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Comparison of various methods for evaluating the membrane-type total heat exchanger performance

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ABSTRACT

Four methods are used to evaluate the performance of a membrane-type total heat exchanger, they are the numerical method with consideration of moisture adsorption heat, the numerical method with no consideration of that heat, the effectiveness-NTU method with consideration of that heat, and the effectiveness-NTU method with no consideration of that heat. Calculations are conducted for typical exchanger parameters and operating conditions. The results generated by these four methods are presented and compared. It is found that, although the effectiveness-NTU method is easy to use, it is incapable of yielding accurate results on moisture and enthalpy effectivenesses, while the numerical method can provide not only more accurate various effectivenesses but also the distributions of various physical parameters. Of the four performance evaluating methods, the numerical method with consideration of the adsorption heat can give the best results.

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1. Introduction

Ventilation plays a significant role on modern society because people spend almost 90% of the time in indoor spaces [1]. Membrane-type total heat exchangers (THX) are often used to reduce the building energy consumption associated with forced ventilation through recovering both heat and moisture from ventilation air. There are typically two methods for evaluating the performance of such exchangers: the first is to build governing equations which include a set of partial differential equations describing the heat and moisture transfer in the THX core and solve them numerically under certain constraint conditions to obtain various physical parameter distributions as well as the exchanger effectiveness, the examples include researches [2–10], and the second is to use the existing heat exchanger effectiveness-NTU equations to calculate the exchanger effectiveness, the examples include researches [11–18]. For convenience, the former is called the numerical method and the latter the NTU method. The strong point of the numerical method is that it can provide not only more accurate effectiveness but also various quantity distributions, while the merit of the NTU method is that it is easy to use and suits for fast estimation of effectiveness.

When water vapor transfers from air fluid with high humidity to that with lower humidity across a membrane, it is thought to first adsorb at the membrane surface contacting the high humidity air, with release of adsorption heat, then diffuses through the membrane, and eventually desorbs from the membrane surface contacting the lower humidity air, with gain of desorption heat [19–22]. The heats of adsorption and desorption can be collectively referred to as the heat of adsorption or the adsorption heat. On evaluation of the THX performance, some researchers took into account the heat of adsorption [5–13] while some ignored it [14–18]. In combination with the aforementioned numerical and NTU methods, there are totally four methods for evaluating the THX performance: (1) the numerical method with consideration of the heat of adsorption, as in Dugaria et al. [5], Min and Su [6–8], Min et al. [9] and Min and Duan [10], (2) the numerical method with no consideration of such a heat, as in Zhang and Jiang [2], Niu and Zhang [3] and Pastor [4], (3) the NTU method with consideration of the heat of adsorption, as in Lee et al. [11,13] and Nasif et al. [12], and (4) the NTU method with no consideration of that heat, as in Zhang and Niu [14,15], Kistler and Cussler [16], Razak and Hafizzal [17], and Kadylak et al. [18]. These four methods will be called the Num-L, Num-0, NTU-L, and NTU-0 methods, respectively, where L means consideration of the adsorption heat, and 0 means no consideration of the adsorption heat.

Zhang and Jiang [2] and Niu and Zhang [3] modeled and investigated the THX performance, they considered the heat of moisture adsorption when developing the model but ignored it when evaluating the THX performance, so the numerical approach they adopted can be classified as either the Num-L or the Num-0 method. Because of the ignorance of the adsorption heat, their results showed that the sensible effectiveness was independent

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Nomenclature

A	surface area, m^2
C	membrane adsorption constant
c_p	specific heat, J/kg K
D	diffusivity, kg/m s
d	channel height, m
h	convective heat transfer coefficient, W/m^2 K
H	specific enthalpy, J/kg
J	transmembrane moisture flux, kg/m^2 s
k	convective mass transfer coefficient, kg/m^2 s
Le	Lewis number
L	moisture adsorption heat, J/kg
m	air mass flow rate, kg/s
n	number of channels
NTU	number of transfer units
Nu	Nusselt number
P_v	water vapor partial pressure, Pa
P_{sat}	water vapor saturation pressure, Pa
P_0	atmospheric pressure, Pa
q	heat flux, W/m^2
q_S	sensible heat flux, W/m^2
q_L	latent heat flux, W/m^2
r_{mM}	membrane moisture resistance, m^2 s/kg
r_{mT}	membrane thermal resistance, m^2 K/W
T	temperature, K or °C
W	humidity ratio, kg/kg
w_{max}	maximum moisture content of membrane, kg/kg
x, y, z	coordinates
x_F, y_F	channel length, m

Greek symbols

δ	membrane thickness, m or mm
ε	effectiveness
ε_H	enthalpy effectiveness
ε_M	moisture effectiveness
ε_T	temperature effectiveness
θ	membrane moisture content, kg/kg
λ	thermal conductivity, W/m K
ϕ	air relative humidity

Subscripts

a	air
e	exhaust
i	inlet
m	membrane or moisture
M	Moisture or mass transfer
min	minimum
o	outlet
s	supply
T	Temperature or heat transfer
w	water vapor

of the supply air humidity. Min and his co-workers [6–10] conducted a series of studies on THX, they built mathematical model for describing the heat and mass transfer in the THX core with consideration of the heat of adsorption, and proposed formulas for evaluating the membrane thermal and moisture resistances which involves the effects of such a heat, their simulation results support that the sensible effectiveness tends to decrease as the outdoor air humidity increases. Lee et al. [11] and Nasif et al. [12] evaluated the THX performance using the effectiveness-NTU method, they took into account the effect of the adsorption heat by combining the effectiveness-NTU equation with the membrane heat transfer resistance formula proposed by Min and Su [6]. Zhang and Niu [14,15] summarized the effectiveness-NTU equations for both heat and mass transfer across membrane and investigated the THX performance based on these equations, in which they ignored the effect of the adsorption heat.

Although there exist the abovementioned four THX performance evaluating methods in reality, no research has been reported on comparison and evaluation of these methods in the open literatures. The effectiveness-NTU equation can be used to calculate the effectiveness of a conventional heat exchanger, but it is unclear if such an equation can be employed to compute the effectiveness of a total heat exchanger (THX) which involves the combined heat and mass transfer. Further, it is also significant to clarify the effects of the moisture adsorption heat on the THX performance. The present research seeks to compare the Num-L, Num-0, NTU-L and NTU-0 methods to reveal how the results generated by them differ from one another. Calculations are conducted for a typical THX core geometry and for different membrane parameters and outdoor air humidities.

2. Theoretical model

A membrane-type total heat exchanger (THX) is an air-to-air plate-type heat exchanger having a heat exchange core made of a water vapor permeable membrane which transfers both heat and moisture. The outdoor supply air and indoor exhaust air proceed in a cross-flow pattern in the core of a typical THX, as illustrated in Fig. 1. There are four methods for evaluating the THX performance, which will be described in the upcoming four sections, respectively.

2.1. Numerical method with consideration of adsorption heat (Num-L)

Fig. 2 shows the basic physical model used for numerical simulation, which consists of a supply airstream channel, an exhaust airstream channel, and a membrane. The two airstreams travel along the channels in a cross-flow manner and exchange heat and moisture across the membrane separating the channels. Because of the symmetry in geometry, half the volume of the exhaust airstream, half the volume of the supply airstream and the middle membrane are taken to form the computational domain.

The following assumptions are adopted in modeling the heat and mass transfer in the Fig. 2 model: (1) the air and membrane physical properties are constant, and (2) the heat and moisture transfer are at steady state.

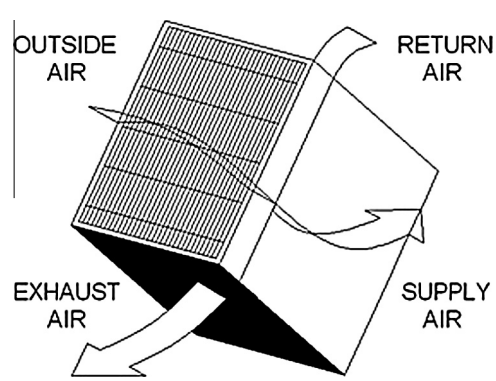

Fig. 1. The core of a typical THX.

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