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Research paper

Condensing droplet behaviors on fin surface under dehumidifying condition Part I: Numerical model

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HIGHLIGHTS

- Numerical model of condensing droplet behaviors was developed.
- Model of mass transfer for droplet formation was developed.
- Model of mass transfer for droplet growth was developed.
- Effects of operation conditions and fin geometry were analyzed.

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ABSTRACT

The condensing droplet behaviors on the fin surface have a significant influence on the performance of fin-tube heat exchangers under dehumidifying conditions. A numerical model for predicting the condensing droplet behaviors was developed. In the model, the mass transfer rates during droplet formation and growth processes and the contact angles of the droplets were introduced into the control equations as source terms; the mass transfer rates were predicted based on the species conservation on the fin and droplet surfaces; the contact angles controlling the droplet movement were predicted based on the modification of existing model by reflecting the effect of air flow force on the droplet movement. Based on the proposed model, the effects of operation conditions and fin geometry on heat and mass transfer characteristics were analyzed. The experimental validation of the proposed model will be performed in the Part II of the present study.

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1. Introduction

Fin-tube heat exchangers are widely used in a variety of applications in the air-conditioning, refrigeration and process industries [1–3]. The dominant thermal resistance for fin and tube heat exchangers is generally on the air side [4–6], and the key point for improving the performance of the fin-tube heat exchanger is to enhance the air side performance [7]. Under the real operation conditions of the room air conditioner, the fluid on the air side of fin-tube heat exchanger is moist air, and water vapor in the moist air condenses onto the fin surface when the fin surface temperature is lower than the dew point temperature [8–10]. The condensates form small water droplets on fin surface, and the small water droplets grow up to greater ones and move down under the coupling effect of gravity, surface tension and air flow [9,11]. During the condensing process, the droplet formation, growth and movement on the fin surface may influence each other, resulting in the complicated influence of droplets on the heat and mass transfer characteristics of moist air [11,12]. In order to quantitatively know the influence of the retained droplets and further to improve the air side performance of fin-and-tube heat exchanger, a model for simulating the condensing droplet behaviors on the fin surface is needed, including the droplet formation, growth and movement.

The existing research on the droplet formation and growth mainly focuses on the macroscopic heat and mass transfer

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Nomenclature

D	binary mixture diffusivity, m^2/s
F	force, N
g	gravity acceleration, 9.81 m/s^2
h_{fg}	specific latent heat of water, kJ/kg
m	mass transfer rate, kg/m^2 s
n	unit vector
S	surface area, m^2
t	time, s
u	velocity, m/s
V	volume, m^3
$w_{m,v}$	mass fraction of water vapor in the moist air
Greek	
α	volume fraction
θ	contact angle, radian
κ_w	surface curvature
μ	dynamic viscosity, Ns/m^2
ρ	density, kg/m^3
σ	surface tension, N/m
φ	azimuthal angle, radian
χ	deviation angle, radian
Subscript	
a	air
f	fin
g	gravitation
m	moist air
max	maximum value
min	minimum value
v	water vapor
w	liquid water
x, y, z	coordinate axis
σ	surface tension

characteristics of moist air in fin-tube heat exchanger under the dehumidifying conditions, including the experimental investigation and numerical model. For the existing research on experiments, the heat and mass transfer characteristics of the fin-tube heat exchanger with the four types of fins were measured, covering the plain fin [8,13,14], the wavy fin [7,15–17], the slit fin [6,18] and the louver fin [5,19,20], and the prediction correlations were also developed based on the experimental data. For the existing research on numerical model, the finite-element method was adopted for simulating the heat and mass transfer characteristics of moist air in the heat exchanger by assuming no droplet on the fin surface [21,22]. However, no study has been reported concerning the numerical model for simulating the droplet formation and growth processes.

The existing research on the droplet movement covers the experimental test and numerical model of droplet. The movement of droplet with fixed mass was governed by the contact angles along the triple contact line [23–26]. The contact angles of droplets on the incline were obtained experimentally, and the profile of droplet at arbitrary azimuthal angel was approximated by two circles method [27]; the contact angles of droplets under the coupling effect of gravity and surface tension were correlated as the function of the azimuthal angle, the receding angle and the advancing angle [28,29]. Based on the correlation of ElSherbini and Jacobi [28], a numerical model for liquid droplet motion on the incline was established by employing the Volume of Fluid-Continuous Surface Force (VOF-CSF) method [30]. The coupling effect of gravity and surface tension was reflected in the above research [27–30]. In the operation conditions of room air conditioners, the condensation process is under the coupling effect of gravity, surface tension and air flow in the fin-tube heat exchanger [31], and a modified model reflecting the effect of air flow force was proposed by Zhuang et al. [31]. However, the droplet movement characteristics are affected by the heat and mass transfer during the condensation process, which was not reflected in the model of Zhuang et al. [31].

The purpose of the present study is to propose a numerical model for simulating the simultaneous droplet behaviors (formation, growth and movement). Moreover, a specific experimental rig for validating the model of droplet behaviors should be developed, and the model validation should be performed. Part I of the present study focuses on the model development, and Part II focuses on the model validations.

2. Numerical model

2.1. Modeling object and technical road map

The schematic diagram of droplet behaviors on fin surface of fin-tube heat exchanger is shown in Fig. 1(a) and (b). When the condensation occurs, firstly small water droplets form on the fin surface (as shown in Fig. 1(c)); then the droplets may grow due to the mass transfer between moist air and condensing droplets (as shown in Fig. 1(d)); finally the droplets move on the vertical fin surface (as shown in Fig. 1(e)). Therefore, the droplet behaviors during condensation process consist of droplet formation, growth and movement in sequence.

The droplet formation and growth are the processes of mass transfer from the water vapor of the moist air onto the fin surface, in which water molecule concentration difference is the driving force of mass transfer, as shown in Fig. 2. At the beginning, the water molecules transfer from the moist air onto the fin surface, forming small water droplet. Adjacent to the small water droplet, the water vapor is saturated, while the water vapor in the main fluid is oversaturated; the water molecule concentration difference causes the water molecule transferring from main fluid to small water droplet, leading to the growth of droplet. Therefore, the key for simulating the droplet formation and growth is the mass transfer models of water during these processes.

The droplet movement characteristics are governed by the coupling effect of gravity, air flow and surface tension [11], as shown in Fig. 2. The gravity and air flow force are the driving force of droplet movement, while surface tension resists the movement. For simulating the droplet movement process, the gravity, air flow force and surface tension should be known. The gravity and air flow force are the functions of droplet mass, which is obtained from the mass transfer models of droplet formation and growth. The surface tension is governed by the contact angles along the triple phases contact line. Therefore, the key for simulating the droplet movement is the model of contact angles.

Moreover, the droplet behaviors are derived from the heat and mass transfer between the moist air and fin. For simulating the droplet behaviors, the continuity, momentum and energy equations for the moist air and water droplets need to be developed together with the models of mass transfer and contact angles.

The technical road map for model development is demonstrated in Fig. 3. In the continuity conservation equation, the mass source

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