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Match properties of heat transfer and coupled heat and mass transfer processes in air-conditioning system

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ABSTRACT

Sensible heat exchangers and coupled heat and mass transfer devices between humid air and water/desiccant are commonly used devices in air-conditioning systems. This paper focuses on the match properties of sensible heat transfer processes and coupled heat and mass transfer processes in an effort to understand the reasons for performance limitations in order to optimize system performance. Limited heat transfer capability and flow mismatching resulted in heat resistance of the sensible heat transfer process. Losses occurred during the heat and mass transfer processes due to limited transfer capability, flow mismatching, and parameter mismatching. Flow matching was achieved when the heat capacities of the fluids were identical, and parameter matching could only be reached along the saturation line in air–water systems or the iso-concentration line in air–desiccant systems. Analytical solutions of heat transfer resistance and mass transfer resistance were then derived. The heat and mass transfer process close to the saturation line is recommended, and heating sprayed water resulted in better humidification performance than heating inlet air in the air humidifier.

1. Introduction

The purpose of air-conditioning systems is to provide a suitable indoor environment with respect to temperature, humidity, fresh air, etc. There are many kinds of heat transfer devices in air-conditioning systems, including evaporators, condensers, and sensible heat recovery devices. Also, there are many kinds of coupled heat and mass transfer devices, such as cooling towers and humidifiers in air–water contact devices and dehumidifiers and regenerators in air–liquid desiccant contact devices. Many researchers have studied the performance of heat or coupled heat and mass transfer processes in air-conditioning systems both theoretically [1–4] and experimentally [5–11]. The optimization of these heat and mass transfer processes involves making structural improvements to handling processes, distributing the heat transfer area differently in various devices, adjusting flow rates, etc. With the help of optimization, inefficient structures can be avoided, heat and mass transfer areas can be placed in the most effective positions, and the energy consumption of the air-conditioning system will be reduced. In analyzing these heat and mass transfer processes, certain principles are expected to guide the optimization.

Pinch technology, which is widely utilized in certain industrial processes [12–14], is used to optimize the heat transfer network from the perspective of the whole system and determine the match properties of simultaneous heating and cooling processes, thus minimizing the required additional input of heat or cold as much as possible. However, in air-conditioning systems, buildings require cooling in summer and heating in winter, so simultaneous heating and cooling requirements are rare. Entransy is a thermological parameter that was introduced to analyze the heat transfer process [15]. Equivalent heat resistance on the basis of entransy loss is used to optimize the heat transfer process, in which achieving the lowest equivalent heat resistance under certain constraints is the most important goal [16,17].

Existing research has mainly focused on the transfer characteristics of a single heat or mass transfer process, but many issues regarding performance optimization remain unaddressed, such as how to achieve better performance at limited heat and mass transfer areas, how to design and arrange the air handling process, and what special principles or rules apply.

This paper focuses on the match properties of heat and mass transfer processes. The conditions of flow matching and parameter matching are analyzed, and the unmatched coefficients are derived through the entransy loss method. It is hoped that the results will benefit the optimization of sensible heat or coupled heat and mass transfer processes in air-conditioning systems.

2. Match properties of the sensible heat transfer process

According to the fluids' temperature variation through the heat transfer process, the heat exchangers in air-conditioning systems

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Nomenclature

A	heat transfer area (m^2)
A_M	mass transfer area (m^2)
c_p	specific heat capacity (kJ/kg K)
H	height of coupled heat and mass transform device (m)
h	enthalpy (kJ/kg)
ΔJ_{loss}	entransy loss (kW K)
$\Delta J_{loss,H}$	entransy loss of heat transfer process (kW K)
$\Delta J_{loss,M}$	entransy loss of mass transfer process (g/kg g/s)
NTU	number of transfer unit (dimensionless)
m^*	heat capacity ratio of two fluids (dimensionless)
$\dot{m}$	mass flow rate (kg/s)
p	partial vapor pressure (Pa)
Q	heat exchange (kW)
Q_S	sensible heat exchange (kW)
R_H	resistance of heat transfer process (K/W)
R_M	resistance of mass transfer process (s/kg)
r	vaporization latent heat (kJ/kg)
T	temperature (°C)
ΔT_m	logarithmic mean temperature difference in the heat transfer process (°C)
U	heat transfer coefficient (kW/(m^2 K))
U_M	mass transfer coefficient (kg/(m^2 s))

Greek symbols

ξ	unmatched coefficient (dimensionless)
ξ_H	unmatched coefficient of heat transfer process (dimensionless)
ξ_M	unmatched coefficient of mass transfer process (dimensionless)
φ	relative humidity ratio (%)
ω	humidity ratio (kg/kg)

Subscripts

a	air
c	low-temperature fluid
cond	condenser of a separate heat pipe
e	air in equilibrium with water or desiccant
evap	evaporator of a separate heat pipe
h	high-temperature fluid
in	inlet
m	intersection point of air inlet isenthalpic line and saturation line
out	outlet
s	liquid desiccant
w	water

can be divided into two types. In one type, the temperature of each fluid changes during the process, such as in air–water heat exchangers, air–air heat exchangers, and water–water heat exchangers. In the other type, the temperature of one side changes while the reverse side maintains a constant temperature, such as in evaporators and condensers. The heat transfer performances of these two kinds of heat exchangers will be analyzed in the following sections.

2.1. When the temperatures of both fluids change in the heat transfer process

A counter-flow heat exchanger, shown in Fig. 1a, is selected as an example to analyze the match properties of the heat transfer process. Assuming the specific heat capacities of the fluids are constant, the temperature changes of the two fluids can be represented by the lines in a *T*–*Q* (temperature–heat flux) chart, as shown in Fig. 1b.

Entransy loss of this heat transfer process [15] is calculated by Eq. (1), where Q is total transferred heat of this process.

$$\Delta J_{loss} = \frac{1}{2}(T_{h,in} + T_{h,out} - T_{c,in} - T_{c,out})Q \tag{1}$$

Heat resistance of the heat transfer process [17] is:

$$R_H = \frac{\Delta J_{loss}}{Q^2} = \frac{(T_{h,in} + T_{h,out} - T_{c,in} - T_{c,out})}{2Q} \tag{2}$$

The outlet temperatures can be obtained using the ε-*NTU* method. The heat resistance can be expressed as Eq. (3), where ξ is the flow unmatched coefficient and is expressed as Eq. (4).

$$R_H = \frac{\xi}{UA} \tag{3}$$

$$\xi = \frac{P}{2} \cdot \frac{e^P + 1}{e^P - 1}, \quad \text{where } P = UA \cdot \left(\frac{1}{c_{p,h}\dot{m}_h} - \frac{1}{c_{p,c}\dot{m}_c}\right) \tag{4}$$

The flow unmatched parameter is always greater than or equal to 1, but only when the calorific capacities of the two fluids are equal will the flow unmatched parameter be equal to 1. As indicated by Eq. (3), $1/UA$ denotes the resistance caused by the limited heat transfer capacity, and the heat resistance will increase by a

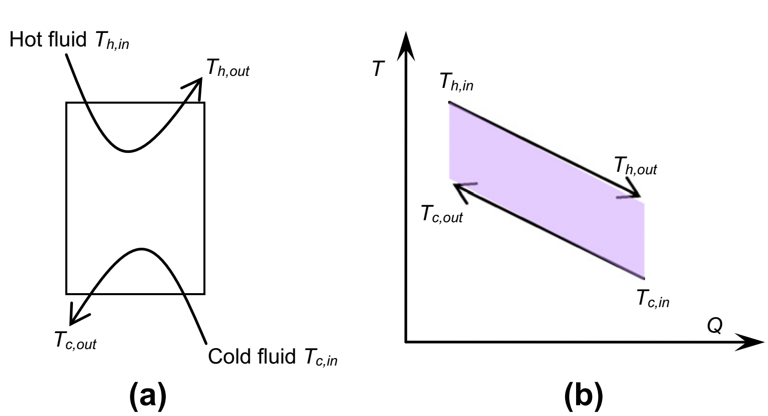

Fig. 1. Heat transfer process in a counter-flow heat exchanger: (a) hot and cold fluids and (b) heat transfer process shown in a *T*–*Q* chart.