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Research Paper

A mathematical model for flow maldistribution study in a parallel plate-fin heat exchanger

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HIGHLIGHTS

- A mathematical model to evaluate the flow maldistribution effect is proposed.
- A conventional, punched baffle and quasi-*S* header configurations are studied.
- A good synergy of flow rates for cold and hot fluids can enhance heat transfer.
- The thermal-hydraulic performance of a quasi-*S* header configuration is the best.

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ABSTRACT

In this paper, a mathematical model is developed to quantitatively evaluate the effect of flow maldistribution in a multi-channel heat exchanger. A computational fluid dynamics (CFD) technology is used to obtain the fluid distribution in the core of heat exchanger, taking into account the effects of gross passages, headers and distributors, etc. Based on the CFD simulation profile, a heat exchanger model is then developed. A parallel plate-fin heat exchanger with N flow passages is divided into N sub-exchangers when only one fluid is in maldistribution mode or 2N-1 sub-exchangers when both fluids are in nonuniformity modes to guarantee the uniform flow patterns in each sub-exchanger. Based on ε-NTU theory, the effectiveness of the heat exchanger is calculated by modeling the heat exchanger as a parallel coupling of the sub-exchangers. The core pressure drop of the whole heat exchanger is taken as the average pressure drop of the sub-exchangers. The mathematical model combining with the achieved flow distribution was utilized to investigate the performance of the heat exchanger with conventional header configurations, a punched baffle header configuration and a quasi-*S* header configuration, respectively. Results indicated that a good synergy of flow rates for both cold and hot fluids in the adjacent sub-exchangers can effectively reduce effectiveness deterioration. The performance of the heat exchanger is improved by using the improved header configurations. And the performance with a quasi-*S* header configuration is the best. The proposed mathematical model provides a theoretical basis for multi-channel heat exchangers in solving the problem of flow maldistribution.

1. Introduction

A basic assumption of heat exchanger design theory, such as the effectiveness-NTU method, temperature effectiveness-NTU method and log-mean temperature difference method, is that fluid is distributed uniformly in the core of the heat exchanger [1]. However, due to geometry design features or operating conditions, flow maldistribution is more common that can significantly reduce the desired heat exchanger performance. Performance deterioration in plate-fin heat exchanger (PFHE), a commonly used heat exchanger in the industries, due to flow maldistribution practically undergo because it can intensify the longitudinal wall heat conduction and the maldistribution of the interior temperature, which are the three main reasons that cause the deterioration of heat exchanger efficiency [2]. Therefore, a design theory of PFHEs that can evaluate quantitatively the effect of flow maldistribution is highly desirable since it is advantageous to design the margin of the heat transfer areas and help to select better fluid pumping device.

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Nomenclature

A	heat transfer area, m^2
c_p	specific heat at constant pressure, kJ·kg^{-1}·K^{-1}
C	heat capacity rate
D	diameter, m
f	friction factor
h	fin height, mm
H	dimension of length, mm
j	serial number of outlet passages or Colburn factor
K	heat transfer coefficient, W·m^{-2}·K^{-1}
l	fin length, mm
L	length, mm
m	mass flow rate, kg·s^{-1}
M	dimensionless parameter
N	number of channels
NTU	number of transfer units
Δp	pressure drop, Pa
Pr	Prandtl number
R	radius of the header, m
Re	Reynolds number
s	fin spacing, mm
S_v	flow maldistribution parameter
t	fin thickness, mm
$\bar{T}$	average temperature, K
T	temperature, K
u	velocity, m·s^{-1}
U	total heat transfer coeffient, W·m^{-2}·K^{-1}

Greek symbols

ε	effectiveness
δ	thickness of partition wall
λ	thermal conductivity, W·m^{-1}·K^{-1}
ρ	density of the fluid, kg/m^3
ζ	local resistance coefficient
η_f	fin efficiency
η_o	overall efficiency

Subscripts

ave	average
B	width
c	cold side
f	the secondary
h	hot side
i	inlet
L	length
max	maximum
min	minimum
non	non-uniform
o	outlet
p	primary surface
uni	uniform
w	wall

The effects of non-uniform flow on the heat exchanger performance deterioration have been well investigated over the past few decades. Ranganayakulu et al. [3] studied the effect of two-dimensional nonuniform inlet fluid flow distribution on thermal-hydraulic performance in cross-flow PFHEs using a finite element model. The results showed that the performance deteriorations and variation in pressure drops are quite significant in some typical applications due to fluid flow nonuniformity. Mueller [4] investigated different types of flow distribution pattern in plate heat exchangers and discussed the reason leading to maldistribution. His study revealed that flow distribution has little effect on the effectiveness in turbulent flows and high Reynolds numbers, while the flow distribution pattern is important under laminar flows and low Reynolds numbers. Shah [5] investigated the effect of flow maldistribution on heat transfer and it was found that flow maldistribution is generated by velocity profile in inlet ducts. Tereda et al. [6] measured the pressure inside the inlet and ourlet ports at different locations to analyze the flow and pressure distribution in a plate heat exchanger. The measurements indicated the existence of non-uniform flow distribution that increases with flow rate and decreases with port diameters. Camilleri et al. [7] found that the tube to header area ratio is an important parameter for controlling maldistribution in compact multi-channel parallel flow heat exchangers. As the area ratio increases, flow maldistribution becomes more remarkable and more sensitive to increased Reynolds number and decreased parallel pipe length. Lalot et al. [8] experimentally investigated the effect of flow nonuniformity on the performance of heat exchangers and found that the flow maldistribution leads to a loss of effectiveness of about 25% for cross-flow heat exchangers. Blecich [9] experimentally studied the effect of airflow nonuniformity on the thermal–hydraulic performance of a fin-and-tube heat exchanger. An effectiveness thermal deterioration of up to 30% and a pressure drop increase up to 90% were measured for extremely nonuniform airflow profiles. Yang et al. [10] proposed a perforated-wing-panel header configuration to be installed in the plate-fin heat exchanger. The results showed that the effectiveness degradation rate decreases by 91.9–93.0% and the pumping power penalty increases by 88.1–90.0% when the conventional header was replaced by the perforated-wing-panels header. Besides, Wang et al. [11] and Kitto and Robertson [12] found that flow maldistribution is more serious for two-phase flow compared to that for single phase flow. Zhang et al. [13] studied a header with a two stage-distributing structure in two-phase PFHEs. The results showed that the flow non-uniformity degree is reduced to 16.8% under the main test condition. Actually, flow maldistribution can more serious in cryogenic processes. In the case of liquefaction of helium, Atrey [14] calculated that 12% less liquid is obtained if effectiveness is reduced from 97% to 95%, and Barron [15] stated that no liquid is produced if effectiveness is less than 85%. Kanoglu et al. [16] predicted a reduction of 22% in the production of liquid if the heat exchanger effectiveness departs from the ideal value of 100% to a more practical one of 96.5%.

The flow maldistribution of PFHE is closely related to header design and the fabrication of heat exchanger core, while the influence on the thermal-hydraulic performance due to header design is more serious compared with that of the heat exchanger core fabrication. Therefore, finding a way to improve flow uniformity in header of PFHEs so as to reduce the heat exchanger size, design margins or achieve the desired production rate is of vital importance. Said et al. [17] proposed orifice and nozzle approach to reduce the flow maldistribution in the header of PFHE. Zhang et al. [18] put forward a concept of second header installation for the inlet header of PFHE. The results showed that the flow distribution in PFHE is more uniform if the ratios of outlet and inlet equivalent diameters for both headers are equal. Wen et al. [19] presented that punched baffle could improve fluid flow distribution in the header. Similarly, Ismail et al. [20] also found that flow