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Effect of flow maldistribution on the optimal design of a cross flow heat exchanger

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ABSTRACT

In this study, a cross flow heat exchanger is optimized based on multi objective optimization algorithm by considering the effects of flow maldistribution for both cold and hot sides. For this purpose, total annual cost (TAC) and effectiveness of exchanger are selected as fitness functions and six decision variables including the heat exchanger and fin geometries are considered as decision variables. The optimization is performed for the three non-uniform velocity inlet profiles including linear, parabolic and power law and their optimum results are compared with the uniform (constant) profile. It is observed that, the Percentages of reduction in effectiveness for the final optimum solution are in the range of 2.93–4.88%, 1.50–3.38% and 0.79–1.24% respectively in the cases of linear, parabolic and power law profiles compared with constant inlet profiles. Moreover, Percentages of growth in the TAC for the final optimum solution are in the range of 13.00–16.49%, 6.97–10.49% and 0.77–1.63% respectively in the cases of linear, parabolic and power law profiles compared with constant inlet profiles. In addition, the higher hot and cold stream flow lengths and lower fin height and fin spacing are needed in the cases of linear, parabolic and power law profiles compared with the constant velocity profile for the fixed value of effectiveness.

1. Introduction

In the design of heat exchangers, especially the air side of compact heat exchanger, it is generally assumed that the inlet temperature and flow distribution are uniform. However, the assumption is generally not realistic in the real conditions because of several reasons. One of the main reason is due to the flow non-uniformity and misdistribution.

In order to examine the effects of flow maldistribution in heat exchangers, some experimental research were done in this field. To assess the resultant change in its flow distribution and thermal performance, various distributors configuration were used with a plate-fin heat exchanger under different operating conditions by Zhang et al. [1]. The experimental results showed that improved distributors were very effective in improving the flow distribution in heat exchangers, and consequently, their thermal performance. In the other new study the effects of airflow non-uniformity on the thermal-hydraulic performance of a fin-and-tube heat exchanger were investigated experimentally by Blecich et al. [2]. It was found that airflow non-uniformity caused thermal effectiveness deterioration and pressure drop increased. In another paper an experimental investigation had been carried out by Bobbili et al. to find the flow and the pressure difference across the port to channel in plate heat exchangers for a wide range of Reynolds numbers [3]. The results indicated that the flow maldistribution increased with increasing overall pressure drop in the plate heat exchangers.

Many numerical applications were presented in which the heat exchangers were simulated by means of CFD to investigate the influence of flow maldistribution. Yaïci et al. presented the results of three-dimensional (3D) Computational Fluid Dynamics (CFD) simulations aimed to investigate the effect of inlet air flow maldistribution on the thermo-hydraulic performance of heat exchangers [4]. The CFD results confirmed the importance of the influence of inlet fluid flow non-uniformity on heat exchanger efficiency. Chu et al. analyzed the large fluid flow maldistribution occurring at the inlet manifold configurations of a high temperature heat exchanger with CFD (computational fluid dynamics) method [5]. They showed, the Nusselt number could be increased by 24% averagely due to the produced spiral fluid flow while the pressure drop was in a suitable range. Furthermore, the

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Nomenclature

A_{flow}	cross section area of free flow (m^2)
A_{tot}	heat transfer surface area (m^2)
a	annualized coefficient (–)
b	fin height (m)
c	specific heat (j/kgK)
c	lateral fin spacing (m)
C_{min}	minimum total heat capacity (W/K)
C_{max}	maximum total heat capacity (W/K)
C^*	total heat capacity ratio (C_{min}/C_{max})
C_{in}	capital or investment cost ($/year)
C_{op}	operational cost ($/year)
D_h	hydraulic diameter (m)
f	Fanning friction factor (–)
G	mass flux (kg/m^2s)
h	heat transfer coefficient (W/m^2K)
i	rate of interest (–)
j	Culburn factor (–)
L_c	length of cold stream flow (m)
L_h	length of hot stream flow (m)
L_n	no-flow length (m)
NTU	number of transfer units (–)
n	life time (year)
Pr	Prandtl number (–)
Q	rate of heat transfer (kW)
Re	Reynolds number (–)
St	Stanton number (–)
TAC	total annual cost ($/year)
t_f	fin thickness (m)
U	overall heat transfer coefficient (W/m^2K)
V	volumetric flow rate (m^3/s)
x	fin length (m)

Greek abbreviation

ε	effectiveness (–)
η	compressor efficiency (–)
β	ratio of hot and cold surface area (–)
τ	operational hours in a year (Hours/year)
μ	viscosity (Pa s)
ν	specific volume (m^3/kg)
ΔP	pressure drop (Pa)
σ	ratio betweenA_{flow} and A_{front}
ϕ_e	electricity tariff ($/kWh)

Subscripts

c	cold
h	hot
in	inlet
max	maximum
min	minimum
out	outlet

corresponding correlation of Nusselt and friction factor was obtained according to CFD results. Mao et al. developed a verified model and methodology for the cross-flow condenser modeling based on the finite volume method (FVM), with multi-louvered fin and tube structure, for evaluating the coupling effects on the performance of multi-louvered fin and flat tube heat exchangers under airflow maldistribution [6]. The results indicated that airflow maldistribution affected the condensation capacity, refrigerant pressure drop as well as the theoretical fan power consumption. In another paper, Rossetti et al. studied the effects of the flow maldistribution in the air channel of an open refrigerated display cabinet by means of CFD simulations [7]. This thermal CFD model allowed to evaluate the 3D effects of the maldistribution in terms of temperature, heat transfer coefficients, and cooling power in the full channel model.

The maldistribution of gas and liquid is the critical issue that can lead to the heat transfer deterioration in plate-fin heat exchangers which was investigated by several authors. Zhang and Li-Zhi investigated the flow maldistribution and thermal performance deterioration in cross-flow air to air heat exchangers [8]. A CFD code was used to calculate the flow distribution, by treating the plate-fin core as a porous media. The study proved that the inlet duct, the outlet duct and the core should be coupled together to clarify flow maldistribution problems. Flow characteristics of flow field in the entrance of plate-fin heat exchanger have been investigated by means of particle image velocimetry (PIV) by Wen et al. [9]. The results validated that PIV was well suitable to investigate complex flow pattern.

Flow maldistribution is a practical challenge in most microchannel heat exchangers (MCHXs) applications. In a new research R410A and R134a upward flow in the transparent vertical header and distribution into the horizontal parallel microchannel tubes were investigated by Zou et al. [10]. It was found that the capacity was reduced by up to 30% for R410A and 5% for R134a, respectively, for the conditions examined. Siva et al. brought out the phenomenon of the influence of flow maldistribution on temperature distribution in parallel microchannel system [11]. It was observed that a higher heat flux induced a reduction in viscosity of the fluid resulting in higher flow maldistribution.

Finally, Hajabdollahi et al. performed the thermoeconomic and multi objective optimization of cross flow plate fin heat exchanger using different objective functions such as effectiveness, pressure drop, entropy generation and annual cost [12–15]. In their work, the flow distribution in the inlet of heat exchanger was assumed to be uniform.

In this paper, a cross flow plate fin heat exchanger with rectangular offset strip fin (Fig. 1) is modeled and optimized using two simultaneous fitness functions including effectiveness and total annual cost. In addition, the exchanger is modeled and optimized by considering the effects of flow maldistribution. Three different inlet velocity profiles including linear, parabolic and power law are optimized and their results are compared with the constant or uniform profile. To generalize the optimum results, the optimization is performed for different hot and cold side mass flow rates and results are reported.

2. Thermal modeling

Usually logarithmic mean temperature difference (*LMTD*) or effectiveness-Number of transfer unit ($\varepsilon - NTU$) are used for thermal modeling and design of heat exchanger. $\varepsilon - NTU$ method is more straightforward for the heat exchanger design problem in which both of hot and cold side outlet temperatures are unknown.

The thermal modeling of the system considering the effect of maldistribution is performed under the following assumptions:

- The same fin configuration is used for the both hot and cold sides.