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A new design approach for shell-and-tube heat exchangers using imperialist competitive algorithm (ICA) from economic point of view

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ABSTRACT

Cost minimization of shell-and-tube heat exchangers is a key objective. Traditional design approaches besides being time consuming, do not guarantee the reach of an economically optimal solution. So, in this research, a new shell and tube heat exchanger optimization design approach is developed based on imperialist competitive algorithm (ICA). The ICA algorithm has some good features in reaching to the global minimum in comparison to other evolutionary algorithms. In present study, ICA technique has been applied to minimize the total cost of the equipment including capital investment and the sum of discounted annual energy expenditures related to pumping of shell and tube heat exchanger by varying various design variables such as tube length, tube outer diameter, pitch size and baffle spacing. Based on proposed method, a full computer code was developed for optimal design of shell and tube heat exchangers and different test cases are solved by it to demonstrate the effectiveness and accuracy of the proposed algorithm. Finally the results are compared to those obtained by literature approaches. The obtained results indicate that the ICA algorithm can be successfully applied for optimal design of shell and tube heat exchangers with higher accuracy in less computational time.

1. Introduction

Heat exchangers are devices used to transfer heat between two or more fluids that are at different temperatures and which in most of the cases they are separated by a solid wall. Shell and tube heat exchangers (STHEs) are probably the most common type of heat exchangers applicable for a wide range of operating temperatures and pressures. Shell and tube heat exchangers are widely used in heating and air conditioning, chemical processes, power generation, refrigeration, manufacturing and medical applications. A typical shell and tube heat exchanger is shown in Fig. 1 [1,2]. This widespread use can be justified by its versatility, robustness and reliability.

The design of STHEs involves a large number of geometric and operating variables as a part of the search for an exchanger geometry that meets the heat duty requirement and a given set of design constrains. Usually a reference geometric configuration of the equipment is chosen at first and an allowable pressure drop value is fixed. Then, the values of the design variables are defined based on the design specifications and the assumption of several mechanical and thermodynamic parameters in order to have a satisfactory heat transfer coefficient leading to a suitable utilization of the heat exchange surface. The designer's choices are then verified based on iterative procedures involving many trials until a reasonable design is obtained which meets design specifications with a satisfying compromise between pressure drops and thermal exchange performances [1–4]. Although well proven, this kind of approach is time consuming and may not lead to cost-effective designs as any cost criteria are explicitly accounted for. Considering the functional importance and widespread utilization of heat exchangers in process plants, their minimum cost design is thus an important goal. In particular, the minimization of energy related expenses is critical in the optic of energy savings and resources conservation.

Due to the important role of shell-and-tube heat exchangers, a variety of techniques have been proposed to the design optimization problem such as, numerical resolution of the stationary point equations of a nonlinear objective function [5,6], graphical analysis of the search space [7,8], simulated annealing [9], mixed integer nonlinear programming [10], and systematic screening of tube count tables [11,12]. For example Chauduri et al. [9] used simulated annealing approach for the optimal design of heat exchanger and developed a command procedure to link HTRI (Heat Transfer Research Inc.) design program to the annealing algorithm. The authors had analyzed the problem considering two different objective functions namely, total heat transfer area and a linearized purchased cost index. These techniques were employed according to distinct problem formulations in relation to: (i) objective function: heat transfer area or total annualized costs

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Nomenclature

a_1	numerical constant
a_2	numerical constant
a_3	numerical constant
B	baffles spacing (m)
Cl	clearance (m)
C_p	specific heat(kJ/kg K)
C_i	capital investment (€)
C_E	energy cost (€/kW h)
C_o	annual operating cost (€/year)
C_{oD}	total discounted operating cost (€)
C_{tot}	total annual cost (€)
d	tube diameter (m)
D	shell diameter (m)
f	friction factor
F	correction factor
h	heat transfer coefficient (W/m^2 K)
H	annual operating time (h/year)
i	annual discount rate (%)
k	thermal conductivity (W/m K)
K_1	numerical constant
L	tubes length (m)
m	mass flow rate (kg/s)
n	number of tubes passages
n_1	numerical constant
n_y	equipment life (year)
N_t	number of tubes
P	pumping power (W)
p	numerical constant
Pr	Prandtl number
P_t	tube pitch (m)
Q	heat duty (W)
Re	Reynolds number
R_f	fouling resistance (m^2 K/W)
S	heat transfer surface area (m^2)
T	temperature (K)
U	overall heat transfer coefficient (W/m^2 K)
v	fluid velocity (m/s)

Greek symbols

ΔP	pressure drop (Pa)
ΔT_{LM}	logarithmic mean temperature difference (°C)
π	numerical constant
μ	dynamic viscosity (Pa s)
υ	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
η	overall pumping efficiency

Subscripts

e	equivalent
i	inlet
o	outlet
s	belonging to shell
t	belonging to tube
w	tube wall

(i.e. capital costs of the heat exchanger and pumps/compressors associated to fluid flow operating costs); (ii) constraints: heat transfer and fluid flow equations, pressure drop and velocity bounds, etc.; and (iii) decision variables: selection of different search variables and its characterization as integer or continuous (e.g., tube diameter can be considered a fixed parameter, a continuous variable or a discrete variable). In spite of the algorithmic developments applied to heat exchanger design, the complexity of the task allows some criticism of the effectiveness of optimization procedures for real industrial problems [2].

In addition, there are some studies based on artificial intelligence techniques for the optimization of shell and tube heat exchangers. These approaches overcome of some of the limitations of traditional design methods based on mathematical programming techniques. Selbas et al. [13] used genetic algorithm (GA) for optimal design of STHEs, in which pressure drop was applied as a constraint for achieving optimal design parameters. The authors had considered minimization of total heat exchanger cost as an objective function. A case study has been made for examination of the performance of genetic algorithm. From this study they concluded that the combinatorial algorithms such as genetic algorithm provided significant improvement in the optimal designs compared to the traditional designs. Caputo et al. [14] carried out heat exchanger design based on economic optimization using GA. They minimized the total cost of the equipment including capital investment and the sum of discounted annual energy expenditures related to pumping. In order to verify the capability of the proposed method, three case studies are also presented showing that significant cost reductions are feasible with respect to traditionally designed exchangers. In particular, in the examined cases a reduction of total costs up to more than 50% was observed. Ponce-Ortega et al. [15] also have used genetic algorithms for the optimal design of STHEs. The approach uses the Bell–Delaware method for the description of the shell-side flow with no simplifications. The optimization procedure involves the selection of the major geometric parameters such as the number of tube-passes, standard internal and external tube diameters, tube layout and pitch, type of head, fluids allocation, number of sealing strips, inlet and outlet baffle spacing, and shell side and tube-side pressure drops. The methodology takes into account the geometric and operational constraints typically recommended by design codes. Several other investigators also used strategies based on genetic optimization algorithms [15–22] for various objectives like minimum entropy generation [19] and minimum cost of STHEs [15–18,21,22] to optimize heat exchanger design. Patel and Rao [23] applied particle swarm optimization (PSO) for minimization of total annual cost of STHEs where three design variables: shell internal diameter, outer tube diameter and baffle spacing were considered for optimization, with two tube layouts. However, in that study the main focus was the analyses of the heat exchangers principles, while the optimization approach was just a tool. Shahin et al. [24] presented an artificial bee colony (ABC) algorithm for optimization of a shell and tube heat exchanger. Recently Mariani et al. [25] used a PSO method to optimal designing of a shell and

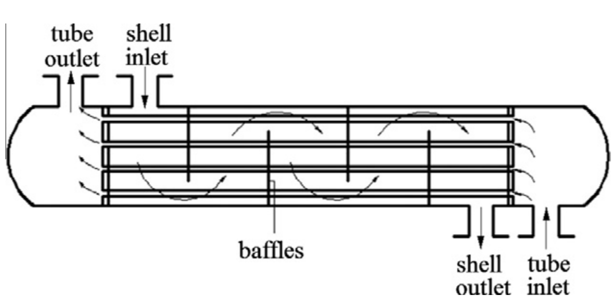

Fig. 1. Diagram of a typical shell and tube heat exchanger [1,2].