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Three-dimensional turbulent flow and conjugate heat and mass transfer in a cross-flow hollow fiber membrane bundle for seawater desalination

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ABSTRACT

A cross-flow hollow fiber membrane bundle for humidification (MBH) is used for seawater desalination. Fluid flow and conjugate heat and mass transfer in the bundle are studied by numerically solving the continuity, momentum, energy and concentration equations for air side, water side and membrane side, simultaneously in a conjugated way. Contrary to previous studies which considered only 2D laminar or turbulent flow, in this research the full three-dimensional turbulent flow in air side is modelled with a three-dimensional low-Reynolds-number k-ε turbulence model (3D Low Re k-ε). For comparison, besides the proposed 3D turbulence model, other three previously used models, namely, a 2D Low Re k-ε turbulence model, a 2D laminar model, and a 3D laminar model, are also used to investigate the effects of air side turbulence on fluid flow and heat and mass transfer properties in the bundle under a wide range of Reynolds numbers from 100 to 900. It is found that the 3D turbulence model best predicts the friction factors and Nusselt and Sherwood numbers for various module packing fractions under higher Reynolds numbers above 650. The results are validated by velocity measurement and performance test with a seawater desalination system.

1. Introduction

Desalination is one of mankind's earliest technologies of water treatment, and until today it is still a widely adopted treatment solution to overcome fresh water shortage throughout the world. Among the numerous seawater desalination technologies, the newly proposed membrane-based air humidification-dehumidification desalination (MHDD) is promising because it can work well at lower operating temperatures and hydrostatic pressures, which would be powered by low grade energy sources such as solar energy or industrial waste heat [1–4]. The humidification process with a membrane fiber bundle is the key limiting factor for system performance. Therefore, the fluid flow and conjugate heat and mass transfer in the membrane bundle is of interest for the development of this technology.

For the humidification process of MHDD system, hollow fiber membrane bundles with cross-flow arrangement are commonly used to intensify heat and moisture transfer due to their higher packing densities as well as the successive disturbances of air side fluid flow from the numerous fibers [5,6]. The mentioned membrane bundle for humidification (MBH) is like a cross-flow shell-and-tube heat mass exchanger. The heated saline water flows inside the fiber tubes, while the sweeping air flows across the fiber bank. The two fluids are separated from each other by the semi-permeable membranes, which only selectively allow the permeation of water vapor but prohibit the transports of liquid solution through the membrane. The problems of liquid solution droplets cross-over and flow maldistribution in liquid side which are usually encountered in direct contact packed column humidification technologies, are thus overcome. The fluid flow and conjugate heat and mass transfer in such a cross-flow membrane bundle have been investigated by many studies [7–10]. The models are either laminar or turbulent. Huang et al. studied the fluid flow and conjugate heat and mass transfer in a membrane bundle with a two-dimensional laminar model [7]. They found that generally the air side mean Nusselt numbers under conjugate boundary conditions lie between those under uniform temperature and those under uniform heat flux boundary conditions. The Nusselt and Sherwood numbers for the staggered arrangement of fibers are larger than those for the in-line arrangement. Li et al. also used laminar model [8]. They found that the fully developed mean Sherwood numbers

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Nomenclature

A	area (m^2)
A_m	fibers membrane area in the air stream side
A_v	packing density (m^2/m^3)
A_{tot}	total membrane areas of the module (m^2)
d	diameter (m)
d_h	hydraulic diameter of the flow channels (m)
D_{ws}	water diffusivity in saline water (m^2/s)
D_{va}	moisture diffusivity in air (m^2/s)
D_{vm}	moisture diffusivity in membrane (m^2/s)
f	friction factor
H	module height (m)
L	fiber tube length (m)
k	turbulent kinetic energy (m^2/s^2)
n_f	number of fibers
Nu	Nusselt number
p	pressure (Pa)
Pe	Peclet number
P_D	diagonal pitch
P_L	longitudinal pitch
P_T	transverse pitch
Pr	Prandtl number
r	radius (m)
Re	Reynolds number
RH	relative humidity (%)
Sc	Schmidt number
Sh	Sherwood number
T	temperature (K)
u	velocity (m/s)
W	module wide (m)
$x/y/z$	coordinates for physical domain (m)
X	mass fraction of water in saline water (kg water/kg saline water)

Greek letters

δ_m	membrane thickness (m)
ε	dissipation rate of turbulent kinetic energy (m^2/s^3)
ζ_a^*	dimensionless temperature for periodic boundary condition
λ	heat conductivity ($W\,m^{-1}K^{-1}$)
ν	kinematic viscosity (m^2/s)
ξ_a^*	dimensionless humidity for periodic boundary condition
ρ	density (kg/m^3)
φ	packing fraction
ψ	variable
ω	humidity (kg moisture/kg dry air)

Superscripts

$*$	dimensionless

Subscripts

a	air
b	bulk
e	equilibrium
i	inlet
m	membrane
max	maximum value
o	outlet
s	saline water
t	turbulence
tot	total
v	vapor
w	wall, water
x	x axis direction
y	y axis direction
z	z axis direction

for the saline water stream are larger than the values for air dehumidification which uses a 35% LiCl solution as the liquid desiccant. The reason behind is that the concentration entry length for the saline water is larger than that for the LiCl solution. The laminar models are simple and convenient to solve. However, the air side Reynolds numbers are relatively high as a result of high packing fractions and high flow rates, which leads to turbulence inside the bundle. The turbulence is further contributed by the successive disturbances from the numerous fibers when the air flows across the fiber bank. Actually, the flow tends to be turbulent even under very lower Reynolds numbers. As a result, several authors have investigated the transport phenomena in the bundle with turbulent model. Zhang et al. [9] used a turbulence model to investigate the friction factors and Nusselt and Sherwood numbers in the bundle for air dehumidification. They found that for both the in-line and the staggered arrangements, the turbulence intensities are higher than 0.07, meaning that the fluctuations of velocities in the bundle are relatively large. The current authors also used the standard k-ε model (STD k-ε) and the low-Reynolds k-ε (Low Re k-ε) turbulence model for heat and mass transfer in membrane bundles for seawater desalination [10]. It is found that the Low Re k-ε model shows a better agreement with the experiments than the STD k-ε model in the tested Re range from 50 to 600, especially when Re is greater than 300.

These studies are very interesting. Regretfully however, all of the above mentioned studies used two-dimensional (2D) formulations for the three-dimensional (3D) turbulent flows. In these studies, the velocity is assumed homogeneous in the depth direction by only considering velocity distributions in axial and vertical directions. Although the 2D simulation is simple and useful to gain the basic idea about the flow and thermal field distribution, the 3D effects generally encountered in most of the experiments and practical situations were neglected. As pointed out by [11,12], the asymmetric distributions in velocity vector and turbulent kinetic energy in depth direction have a tremendous three-dimensional effect on the flow distribution.

As a step forward, in this research, a full 3D Low Re k-ε turbulence model is proposed to investigate the fiber side turbulent fluid flow and heat and mass transfer in the membrane bundle for humidification (MBH) in desalination applications. Compared to those 2D models, the proposed 3D models take full account of the inhomogeneity in flow distribution and the velocity fluctuation in the normal (depth) direction not just in axial and vertical directions. In addition to the continuity, momentum, energy and concentration equations, two additional equations, i.e., the turbulent kinetic energy and the dissipation rate equations are solved numerically in a three-dimensional coordinate system to obtain the air side friction factors, Nusselt numbers and Sherwood numbers. Those fundamental data is of interest for the effective design and optimization of the MHDD system. For comparison, besides the proposed 3D Low Re k-ε model, a 2D Low Re k-ε model, a 2D laminar model, and a 3D laminar model are also used for modeling. All are solved as conjugate problems. Their results for the frictions and heat and mass transfer properties are compared. To validate the numerical results, velocity oscillations and heat and mass transfer performance are measured with a previously built test rig.