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Gas-to-gas heat exchanger design for high performance thermal energy storage

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ABSTRACT

The mathematical modelling and optimization of a gas-to-gas heat exchanger with a non-constant cross sectional area is presented. The design of the cross sectional area of the heat exchanger analyzed is based on an hexagonal mesh, which would be highly impractical to fabricate in a conventional way but could be built relatively easily through modern manufacturing techniques. The geometric configuration proposed allows attaining a high exergy efficiency and a significant cost reduction, measured in terms of volume per unit of exergy transfer. The relationship that exists between the overall exergy efficiency of the heat exchanger and its cost is thoroughly explained throughout the study.

The results obtained from the modelling demonstrate the premise that it is possible to realize designs for heat exchangers that are highly exergy-efficient and very cheap, owing to the small volume of material required, if the constrains imposed by the limitations of traditional manufacturing methods are set aside. Furthermore, the study reveals a very important fact: the volume of material in a heat exchanger increases in quadratic proportion to its characteristic dimension, which implies that scaling up the geometry has a strong impact on its cost-effectiveness.

1. Introduction

Heat exchangers (HX) are extensively used in diverse industrial processes nowadays. Several different types of heat exchangers have been developed for different applications; being the shell-and-tube and plate-fin the most commonly utilized configurations [1].

The design of a HX involves a number of highly interdependent geometric and operating variables that often exhibit trade-offs [2] however, through a careful selection of parameters cost-effective designs with a high efficiency can be realized. This is of great importance for the industry and in particular, for the development and widespread deployment of utility-scale energy storage technologies, such as compressed air energy storage (CAES) systems.

A vast amount of research has been dedicated in past years to develop design strategies for achieving substantial reductions in the cost of a HX. The use of evolutionary algorithms and other population-based optimization methods for minimizing the total cost of HXs has been studied by many researchers. Following a literature review can be found, in which examples of the work aimed at optimizing the design of HXs in terms of maximizing performance and/or minimizing cost carried out by different authors are discussed.

Sanaye and Hajabdollahi carried out by means of a genetic algorithm the optimization in terms of cost and effectiveness of a shell-and-tube HX [3] and a plate-fin HX [4] presenting in both studies a set of multiple optimum solutions (Pareto front) for the objective functions. In a different study, Hajabdollahi et al. [5] used a genetic algorithm to optimize a compact plate-fin HX in terms of effectiveness and pressure drops. The authors observed that any geometric change that reduces pressure drops in the optimum situation has a negative impact in the effectiveness of the HX and vice versa, therefore a set of Pareto optimal solutions was presented. Similarly, Najafi et al. [6] carried out the optimization of a HX of the same type, albeit focusing on different objective functions. The researchers provide a number of Pareto optimal solutions, which exhibit the trade-off that exists between the maximum total rate of heat transfer and the minimum total cost of the component.

Patel and Rao used a particle swarm optimization (PSO) algorithm to minimize the total annual cost of a shell-and-tube [7] and a plate-fin HX [8]. Several different case studies are presented through which the effectiveness and accuracy of the

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Nomenclature

Acronyms
- *HP* high pressure
- *HX* heat exchanger
- *LP* low pressure

Symbology
- A cross sectional area (m^2)
- A_s heat transfer area (m^2)
- $\overline{B}$ mean exergy transfer (W/m)
- $\dot{B}_{HP}$ exergy of the heat at the HP side (W/m)
- $\dot{B}_{LP}$ exergy of the heat at the LP side (W/m)
- $\dot{B}_{LOSS}$ total exergy losses (W/m)
- $\dot{B}_{LQ}$ exergy loss due to heat transfer (W/m)
- $\dot{B}_{\Delta P}$ exergy loss due to pressure drop (W/m)
- $\dot{B}_{\Delta HP}$ exergy loss due to pressure drop in the HP side (W/m)
- $\dot{B}_{\Delta LP}$ 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)
- $\varepsilon/\emptyset$ 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)
- n number of rings of HP pipes
- Nu Nusselt number
- $\emptyset$ pipe diameter (m)
- ψ fraction of the pipe being analyzed
- 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)
- $V/\overline{B}$ 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

algorithm is demonstrated. The results show an improvement with respect to the results obtained by previous researchers via more standard genetic algorithms. Furthermore, Sadeghzadeh et al. [9] presented a comparison between the PSO and a genetic algorithm for the optimization of a shell-and-tube HX in terms of cost, expressed as a function of surface area and power consumption. The PSO method produced superior results for the problem, which supports the conclusions from Patel and Rao [7,8].

Some authors have explored the use of variants of the PSO method. Mariani et al. [10] optimized the design of a shell-and-tube HX through a quantum PSO algorithm. The researchers reported that considerable reductions in capital investment (~20%) and annual pumping cost (~72%) were achieved. Turgut [11], on the other hand, investigated the use of a hybrid-chaotic PSO algorithm for the multi-objective optimization of a plate-fin HX in terms of heat transfer area, total pressure drops and total cost. The author observed that the PSO algorithm produced more accurate results than many other optimization algorithms discussed in the literature.

Besides the techniques aforementioned, several other evolutionary and population based optimization algorithms have been used by many researchers for optimizing the design of HXs from different perspectives such as the imperialist-competitive, cuckoo-search, biogeography-based optimization, teaching-learning and firefly algorithms, among others.

Hadidi et al. [12] optimized the design of a shell-and-tube HX by means of an imperialist-competitive algorithm. The authors achieved reductions in capital cost of up to 6.1% with respect to selected reference cases. Yousefi et al. [13] used an improved harmony-search algorithm to optimize the design of a plate-fin HX with aims at minimizing heat transfer area and pressure drops. The results obtained indicate that the approach studied can produce more accurate solutions than genetic and PSO algorithms.

Wang and Li [14] carried out a multi-objective optimization (maximizing efficiency and minimizing cost) of a plate-fin HX via a cuckoo-search algorithm (CSA). The authors reported satisfactory results and concluded that the CSA method is capable of generating more accurate solutions than single-objective approaches while requiring less iterations. Likewise, Asadi et al. [15] used a CSA for the minimization of the cost of a shell-and-tube HX. The authors achieved reductions in cost of 9.4% and 13.1% with respect to results produced by genetic and PSO algorithms, respectively.

Hadidi and Nazari [2] carried out a cost optimization of a HX through a biogeography-based optimization (BBO) algorithm with which reductions in capital investment and operating costs in comparison to literature reference cases of up to 14% and 96%, respectively, were achieved. Patel and Savsani [16] and Rao and Patel [17] carried out, by means of a modified version of the teaching-learning algorithm, a multi-objective optimization focused on effectiveness and total cost of a shell-and-tube and a plate-fin HX, respectively. The authors reported that better Pareto optimal solutions were attained than those found by generic algorithms for an analogous problem.

More recently, Mohanty [18] published the results of the cost optimization of a shell-and-tube HX carried out via a firefly algorithm. The study shows that the total surface area and total cost can be reduced by 27% and 29%, respectively, with respect to the reference designs. Furthermore, the study presents a comparison of the firefly algorithm against some of the aforementioned

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