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Research Paper

Fast and efficient prediction of finned-tube heat exchanger performance using wet-dry transformation method with nominal data

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HIGHLIGHTS

- A fast and efficient water-to-air finned-tube heat exchanger model is proposed.
- The model uses wet-dry transformation method under wet-cooling conditions.
- It is capable of predicting heat transfer performance with only nominal data.
- It does not need geometric data or full performance data of the heat exchanger.
- It is evaluated by comparing with experimental data and an existing model.

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ABSTRACT

Water-to-air finned-tube heat exchanger (FTHE) is a common component in air-conditioning systems. Mathematical models of water-to-air FTHE under the wet-cooling condition are necessary in evaluating the performance of air-conditioning system with water-to-air FTHEs during the system design phase. However, existing water-to-air FTHE models are computationally expensive and require detailed geometric data, which hinder the model applications during the system design phase. To address the above limitations, the current paper proposes a new water-to-air FTHE model which is computationally efficient, relatively accurate and only requires nominal data as inputs. The new water-to-air FTHE model is derived using wet-dry transformation method and the heat transfer process is calculated using the nominal data. Then the model is implemented in Modelica, which is an equation-based, object-oriented modeling language. In addition, experimental measurements of a water-to-air FTHE are conducted. The new model is then evaluated by experimental data and an existing model. The results show that the relative deviations of outlet temperatures and heat transfer rate between the modeled and experimental data are within 7% and 11%, respectively, which is much better than the existing model (19% and 13%). In addition, the new model is 1047 times faster than the existing model.

1. Introduction

As a common component in air handling units, water-to-air finned-tube heat exchangers (FTHEs) are widely used for various air-conditioning systems to control air temperature and humidity [1]. The water-to-air FTHE consists of a set of parallel round tubes which are distributed uniformly in a block with parallel fins. Water flows inside the tubes and indirectly interacts with the air passing over the tubes. Air dehumidification occurs if the surface temperature of the heat exchanger is lower than the air dew point temperature. As a result, there are simultaneous heat and mass transfers on the external surface of tubes and fins [2]. This condition is called “wet-cooling process” [3–5]. A model of water-to-air FTHE with wet-cooling condition is usually necessary to evaluate performances and conduct optimizations. In order to achieve wide engineering applications, it is of great importance to develop an accurate and computationally efficient water-to-air FTHE model [6]. In addition, the model utilized in design phase should be independent of operational data, only with input data which are available during the design phase [7].

The existing water-to-air FTHE models under the wet-cooling

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Nomenclature

A	heat transfer area, m^2
B	local atmospheric pressure, Pa
b	coefficient from the boundary layer analysis
c_p	specific heat capacity under constant pressure, J/(kgK)
$\dot{C}$	heat capacity rate, J/(Ks)
c	constant
d	humidity ratio, kg/kg_{da} or differential symbol
H	specific enthalpy, J/kg_{da}
h	sensible convective heat transfer coefficient, $W/(m^2K)$
h_m	convective mass transfer coefficient, $kg/(m^2s)$
Le_f	Lewis factor, dimensionless
Le	Lewis number
$\dot{m}$	mass flow rate, kg/s
N	number of pipe segments in WCCF model
n	exponent of heat transfer correlation
NTU	number of heat transfer units, dimensionless
Nu	Nusselt number, dimensionless
$\dot{Q}$	(total) heat transfer rate, W
Re	Reynolds number, dimensionless
RH	relative humidity, dimensionless
r	ratio of convective heat transfer coefficients, dimensionless
T	temperature, K
X	water vapor mass fraction, dimensionless
U	overall heat transfer coefficient, $W/(m^2K)$

Greek letters

ε	heat transfer effectiveness, dimensionless
ζ	contact factor, dimensionless
η	fin efficiency, dimensionless
χ	factor for thermal variation of fluid properties

Subscripts

0	nominal condition
3	saturation state point of tube surface
a	air side of heat exchanger
in	inlet
max	maximum
min	minimum
out	outlet
s	sensible heat or saturation state
t	overall
v	condensed water vapor
w	water side of heat exchanger
i	mark number of the microelements

condition can be classified into three catagories [8,9]: Numerical models [10–18], Analytical models [5,19–22] and lumped models [23–35]. The numerical models discretize the space of cooling coil into numerous elements and the results of each element are obtained by using iterative algorithms [10–14]. These models can be used to systematically and comprehensively analyze the heat transfer process and provide accurate and informative results for optimal design of the heat exchanger. However, those models are computationally expensive [5,8,26,36]. In some cases, numerical models have problems related to convergence, stiffness and stability [21,33]. Moreover, most of models require details of geometric data (e.g. length and diameter of tubes, thickness of the fins), which are difficult to obtain during the design phase.

The analytical models solve differential equations for the heat and mass transfer process in FTHE using advanced algorithms, such as Fourier transformations [37], Laplace transformations [19,20,22], matrix operations [38], and integral methods with simplification [5,21]. Although analytical models have high computational efficiency, some transform methods (e.g. Laplace transformations) need to inverse the solution from the s-domain to the time domain, but the inversation may fail in some cases[21,33]. In addition, the analytical models still require the details of geometric data, which hinders its engineering appliations.

The lumped models utilize the enthalpy difference between air and coolant to simulate the heat and mass transfer process [23–35]. The lumped models are relatively accurate and computationally efficient [5,8,26]. However, the existing lumped models still require geometric data, specific heat transfer coefficients, and some operational data, which are difficult to obtain during the design phase.

To improve the existing models for the water-to-air FTHE with wet-cooling conditions, current research proposes a new model with two innovations: (1) It adopts a wet-dry transformation method (WDTM) [27] so that a classic effectiveness-NTU method [25] can be applied in these equivalent dry-cooling processes of the wet-cooling conditions. As a result, the new model is faster than the numerical models and simpler than the analytical models; (2) The new model calculates the heat transfer using nominal data available in the design phase and does not require geometric data, specific heat transfer coefficients, and operational data. These characteristics of the new model will facilitate the optimal design of the air-conditioning system in the design phase.

In the current paper, Section 2 illustrates derivation of the new proposed water-to-air FTHE model and determinations of model parameters. Section 3 shows the implementation in Modelica. Then, experimental measurement is shown in Section 4. Finally, the new model is evaluated by experimental data and an existing model in Section 5.

2. Mathematical description

The newly proposed water-to-air FTHE model is based on the wet-dry transformation method [27], utilizing a hypothetical equivalent dry-cooling condition to reflect the water-to-air FTHEs performance in the presence of wet-cooling condition. Then the classic effectiveness-NTU method [25] is applied in this equivalent dry-cooling process to calculate heat tranfer under wet-cooling condition. To simplify the model, several assumptions are adopted as follows: (1) The fouling and thermal resistances of different materials are neglected; (2) There is no water leakage or heat loss; (3) The air pressure is 1 bar; (4) The specific heat capacity and the overall fin efficiency are constant values; (5) The model is applied in steady state. The following description of the new FTHE model summaries the main steps of mathematical derivation and the relevant detailes are provided in Appendix A.

2.1. Equivalent dry-cooling condition

Compared with a wet-cooling condition, the equivalent dry-cooling condition has the same mass flow rate (air/water), contact factor, inlet and outlet air enthalpies or water temperature [27]. The contact factor ζ reflects the close extent of the final air state to its saturation state. According to the above definitions, the heat transfer rates of the wet-cooling condition and its equivalent dry-cooling condition are identical.

Fig. 1 shows the wet-cooling process and its equivalent dry-cooling process on the air side [27]. Line “1-2” represents a wet-cooling process with moist air flowing through a FTHE. Line “1′-2′′” is the equivalent dry-cooling condition of process “1-2”. Line “1-2′′” and “2-2′′” are two constant enthalpy lines. Point 1 and point 2 represent the inlet and outlet states in the wet-cooling process respectively. Similarly, point 1′