obstacles on flow air proprieties. Furthermore, the air flow around a square obstacle or the partially blocked geometry proves that both air temperature and humidity ratio distributions are enhanced which can be seen in the results as shown in Fig. 4 and Fig. 5.

A significant parameter obstacles form ratio (r) is defined to estimate the impact of obstacle form on the heat and mass transfer rates:

$$r = \frac{H}{a} \tag{15}$$

Where a denotes the obstacle height.

The variation of air temperatures at the outlet fresh and exhaust sides is shown in Fig. 6. When the obstacles form ratio (r) increases from 0.25 to 0.5, the fresh air temperature at the outlet channel diminishes however the exhaust air temperature increases, with a comparable variation (0.35°C).

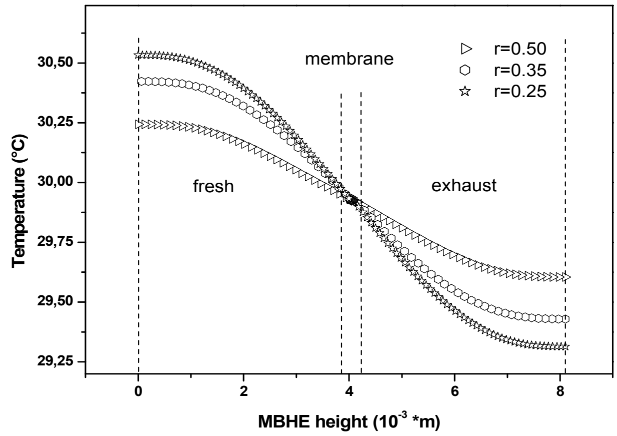

Fig. 6. Temperature values in channels partially blocked geometry membrane based heat exchanger at various obstacles form ratio (r).

Fig. 7 plotted the air humidity ratio variations at the outlet fresh and exhaust sides of the partially blocked (PB) membrane based heat exchanger. The specific humidity ratio increases by 0.5 $g.kg^{-1}$ at the outlet exhaust side, but decreases by 0.45 $g.kg^{-1}$ at the outlet fresh side.

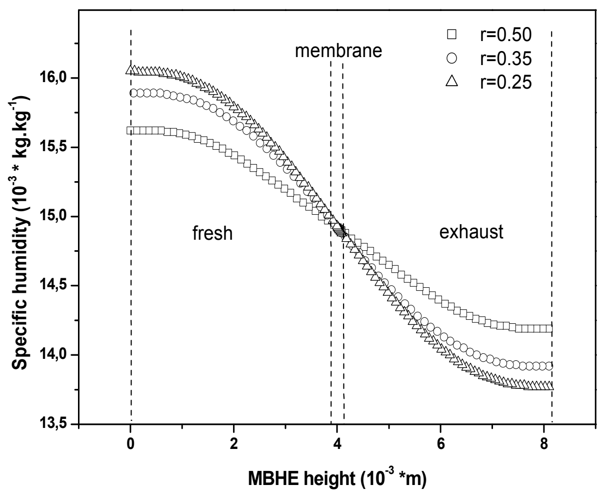

Fig. 7. Humidity ratio values in channels partially blocked geometry membrane based heat exchanger at various obstacles form ratio (r).

As depicted from Fig. 6 and Fig. 7 that the air proprieties changed adequately with PB form ratio (r) which have a great influence on the mass and heat destitutions between two air sides of PB MBHE [11].

TABLE II. SHERWOOD AND NUSSELT NUMBERS UNDER DIFFERENT OBSTACLES FORM RATIO (R).

n=4obstacles r=0.25		*n=4obstacles r=0.35*		*n=4obstacles r=0.5*	
Nu	**Sh**	**Nu**	**Sh**	**Nu**	**Sh**
4.17	4.01	2.91	2.80	2.95	2.84
For normal MBHE geometry (n=0): ***Nu=3.99*** and ***Sh=3.84***.					

Table II illustrates the Sherwood and Nusselt. As mentioned, when the obstacles form ratio (r) increases from 0.25 to 0.5, the Sherwood number decreases from 4.01 to 2.84, (similarly) as well as that the Nusselt number decreases from 4.17 to 2.95. Also, the heat and mass transfer rates enhanced when the specifications of the obstacles are taken at the adequate values. Therefore, the Nusselt and Sherwood numbers (at n=4 obstacles and r= 0.25) are acceptable higher than the normal geometry MBHE. n is defined by the number of obstacles in the membrane based heat exchanger channels.

I. Conclusion

Mass and heat transfer in partially blocked membrane based heat exchanger are studied. The momentum, energy and mass transport equations are developed to describe the hydrodynamic, heat and mass transfer in the considered MBHE. The agreement between our numerical results and Zhang experimental measurements allowed us to study the influence of the obstacles presence in the MBHE design on the heat and mass transfer. Therefore, the results can be established:

The presence of obstacles in the MBHE enhances the heat and mass transfers between the fresh and exhaust air channels. Thus, the air temperature and humidity ratio values in the PB geometry are greater than normal MBHE geometry.

Finally, the dimensionless temperature and humidity ratio distributions in the fresh and exhaust air channels for both different obstacle form ratio (r) are established.

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