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Research Paper

Effect of inlet flow maldistribution on the passage arrangement design of multi-stream plate-fin heat exchanger

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HIGHLIGHTS

- Inlet flow maldistribution has deteriorative influence on the thermal performance.
- A thermal model based on integral-mean temperature difference is developed.
- Passage arrangement under inlet flow maldistributions are optimized.
- Heat transfer rate under flow maldistribution is enhanced using proposed method.

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ABSTRACT

Inlet flow maldistribution has deteriorative influence on the thermal performance of multi-stream plate-fin heat exchanger, which affects the design of passage arrangement. In this paper, the optimization design of passage arrangement considering inlet flow maldistribution is investigated. A thermal model based on integral mean temperature difference is developed for evaluating the coupling effects of inlet flow distribution and passage arrangement on the total heat transfer rate of multi-stream plate-fin heat exchanger, the model is validated with ±6.71% root-mean-square errors of heat transfer rate under uniform flow with 20 groups of simulation data of Aspen Plate Fin Exchanger (Single)®. Then three representative one-dimensional inlet mass flow distributions are adopted to characterize the inlet flow maldistribution. Passage arrangement under these flow maldistributions are optimized using hybrid particle swarm algorithm. By carrying out the optimization, the total heat transfer rate increased 2.50% and 4.52% under different inlet flow maldistributions of Flow A; and increased by 2.58–3.98% under different inlet flow maldistributions of Flow A of Flow B simultaneously.

1. Introduction

Heat exchangers are classified to tubular-type, plate-type, extended surface type and regenerative exchangers according to construction types [1]. As an important type of extended surface heat exchanger, multi-stream plate-fin heat exchangers (MPFHE) are characterized by high heat transfer surface area-to-volume ratio, high heat transfer coefficient, high compactness for desired heat-duty and pressure-loss constraints, and then they are applied to a wide variety of engineering applications (automobile, aerospace, cryogenic air separation equipment, electronic cooling device, condenser, etc.).

The flow distribution across the MPFHE is assumed to be uniform and steady in the traditional design method, such as the effectiveness-NTU method and the log-mean temperature difference method [2]. However, there are inlet flow maldistribution and passage-to-passage flow maldistribution under the actual operation conditions. The inlet flow maldistribution is mainly associated with the improper entrance structure (such as poor design of header and distributor configuration) and the operation conditions. The passage-to-passage flow maldistribution is caused by various manufacturing tolerances, frosting of condensable impurities, etc. [3].

To characterize the inlet flow maldistribution, the standard deviation of mass flow rate entering the passages is proposed by Chiou [4]. The larger value of the standard deviation indicates the higher flow non-uniformity in the inlet header. The effects of inlet header geometry and operation conditions on the flow distribution of the passages have been investigated by experimental and numerical methods. Jiao [5] established the correlation equation between the dimensionless standard deviation and inlet mass flow

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Nomenclature

$a_1 - a_6$	function defined in Eq. (7)
A_w	first heat transfer area, m^2
A_f	second heat transfer area, m^2
ASU	air separation unit
$C_1 - C_4$	constants using in Eqs. (5) and (6)
C_p	specific heat at constant pressure, kJ/kg K
C_r	heat capacity rate ratio
f_h	fin height, m
f_t	fin thickness, m
f_f	fin frequency, m^{-1}
gPest	best global position
h_i	heat transfer coefficient, kW/m^2 K
i	*i*th sub-exchanger or *i*th stream
IMTD	integral mean temperature difference
j_i	flow direction of *i*th stream
k	evolutionary generation
k_f	heat conductivity of fins, kW/m K
L	length of heat exchanger, m
$\dot{m}$	mass flow rate, kg/s
MHE	main heat exchanger
MPFHE	multi-stream plate-fin heat exchangers
N	number of streams
pPest	best position each particle
Q_i, Q_i'	heat transfer rate from stream i to stream $(i+1)$, W
$r_1 - r_4$	real roots using in Eqs. (5) and (6)
T	temperature, K
ΔT	temperature difference, K
$(UA)_{i+1,i}$	the overall thermal resistance, W/K
W	width of heat exchanger, K
x	direction along the length of heat exchanger

Greek letters

α	random number in the range [0, 1]
β_1	cognitive parameter
β_2	social parameter
w	inertia weight
ε	thermal effectiveness
γ	fin parameter
η	fin efficient

Subscripts

i	fluid stream *i*
in	inlet
out	outlet
hot	hot streams
k	streams in Eq. (15)
sim	results using proposed method
exp	results using Aspen Plate Fin Exchanger (Single)

rate, inlet angle, distributor configuration parameter through experimental analysis. Habib [6] analyzed the effects of nozzle number, nozzle diameter and second header geometry on the flow maldistribution through numerical solution of the flow field in the inlet and return headers. Wang [7] studied experimentally the two-phase flow distribution of inlet header in a plate-fin heat exchanger, their results indicated the distribution uniformity of liquid-phase deteriorated with the decrease of mass flow rate of gas and liquid flow, while the distribution uniformity of gas-phase deteriorated with mass flow rate of liquid flow, but improved with mass flow rate of gas flow.

In order to reduce the inlet flow maldistribution, certain inlet header configurations were proposed and optimized. Zhang [8] proposed two modified headers with a two-stage-distributing structure to decrease the inlet flow maldistribution, numerical and experimental results showed that the inlet fluid flow distribution was more uniform if the ratios of outlet and inlet equivalent diameters for two-stage inlet structures were kept equal. Then the modified header was applied to two-phase plate-fin heat exchanger, and the flow non-uniformity degree was reduced to 16.8% under the main test condition [9]. Wen [10] constructed three different improved header configurations with punched baffle, and analyzed the fluid flow performances of these headers by CFD simulation and PIV experiment their experimental results showed that the baffle with small staggered distributional holes was the best for the improvement of inlet flow maldistribution. Jung [11] developed the transverse bypass structure to redistribute the fluid flow among the channels, and then reduced the negative effect of inlet flow maldistribution on the thermal performance of heat exchanger. Chu [12] analyzed the fluid maldistribution of four different inlet headers (inclined baffle, segmental baffle, helical baffle and improved helical baffle), and found that the inlet header with equidifferent helical baffles was the best by comparing the flow non-uniformity, the Nusselt number and the friction factor. Singh [13] summarized the research of temperature and flow non-uniformities in compact heat exchangers. The effects of temperature and flow non-uniformities on the performance of compact heat exchangers were also reviewed along with the effects of a few non-dimensional parameters. Said [14] proposed orifice approach and nozzle approach to reduce the flow maldistribution in the header of heat exchanger, the flow maldistribution was reduced by approximately 12 times the original by using orifice approach, and 7.5 times by using nozzle approach.

Though the inlet flow maldistribution can be decreased through optimizing the structure of inlet header, it cannot be eliminated due to complex structure of heat exchanger. The deteriorative effects of inlet flow maldistribution on the thermal performance have been well recognized and presented in recent years. Ismail [15] analyzed numerically the influence of inlet flow maldistribution and fin geometries on the thermal performance, and then the correlation equations between Colburn factor *j*, Fanning friction factor *f* and Reynolds number *Re* were generated and validated under known construction of inlet header and fins. Shaji [16] proposed an axial dispersion model which considered the influence of inlet flow maldistribution and fluid back-mixing within the channels to determine the number of exchanger heat transfer units (NTU) and dispersive Peclet number. The results indicated that it was essential to isolate inlet flow maldistribution from back-mixing for measuring Peclet number values accurately. Hoffmann [17] measured experimentally the effect of inlet header configuration and inlet flow maldistribution on the hydraulic resistance of heat exchanger, and concluded that the flow maldistribution in the axial direction resulted in the increasement of anisotropic resistance. Chin [18,19] investigated quantitatively the degradation effect of statistical moments of inlet flow maldistribution (mean, standard deviation, skew and kurtosis) on the thermal and hydraulic performances of plate-fin heat exchange, and found that mean and standard deviation had the highest effect on the performance degradation. Mao [20] established a verified model for the multi-louvered fin cross-flow condenser under the airflow