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Research Paper

Numerical investigation of membrane based heat exchanger with partially blocked channels

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HIGHLIGHTS

- A partially blocked membrane based heat exchanger is numerically investigated.
- Impacts of two parameters ((*n*), (*r*)) on heat and mass distributions are evaluated.
- Impacts of air velocity on the fresh and exhaust air channels are established.
- Impacts of membrane proprieties on the Nusselt and Sherwood numbers are mentioned.
- Comparison between two flow arrangements is illustrated.

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ABSTRACT

Contrary to the traditional approach assuming the same parallel plate membrane based heat exchanger, a new proposition of exchanger design is investigated in this paper. The channels of membrane based heat exchanger are partially blocked by insertion of metal blocks. In order to evaluate their impacts 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 obstacles number and form ratio are mentioned. The results show that the including of obstacles enhances the heat and mass transfer rates between the fresh and exhaust air channels. A low obstacles number leads to a large (small) air temperature and specific humidity ratio values in the exhaust (fresh) air channel. In addition, obstacle form ratio has a strong effect on the temperature and humidity distributions when it becomes higher. Also, this investigation takes into account the effect of membrane proprieties and flow arrangements which also have a strong effect on the heat and mass transfer rates.

1. Introduction

The Membrane Based Heat Exchangers (MBHEs) are not just significant equipments to provide a comfortable ambiance but also to control respiratory diseases [1]. Due to their high thermal conductivity, diffusion coefficient and homogenous pore distribution in comparison with other types of membranes, the modified Polyvinylalcohol (PVA) is one of the most used in the MBHEs [2,3]. In reality, the MBHEs operation involves simultaneous and complex processes such as fluid flow as well as heat and mass transfer [3]. It is obvious that one of the most important processes significantly influencing heat exchanger performances is the heat and mass transmission through the membrane. Therefore, design of the heat exchangers is a significant factor to improve the global system performance. During the last years, a lot of studies have been focused on the impact of the various flow arrangements such as co-current, counter-current and cross-flow [4,5].

In general, hydrophilic polymer membranes are characterized by their permeability only to the vapor and are applied in air dehumidification processes. Recent studies specify that the MBHE performance may be related to the membrane proprieties [6–8]. The permeability is a material parameter that describes the resistance to the humid air flow exhibited by the porous media. In literature, several materials have been investigated such as Nafion [9,10], cellulose triacetate [11], polyether-polyurethane [12], polyethersulfone [13,14], polyvinylidene fluoride [15], and polystyrene-sulfonate [16].

Mathematical modeling of mass and heat transfer mechanisms in the channels and within hydrophilic membrane is presented and then, numerical simulations are considered to obtain the operational status and to analyze mass and heat exchange in the MBHEs.

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Nomenclature

a	obstacle height (m)
b	obstacle width (m)
c	distance between two successive obstacles (m)
D_v	vapor diffusivity in the vapor-air mixture ($m^2\,s^{-1}$)
D_h	hydraulic diameter (m)
h	convective heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
H	channel height (m)
k	convective mass transfer coefficient ($m\,s^{-1}$)
Nu	Nusselt number ($Nu = \frac{hD_h}{\lambda_a}$)
P	pressure (Pa)
Pr	Prandtl number ($Pr = \frac{\nu}{\alpha}$)
Re	Reynolds number ($Re = \frac{u_0 D_h}{\nu}$)
Sc	Schmidt number ($Sc = \frac{\nu}{D_v}$)
Sh	Sherwood number ($Sh = \frac{kD_h}{D_v}$)
T	temperature (K)
u, v	velocity ($m\,s^{-1}$) for x and y directions respectively
u_0	mean velocity value ($m\,s^{-1}$)
x, y	coordinates (m)
x_f	channel length (m)
y_f	channel width (m)

Greek letters

α	thermal diffusivity ($m^2\,s^{-1}$)
ρ	air density ($kg\,m^{-3}$)
λ_a	air heat conductivity ($W\,m^{-1}\,K^{-1}$)
ν	kinematic viscosity ($m^2\,s^{-1}$)
δ	membrane thickness (μm)
τ_h	conductivity ratio $\left(\tau_h = \frac{\lambda_m}{\lambda_a}\right)$
τ_m	diffusivity ratio $\left(\tau_m = \frac{D_m}{D_v}\right)$
ω	humidity ratio ($kg\,kg^{-1}$)

Subscripts

ei	inlet exhaust air
fi	inlet fresh air
fo	outlet fresh air
m	membrane

A few numerical models for the heat exchanger and thermal management have been established in previous works. Min and Su [17] developed a mathematical model to analyze the heat and mass transfer in the MBHE core. Their results show that, as the moisture diffusivity in membrane increases with a constant sorption, the sensible effectiveness maintains almost unchanged. In a theoretical study, Min and Duan [18] analyzed the heat and mass transfer in total heat exchanger core and investigated his performance under various weather conditions. They concluded that the variation of the outdoor air humidity has a strong effect on the latent effectiveness when the heat and moisture transferred in either co-current or counter direction across membrane. Chung et al. [19] developed a numerical model to describe heat and mass transfer in a cross flow direct contact membrane distillation. Statistical analyses results showed a predominant feed flow rates and a smallest feed temperatures effects on mass transfer coefficients. Moghaddam et al. [20] studied numerically the steady state effectiveness of the small scale single panel liquid to air membrane energy exchanger. Their results showed that the latent and total effectiveness of the small scale liquid to air membrane energy exchanger are increased with reducing the membrane-vapor diffusion resistance, whereas the sensible effectiveness is unchanged.

Recently, Zhang [21] studied the heat and mass transfer in a quasi counter flow MBHE; their results showed that the quasi flow arrangement has better performance than cross flow due to the important heat and mass transfer caused by the counter flow zones. In consequence, the sensible and latent effectiveness are improved by 5%. Yu et al. [22] developed a numerical simulation of heat and mass transfer of laminar flow in a hollow fiber module for direct membrane distillation. They concluded that at the feed and permeate sides, the deviation of the membrane wall temperature from the fluid bulk phase leads to the temperature polarization effect which is decreased initially and then increased along the fiber length.

A comprehensive investigation of different air channel designs and their impacts on the thermal behaviors and moisture recovery in the MBHE is still important. This paper presents our attempts in this direction to investigate the effects of a few important operating parameters on the thermal management with newly MBHE design. The purpose is to develop the appropriate heat exchanger design under different conditions. Parametric study based on numerical simulation can be considered as an efficient method to attain our objective. The originality of our work is to insert metal blocks along the two channels and investigate their effects on the heat and mass transfer. This investigation is based on the partial blocks form ratio. The air flow channel has a tight, solid layer as a side-wall which their morphology may influence on the heat and mass transport from channel to the membrane surface and consequently, may affect the overall exchanger performance.

2. Mathematical formulation

In the proposed geometry, the Partially Blocked Membrane Based Heat Exchanger (PB MBHE) is similar to the simple MBHE developed by [23–26] with an addition of tetragon obstacles in solid layer configuration as shown in Fig. 1. The specific parameters of the PB MBHE are illustrated in Table 1.

The fresh and exhaust air streams in the PB MBHE are separated by hydrophilic membrane (modified PVA (poly-vinyl-alcohol)) that permits moisture transmission between two channels as shown in Fig. 1. The moisture transfers from highly to less humid air streams through the modified PVA membrane.

To solve the model of MBHE domain, a mathematical formulation is developed on the steady two-dimensional model. The following assumptions are made:

- The air flows in the MBHE are assumed to be laminar and incompressible.
- The membrane is isotropic and homogeneous porous medium.

The following equations governing the conservation of mass, momentum, energy, and vapor water concentration can be written as below:

The mass conservation equation of the air streams in channels is:

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{V}) \quad (1)$$

Eq. (1) in two dimensional can be expressed as:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (2)$$

Conservation of momentum equations in 2D can be written as: