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Techno-economic optimization of a shell and tube heat exchanger by genetic and particle swarm algorithms

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The use of genetic and particle swarm algorithms in the design of techno-economically optimum shell-and-tube heat exchangers is demonstrated. A cost function (including costs of the heat exchanger based on surface area and power consumption to overcome pressure drops) is the objective function, which is to be minimized. Selected decision variables include tube diameter, central baffles spacing and shell diameter. The Delaware method is used to calculate the heat transfer coefficient and the shell-side pressure drop. The accuracy and efficiency of the suggested algorithm and the Delaware method are investigated. A comparison of the results obtained by the two algorithms shows that results obtained with the particle swarm optimization method are superior to those obtained with the genetic algorithm method. By comparing these results with those from various references employing the Kern method and other algorithms, it is shown that the Delaware method accompanied by genetic and particle swarm algorithms achieves more optimum results, based on assessments for two case studies.

1. Introduction

Shell and tube heat exchangers are significant components in many industries, particularly in energy conversion systems. The heat transfer requirements and the total cost of shell and tube exchangers are important factors in their incorporation in designs in industrial applications. An optimum design, in terms of both economics and efficiency, can be obtained through appropriate selection of design parameters. A typical shell and tube heat exchanger is shown in Fig. 1.

Much research has been carried out in this area. In such optimization activities, some researchers utilize objective functions aimed at decreasing total cost and heat transfer area [1–5]. Patel and Rao [6] optimized shell and tube heat exchangers using three design parameters (inside and outside tube diameter and spacing of baffles) for two types of tube arrangements using a particle swarm optimization (PSO) algorithm. Selbaş et al. [7] optimized a shell and tube heat exchanger economically using a genetic algorithm and heat transfer area as an objective function. They demonstrated the relationship between heat transfer area and total cost, showing that heat transfer area increases as total cost increases. Using Delaware's approach, Ponce et al. [8] described shell side flow and used a genetic algorithm with a small number of decision variables to minimize total cost (their objective function). Their results had a lower pressure drop and total cost compared to those for a problem reported in the literature. Caputo et al. [9] used a Toolbox genetic algorithm for optimizing a heat exchanger on the basis of total cost as an objective function and the following decision variables: tube diameter, shell diameter and spacing of baffles. They obtained results that were superior to those using traditional approaches on a similar heat exchanger. Jose et al. [10] improved heat exchange efficiency for several practical cases through optimizing a shell and tube heat exchanger using a genetic algorithm, while Hilbert et al. [11] used a multi-objective optimization approach to maximize heat transfer and minimize pressure drop over a tube bank. Sanaye and Haj Abdollahi [12] consider as objective functions (maximum effectiveness and minimum total cost) for a plate fin heat exchanger and choose six decision variables; they use a multi-objective genetic algorithm (NSGA-II) and depict a set of solutions on a Pareto curve. Guo et al. [13] optimized a shell and tube heat exchanger with segmental baffles based on field synergy theory and using a genetic algorithm. Gholap and Khan [14] used a genetic algorithm for optimization of a forced air heat exchanger and minimized objective functions. Doodman et al. [15] optimized an air cooled heat exchanger using global sensitivity analysis and a harmony search algorithm, and minimized a

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Nomenclature

$A_{o,cr}$	flow area at or near the shell centerline for one cross flow section (m^2)
$A_{o,sb}$	shell-to-baffle leakage flow area (m^2)
C_{in}	total investment cost (€)
C_o	annual operating cost (€/yr)
C_{op}	total operating cost (€)
c_p	specific heat at constant pressure (J/kg K)
C_{total}	total cost (€)
d_i	tube side inside diameter (m)
d_o	tube side outside diameter (m)
D_{otl}	tube bundle outer diameter (m)
d_s	shell diameter (m)
F	correction factor for the number of tube passes (–)
h_i	tube side heat transfer coefficient (W/m^2 K)
h_o	Shell side heat transfer coefficient (W/m^2 K)
λ	annual discount rate (%)
J	correction factor for the shell side heat transfer
k	thermal conductivity (W/m K)
k_{el}	price of electrical energy ($/kW h)
L	tube length (m)
L_{bc}	central baffles spacing (m)
$\dot{m}$	mass flow rate (kg/s)
N_b	number of baffles (–)
n_p	number of tube passes (–)
N_s	number of shells connected in series
N_t	number of tubes (–)
n_y	equipment life (yr)
P	pumping power (W)
Pr	Prandtl number (–)
P_t	tube pitch (m)
Q	heat transfer rate (W)
Re	Reynolds number (–)
$R_{i,f}$	fouling resistance shell side (m^2 K/W)
$R_{o,f}$	fouling resistance shell side (m^2 K/W)
S	heat transfer surface area (m^2)
U	overall heat transfer coefficient (W/m^2 K)

Greek symbols

τ	hours of operation per year (h/yr)
Δp	pressure drop (Pa)
μ	dynamic viscosity (Pa s)
η	pump efficiency (–)
ΔT_{lm}	log-mean temperature difference

Subscripts

i	inner
o	outer
s	shell side
t	tube side
W	tube wall

cost function. Wang et al. [16] and Rao and Patel [17] also used genetic algorithms and particle swarm to optimize heat exchangers. Najafi et al. [18] optimize a plate and fin heat exchanger using genetic algorithm, considering two different objective functions: total heat transfer rate and annual cost. They propose multi-objective optimization as the best way to optimize cases by accounting properly for contradictory objective functions. For their case, increasing heat transfer leads to increased cost (an undesirable state); among the set of solutions, the designer can choose the most desired solution considering limitations related to the project and investment. Hajabollahi et al. [19] report on the optimization of a compact heat exchanger using a multi-objective genetic algorithm to maximize effectiveness and minimize total pressure drop. When varying decision variables leads to a decrease in pressure drop, effectiveness decreases too. Their Pareto curve indicates the contradictory nature of the two objective functions. Hajabdollahi et al. [20] optimized a shell and tube condenser using both a genetic algorithm and particle swarm. They minimized their objective function (total cost) by selecting tube number, number of tube passes, inlet and outlet tube diameters, tube pitch ratio and tube arrangement parameters, and compared GA and PSO results to show that PSO yields better results. Munawar and Babu [21] used differential completion for optimizing a shell and tube heat exchanger, and minimized their cost function using seven decision variables: outside tube diameter, tube pitch, type of shell, number of tube passes, tube length, spacing of baffles and baffle cut. Sanaye and Haj Abdollahi [22] used a two- objective optimizing genetic algorithm method for minimizing total cost and maximizing heat transfer. Liu and Chang [23] considered maximum heat transfer effectiveness and minimum heat exchanger weight and pressure drop in their optimization. Recently, Hadidi et al. [24] optimized a shell and tube heat exchanger using an imperialist competitive algorithm for calculating of heat transfer coefficients and the Kern method for evaluating the shell-side pressure drops.

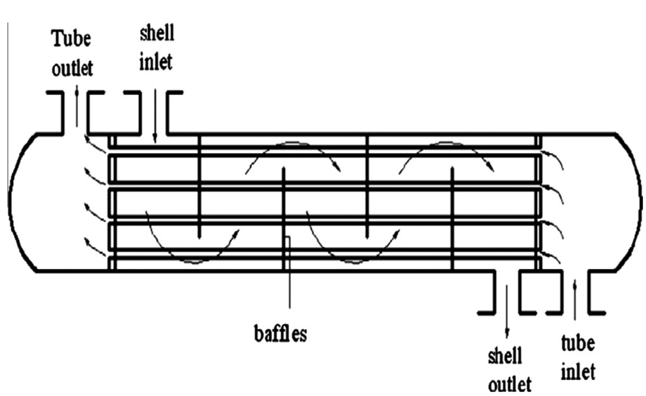

Fig. 1. Diagram of a typical shell and tube heat exchanger.

Salim Fettaka et al. [25] performed multi-objective optimization of shell and tube heat exchanger using NSGA-II with objective functions based on heat transfer area and pumping power. They minimized both objective functions using continuous and discrete decision parameters. Rao and Patel [26] in 2013 optimized heat used modified teaching–learning-based optimization algorithm. They minimized their objective functions using this algorithm while selecting decision variables for any of the shell and tube and plate fin heat exchanger. Rao and Patel present their results for two examples and compare with GA results to show that TLBO achieves better results than GA.

The previous studies exhibit some shortcomings. The most important relates to the use of the Kern method in calculating heat transfer coefficients and the shell-side pressure drops, because the method sometimes has inadequate accuracy. The accuracy of the Kern method is less than the Delaware method [27], as confirmed in the research reported here. Hence, we use the Delaware method to determine heat transfer coefficients and the shell-side pressure drops in this article. Consequently, the present study investigates the optimization of objective functions using genetic algorithm (GA) and PSO methods, with the objective of improving understanding of the techno-economic optimization of heat exchangers.