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Optimal design of shell-and-tube heat exchangers using genetic algorithms

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Abstract

This paper presents an approach based on genetic algorithms for the optimal design of shell-and-tube heat exchangers. The proposed approach uses a compact formulation of the Bell-Delaware method to describe the shell-side flow pattern. The optimization procedure involves the determination of suitable values of major geometric parameters such as the number of tubes passes, standard internal and external tube diameters, tube layout and pitch, type of head, fluid allocation, number of sealing strips, inlet and outlet baffle spacing, and shell-side and tube-side pressure drops. The proposed methodology takes into account several geometric and operational constraints typically recommended by design codes, and may provide global optimum solutions as opposed to local optimum solutions that are typically obtained with many other optimization methods. An example previously solved with a disjunctive programming method is used to show the application of the proposed approach. The results show how the previous design was significantly improved through the use of the optimization approach based on genetic algorithms.

Keywords: heat exchanger, shell and tube, Bell-Delaware, genetic algorithms.

1. Introduction

Shell and tube heat exchangers are widely used in many industrial power generation units, chemical, petrochemical, and petroleum industries. These types of heat exchangers are robust units that work for wide ranges of pressures, flows and temperatures (Taborek, 1983). A typical optimization problem for heat exchangers consists of finding a unit that meets a given heat duty at the minimum total annual cost, subject to a given set of constraints. The total annual cost should include the annualized capital cost of the exchanger plus two pumping devices (one for the tube-side fluid and another one for the sell-side fluid), and the operating (power) costs of such pumps.

The traditional design algorithm for shell and tube heat exchanger consists of rating a large number of different exchanger geometries to identify those that meet the given heat duty and certain geometric and thermo-hydraulic constraints. This approach is not only time-consuming, but it is also restricted in terms of ensuring an optimal design (Muralikrishna and Shenoy, 2000).

Recently, novel algorithms for the optimal design of shell and tube heat exchangers have been proposed (Serna and Jimenez, 2005). However, most of such algorithms use standard optimization techniques based on gradient methods and, as a consequence, they may be trapped at local optimum solutions because of the nonconvexities of the design model. Moreover, in these algorithms the following geometric and operational variables of the exchanger are fixed as design data by the designer: the number of tube passes, tube internal and external diameters, layout pattern and pitch, as well as type of head construction and fluid flow allocation (i.e., the allocation of the fluid streams to the shell or tube side). As a result, the optimization problem is oversimplified since several potential parameters that may be optimized are regarded as constant.

To overcome the above limitations, this work presents an approach based on genetic algorithms for the optimal design of shell and tube heat exchangers. The proposed approach uses a compact formulation of the Bell-Delaware method to describe the shell-side flow with no simplification; this approach, therefore, has the same degree of accuracy as the full Bell-Delaware method, and can incorporate the entire range of geometric parameters of practical interest. The optimization procedure involves the selection of suitable values for major geometric parameters such as the number of tube passes, standard internal and external tube diameters, tube layout and pitch, type of head, fluid allocation, number of sealing strips, inlet and outlet baffle spacing, and shell-side and tube-side pressure drops. The proposed methodology ensures that a global optimum and/or a set of excellent near-optimal solutions are obtained.

2. Fundamental relationships

The heat exchanger area must satisfy the basic design equation:

$$A = \frac{Q}{F_T \Delta T_{ML}} \left(\frac{1}{h_s} + R_{ds} + \frac{D_t}{2k_w} \ln\left(\frac{D_t}{D_{ti}}\right) + \frac{D_t}{D_{ti} h_T} + \frac{D_t}{D_{ti}} R_{dt} \right) \quad (1)$$

Two additional equations are needed that relate the exchanger area to the film coefficients and the allowable pressure drops. The compact formulations developed by Serna and Jimenez (2004) are used for that purpose. For the tube side one obtains:

$$\Delta P_T = K_T A (h_T)^n \quad (2)$$

while for the shell-side fluid, the following compact formulation based on the Bell-Delaware method is used,

$$\Delta P_S = K_S A (h_S)^m \quad (3)$$

where K_S, K_T, m and n depend on the geometric parameters of the exchanger and the fluid physical properties. It must be emphasized that these compact formulations are the consequence of an analytical treatment of the original equations, not empirical correlations. The problems with this formulation is that the parameters K_S, K_T, m and n depend on the exchanger geometry, which is not initially known. To develop an efficient algorithm, we use such parameters as search variables, and decoupled the equations that contain the unknown variables, as shown by Serna and Jiménez (2004).

2.1. Constraints for the model

To get a practical design, the shell and tube heat exchanger must satisfy the given heat duty and the following operational and geometric constraints:

$$\begin{aligned}
&\Delta P_t \le \Delta P_{t,\max} \\
&\Delta P_s \le \Delta P_{s,\max} \\
&v_{t,\min} \le v_t \le v_{t,\max} \\
&v_{s,\min} \le v_s \le v_{s,\max} \\
&D_s \le D_{s,\max} \\
&L \le L_{\max} \\
&R_{bs,\min} \le R_{bs} \le R_{bs,\max} \\
&R_{smsw,\min} \le {}^{S_m}\!/_{S_w} \le R_{smsw,\max}
\end{aligned} \tag{4}$$

where ΔP is the pressure drop, v the velocity, D_s the shell diameter, L the total length, R_{bs} the ratio baffle spacing to shell diameter, R_{smsw} the ratio cross flow area to window flow area, S_m the cross flow area and S_w the window area. The first four equations are thermo-hydraulic constraints and the last four equations represent geometric constraints. Typical design limits to be used in this set of constraints are given by Muralikrishna and Shenoy (2000).

2.2. Objective function

The objective function consists of the minimization of the total annual cost. A typical total cost includes five components: the capital cost of the exchanger, the capital cost for two pumps, and the operating cost of the two pumps,

$$\begin{aligned}
TAC = {} & A_f \left\{ C_a + C_b A^c + C_e + C_f \left(M_t \Delta P_t / \rho_t \right)^g + C_e + C_f \left(M_s \Delta P_s / \rho_s \right)^g \right\} \\
& + C_{pow}\, H/\eta \left\{ M_t \Delta P_t / \rho_t + M_s \Delta P_s / \rho_s \right\}
\end{aligned} \tag{5}$$

Also, for a proper degree of accuracy, the estimation of the heat exchanger capital cost must include the costs for component parts and manufacturing procedures. For such estimation, we use in this work the relations reported by Purohit (1983).

2.3. Optimization variables

The problem includes the following optimization variables: tube-side and shell-side pressures drops, baffle cut, number of tube passes, standard inside and outside tube diameters, tube pitch, tube pattern arrangement, fluid allocation, and sealing strings.

3. Optimization model

The model consists of minimizing Eq. (5), subject to the design equation, the compact formulations for the pressure drops, the implicit relations for the exchanger geometry and the correction factors for the Bell-Delaware method, as well as the explicit constraints given by Eq. (4). It is well known that the non-convexities of these types of design models may affect the application of typical solution algorithms, with potential convergence problems and the possibility of getting trapped into a local optimum solution. To overcome this problem, we use in this work a genetic algorithm for the solution of the optimization problem. Genetic algorithms are search methods based on the combination of natural selections and genetics. They are based on the principle of survival of the fittest, and provide a search method that is extremely efficient and virtually independent of the non-convexities of mathematical models (Goldberg, 1989).
Fig. 1 shows the main steps of the proposed approach; notice how Eq. (4) is implemented trough the use of a penalty term.

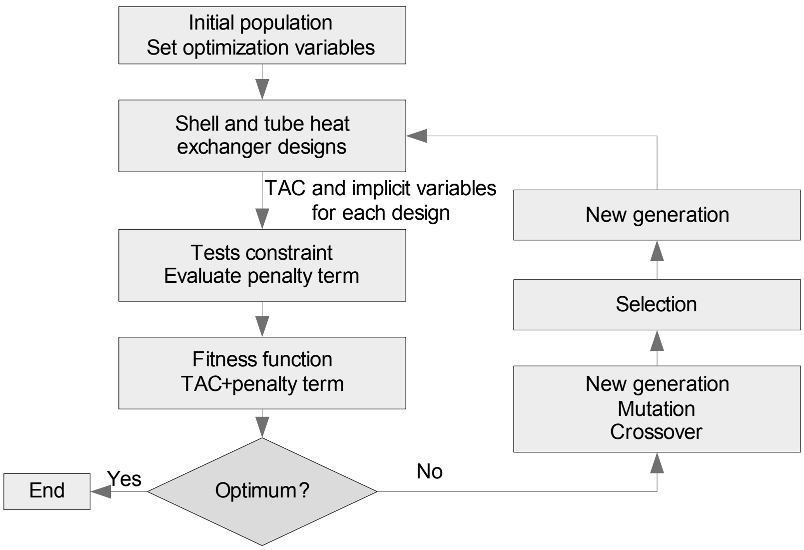

Fig. 1. Solution strategy for the optimization problem

4. Results and Discussion

The example presented here was reported by Mizutani et al. (2003). The design data are shown in Fig. 2. For the solution of this example, a constraint in the tube length of 4.88 m was imposed.
A summary of the results obtained with the proposed model is given in Table 1, where the solution reported by Mizutani et al. (2003) is also shown for comparison. Mizutani et al. (2003) used a disjunctive programming optimization method to solve this problem. It can be observed that the proposed algorithm provided a better solution than the one obtained by Mizutani et al. (2003). This is a clear case in which the solution provided by a standard optimization approach was trapped into a local optimum value. In contrast, the proper use of genetic algorithms can provide a global optimum (or an

excellent near-optimal) solution. For the solution of this problem we used a population size of 20 individuals, and obtained the final solution in 30 min of real time.

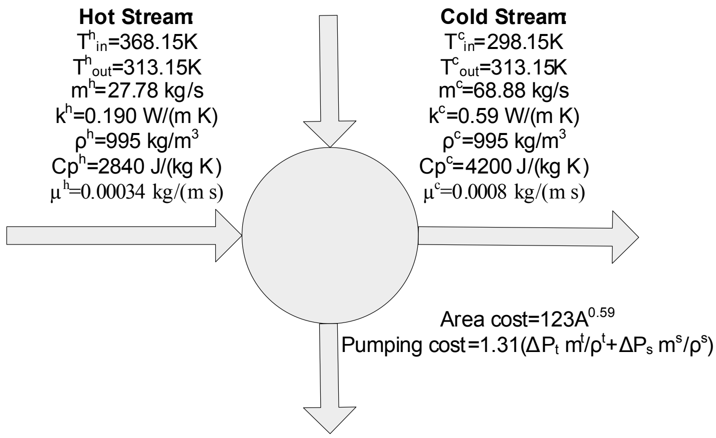

Fig 2. Data for the example

Table 1. Example results

	Mizutani et al.	**This work**
Area (m^2)	202	242.881
U (W/m^2 K)	860	714.511
Number of tubes	832	653
Tube layout	square	triangular
Number of tube passes	2	6
D_{in} (mm)	12.6	22.918
D_{out} (mm)	15.9	25.4
Number of baffles	8	8
Head type	fixed	pull floating
Hot fluid allocation	shell	tube
$F_T*\Delta T_{LM}$	24.9	25.004
Shell diameter (m)	0.687	1.10534
Tube length (m)	4.88	4.88
Baffle spacing (m)	0.542	0.516275
ΔP_t (Pa)	22676	10981.3
ΔP_s (Pa)	7494	4714.28
Pumping cost ($/year)	2424	960.361
Area cost ($/year)	2826	3142.59
Total annual cost ($/year)	**5250**	**4102.95**

5. Conclusions

In this work, an optimization model for the design of a shell and tube heat exchanger has been proposed. The model includes the Bell-Delaware correlations for the shell-side fluid, which provides a suitable representation of the fluid flow pattern within the shell. The optimization strategy is based on the use of a genetic algorithm, in which the geometric and operational constraints have been implemented through the use of a penalty function. Genetic algorithms are in general more efficient in terms of providing excellent optimum solutions than other standard optimization methods, which frequently get trapped into local optimum solutions when applied to nonconvex models. The results of the case study show how a reported optimum solution using a disjunctive programming technique was noticeably improved with the use of the proposed method. The main limitation of the proposed algorithm is its high demand of CPU time, but this problem is overcome satisfactorily with the advance in the speed of the current computers.

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