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Analysis of a membrane based air-dehumidification unit for air conditioning in tropical climates

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HIGHLIGHTS

- A simple cross-flow membrane based air-dehumidification unit is analysed for tropics.
- Experiments, physical modeling and computer simulations have been performed for the analyses of a laboratory type dehumidification unit.
- A moisture reduction of up to 8 g per kg of dry air for humid ambient air having a moisture content of 20 g per kg of dry air while the air flow rate is of 20 m^3/h.
- Results show the membrane based dehumidification is driven by vapor pressure gradient between incoming ambient air and the relatively dry exhaust air from a building.
- No electricity consumption for the process except for air transport.

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ABSTRACT

The dehumidification potential of a cross-flow membrane based air-dehumidification unit is analysed for tropical climatic conditions. The process of dehumidification is driven by the gradient of the concentration of water vapour between the incoming ambient air and the relatively dry exhaust air from a building. Electric energy is used for air transport only. This paper reports on experiments, physical modelling and computer simulations performed for the analysis of a laboratory-type dehumidification unit in Singapore. Experimentally moisture reductions between 4 g and 8 g of moisture per kg of moist air have been achieved for high humidity ambient air conditions (16 g/kg and 20 g/kg, respectively). Membrane dehumidification units may be used as stand-alone dehumidification units or as pre-dehumidification devices in the context of more complex air-conditioning systems in tropical climates.

1. Introduction

Worldwide application of air-conditioning systems in residential, industrial and commercial buildings is increasing significantly, leading to a growing electricity demand. Conventional air cooling machines handle both air dehumidification (latent loads) and air cooling (sensible loads) simultaneously in an electric energy-intensive manner. In particular in tropical regions, electricity consumption will be high because of the large amount of latent load. Separate handling of latent and sensible loads using different components may be advantageous as the air dehumidification process can be effectively done by electricity efficient techniques, e.g., membrane, absorption and desiccant adsorption technologies driven by heat energy [1–5].

This paper focuses on the analysis of a laboratory-type membrane dehumidification unit that offers an electricity efficient way of air dehumidification. In general, air dehumidification has to be followed by a separate cooling step of the dehumidified air (sensible cooling). Membrane technology is a powerful method for the energy efficient separation of substances. Membrane separation technologies are widely applied in areas like food processing, water treatment, electrochemistry, etc. [6–11]. A plethora of research has been done on the analysis and the development of such technologies. The application of membrane technologies to air dehumidification in electricity efficient air-conditioning systems has gained importance during the last decade. Zhang et al. [12–15] conducted in-depth theoretical and experimental analyses of membrane based mass and heat transfer processes using different membrane materials and different physical configuration of membrane units. Scovazzo et al. [16], investigated membrane based humidity control methods using different types of membranes. Some research

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groups focused on the optimization of membrane structures for air dehumidification applications [e.g. Refs. [17,18]]. These analyses point out that the membrane based mass and heat transfer could be fruitfully utilized for air dehumidification in air-conditioning systems. However, many challenges are still remaining to improve membrane technologies for moisture and heat transfer processes. In particular a lack of membrane based air-dehumidification research for tropical climates is found. Additionally, the primary advantages of membrane based technologies such as low initial investment, energy efficiency, simplicity of operation and low operation cost encourage us to evaluate the potential application of membrane technology in tropical regions. This work is focussing on a membrane based air dehumidification system for the tropics.

In this paper, we report on experimental and theoretical simulations (using COMSOL software) of a laboratory-type membrane based air-dehumidification research unit operated under Singapore climate. For simplicity, the unit is designed as an air-to-air cross flow moisture and heat exchanger. The driving force of the air-dehumidification is the gradient of the concentration of water vapour between the incoming ambient supply air (high humid air) and the relatively dry exhaust air from an air-conditioned room. Except for air transportation, no electric energy is used in this configuration.

2. Experimental set up of membrane moisture exchanger

The principle of a membrane based moisture and heat exchanger is shown in Fig. 1. A humid primary air stream and a relatively dry secondary air stream enter the unit on either side of a membrane layer. The moisture permeation takes place between the primary air and secondary air through the membrane.

An experimental test facility for the experimental analysis of a cross-flow membrane moisture exchanger unit integrating variable speed controlled fans and a humidity control chamber (see Fig. 2) was installed in a laboratory of the Solar Energy Research Institute of Singapore (SERIS). The membrane unit is composed of 40 pieces of frames (see Fig. 3) made of the Bakelite material with the thermal conductivity of 0.23 W/(m K). A fibre-type membrane sheet from a membrane unit (ZehnderComfoAir 350) as shown in Fig. 4 was fastened with glue on each side of the frame. The Bakelite frames with the membrane layers were then assembled together to form the cross-flow membrane unit. The detailed information of the cross-flow membrane moisture exchanger is given in Table 1. A humidity control chamber was designed and fabricated in order to control and maintain the moisture content of the primary air stream during the experiments. This chamber simulates primary air streams with different moisture contents. The secondary air stream is taken from an air conditioned space. Steady state conditions of the air streams were maintained. During the experiments, the relative humidity (RH), temperature and air flow rates of various air streams were measured. The specifications of the applied sensors are listed in Table 2. In order to reduce the systematic error in experiments, the air temperature was measured by 4-wire RTD temperature sensor. The RH sensors reading were checked with a

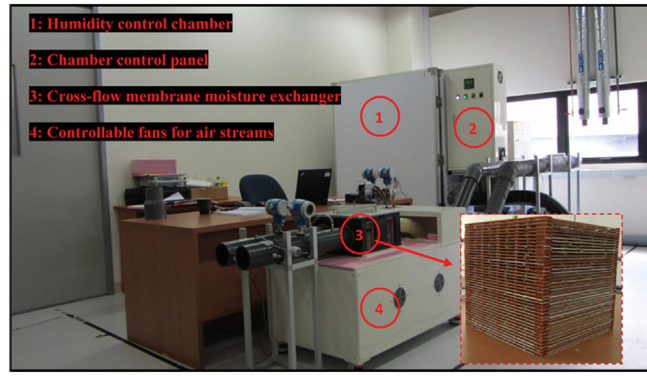

Fig. 2. Experimental set up for the analysis of membrane based air dehumidification systems. The primary air (ambient air) is simulated using the humidity control chamber (1). The secondary air is taken from an air conditioned room. The primary and secondary air streams can be adjusted using the controllable fans in subsystem 4, and the two air streams are sent into the membrane moisture exchanger unit (3).

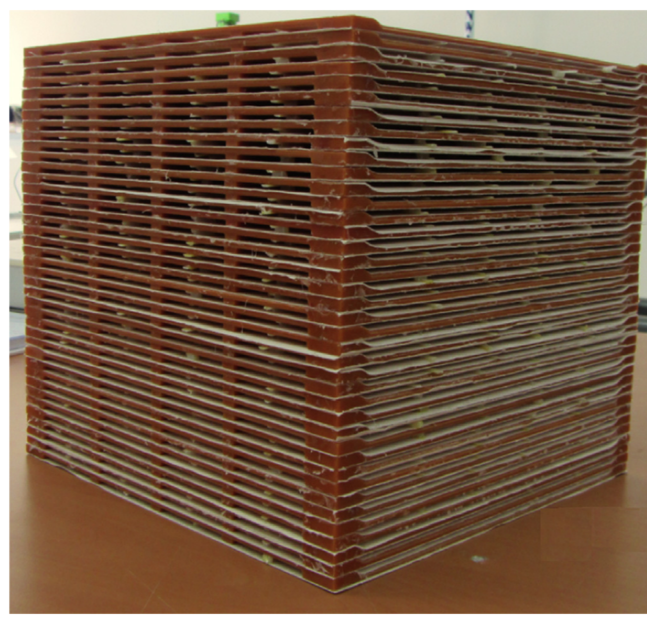

Fig. 3. Membrane based moisture exchange unit ($L \times W \times H$: 17 cm $\times$ 17 cm $\times$ 19 cm). The height includes the thickness of the frames, membrane papers and glue.

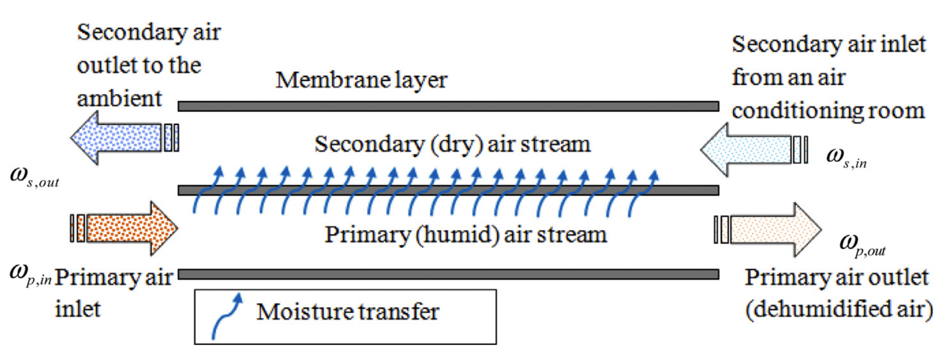

Fig. 1. Principle of a membrane based moisture and heat exchanger. The ω characterizes the humidity ratio of the corresponding air flows (a counter flow diagram is shown in this figure; in the experiments a cross flow scheme was applied, see Fig. 5).