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Research Paper

A frosting limit model of air-to-air quasi-counter-flow membrane energy exchanger for use in cold climates

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HIGHLIGHTS

- Developed a frosting limit model for the quasi-counter-flow membrane energy exchanger.
- Designed and constructed a prototype of membrane energy exchanger with quasi-counter-flow arrangement.
- Validate the frosting limit model with experimental data.
- Conducted parametric studies on the frosting limits model.

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ABSTRACT

Membrane energy exchangers (MEEs) can reduce or avoid frosting in cold climates since the moisture transfer lowers the dew point of the exhaust air and as a result, the exchanger can be frost-free at lower outdoor air temperatures or higher indoor humidities. A frosting limit is necessary to predict at which conditions the onset of frost occurs for a given membrane energy exchanger. The frosting limit model provides criteria for energy exchanger selection and frost control methods to avoid frosting.

A theoretical frosting limit model is developed in this study for a quasi-counter-flow MEE. The frosting limit model uses analytical relationship between the onset of frosting at the coldest location of the exchange and the inlet air conditions. The model is validated with experimental data and consistent agreements are obtained between the theoretical and experimental data. Parametric studies are conducted using the validated model. The influence of airflow rates, exhaust air temperature and channel spacing on the frosting limit is rather limited compared to the diffusive resistance of moisture transfer. A membrane with improved moisture transfer properties is crucial to implement frost-free operation at normal indoor relative humidities.

1. Introduction

An air-to-air heat/energy exchanger is a device that transfers heat or/and moisture from one air stream to another [1]. Application of ventilation heat/energy exchangers reduces the energy consumption in building sector considerably. In most new buildings, which are designed to be air-tight and well insulated, supply of sufficient outdoor air is required for maintaining a healthy indoor air quality and satisfactory thermal comfort [2]. Heating and cooling the fresh outdoor air to obtain a good indoor climate is an energy intensive process. In cold climate regions defined by Ref. [3], the energy demands for heating the cold outdoor air can reach 60% of overall energy use of buildings [4]. Heat recovery systems are able to reduce heating energy demands through recovering the otherwise wasted energy from the exhaust air [2,4].

Ice and frost are observed in cross or counter flow exchanger cores when the heat recovery system is applied in cold climates [5–7]. The warm and moist exhaust air tends to condense on the cold energy transfer surfaces and the condensation water starts to form ice when the cold surface temperature is below freezing point [8]. Water vapour can also form frost directly if the surface temperature is lower than dew point and freezing point. The ice/frost increases the pressure drop across the exchanger core resulting in increased fan power to move the air. The accumulation of the frost on the plate acts like a fouling layer and increases resistance to heat and moisture transfer. Consequently, the frost substantially

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Nomenclature

c_p	specific heat capacity of air (J/kg K)
$\dot{m}$	mass flow rate of dry air (kg/s)
W	humidity ratio (kg/kg)
h	convective heat transfer coefficient (W/m^2 K)
A	total heat transfer surface area (m^2)
B	bias error
D	diffusivity (m^2/s)
J	water vapour flux (m^3/m^2 s)
P	precision error or pressure (Pa)
S	sample standard deviation
t	constant
U	total heat/mass transfer coefficient or uncertainty
X	variable
j	Colburn factor
k	convective mass transfer coefficient kg/(m^2 s)
Acronyms	
Le	Lewis number
NTU	number of transfer unit
Nu	Nusselt number
RH	relative humidity
Re	Reynolds number
Sh	Sherwood number
Greek letters	
λ	thermal conductivity (W/m K)
δ	thickness (m)
Subscripts	
h	heat
1	first passage in exhaust air side closest to supply air
cou	counterpart
cro	cross-like part
e	exhaust
i	inlet
m	moisture or membrane
min	minimum
o	outlet
s	supply or sensible
v	vapour
w	water

degrades the performance of the heat/energy recovery systems [5,9–11]. As a result, a freezing control strategy is needed in cold climates. Freezing control can be categorized as frosting control (avoiding frost) and frosting-defrosting (periodic cycling between frost accumulation and removal) [5]. Both freezing control strategies either consume extra energy or disturb indoor thermal comfort [5,12–14]. According to a recent review on frosting in heat recovery system, the frost problem is still not solved [5].

The membrane energy exchanger (MEE) is able to recovery heat and moisture simultaneously and has a similar structure as a flat plate heat exchanger. The major difference is that the impermeably metal or plastic plates in the heat exchanger are replaced by permeable membranes [15]. The moisture transfer from the exhaust air to supply air lowers the dew point of exhaust air which results in frost starting at lower outdoor air temperatures. The membrane energy exchanger tends to reduce or even avoid frosting due to the moisture transfer. A concept of frosting limit is defined and investigated for cross-flow MEE by the author in Ref. [8].

The frosting limit in this research is defined as the combination of indoor and outdoor air conditions at which frost start to form for a given heat/energy exchanger. The frosting limit can be a criterion in selecting/designing appropriate heat/energy exchangers and determining frost control heating set-point. However, in open publications only scarce research related to the frosting limit are found especially for flat plate energy exchangers. Ruth et al. [10] conducted experimental investigations on frosting limits for an aluminium heat-wheel. Frost was observed when outdoor air temperature ranges from −26 to −16 °C and indoor relative humidies between 25% and 30%. They also found that frosting is strongly dependent on indoor relative humidity (RH). Fisk et al. [16] experimentally compared frosting limits of different cross-flow heat exchangers. Their experiments showed that heat released from condensation at high indoor relative humidity increased the plate temperature and reduce frosting. However, a theoretical frosting limit model was not presented in their research. Sauer et al. [11] measured the frosting limit of a pure-counter-flow heat exchanger and the limit was plotted linearly from −23 to −9 °C of outside temperature and 58 to 32% of indoor air relative humidity. The theoretical frosting limit was not either available. Holmberg [17] numerically studied energy wheels and proved that the frost starts at lower outdoor air temperatures than a static heat exchanger due to the moisture transfer. Recently, Anisimov et al. [18] conducted numerical simulation and analysis of coupled heat and mass transfer in cross-flow heat exchanger under frosting conditions. Frosting limits were estimated to maintain the safe operating conditions (no frost) under different inlet relative humidity, outdoor air temperatures and thermal efficiencies. Liu et al. [8] developed an analytical frosting limit model for cross-flow membrane energy exchanger neglecting influence of condensation on membrane temperature under low inlet relative humidity. Two dimensional heat and mass transfer were simplified to one dimension by considering the flow channel where frosts will first occur (i.e., the exhaust air flow closest to the supply air inlet). Experimental validations were carried out and good agreements between theoretical and experimental frosting limits were obtained. Some available frosting limits are summarized in Table 1. Based on the author's knowledge, neither experimental nor theoretical frosting limits of quasi-counter-flow MEE are available in the open publications.

This paper first presents the development of the theoretical frosting limit model for a quasi-counter-flow MEE. The design of a quasi-counter-flow MEE and the test rig of detecting frosting limit are described. Parametric studies are then performed based on the verified analytical model.

2. Frosting limit model for quasi-counter-flow MEE

The most likely frosting areas in a quasi-counter-flow MEE are shown in Fig. 1(a) and (b) (cold corner). The heat and moisture transfer area for developing the frosting limit model is also shown in Fig. 1. The quasi-counter-flow can be divided into three parts: two cross-like parts and one counterpart.

To develop the theoretical frosting limit model for a quasi-counter-flow MEE, the following assumptions are applied in this study.

Assumptions.

1. The most likely frosting parts in the quasi-counter-flow MEE are the outlets in exhaust airstream that are closest to the supply inlets ("cold corner" in Fig. 1);