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Development of a numerical analysis model using a flow network for a plate heat exchanger with consideration of the flow distribution

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ABSTRACT

A numerical analysis model using a flow network approach is developed to evaluate the performance of a plate heat exchanger (PHE). In order to consider complex flows in PHEs in the model, the flow paths in the channels are represented by a flow network consisting of nodes and branches. This model is able to evaluate the node-average local properties of the working fluids of each channel in a PHE. Several empirical correlations for the pressure drop and the heat transfer are evaluated against various experimental data to implement the selected correlations into the numerical analysis model according to the flow conditions and geometry of the heat transfer plates used. The pressure drop and heat transfer capacity of a PHE were experimentally measured with a range of operating parameters and the measured values were then compared with the prediction by the numerical analysis model. The predictions of the heat transfer capacity are in good agreement with the experimental data within a discrepancy of 10%, whereas the prediction of the pressure drop significantly deviated from the experimental data. The analysis also demonstrates that the total heat transfer rate varies little whereas the pressure drop increases sharply as the maldistribution of the flow is intensified.

1. Introduction

In the 1920s, Dr. Richard Seligman developed a gasketed plate heat exchanger (PHE) for use in the dairy and paper industries. The gasketed PHE is easy to disassemble and change with regard to the number of channels. However, the available fluid and temperature ranges are limited by the material of the gasket and the allowable pressure is low. In the 1990s, a brazed PHE was developed (Fig. 1). The brazed PHE can be used under much higher pressure conditions than the gasketed PHE, but the brazed PHE cannot be disassembled, and it is not possible to change the number of channels after production. The PHE has better thermal performance than other heat exchangers of the same volume. The sinusoidal pattern of the heat transfer plates in a PHE increases the heat transfer area and rigidity of the plates in the PHE. This allows the operating pressures of the PHE to exceed 10 MPa. A unique feature of the PHE, i.e., the chevron or herringbone pattern of the heat transfer plates, makes the PHEs more robust and converts the flow into a turbulent flow at low Reynolds number, increasing the heat transfer performance. At present, PHEs are widely used in areas such as the refrigeration and air conditioning, chemical, food, shipbuilding, power plant, architecture, automobile, and medical industries. Studies of PHEs are increasing as their applications witness a tremendous upsurge.

Considering the fact that various correlations for tubular and micro-channel heat exchangers are well developed [1,2], to the best of the authors' knowledge, reliable functional formulae correlating the pressure drop and heat transfer and PHEs over a wide range of parameters are rare at the present time. Specifically, in-depth research on the phase-change heat transfer in PHEs is scant [3]. In general, a brazed PHE is constructed such that multiple heat transfer plates are stacked and hot fluid and cold fluid alternately flow through the channels constructed between two adjacent heat transfer plates. A working fluid is supplied to each channel through a manifold on the end of the plates and returns through a manifold on the other end of the plates. Many previous researchers investigated the performance capabilities of PHEs by experimental and numerical methods considering the flow conditions and geometry of the heat transfer plate. They presented results based on the average mass flux considering the total cross-sectional area of the channels in a PHE. However, the mass flow rate through each channel should vary from the first channel (connected to the entrance of a manifold) to the last channel (connected to the dead end of a manifold) because the pressure drop of each flow path from the entrance of the inlet manifold to the exit of the outlet manifold should be identical. Nevertheless, few studies have suggested a relationship between the flow distribution over multiple

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Nomenclature

A	area
A_c	cross-sectional area of the unit cell
A_s	heat transfer area of the unit cell
b	corrugation depth
br	branch number
Bo	boiling number
ch	channel number from the entrance plate
C	heat capacity
Co	convection number
c_p	specific heat at constant pressure
D_h	hydraulic diameter of the unit cell
en	enlargement factor
F	force
Fr	Froude number
f	frictional factor
G	mass flux
g	gravitational acceleration
h	convection heat transfer coefficient
i	enthalpy
i_{fg}	latent heat
J	matrix
j	the number of closed loops
k	thermal conductivity
L	length of the plate heat exchanger
MAE	mean absolute error
$\dot{m}$	mass flow rate
m^2	distribution parameter
n	node number
N_{branch}	number of branches
$N_{channel}$	number of channels
N_{node}	number of nodes
Nu	Nusselt number $\left(=\frac{hD_h}{k}\right)$
P	pressure
Pr	Prandtl number
p	pitch of unit cell
Q	flow rate
q	heat transfer rate
q''	heat flux
Re	Reynolds number
S	matrix
T	temperature
t	thickness of the heat transfer plate
U	total heat transfer coefficient
u	velocity
u^*	velocity in the exhaust port
V	volume
v	specific volume
W	width of the plate heat exchanger
x	quality
Y	matrix

Greek symbols

β	chevron angle
ΔP	pressure drop
ε	effectiveness
ρ	density
μ	viscosity

Subscripts

cr	critical
eq	equivalent
g	gas phase
exp	experiment
l	liquid phase or laminar
m	average
r	refrigerant
v	vapor
$wall$	wall

channels and performance capabilities, most likely because it is challenging to measure the flow rate through an individual channel and the pressure distribution across a channel in a PHE.

Eldeeb et al. [4] investigated various pressure drop and heat transfer correlations for condensation and evaporation. They observed a lack of research on flow distributions in manifolds and emphasized the need for further research. Bassiouny and Martin [5,6] developed theoretical model for predicting flow distributions and pressure drops in PHEs with respect to flow maldistributions. They derived a distribution parameter (m^2) for a manifold of a PHE based on mass and momentum conservation equations, as follows:

$$m^2 = \left[\left(\frac{2-(u_c^*/u^*)}{2-(u_c/u)}\right)\left(\frac{A}{A^*}\right)^2 - 1\right]\frac{2-(u_c/u)}{f_c}\left(\frac{nA_c}{A}\right)^2 \tag{1}$$

Here, u, u_c, u^*, and u_c^* are the velocities of the port entrance, channel entrance, port exit and channel exit, respectively. The flow maldistribution is calculated from this distribution parameter. If the absolute value of m^2 is less than 0.1, it is assumed to be zero and the

Fig. 1. Brazed plate heat exchanger.