Energy 65 (2014) 364–373

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Systematic analysis of the heat exchanger arrangement problem using multi-objective genetic optimization

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A R T I C L E I N F O

Article history:
Received 22 July 2013
Received in revised form
4 October 2013
Accepted 12 November 2013
Available online 12 December 2013

Keywords:
Heat exchanger
Laminar flow
Optimization
Multi-objective
Genetic algorithm

A B S T R A C T

A two-dimensional cross-flow tube bank heat exchanger arrangement problem with internal laminar flow is considered in this work. The objective is to optimize the arrangement of tubes and find the most favorable geometries, in order to simultaneously maximize the rate of heat exchange while obtaining a minimum pressure loss. A systematic study was performed involving a large number of simulations. The global optimization method NSGA-II was retained. A fully automatized in-house optimization environment was used to solve the problem, including mesh generation and CFD (computational fluid dynamics) simulations. The optimization was performed in parallel on a Linux cluster with a very good speed-up.

The main purpose of this article is to illustrate and analyze a heat exchanger arrangement problem in its most general form and to provide a fundamental understanding of the structure of the Pareto front and optimal geometries. The considered conditions are particularly suited for low-power applications, as found in a growing number of practical systems in an effort toward increasing energy efficiency. For such a detailed analysis with more than 140 000 CFD-based evaluations, a design-of-experiment study involving a response surface would not be sufficient. Instead, all evaluations rely on a direct solution using a CFD solver.

1. Introduction

In our rapidly changing world the speed of engineering design and manufacturing processes are accelerating, driven by the increasing customer demands, stricter legal regulations and environmental concerns. These factors result in shorter design processes and more rigorous requirements. However, it is usually impossible to improve directly all aspects of a design simultaneously, since engineers have to meet competing factors (e.g., engine efficiency, production cost, and lifetime of product).

Fortunately, such challenges can be answered thanks to multi-objective optimization; and a faster design process could rely on automatization and parallelization of the underlying simulations. In this article, a systematic analysis and optimization of a two-dimensional heat exchanger configuration is presented using such tools in order 1) to analyze the advantages of a symmetrical vs. asymmetrical design, 2) to quantify the effect of constraints on the speed of exploration and 3) to provide a better fundamental understanding of the structure of the Pareto front for a basic heat exchanger.

The optimal placement of the heat sources or sinks in a channel, a cavity or a heat exchanger may affect dramatically the performance of the considered device. For this purpose, CFD (computational fluid dynamics) coupled with GA (genetic algorithms) have a high potential to explore a large number of different configurations.

One efficient way to further speed up an optimization process is to use a DOE (design of experiment) with a limited number of evaluations as starting point, followed by the generation of a Response Surface using one of the available RSM (response surface methods). Finally, a virtual optimization can be performed on this surface using, e.g., again GA. However, the global quality of such an advanced interpolation technique completely depends on the complexity of the problem. While it works well for simple configurations, it may completely fail for concurrent objectives involving local minima and stiff surfaces, as often found in practical applications. Therefore, this approach is computationally efficient, but might be misleading without a priori information and/or appropriate expert knowledge. In order to avoid this issue and to eliminate any interpolation error resulting from the technique, all designs considered here were directly evaluated using CFD simulations.

To the best of our knowledge, such a systematic and extensive analysis of a tube bank heat exchanger arrangement problem using multi-objective optimization tools coupled with CFD (an approach

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http://dx.doi.org/10.1016/j.energy.2013.11.035

Nomenclature

c_p	specific heat capacity
f	objective function
g	constraint
k	thermal conductivity
p	pressure
Q	volume flow rate
$\dot{Q}$	total heat transfer
R	radius
Re	Reynolds number
T	temperature
v	flow velocity
VV	variable volume
$\mathbf{X}$	set of feasible designs
$\mathbf{x}$	decision variable vector
x	first spatial coordinate
y	second spatial coordinate
Greek symbol	
Δ	difference
η	efficiency
μ	dynamic viscosity
ξ	hydraulic resistance
ρ	density
Ω	boundary

called CFD-based Optimization, or CFD-O [1]) to analyze the effect of the constraints and of asymmetrical designs cannot be found in the literature.

On the other hand, the investigation of heat exchangers and heat exchange processes in general is an intensive field of research due to its practical importance. For instance, Monteiro and Mello analyzed the thermal performance and pressure drop in ceramic heat exchangers [2]. Arsenyova et al. [3] investigated the optimal design of plate-and-frame heat exchangers, while Soltani and Shafiei [4] studied the pressure drop of heat exchanger networks using GA. Elshafei et al. [5] analyzed experimentally the heat transfer process in corrugated channels.

Additionally, the coupling of optimization with CFD is an increasingly considered area. Giangaspero and Sciubba [6] analyzed solar heat exchangers using a pseudo-optimization process. Micro-channel heat sinks were optimized concerning pressure-drop and thermal resistance by Baodong et al. [7]. Shape improvement of a cylinder with heat transfer was carried out by Cheng and Chang [8]. The optimal spacing problem of three chips in an enclosure is described in Ref. [9]. The optimal location of heat sources was investigated by da Silva et al. [10] for forced convection and in Ref. [11] for natural convection. The optimal shapes of heat exchangers have been discussed by various authors [12,13]. Bello-Ochendo et al. [14] performed gradient-based optimization of conjugate cooling channels. Pussoli et al. [15] optimized finned-tube evaporators. Arrangement problems have also been considered; for instance, Sudhakar et al. [16] analyzed the optimal arrangement of heat sources for a laminar, steady flow using ANSYS-Fluent for CFD, as in the present work. Beck et al. [17] analyzed improved geothermal borehole arrangements, while Hájer [18] investigated the design optimization process of thermal waste treatment technology using CFD methods.

Thanks to recent progress concerning multi-objective optimization problems, corresponding studies become increasingly popular. Lee et al. [19] performed multi-objective optimization of plate heat exchangers using MOGA. Ranut et al. [20] studied the optimal shape of tube bundles using multi-objective optimization. Seung-Hwan et al. [21] considered the optimization of radial heat sinks for weight and thermal resistance using a weighted sum method. Their approach relies on a response surface based on measurements, followed by a GA study. Hilbert et al. [22] performed a multi-objective shape optimization of 2D laminar tube bank heat-exchanger using GA. Copiello and Fabbri analyzed and optimized the heat transfer process considering longitudinal wavy fins [23] and using SPEA2 optimization method [24]. Foli et al. [25] and Okabe et al. [26] have obtained optimal results for a micro heat exchanger based on different multi-objective optimization methods. Iqbal et al. [27] determined optimal configuration for heat transfer processes under laminar conditions using GA. Multi-objective genetic optimization of tube arrangement for cooling of prismatic bodies was analyzed by Robbe and Sciubba [28]. Researchers did not only address the optimization of fluid dynamics and heat transfer in heat exchangers, but considered also cost and lifetime. Nemet et al. [29] optimized heat exchanger networks for minimal cost, while Azad and Amidpour [30] optimized with the same objective shell and tube heat exchangers using GA.

This long list of publications demonstrates the importance of this issue. Developing an efficient, robust and accurate multi-objective optimization technique for such problems involving complex geometries, flow and heat transfer in a coupled manner, would be extremely important for future applications.

2. Optimization

2.1. Multi-objective optimization

Without any loss of generality, only minimization problems will be considered in what follows. Let us consider an optimization problem with the n-dimensional design vector $\mathbf{x}$ and m objectives. The multi-objective optimization means that we would like to simultaneously improve the values of all objectives, while complying with some additional constraints as well.

The optimization problem can be formulated as

$$\begin{aligned}&\min_{x\in R^n}(f_1(x),f_2(x),\ldots,f_m(x))\\&\text{subject to}\ \begin{matrix}g_k(x)\le 0,\ \forall k=1,2,\ldots,K\\ g_l(x)=0,\ \forall l=1,2,\ldots,L\end{matrix}\end{aligned} \quad (1)$$

where $\mathbf{x}$ is the vector of design variables, $f_1(\mathbf{x}), f_2(\mathbf{x}),\ldots f_m(\mathbf{x})$ are the m objective functions, and $g_k(\mathbf{x})$, $g_l(\mathbf{x})$ are the inequality and equality constraints, respectively. According to constraints, $\mathbf{x}\in\mathbf{X}\in\mathbb{R}^n$ must be satisfied, where $\mathbf{X}$ is the set of feasible designs. In the current study, only inequality constraints are considered ($L=0$).

In many published studies, the resulting problem is solved by linearly combining the values of the objectives, in the form $(\min_{\mathbf{x}\in\mathbf{X}}\sum_{i=1}^{m} w_i f_i(\mathbf{x}))$ [31]. However, such a simplified, fixed-weight method requires some a priori knowledge about the problem. Without such knowledge or due to faulty assumptions, a lumped analysis can rapidly lead to suboptimal results. In the alternative considered in the present work, the problem can be analyzed using the Pareto optimality. This means that a design is better than another one if and only if it is better at least in one objective than the other one, but is not worse for any further objective [31].