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Research Paper

Parametric investigation of a non-constant cross sectional area air to air heat exchanger

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HIGHLIGHTS

- Evaluation of complex geometry aimed at minimizing volume per unit of exergy transfer.
- The use of a non-constant cross-section for the heat exchanger is proposed.
- The performance gains attainable via modern manufacturing techniques are discussed.
- The trade-off between overall exergy efficiency and cost is thoroughly analysed.
- A quadratic proportion between volume and characteristic dimension has been found.

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ABSTRACT

The present article addresses the design, mathematical modelling and analysis of a novel highly exergy-efficient air to air heat exchanger. An intricate design based on an hexagonal mesh is proposed for the cross-sectional area of the heat exchanger with aims to explore the performance gains that can be obtained by exploiting the capabilities and benefits offered by modern fabrication techniques such as additive manufacturing. Special attention is paid to understanding the relationship or trade-off that exists between the overall exergy efficiency of the heat exchanger and its cost.

The iterative algorithm used to find the geometrical parameters that yield the best performance in terms of volume of material required per unit of exergy transfer at a certain level of efficiency, as well as the assumptions and simplifications made, are comprehensively explained.

It has been found through the analyses carried out performed, which are thoroughly discussed throughout the paper, that if the characteristic dimension of the heat exchanger is scaled up by a factor of n, the volume of material per kW of exergy transfer at certain exergy efficiency will increase by a factor of n squared. This is a very important observation, possibly applicable to other types of heat exchangers, that indicates that performance improves dramatically at smaller scales.

The overall performance of the case study presented is satisfactory, a volume of material as low as 84.8 cm^3 for one kW of exergy transfer can be achieved with a 99% exergy efficiency.

1. Introduction

Heat exchangers (HX) are devices that allow the transfer of thermal energy between two or more streams of fluids at different temperatures. Nowadays they are employed for countless industrial processes. Several different types of heat exchangers have been developed for different applications; being the Shell and Tube (STHX) and Plate-Fin (PFHX) two of the most widely used configurations [1].

The design of a HX is far from being a trivial task as it involves a number of highly interdependent geometric and operating variables that often pose technical contradictions (or trade-offs) [2]; however, through a careful selection of design parameters a highly efficient and cost-effective design can be realised, which is of growing importance for the industry given their extensive utilization in a multitude of processes.

Considerable amount of research has been devoted in the past years to develop design strategies that allow achieving significant cost reductions in the design of a heat exchanger for a specific heat duty. Various researchers have resorted to the use of evolutionary

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Nomenclature

Acronyms

HP	high pressure
HX	heat exchanger
LP	low pressure

Symbology

A	cross sectional area (m^2)
A_r	ratio of cross sectional areas HP/LP
$\bar{B}$	mean exergy transfer (W/m)
B_{HP}	exergy of the heat at the HP side (W/m)
B_{LP}	exergy of the heat at the LP side (W/m)
B_{LOSS}	total exergy losses (W/m)
B_{LQ}	exergy loss due to heat transfer (W/m)
$B_{\Delta P}$	exergy loss due to pressure drop (W/m)
$B_{\Delta HP}$	exergy loss due to pressure drop in the HP side (W/m)
$B_{\Delta LP}$	exergy loss due to pressure drop in the LP side (W/m)
C_P	specific heat capacity (J/kg K)
ΔP	pressure drop per unit length (Pa/m)
ΔP_{HP}	pressure drop in the HP side (Pa/m)
ΔP_{LP}	pressure drop in the LP side (Pa/m)
ΔT	temperature delta from T_{avg} (K)
D	distance between centres of HP pipes (m)
ε	roughness height (m)
$\varepsilon/\varnothing$	relative pipe roughness
f_D	Darcy-Weisbach friction factor
h	convection coefficient (W/m^2 K)
k_{air}	thermal conductivity of air (W/m K)
k_{wall}	thermal conductivity of wall (W/m K)
λ	fraction of HP pipe perimeter covered by flanges
L	height of the flange (m)
μ	dynamic viscosity of air (Pa s)
$\dot{m}_{HP}$	mass flow rate per HP pipe (kg/s)
$\dot{m}_{LP}$	mass flow rate per LP pipe (kg/s)
mm	flange performance factor
n	number of rings of HP pipes
Nu	Nusselt number
$\varnothing$	pipe diameter (m)
$\varnothing_h$	hydraulic pipe diameter (m)
ψ	fraction of the pipe being analysed
p	perimeter of flow area of pipe (m)
P	pressure (Pa)
P_{HP}	pressure of the HP side (Pa)
P_{LP}	pressure of the LP side (Pa)
Pr	Prandtl number
$\dot{Q}$	heat transfer rate per unit length (W/m)
ρ	density of air (kg/m^3)
r_{HP}	radius of the HP pipe (m)
Re	Reynolds number
S	allowable stress of pipe material (Pa)
t_{HP}	thickness of HP pipes (m)
t_{LP}	thickness of the flange at the base (m)
t_{mf}	thickness of the flange at midpoint (m)
T_{amb}	ambient temperature (K)
T_{avg}	average temperature of HX section (K)
T_{HP}	temperature of the HP stream (K)
T_i	temperature of inner wall of HP pipe (K)
T_{LP}	temperature of the LP stream (K)
T_{mf}	temperature of the flange at middle (m)
T_O	temperature of outer wall of HP pipe (K)
$T(x)$	temperature at a point x in flange (K)
∇T	temperature gradient of HX segment (K/m)
U	mean flow velocity of air (m/s)
$V/\bar{B}$	volume of material per unit exergy transfer (m^3/kW)
W	exergy efficiency
X	ratio of proportional pressure drops
Y	ratio of temperature differences
Z	fraction of total exergy losses caused by pressure drops

algorithms and other population-based optimization methods with objective functions aimed at minimizing the total cost due to their ability to handle the large amount of design parameters [3].

Sanaye and Hajabdollahi carried out a multi-objective (cost and effectiveness) optimization of a shell and tube heat exchanger [4] and a plate fin heat exchanger [5] through a genetic algorithm. In both cases the authors presented a set of multiple optimum solutions due to the conflict between the two objective functions. Hajabdollahi et al. [6] presented a multi-objective (maximum effectiveness and minimum pressure drop) optimization of a compact PFHX done by means of a genetic algorithm. The study reveals that any geometrical changes which decrease the pressure drop in the optimum situation, lead to a decrease in the effectiveness and vice versa, therefore a set of multiple optimum solutions is presented.

Najafi et al. [7] optimized the design of a PFHX in terms of total rate of heat transfer and the total annual cost of the system through a genetic algorithm. They provide a wide range of optimal solutions, each of which is a trade-off between the highest total rate of heat transfer and the least total annual cost. Fettaka et al. [8] carried out, through a genetic algorithm, a multi-objective optimization of two different STHX trying to minimize simultaneously heat transfer area and pumping power. The authors report, for both case studies, better values for the two objective functions and for the cost of the different optimal designs in comparison to the values previously reported in the literature.

Patel and Rao [9] applied a particle swarm optimization (PSO) algorithm for minimizing the total annual cost of a STHX. The four different case studies presented demonstrate the effectiveness and accuracy of the proposed algorithm. Rao and Patel [10] repeated the study with a PFHX, in which two case studies were analysed. An improvement was observed over the results obtained through genetic algorithms by previous researchers. Mariani et al. [11] used a quantum PSO method for optimizing the design of a STHX. The authors presented two case studies in which significant cost reductions, a 20% reduction of capital investment and a 72% reduction in the annual pumping cost are observed. Furthermore, the results of the two case studies using the quantum PSO are compared with those obtained by genetic algorithms and classic particle swarm showing the superiority of quantum PSO.

Sadeghzadeh et al. [12] carried out a comparison between a genetic algorithm and a particle swarm algorithm for the techno-economic optimization of a STHX. The objective function to minimize is a cost function containing costs of the heat exchanger based on surface area and power consumption to overcome pressure drops. It was found, in agreement with Mariani et al. [11], that results obtained with the particle swarm optimization method are superior to those obtained with the genetic algorithm method. Turgut [13] investigated the utilization of a hybrid chaotic quantum PSO algorithm for the optimization of PFHX in terms of minimizing the heat transfer area, total pressure drop and total cost for a specified heat duty. It was observed that the proposed algorithm con-