Applied Thermal Engineering 143 (2018) 137–148

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Modeling air-to-air plate-fin heat exchanger without dehumidification

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HIGHLIGHTS

- A new air-to-air plate-fin heat exchanger model is proposed.
- It can calculate both heat transfer and flow resistance.
- It is capable of predicting performance with only nominal data.
- It does not need geometric data as inputs or require numerical discretization.
- The deviations of model predictions to the experimental data are within 10%.

ARTICLE INFO

Keywords:
Plate-fin heat exchanger
Air-to-air
Mathematical model
Modelica

ABSTRACT

In heating, ventilation and air-conditioning (HVAC) systems, air-to-air plate-fin heat exchangers (PFHEs) can be used as heat recovery devices to reduce the building energy consumption. However, existing heat exchanger models have limitations in simulating the performance of air-to-air PFHEs. For example, some models adopt heat transfer correlations which are not suitable for PFHEs, while others require detailed geometric data which are usually difficult to access, etc. To address these limitations, we developed a new model for air-to-air PFHE without dehumidification. Based on empirical correlations dedicated to air-to-air PFHEs, the mathematical models of the heat transfer and the flow resistance were built. The new model considers the impacts of the changing air flow rates and temperatures. Additionally, it only requires readily available nominal parameters as inputs and does not need any geometric data. Furthermore, no numerical discretization is needed to solve the equations, which makes the model computationally more efficient than models using the finite-element method. To evaluate the performance of the new model, it is implemented using an object-oriented, equation-based modeling language Modelica. Case studies show that the new model can predict the results with a relative deviation less than 10% compared to the experimental data.

1. Introduction

The building sector is under pressure to improve its overall energy efficiency due to its colossal energy demand [1]. Advanced energy-efficient Techniques (e.g. heat recovery, grounded source heat pump) draw more attentions [2,3]. In HVAC systems, air-to-air plate-fin heat exchangers (PFHEs) can be used as heat recovery devices to reduce the building energy consumption. The plate-fin heat exchanger (PFHE) is a compact heat exchanger that consists of a stack of alternating plates called parting sheets, and fins brazed together as a block [4,5]. Fig. 1 shows the structure of a typical PFHE. Common PFHE fin types are: plain fin, wavy fin, offset fin and louvered fin etc. [6]. An existing study [7] compares the performance of different plate-fin channels, which can be taken as a reference to the optimal design of the PFHEs. PFHE has some advantages over other kinds of heat exchangers. For example, it has close temperature approaches, high thermal effectiveness, a large heat transfer area per unit volume (typical 1000 m^2/m^3), a low weight per unit transfer, and the capability of heat exchange between many process streams [4]. For these reasons, air-to-air PFHEs have been used in building HVAC systems as high-efficient energy recovery devices. A study [8] shows that using air-to-air PFHEs in the HVAC system for heat recovery can lead to great energy saving, as the load of the fresh air handling unit is reduced by 45–70%. Besides, since the fresh air and exhaust air do not have contact with each other, there is no cross contamination between them, which will benefit the indoor air quality.

A review of existing air-to-air heat exchanger models from the

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https://doi.org/10.1016/j.applthermaleng.2018.07.064
Received 23 December 2017; Received in revised form 23 June 2018; Accepted 12 July 2018

Nomenclature

A	total heat transfer area, m^2
A_f	fin area, m^2
A_{min}	minimum flow area, m^2
c_p	specific heat capacity under constant pressure, J/(kg K)
$\dot{C}$	capacity rate, J/(K s)
C	constant
c	constant
D_h	hydraulic diameter, m
D_P	pressure drop, Pa
e	relative error
f	friction factor, dimensionless
h	convective heat transfer coefficient, W/(m^2 K)
j	heat transfer factor, dimensionless
K	constant or the unit of temperature
k	constant
L	characteristic length, m
L_P	louver pitch, m
$\dot{m}$	mass flow rate, kg/s
m	exponent of Reynolds number in the correlation of heat transfer factor
n	exponent of Reynolds number in the correlation of Nusselt number
N	exponent of Reynolds number in the correlation of the friction factor
NTU	number of heat transfer units, dimensionless
Nu	Nusselt number, dimensionless
P	total pressure, Pa
Pr	Prandtl number, dimensionless
$\dot{Q}$	heat transfer rate, W
R	ideal gas constant, J/(kg K)
R_C	capacity rate ratio, dimensionless
Re	Reynolds number, dimensionless
r	ratio of convective heat transfer coefficients, dimensionless
T	temperature, K
U	overall heat transfer coefficient, W/(m^2 K)
u	characteristic velocity, m/s
V	air velocity, m/s
x	factor for thermal variation of fluid properties in heat transfer module, dimensionless
x_f	factor for thermal variation of fluid properties in flow resistance module, dimensionless

Greek letters

Δ	Difference
ε	heat transfer effectiveness, dimensionless
ζ	pressure loss coefficient, dimensionless
η	efficiency, dimensionless
ϑ	non-dimensional temperature
λ	thermal conductivity, W/(m K)
μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3
χ	ratio of x under a special condition, dimensionless
φ	imbalance rate of heat transfer rates of both sides

Subscripts

0	nominal condition
1	side 1 of heat exchanger or subscript of constant
2	side 2 of heat exchanger or subscript of constant
c	the abrupt narrowing of the circulation area
e	the abrupt widening of the circulation area
f	fin
i	side number of heat exchanger
in	inlet
max	maximum
min	minimum
out	outlet
t	total

literature and mainstream simulation platforms shows that they have limitations in the modeling of air-to-air PFHEs. Wetter [9] presented a simple simulation model of an air-to-air plate heat exchanger with effectiveness-NTU method. However, Wetter's model is designed for plate heat exchangers and calculates the convective heat transfer coefficient based on an empirical correlation with a fixed exponent of velocity, which makes it not applicable for the PFHEs. Nakonieczny [10] described a numerical model of the air-to-air PFHE under unsteady flow conditions. In this model, geometric parameters of the heat exchanger are needed, which are usually difficult to access. The unsteady-flow equations in this model are discretized with a semi-discrete finite-element method, which can lead to a longer computational time and may cause difficulties in achieving convergence. Rose, Nielsen, Kragh and Svendsen [11] and Nielsen, Rose and Kragh [12] presented a quasi-steady-state model and a dynamic model of a counter-flow air-to-air heat exchanger, respectively. In these two models, the effects of dehumidification and frost formation are taken into account and geometric data are needed in the calculation of the Reynolds number. Similarly, Liu, Rafati Nasr, Ge, Justo Alonso, Mathisen, Fathieh and Simonson [13] developed a theoretical model to predict frosting limits for cross-flow air-to-air heat exchangers, which needs geometric data for the calculation of the heat transfer coefficient.

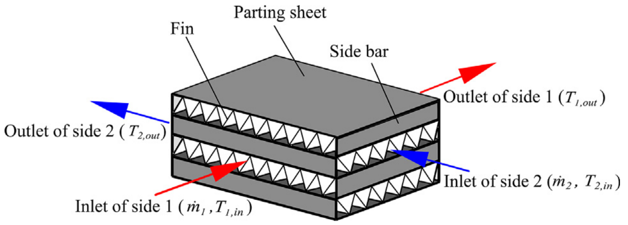

Fig. 1. Diagram of the structure of a PFHE.

As for the mainstream simulation platforms, in Modelica Buildings Library [14], the heat exchanger model *Fluid.HeatExchangers.ConstantEffectiveness* can simulate air-to-air heat transfer, but it uses constant heat effectiveness ε without considering the impacts of changing air flow rates and temperatures. In EnergyPlus [15], there are three air-to-air heat exchanger simulation models. The model *Air-To-Air Sensible and Latent Effectiveness Heat Exchanger* models a full heat exchanger, which is different from PFHE in structure and material. The *Air-To-Air Flat Plate Heat Exchanger* model adopts Wetter's model [9] mentioned above. The *Balanced Flow Desiccant Heat Exchanger* model is dedicated for desiccant heat exchangers, which is also different from PFHE. In the Standard Component Library of TRNSYS 17 [16], *Type 5* and *Type 91* can be used in the modeling of air-to-air heat exchangers. The heat transfer effectiveness ε of *Type 5* is calculated based on a fixed overall heat transfer coefficientUA. *Type 91* uses a constant effectiveness. In the Standard Component Library of TRNSYS 18 [17], no new air-to-air heat exchanger model is developed. In TESS Library 17 [18], *Types 512*, *650*, *652*, *657*, *667*, *699*, *760*, and *761* can be used to model air-to-air heat exchangers, but all of them use constant heat transfer effectiveness. However, almost all the above-mentioned models do not involve the calculation of flow resistance, except for the model in Modelica Buildings Library. Since the flow resistance directly affects the