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A general three-dimensional simulation approach for micro-channel heat exchanger based on graph theory

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HIGHLIGHTS

- A three-dimensional simulation approach for MCHX is developed.
- A fast method to calculate three dimensional heat conduction via fins is developed.
- A theory-based model is developed to predict quality distribution among MC tubes.
- A graph theory-based method is developed to describe complex refrigerant circuit.

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ABSTRACT

For meeting the requirements of quickly designing high performance micro-channel heat exchanger, a general three-dimensional simulation approach considering the factors of heat conductions via fins, quality distribution among micro-channel tubes and flexible flow circuit arrangements is proposed in this paper. In the simulation approach, an approximate analytical solution for describing the three-dimensional heat conductions via fins is presented, having higher computation speed over the numerical method of directly calculating heat conductions; a theory-based refrigerant distribution model for predicting the quality distribution among micro-channel tubes is established instead of using homogeneous quality distribution, resulting in the improvement of evaporator model accuracy; and a graph-theory based computation algorithm is developed to calculate any possible flow circuit conveniently and quickly. The presented model is validated by experiments, and the deviations of the predicted heat capacity of micro-channel evaporator, condenser and gas cooler from the measured ones are within ±5%.

1. Introduction

Micro-channel heat exchangers show great advantages over traditional fin-and-tube heat exchangers in compactness, effectiveness, lower refrigerant charge and higher mechanical strength, etc. Due to these advantages, micro-channel heat exchangers are increasingly used in automobile and residential air conditioning systems [1–4] recently, and correspondingly the tasks of designing micro-channel heat exchangers have increased. In order to quickly design a micro-channel heat exchanger with good performance, an effective design method is needed.

Simulation based design methods are widely used in heat exchanger design and optimization due to the advantages of high effectiveness and less resource requirements. Distributed-parameter models have been applied as the basis of simulation based design method for heat exchangers [5]. An effective distributed-parameter model should be of high accuracy, good versatility and fast computation speed, as those for fin-and-tube heat exchanger developed by Domanski [6], Liu et al. [7] and Jiang et al. [8], and such a kind of distributed-parameter model is also needed for micro-channel heat exchanger.

Micro-channel heat exchangers have some distinguishing features differing from the traditional fin-and-tube heat exchangers, such as flat tube with mini ports, parallel flow and headers. Due to these features, the impact factors including (i) refrigerant types, (ii) working condition, (iii) air-mal distribution, (iv) mass flow rate distribution, (v) heat conductions via fins, (vi) quality distribution among micro-channel tubes and (vii) flow circuit arrangement have great impacts on the heat exchanger performances [9–13]. Thus, the distributed-parameter model for micro-channel heat exchanger is required to have enough flexibility and accuracy to reflect the impacts of these factors while the computation speed is still fast enough. Among these factors, the first four factors have been well addressed by the existing researches (see Table 1), and

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Nomenclature

a	acceleration (m/s^2)
A	area (m^2)
C_1, C_2, C_3	coefficient in Eq. (3)
D	diameter (m)
D_h	hydraulic diameter (m)
F	force (N)
f	friction factor
G	mass flux (kg m^{-2} s^{-1})
h	specific enthalpy (kJ kg^{-1})
H	variable in Table 2
k	thermal conductivity (W m^{-1} K^{-1})
k_{lg}	correction factor in Eq. (19)
m	mass flow rate (kg s^{-1})
n	number of tubes
N	iteration number
P	pressure (Pa)
Q	heat capacity (W)
q'	heat flux (W/m^2)
r	radius (m)
R	thermal resistance (K W^{-1})
S	perimeter (m)
T	temperature (°C)
t	time (s)
X	quality
V	velocity (m/s)

Greek symbols

α	heat transfer coefficient (W m^{-2} K^{-1})
$\varDelta$	fin thickness (m)
θ	substitute of $T - T_{air}$ (°C)
ρ	density (kg m^{-3})
τ	time consumption (s) or shear stress (N/m^2)
Δp	pressure drop (kPa)
Δt	time interval (s)
Δz	length in z direction (m)

Subscripts

0	initial
air	air
acc	acceleration
adj	adjacent port or control volume
ave	average
conv	convection
energy	energy equation
f	frictional
fin	fin
g	gas
h	header
i	inlet
l	liquid
mom	momentum equation
o	outlet
port	port of micro-channel tube
r	refrigerant or redial direction
s	tangential direction
t	micro-channel tube
total	total

the rest ones including the heat conductions via fins, the quality distribution among micro-channel tubes and the flow circuit arrangement need to be reflected by the models in further investigation.

The heat conductions via fins and quality distribution among micro-channel tubes significantly affect the heat exchange capacity, and the flexible flow circuit arrangement obviously improves the flow circuits design efficiency. The heat conductions among tubes via the connecting fins are three dimensional, varying from fin to fin and conducting in two dimensions in a fin, and they obviously degrade the heat capacity because of the large temperature difference between the tubes, especially for the gas cooler [4,14]. Neglecting the heat conductions via the fins (e.g. Adiabatic-fin-tip) will result in more than 100% error in predicting heat capacity per tube [13]. The quality distribution among micro-channel tube is non-uniform [11,15], and will make around 20% micro-channel tubes dry out even at the tube inlet section, and consequently the heat capacity and system COP are reduced as much as 17% and 58%, respectively [16,17]. The flow circuits significantly affect the heat capacity and pressure drop of heat exchanger simultaneously [12], and the flexibility for calculating any complex circuits obviously improve the flow circuit design efficiency in order to find a good compromise between the heat capacity and pressure drop [7]. As a result, the methods to calculate heat conductions via the fins, quality distribution among micro-channel tube and any complex flow circuits need to be proposed.

The challenge of developing a method to calculate the heat conductions via the fins is resulted from the great number of fins and non-uniform air temperature distribution on a fin surface. More than ten thousand fins exist in a real micro-channel heat exchanger, and tens of iterations are needed in whole heat exchanger simulation because the heat conductions via fins are coupled with the heat transfer of refrigerant side and air side. Thus, the computation for a fin requires being finished in a short time. The analytical solution has the ability to calculate 2-D heat conductions of a fin in high accuracy and fast speed, but it is difficult to find an analytical solution due to the non-uniform air temperature distribution on the fin surface, while the numerical solution can't be applied due to the time consuming iteration process [13,18]. Therefore, a method which has enough accuracy and the ability to avoid the time consuming iterations is needed.

The challenge of developing a method to calculate quality distribution among micro-channel tubes is resulted from the complicated two-phase flow in the header. The quality distribution considered in this paper is mainly focused on evaporator but not to condenser since the supplied refrigerant for evaporator is usually in two-phase state. The quality distribution among micro-channel tube in micro-channel evaporator is affected by the factors including the header geometry, header orientation refrigerant flow regimes inside headers, mass flow rate of header inlet, mass flow rate of each tube and refrigerant type [15,19]. Since an empirical correlation is limited on the specific factors such as geometry and refrigerant type [20], a theory-based quality distribution model which has the ability to reflect all these factors is needed. So far, to the best of the authors' knowledge, such kind of theory-based model is not available in open literature. The difficulty is resulted from describing the complicated two-phase flow separation in a header–tube junction.

The challenge of developing a method to describe any possible flow circuits is resulted from the special structure of headers. A minor revision on baffle distribution inside header may generate a completely new flow circuit, and reverse the flow direction inside header. The flow direction reversal inside a header will lead to the complete change of the mass flow rate and quality distributions among micro-channel tube. As a result, the headers must be