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Multi-objective shape optimization of a tube bundle in cross-flow

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ABSTRACT

Optimization of heat exchangers, as a consequence of their vital role in several industries and applications, has attracted a lot of interest in the last years, and in particular the necessity of improving their performances is well recognized. The coupling of optimization techniques with Computational Fluid Dynamics (CFD) has demonstrated to be a valid methodology for easily explore this work, a CFD-based shape optimization of a tube bundle in crossflow is presented, as a natural extension of the work of Hilbert et al. (2006) [1]. In this study, also the flow inside the tubes has been computed, and the coupled simulation of the external flow and thermal field is performed also on a periodic domain. Two genetic algorithms have been tested and compared, NSGA-II and FMOGA-II: the latter makes an internal use of surrogate models to speed up and improve the optimization process, and proved to be a promising algorithm. The results demonstrate how the search for efficient geometric configurations should also take into account the internal flow field.

1. Introduction

Designing optimal shapes or configurations, or improving the performance of an existing system for practical engineering applications, has been the subject of numerous studies during the last decade. In particular, the optimization of various kinds of heat exchangers, due to their relevance in various fields, has attracted a lot of interest, since any attempt to improve their performance is desirable. Moreover, the increasing cost of energy and materials leads to the production of more and more efficient equipments. Therefore, high effectiveness, small volume (hence low weight) and low cost are the common objectives in heat exchangers' design.

Shape optimization plays a leading role in many engineering applications. In most cases, the process is carried out by using an heuristic approach, i.e., by solving an appropriate boundary value problem for a sequence of intuitively defined shapes, and picking up the best configuration from the available solutions. This methodology presents two serious drawbacks. Firstly, the selected final shape might be far away from the global optimum. Moreover, this simple approach becomes impractical when there is more than one objective, when the number of design variables is large, and when constraints must be satisfied. Therefore, a more systematic approach should be applied: after having defined the shape of the geometry in terms of known trial functions and unknown parameters, an optimization algorithm must be applied. In this way, every evaluation of the objective function requires the solution of a discretized boundary value problem on domains whose geometries vary in the course of the optimization procedure.

Shape optimization of internal channels was investigated by several authors, very often in connection with heat transfer. Corrugated walls were analyzed in [2–6], ribbed surfaces were examined in [7–10], dimpled surfaces were investigated in [11–13] while grooved surfaces were studied by Ansari et al. [14]. Finned surfaces and channels were considered in [15–22], while pin–fin arrays were investigated in [23–25]. Plate and fin heat exchangers were analyzed in [26–30], while Lemouedda et al. [31] optimized the angle of attack of delta-winglet vortex generators in a plate-fin-and-tube heat exchanger.

Optimization studies considering tube bundles in cross-flow are not very common in the literature. Bejan and Fowler [32] performed a theoretical, numerical and experimental study for selecting the best spacing between horizontal cylinders in a fixed volume subjected to natural convection, in order to maximize heat exchange. A similar configuration was considered by Stanescu et al. [33]. The maximization of the heat transfer rate under a volume constraint was achieved also by Matos et al. [34]. In their geometric optimization they considered both circular and elliptic tubes to describe more general configurations. Their work was extended to a 3D domain in [35,36].

In most of the above studies, the optimization process searches for the best configurations, able to maximize the heat transfer rate (for example in order to reduce the volume of the equipment) and

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Nomenclature

c_P	specific heat capacity at constant pressure
i	iteration counter
L	periodic length
$\dot{m}$	mass flow rate
$\dot{m}^*$	desired mass flow rate, see Eq. (12)
p	pressure
$\tilde{P}$	periodic part of pressure, see Eq. (2)
q''	heat flux at the tube surface
S_H	source term of the energy equation
T	temperature
T_w	wall temperature
T_{x^*}	reference bulk temperature at section x^*
$\tilde{T}$	periodic part of temperature, see Eq. (13)
$\mathbf{u}$	velocity vector, $\mathbf{u} = (u, v)$
u	velocity component along x
v	velocity component along y
v_{in}	mean velocity at inlet
x	streamline direction
$xCPi$	x coordinate of the spline's control point
y	spanwise direction
$yCPi$	y coordinate of the spline's control point

Greek letters

α	thermal diffusivity
β	momentum source term, see Eq. (12)
β	pressure gradient across the periodic length
ΔP	pressure drop
Δp	pressure drop per unit length
ΔT	temperature increase at the shell side
ΔT_{per}	temperature increase along the periodic length
λ	temperature decay rate along the periodic unit
λ_L	integral of λ over the periodic length
ϕ	dimensional periodic temperature, see Eq. (10)
θ	non dimensional periodic temperature, see Eq. (4)

Subscripts

shell	shell side
tube	tube side

minimize the pressure losses, which are proportional to the required pumping power. Therefore, the resulting problem is a multi-objective task involving, at least, two conflicting goals: in this case, no one solution can be usually judged the best with respect to all the objectives, but a set of trade-off optimal solutions must be considered. The ensemble of these compromise solutions constitutes the so called *Pareto front*.

To reduce the computational cost, it is common practice [7–9,11,25,23,26] to transform the multi-objective problem into a single objective one, by incorporating all the objectives into a single function with the use of arbitrary weighting factors. However, this strategy is not always advisable, since it does not give access to the whole set of optimal solutions, and the results strongly depend on the chosen weighting factors.

As an alternative, evolutionary algorithms offer several attractive features for solving multi-objective problems. In comparison with classical optimization methods (direct search and gradient-based techniques), evolutionary algorithms present notable advantages. First of all they are robust since they can converge to the global solution and not to a local one, despite of the chosen initial guess. Moreover, they can handle problems with discrete variables. By focusing on CFD-based optimization problems in detail, the benefit of employing evolutionary algorithms is well perceived. In fact, besides the undeniable convenience of parallel computation, evolutionary methods allow the optimization to continue even when the computation of some designs fails. Failed designs may arise due from the possible inconsistency of CAD geometry definition, from the mesh generation, or from the lack of numerical convergence. The presence of failed designs is a considerable problem in the gradient calculation and in the application of a point-by-point approach. It is worth noting that gradient based methods are usually more accurate than evolutionary algorithms, since they exploit the information of the gradient of the function. Therefore, for increasing the accuracy of the solution, a hybrid strategy can be followed, that is a local search can be performed starting from the solutions previously computed with the evolutionary algorithm.

Genetic algorithms (GAs) and evolutionary techniques have been widely used in shape optimization, especially in the aerospace and automotive industry. Concerning heat transfer, the employment of GAs dates back to mid-1990s, and has become more and more common, see, i.e., [37,38,5,21,15–17,2,19,29,1,31,6,27,30,3,20,39,40,28,18,41–43]. In [12–14,24,44] an hybrid method is applied, i.e., a local search is performed starting from the solutions previously computed with GAs. In [10] three different algorithms were used in cascade: the multi-objective game theory (MOGT), the multi-objective genetic algorithm (MOGA-II) and the single objective Nelder and Mead Simplex. An application of the Simulated Annealing technique can be found in [45]. An exhaustive review on the application of GAs in heat transfer was published in 2009 by Gosselin et al. [46].

In this paper, a multi-objective shape optimization of a tube bundle by means of GAs is presented. The project is the natural extension of a previous work performed by Hilbert et al. [1], with many important improvements. In fact, while in [1], just as in most published works, only the flow outside the tube array was simulated, the present study takes into account the flow field within the tubes. This is far more realistic but leads to additional challenges. Therefore, the optimization problem now involves three objectives: (1) the maximization of the heat transfer rate outside the tubes, (2) the minimization of the pressure loss for both the external and (3) the internal flow. To the author's best knowledge, only Borrajo-Peláez et al. [47] solved the fluid and thermal fields also at the tube side, and demonstrated that their extended model provides more realistic predictions. However, no optimization was performed in that work.

In this study, all numerical simulations were performed with the CFD package ANSYS CFX 13.0, while for the optimization the software platform modeFRONTIER 4.3.1 was employed, testing and comparing two evolutionary techniques. The first one is the NSGA-II algorithm developed by Deb et al. [48]. The second one is the fast optimizer FMOGA-II, which employs meta-models (surrogates) to speed up the optimization process.

While for the numerical simulation of the flow inside the tube a periodic domain was employed, for the simulations of the external flow two different domains were used and compared. The first is a non periodic domain, while in the second approach the computation was reduced to a single streamwise-periodic module. This last choice allowed a significant saving in computational resources and was found to be the preferable approach.

Several works published in the literature deal with optimization on periodic domains [3,5,6,7,8,11,12,13,14,24,25,26], but a