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Oblique fluid flow and heat transfer across a hollow fiber membrane bank under uniform temperature conditions

Yu-wen Ouyang [a], Zhen-Xing Li [a], Li-Zhi Zhang [a,b,*]

[a] Key Laboratory of Enhanced Heat Transfer and Energy Conservation of Education Ministry, School of Chemistry and Chemical Engineering, South China University of Technology, Guangzhou 510640, China
[b] State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou 510640, China

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ABSTRACT

Hollow fiber membrane banks have been extensively used in various energy and environmental technologies. Fluid flow and heat and mass transfer in the tube bank have been a focus of study. Previous researches have been focused on either pure parallel flow or pure cross flow. However they are only very ideal flow conditions. This study addresses a more common condition: oblique flow, in which shell side flow impinges the fiber tubes with a skew angle. By solving the fluid flow and heat transfer equations in the shell side, convective coefficients are obtained for impinging angles from 0° to 90°. It is found that the oblique angle influences the heat transfer properties seriously. Heat transfer rates for oblique flows are higher than those for parallel flows but lower than those values for cross flows. Correlations are proposed for the prediction of friction factors and Nusselt numbers at various oblique angles, both for aligned and staggered arrays with various geometrical parameters. Then mass transfer coefficients can be obtained from the calculated Nusselt numbers with heat-mass analogy.

1. Introduction

Hollow fiber membrane has been extensively used in various industries, such as membrane reactor, membrane distillation and product separation [1–3]. It prevents the two fluids from direct contact, besides its packing density is higher and the heat mass transfer capability is larger. The hollow fiber membrane bank may form a shell-and-tube heat exchanger. The hot air and cold liquid flow in the shell side and tube side, respectively. Fluid flow and heat and mass transfer coefficients in the fiber bank are the focus of study. The friction factors and the Nusselt and Sherwood numbers in shell side are the most important parameters for the design, operation and optimization of membrane systems. Since the Sherwood numbers can be estimated from the Nusselt numbers with heat and mass analogy, the unknown pressure drop and convective heat transfer coefficients in shell side have become the parameters of interest. Fluid flow and convective heat transfer in shell side of a membrane contactor have been studied by many investigators. Tahseen et al. [4] numerically studied the two-dimensional laminar forced convection heat transfer in staggered tube banks. Incompressible steady cross flow under constant heat flux boundary conditions is imposed. Sangani and Acrivos [5] simulated the flow across square and hexagonal tube arrays. Temperature differences between the bulk and cylinders are calculated. Li et al. [6] studied mass transfer in a hollow fiber array in cross flow and obtained mass transfer correlations for wide ranges of pitch to tube diameter ratios and Reynolds numbers. Mandhani et al. [7] presented extensive results for heat transfer non-uniformity on the surface of a cylinder. Mehrabian [8] studied the heat transfer and pressure drop characteristics in a tube bank with cross flow and found that the pressure drop show a linear relationship with less than 5 rows of tubes. There are quite a few of these studies [9–21], with various bundle geometries and various fluids. Here just some are mentioned. Most of the studies are either pure parallel flow (co-current or counter flow) or pure cross flow.

It should be mentioned that both parallel flow and cross flow are very ideal extreme conditions of fluid flow. In real applications, where the fluid inlet vent is small but the fibers are long in a membrane contactor, fluid usually impinges the membrane tube bundle with an inclined angle. So the fluid flow and heat transfer in the bank would be affected by the impinging angle. Evaluating the influences of the inclined angle will be the focus of this study.

Literature review found there have been several studies of heat transfer with oblique flow. Ali and Vafai [22] analyzed the heat mass transfer between air and a falling film along a single fiber with inclined flow. They found that the inclination angle can significantly enhance the dehumidification performance compared

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[*] Corresponding author at: Key Laboratory of Enhanced Heat Transfer and Energy Conservation of Education Ministry, School of Chemistry and Chemical Engineering, South China University of Technology, Guangzhou 510640, China.
Tel./fax: +86 20 87114264.
E-mail address: lzzhang@scut.edu.cn (L.-Z. Zhang).

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to parallel flow. Choi et al. [23] measured the flow field around a cylinder with incline flow and visualized the effect of inclination on the vortices and the wakes around the cylinder. Wang and Tao [24] investigated the periodically fully-developed laminar heat transfer of a skewed flow across an array of uniform plate length. They found that heat transfer and pressure drop rises with increasing oblique angle and plate length. Igarashi and Mayumi [25] studied the fluid flow and heat transfer characteristics around a cylinder at small attack angles and summarized the local heat transfer coefficients by empirical equations. Though there have been several studies in this direction, the results are quite limited. Most previous researches are only concerned on oblique flow around a single fiber. The interactions between neighboring fibers have not been considered. Oblique flow in a fiber bank will be studied here.

2. Methodology

2.1. Problem description

A membrane contactor with oblique flow is studied. Both inline and staggered fiber arrays are considered. The problem is schematically depicted in Fig. 1. Only heat transfer is considered. The fibers are made with thin and dense PE (polyethylene) membranes with a thickness of 70 μm. In this study membranes are impermeable. Hot water flows inside the fibers to heat the air flowing outside. Because only heat transfer is considered, there is no mass exchanged between the air and the liquid. Only shell side convective heat transfer is studied. Water is circulated quickly so the tube side temperature drop is minimal. As a result, a uniform wall temperature condition is assumed on membrane surfaces. The boundary conditions are in analogy to constant wall mass concentrations in real membrane contactors for mass exchange. The air stream enters the shell space with an oblique angle α to the axis of the fibers. The configuration of modules is characterized by transverse pitch S_T and longitudinal pitch S_L measured between tube centers, as depicted in Fig. 1. For the membrane contactor, the packing fraction of the module can be given by

$$\phi = \frac{N_{tot}\pi r_o^2}{ab} \tag{1}$$

where N_{tot} is the total number of fibers in a module, r_o is outer radius of a fiber; a and b are width and height of the module respectively.

To better design the hollow fiber membrane module, resistance and heat transfer data are required. Mathematical modeling of the fluid flow and heat transfer in the fiber bank is a convenient tool for analysis. The packing density in a membrane module is usually high. It may have thousands of fibers in a bank. The interactions between the neighboring fibers should be included. However, due to the fact that the number of fibers in a hollow fiber module is numerous (thousands of), the direct modeling of the entire module is unimaginable under current calculating capacity. Hence in this study, only a representative region along the flow in the whole fiber bank is modeled to simplify the problem. A representative cell surrounded by neighboring fibers in the calculating domain is plotted in Fig. 1. The whole calculating domain is comprised of 10 consecutive representative cells along the flow direction. Both inline and staggered arrangements are plotted.

2.2. Governing equations

In most practical applications with hollow fiber membrane modules, the Reynolds numbers are usually much less than 2000. It is far less than the critical Reynolds number deviating from laminar flow across fibers (2×10^5). In this study, Reynolds numbers are varied from 50 to 300 and Prandtl number is taken as 0.71. Hence the air stream is considered to be laminar. Other assumptions include: the fluid is incompressible, Newtonian with constant thermal properties. They are valid because the pressure drop is negligible compared to the total pressure of air.

Navier–Stokes equations are applied to solve the hydrodynamic and heat transfer problem in three-dimensional Cartesian coordinates [26], as shown in Eqs. (2)–(6):

Conservation equation of mass is

$$\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}+\frac{\partial u_z}{\partial z}=0 \tag{2}$$

where x, y, z are transverse, longitudinal and axial coordinates for air flow, respectively; subscript "x", "y" and "z" refers to x-axis, y-axis and z-axis respectively; u is velocity of air flow.

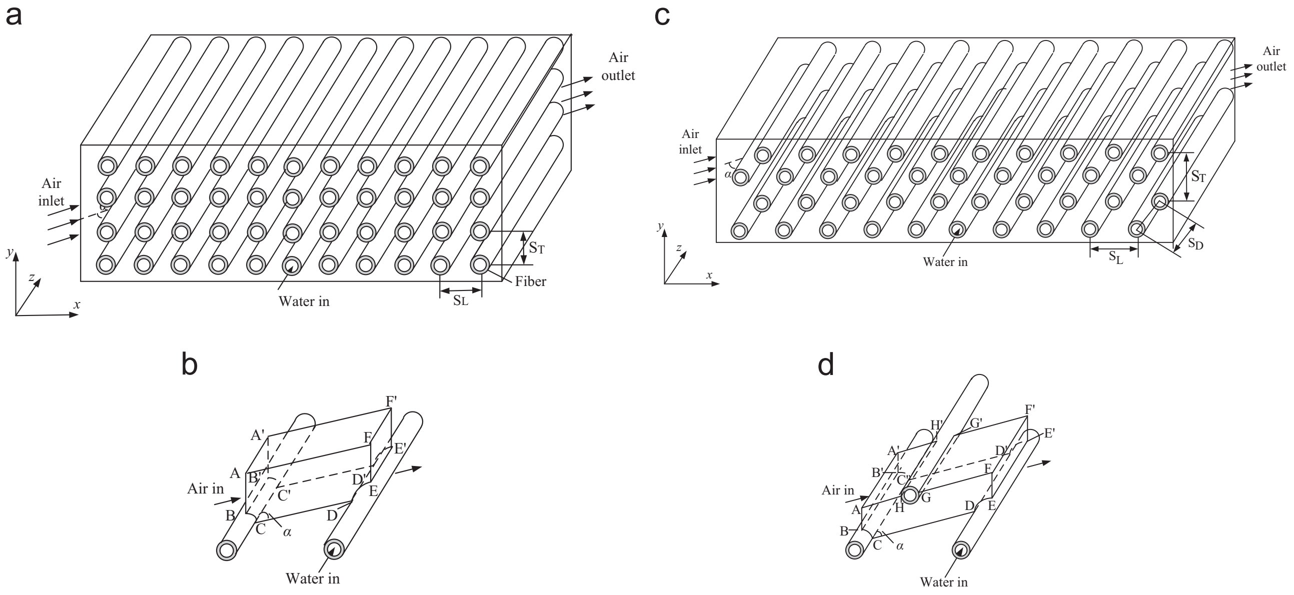

Fig. 1. Schematic of an oblique flow in a hollow fiber membrane bundle: (a) the bundle with inline arrangement; (b) a representative cell in the calculating domain with inline arrangement; (c) the bundle with staggered arrangement; (d) a representative cell in the calculating domain with staggered arrangement.