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Flow maldistribution and performance deteriorations in a cross flow hollow fiber membrane module for air humidification

Li-Zhi Zhang [a,b,*], Zhen-Xing Li [a], Ting-Shu Zhong [a], Li-Xia Pei [a]

[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

The flow maldistribution and the consequent performance deteriorations in a cross flow hollow fiber membrane module used for air humidification are investigated. The effects of structure-induced flow maldistributions on the deteriorations in humidification efficiencies are studied. As a first step, a CFD code is used to calculate the flow distribution in the exchanger, by treating the hollow fiber membrane core as a porous media. Then a coupled heat and moisture transfer model between the air flow and the water flow is set up. The shell-and-tube core is equivalently converted to a cross-flow parallel-plates heat mass exchanger. Using the CFD predicted flow distributions on the core face, the sensible cooling and humidification efficiencies are calculated with a finite difference scheme. The results indicate that the packing fraction affects the flow maldistribution substantially. The consequent sensible cooling and humidification efficiencies are influenced significantly. Depending on air flow rates, the sensible cooling efficiencies can be deteriorated by 3–30%, and the humidification efficiencies can be deteriorated by 26–58%.

1. Introduction

Air dehumidification has become a hot topic in recent years [1–3]. In contrast, air humidification has drawn little attention. It should be noted that air humidification is equally important as air dehumidification in HVAC industry. Relative humidity of 40–60% is the comfort zone for human beings. Dry indoor air has many adverse effects for occupants. People would feel dry and uncomfortable in this environment. Flu epidemic and soaring throat are common in this dry environment. It is necessary to have air humidified in dry seasons. Besides applications in HVAC, air humidification has become a key technology in many other industries like fuel cells.

Recently, membrane modules have been used to realize air humidification [4–6]. For instance, the current research group proposed a hollow fiber membrane module for air humidification [4]. A bundle of several thousand hollow fibers was packed into a rectangular shell to form a shell-and-tube module. The fibers were placed orderly to have better performances. The water flowed inside the hollow fibers. The air flowed transversely across the fiber bundle while being humidified. The benefit with this structure is that the air side pressure drop is suitable for practical applications, while the heat mass transfer coefficients are still high. The performance analysis showed that the humidification efficiencies were satisfactory.

However, the effects of flow maldistribution on performances were not studied before. Previous studies assumed a uniform flow distribution at the inlet face of the core [4–6]. It should be noted that the whole humidification module is composed of not only the membrane fibers (the core), but also the inlet/outlet headers. The inlet and outlet headers are usually in complex structures. They are not straight. They usually have sudden expansions or shrinks, which may lead to unevenly distributed flow at the inlet of the core. This is true even when the fibers are orderly distributed. The problem is the subject of this study.

In other applications like membrane absorption and gas purification operations, there were many studies of flow maldistribution [7–17]. However in these cases, the flow malsdribution was mainly caused by the maldistribution of fibers, not by the exchanger structure itself. In this study, the fibers are packed orderly [16]. The flow maldistribution is resulted from the complex structure of ducts. Further, most of the previous studies were in counter-flow arrangements. In this study the cross flow module is considered. In summary, the effects of the structure-induced flow maldistribution on the performance of a cross-flow hollow fiber membrane module will be investigated. This is the novelty in this research.

* Corresponding author at: South China University of Technology, School of Chemistry and Chemical Engineering, Key Laboratory of Enhanced Heat Transfer and Energy Conservation of Education Ministry, Wushan Road, Guangzhou 510640, China. Tel./fax: +86 20 87114264.

E-mail address: lzzhang@scut.edu.cn (L.-Z. Zhang).

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There were many studies about flow maldistribution for sensible-only heat exchangers [17–25]. However most of them only calculated the flow fields. The coupling of flow fields with heat transfer is scarce. In this study, the flow maldistribution will be coupled with both the heat transfer and the mass transfer. The purpose is to disclose the influences of the maldistributed flow on heat transfer and humidification efficiencies.

2. Module structure and experiments

Fig. 1 shows the hollow fiber membrane module tested for air humidification. The whole module is comprised of the ducting work, the inlet and outlet headers, the shells and the core. The humidification performance of the hollow fiber membrane module is tested in a test rig shown in Fig. 2. The dimensions of the inlet/outlet ducts are: 1000 × 160 × 160 mm. The inlet and outlet headers are necessary to station the core and to connect the shells with the inlet and outlet ducts. They provide transitional ducts between the inlet/outlet ducts and the membrane core. The structures of the headers and the core are shown in Fig. 3. The plane A1-A2-A3-A4 is the inlet face of the module; B1-B2-B3-B4 is the inlet face of the core; C1-C2-C3-C4 is the outlet face of the core; D1-D2-D3-D4 is the outlet face of the module. The transition angles (θ) for the inlet and outlet headers are 12° respectively. The core is assembled with numerous fibers packed together and spaced orderly in the shell, in an inline arrangement. The transverse pitch P_T is equal to the longitudinal pitch P_L. Air stream and water stream exchange moisture through the hollow fiber membrane core. The dimensions for the core are: length (x_F)=380 mm; width (y_F)=200 mm; height (z_F)=250 mm. The water flows in tube side and the air flows in shell side. When water flows in tube side, moisture permeates to air outside the fibers. The module is made with PVDF (polyvinylidene fluoride) porous membranes coated with a layer of dense silicone. They are asymmetric and non-porous. The potential risk of water cross-over problems can be overcome by this modification. Further, the selectivity of the membranes can be realized. The membrane prevents the permeation of liquid water, but selectively allows the permeation of moisture. The geometrical and physical characteristics of the hollow fiber membrane cores are summarized in Table 1. Two cores are tested.

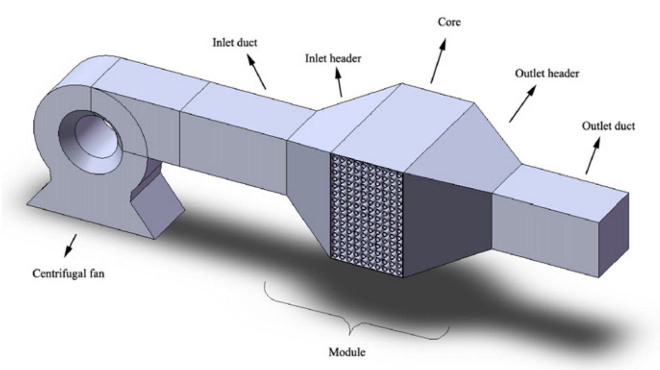

Fig. 1. Configurations of a hollow fiber membrane module for air humidification.

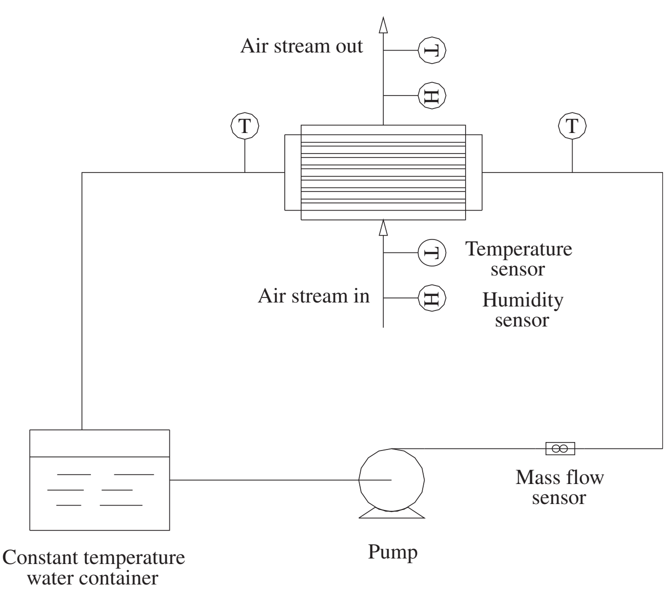

Fig. 2. Schematic of the air humidification test rig.

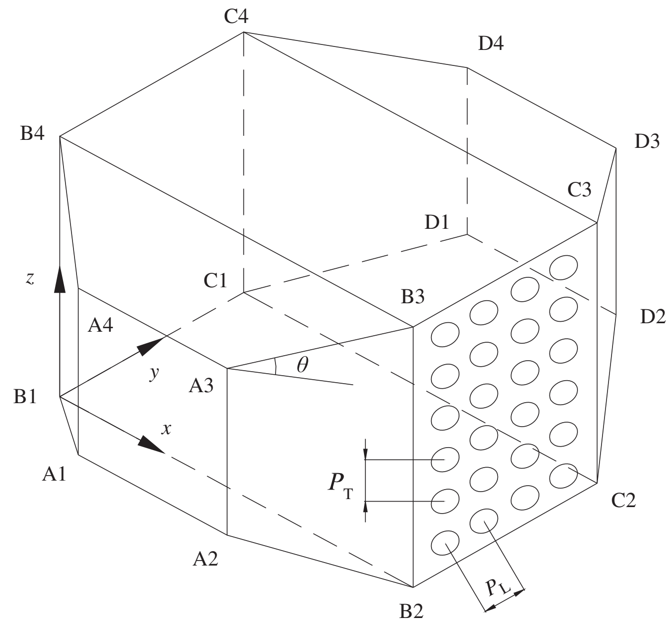

Fig. 3. Schematic of the membrane module comprising of an inlet header, a membrane core and an outlet header. (A1-A2-A3-A4 is the inlet face of the module; B1-B2-B3-B4 is the inlet face of the core; C1-C2-C3-C4 is the outlet face of the core; D1-D2-D3-D4 is the outlet face of the module).

The whole setup is placed in an air-conditioned chamber. Temperature and humidity of inlet air can be adjusted, representing varying inlet air states. Pure water is prepared in a water container under constant temperature (293 K). As can be seen from Fig. 3, water is pumped to the bundle through a plastic hose. It then flows through the tube lumen. Air flows in the shell side, driven by a fan. Temperature and humidity of air to and from the bundle are measured by temperature and humidity sensors (Center313). Nine sensors are uniformly inserted into the connecting surface between the inlet duct and the inlet header to get an average value of the inlet. Another nine sensors are uniformly inserted into the connecting surface between the outlet duct and the outlet header to get an average value of the outlet. Air and water flow rates are measured by mass flow meters. Tube side and shell side pressure drops are measured by electronic pressure gauges. Distilled water is used, so water side mass transfer resistance is negligible. Moisture concentration on the inner surface of membrane is considered as the saturated vapor concentration. The outer diameter of fibers is 1.6 mm. The fiber arrangement tested is an aligned one, with a longitudinal pitch 3.2 mm and a transverse pitch 3.2 mm. The packing fraction is 0.20.

The temperature and humidity are measured by Center313 sensors. The uncertainties for measurement are: temperature, ±0.2 °C; humidity, ±2%; volumetric flow rate, ±0.5%; pressure