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Design optimization of shell and tube heat exchangers using global sensitivity analysis and harmony search algorithm

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ABSTRACT

This study explores the use of global sensitivity analysis (GSA) and harmony search algorithm (HSA) for design optimization of shell and tube heat exchangers (STHXs) from the economic viewpoint. To reduce the size of the optimization problem, non-influential geometrical parameters which have the least effect on total cost of STHXs are identified using GSA. The HSA which is a meta-heuristic based algorithm is then applied to optimize the influential geometrical parameters. To demonstrate the effectiveness and accuracy of the proposed algorithm, an illustrative example is studied. Comparing the HSA results with those obtained using genetic algorithm (GA) reveals that the HSA can converge to optimum solution with higher accuracy.

1. Introduction

Shell and tube heat exchangers (STHXs) are the most widely used heat exchangers in process industries because of their relatively simple manufacturing and their adaptability to different operating conditions. The design of STHXs, including thermodynamic and fluid dynamic design, cost estimation and optimization, represents a complex process containing an integrated whole of design rules and empirical knowledge of various fields [1].

There are many previous studies on the optimization of heat exchangers. Several investigators have used different strategies based on simulated annealing [2], genetic algorithm [1,3–8] and traditional mathematical optimization algorithms [9–11] for various objectives like minimum entropy generation [3,12,13] and minimum cost of the STHXs [1,7–11,14]. Some of these studies focuses mainly on a single geometrical parameter like optimum baffle spacing [9,10,15] and some others try to optimize a variety of geometrical and operational parameters of the STHXs.

Determination of the most influential parameters from a set of the candidate design parameters can greatly affect the performance of the optimization process. There has been some parametric studies on air cooled heat exchangers (ACHEs) trying to investigate the influence of the design parameters on the performance of the ACHEs [13,16] and some similar studies have been done on STHXs [3,9,17]. However, most of these works only study the effect of single parameter change while the other parameters of the heat exchanger are evaluated at a selected point in parameter space. For a problem whose sensitivity feature varies from one region of the parameter space to another, this type of parameter study would not shed much light in understanding the sensitivity behavior of the problem over the entire domain of parameter space. In order to determine the influential input parameters over defined parameter space global sensitivity analysis (GSA) should be performed.

The main objectives of this study are (a) to identify the most influential geometrical parameters that affect total cost of STHXs by means of GSA in order to reduce the size of the optimization problem and (b) to optimize the influential parameters of STHXs from economic point of view. The HSA which is a recently developed meta-heuristic algorithm is used for design optimization of STHXs. The algorithm ability is demonstrated using an illustrative example. The HSA results are compared with those obtained using genetic algorithm (GA) on the same example.

2. Mathematical model

2.1. Heat transfer

The tube side heat transfer coefficient (h_t) for the fluid inside the tube in the turbulent zone and the transitional zone, are given by the following correlations respectively [13]:

$$h_t = h' + \frac{Re-2100}{10000-Re}\left[0.23\frac{\lambda}{D_t}Re^{0.8}Pr^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14} - h'\right] 2100 \leqslant Re_t \leqslant 10000 \quad (1a)$$

$$h' = \left[3.66 + \frac{0.085Gz}{1+0.047Gz^{2/3}}\left(\frac{\mu}{\mu_w}\right)^{0.14}\right]\frac{\lambda}{D_t}$$

$$h_t = 0.23\frac{\lambda}{D_t}Re_t^{0.8}Pr_t^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14} \quad Re_t \geqslant 10000 \quad (1b)$$

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Nomenclature

A	heat transfer area (m^2)	Pr	Prandtl number
B_c	baffle cut	Re	Reynolds number
C_c	capital cost ($)	S_i	first-order sensitivity index
$C_{Capital}$	annual capital cost ($/yr)	S_{Ti}	total sensitivity index
$C_{operating}$	annual operating cost ($/yr)	T	temperature, (°C, K)
C_{Total}	annual total cost ($/yr)	TL	technical life (year)
Cp	Heat capacity (J/kg K)	TP	operating time (h/yr)
D_s	inside shell diameter (m)	$V()$	total variance
D_t	tube outside diameter	ΔP_s	shell side pressure drop (Pa)
ec	energy cost ($/kWh)	ΔP_c	pressure loss of the pure transverse flow (Pa)
$E_{\Delta P}$	pumping power (kW)	ΔP_w	pressure loss in the baffle windows (Pa)
f	friction factor	ΔP_e	pressure loss in the end zones (Pa)
G	mass flow rate per unit area (kg/m^2 s)	ΔP_{bi}	ideal tube bank pressure loss (Pa)
Gz	Graetz number		
h	heat transfer coefficient (W/m^2K)	*Greek letters*	
i_R	interest rate	λ	thermal conductivity (W/m K)
L	length (m)	μ	viscosity (kg/m s)
L_{bc}	central baffle spacing (m)	ρ	fluid density (kg/m^3)
L_{tp}	tube pitch (m)	θ_{tp}	tube layout characteristic angle (deg)
$L_/ D_s$	length ratio	η	pump efficiency
$L_{bc/} D_s$	baffle spacing ratio		
$L_{tp/} D_t$	pitch ratio	*Subscripts*	
$\dot{m}$	mass flow rate (kg/s)	s	shell
Mat	material type	t	tube
N_{ss}	number of sealing strips (pairs)	w	wall
N_{tp}	number of tube passes		

The average shell side heat transfer coefficient is given by Bell-Delaware method [18], in which the effect of the gap and by-pass caused by the baffles is taken in consideration.

$$h_s = h_i J_c J_l J_b J_s J_r \tag{2}$$

where h_i is the heat transfer coefficient for an ideal tube bank and J_c, J_l, J_b, J_s, J_r are the correction factors. Details of the individual heat transfer coefficient calculations and the related correction factors given in Eq. (2) can be found in [19].

2.2. Pressure drop

The tube side pressure drop (ΔP_t) is given by the following expression [20]:

$$\Delta P_t = \frac{2 f_t G_t^2 L N_{tp}}{D_t \rho_t \, (\mu/\mu_w)^{0.14}} \tag{3}$$

where G_t is the tube side mass flow rate per unit cross-sectional area, N_{tp} is the number of tube passes and f_t is the tube side friction factor. The tube side friction factor for commercial pipe or slightly corroded tubes is given by Saunders [20] as

$$f_t = 0.0035 + \frac{0.264}{Re_t^{0.42}} \quad Re_t \geqslant 2100 \tag{4}$$

The shell side pressure drop (ΔP_s) includes the pressure loss of the pure transverse flow in the zone between the tops of the baffles (ΔP_c), the pressure loss in the baffle windows (ΔP_w) and the pressure loss in the end zones of the heat exchanger (ΔP_e) [19]:

$$\Delta P_s = \underbrace{\Delta P_{bi}(N_b - 1) R_b R_l}_{\Delta P_c} + \underbrace{N_b\left[(2 + 0.6 N_{tcc}) \frac{m_s}{2\rho_s} \times 10^{-3}\right] R_l}_{\Delta P_w} + \underbrace{\Delta P_{bi}\left(1 + \frac{N_{tcw}}{N_{tcc}}\right) R_b R_s}_{\Delta P_e} \tag{5}$$

where ΔP_{bi} is the ideal tube bank pressure loss, R_b is the revised factor, R_l is the leakage factor and R_s is the end zone correction factor. Details of the individual pressure drop calculations and the related correction factors given in Eq. (5) can be found in [19].

3. Sensitivity analysis

Sensitivity analysis is a general concept which aim is to quantify the variations of an output parameter of a system with respect to changes imposed to some input parameters. Sensitivity analysis is used for thermal design studies to understand the relationships and study the impact of input parameters on different simulation outputs [21].

3.1. Global sensitivity analysis

The Sobol method [22], a variance-based technique, is used to test the sensitivity of the parameters. The model can be represented in the form of $Y = f(x_1, x_2 \ldots, x_k)$, where $x_1, x_2 \ldots, x_k$ are input factors and Y is the model output. In this study Y represents the total cost of the STHX and related input factors which are the geometrical parameters of the exchanger are shown in Table 1. The range of variation of these parameters is based on recommended values of heat exchanger design handbook [19].

Table 1
The geometrical parameters of heat exchanger

Parameters	Range of variation
D_s	398–1186 mm
D_t	14–44.5 mm
$L_{tp/}D_t$	1.25–1.5
θ_{tp}	30, 45, 90
$L_/D_s$	3–12
B_c	10–40%
$L_{bc/}$ D_s	0.2–1.0
N_{ss}	1–4
N_{tp}	2–6
Mat	Admiralty, carbon steel, copper–brass