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

M. Fesanghary [a,*], E. Damangir [a], I. Soleimani [b]

[a] Department of Mechanical Engineering, Amirkabir University of Technology, 424-Hafez Avenue, 15875-4413 Tehran, Iran
[b] Department of Chemical Engineering, Amirkabir University of Technology, 424-Hafez Avenue, 15875-4413 Tehran, Iran

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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]:

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

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

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

* Corresponding author. Tel.: +98 21 66405844; fax: +98 21 66419736.
E-mail address: fesanghary@gmail.com (M. Fesanghary).

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Nomenclature

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

Greek letters

λ	thermal conductivity (W/m K)
μ	viscosity (kg/m s)
ρ	fluid density (kg/m^3)
θ_{tp}	tube layout characteristic angle (deg)
η	pump efficiency

Subscripts

s	shell
t	tube
w	wall

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

The total variance of Y,$V(Y)$, is partitioned as follows [23,24]:

$$V(Y) = \sum_{i=1}^{k} V_i + \sum_{1 \leqslant i \prec j \leqslant k} V_{ij} + \ldots + V_{1,2,\cdots,k} \tag{6}$$

where $V(Y)$ is the total variance of the output variable Y. $V_i = V[E(Y|x_i)]$ measures the main effect of the parameter x_i, and the other terms measure the interaction effects. The Eq. (6) is used to derive two types of sensitivity indices defined by

$$S_i = \frac{V_i}{V(Y)} \tag{7}$$

$$S_{Ti} = 1 - \frac{V_{-i}}{V(Y)} \tag{8}$$

where V_{-i} is the sum of all the variance terms that do not include the index i. S_i is the first-order sensitivity index for the ith parameter. This index represents the main effect of parameter x_i on the output variable Y and measures the variance reduction that would be achieved by fixing (or reducing the range of) that parameter. The values of S_i, $i = 1 \ldots k$, can be used to provide a mean to rank individual variable importance on the basis of contribution to the variance of Y. This is called 'Factor Prioritisation setting' [25].

S_{Ti} is the total sensitivity index for the ith parameter and is the sum of all effects involving the parameter x_i. S_{Ti} takes into account the interactions between the ith parameter and the other parameters. The total sensitivity index can be thought as the expected fraction of variance that would be left if only the parameter x_i were to stay undetermined. S_{Ti} can be used for model reduction purposes; when a factor does not have any effect both on its own and in cooperation with others, it can be considered as non-influential and can be fixed to any value within its range of uncertainty. This is called 'Factor Fixing setting' [25].

The sensitivity indices can be computed using a Monte Carlo method [26]. The principle is to generate randomly samples of parameters within their permissible ranges and to estimate $V(Y)$,V_i and V_{-i} as follows:

(1) Choose a base sample dimension N.

(2) Generate two random input sample matrices $\boldsymbol{M}_1$ and $\boldsymbol{M}_2$ of dimension $N \times k$:

$$M_1 = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1i} & \cdots & x_{1k} \\ x_{21} & x_{22} & \cdots & x_{2i} & \cdots & x_{2k} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{N1} & x_{N2} & \cdots & x_{Ni} & \cdots & x_{Nk} \end{bmatrix} \quad M_2 = \begin{bmatrix} x'_{11} & x'_{12} & \cdots & x'_{1i} & \cdots & x'_{1k} \\ x'_{21} & x'_{22} & \cdots & x'_{2i} & \cdots & x'_{2k} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x'_{N1} & x'_{N2} & \cdots & x'_{Ni} & \cdots & x'_{Nk} \end{bmatrix}$$

(3) Define a matrix N_i formed by all columns of $\boldsymbol{M}_2$, except the ith column which is taken from $\boldsymbol{M}_1$, and a matrix N_{Ti} complementary to N_i, formed with the ith column of $\boldsymbol{M}_1$ and with all the remaining columns of $\boldsymbol{M}_2$:

$$N_i = \begin{bmatrix} x'_{11} & x'_{12} & \cdots & x_{1i} & \cdots & x'_{1k} \\ x'_{21} & x'_{22} & \cdots & x_{2i} & \cdots & x'_{2k} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x'_{N1} & x'_{N2} & \cdots & x_{Ni} & \cdots & x'_{Nk} \end{bmatrix} \quad N_{Ti} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x'_{1i} & \cdots & x_{1k} \\ x_{21} & x_{22} & \cdots & x'_{2i} & \cdots & x_{2k} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{N1} & x_{N2} & \cdots & x'_{Ni} & \cdots & x_{Nk} \end{bmatrix}$$

(4) Compute the model output for all the input values in the sample matrices M_1, and, obtaining three column vectors of model outputs of dimension $N \times 1$:

$$Y = f(M_1), \quad Y' = f(N_i), \quad Y'_T = f(N_{Ti})$$

(5) The sensitivity indices are computed based on scalar products of the above defined vectors of model outputs.

$$f_0 = \frac{1}{N} \sum_{j=1}^{N} Y^j \quad \text{(The mean)} \tag{9}$$

$$V = \frac{1}{N} \sum_{j=1}^{N} (Y^j)^2 - f_0^2 \ \text{(The total variance)} \tag{10}$$

$$V_i = \frac{1}{N} \sum_{j=1}^{N} Y^{(j)} Y'^{(j)} - f_0^2 \tag{11}$$

$$V_{-i} = \frac{1}{N} \sum_{j=1}^{N} Y^{(j)} Y_T'^{(j)} - f_0^2 \tag{12}$$

and finally

$$S_i = \frac{V_i}{V(Y)} \quad S_{Ti} = 1 - \frac{V_{-i}}{V(Y)}$$

It should be noted that negative values may be obtained for some parameters that have a small influence on the model outputs. This is due to numerical errors in the estimates and increasing the sample size will fix the problem.

4. Objective function and optimization methodology

The harmony search algorithm (HSA) has been recently developed by Geem et al. [27]. The HSA is simple in concept, few in parameters, and easy in implementation. It has been successfully applied to various benchmark and real-world optimization problems [28–31].

The HSA presenting several advantages with respect to traditional optimization techniques such as the following [32]:

(a) The HSA imposes fewer mathematical requirements and does not require initial value settings of the decision variables.
(b) As the HSA uses stochastic random searches, derivative information is also unnecessary.
(c) The HSA is capable of searching for solutions from disjointed feasible domains.

These features increase the applicability of the HSA, particularly in thermal systems design, where the problems are usually nonconvex and have a large amount of discrete variables or discontinuity in the objective function. Based on our earlier experience in engineering optimization [9,10,33–36] a harmony search algorithm has been developed and applied to the design optimization problem.

4.1. Objective function

The final goal is to find the optimal design of a STHX which is capable of accomplishing the prescribed thermal duty with minimum combined investment and operating cost. The capital cost of a STHX can be estimated using the following formula [37,38]:

$$C_c = aA^b \tag{13}$$

where a and b are the cost coefficient constants. These parameters are dependent to material type and total area of exchanger as shown in Table 2.

The pumping power can be determined from the equation below [19]:

$$E_{\Delta P} = \frac{\dot{m}_t \Delta P_t}{\eta \rho_t} + \frac{\dot{m}_s \Delta P_s}{\eta \rho_s} \tag{14}$$

where η is the pump efficiency. The annual operating, capital and total cost can be expressed by Eqs. (15), (16), respectively.

Table 2
Cost coefficients of heat exchanger

Material	A < 9 m^2		9 m^2 < A < 90 m^2		A > 90 m^2	
	a	b	a	b	a	b
Carbon steel (CS)	4284	0.342	2694	0.551	1443	0.680
Admiralty	3135	0.463	1957	0.679	1042	0.810
Copper–brass	3728	0.472	2371	0.679	1268	0.810

$$C_{\text{operating}} = \text{TP.ec.}E_{\Delta P} \tag{15}$$

$$C_{\text{Capital}} = C_{\text{c}} \cdot \frac{i_{\text{R}}(1+i_{\text{R}})^{\text{TL}}}{(1+i_{\text{R}})^{\text{TL}}-1} \tag{16}$$

$$C_{\text{Total}} = C_{\text{operating}} + C_{\text{Capital}} \tag{17}$$

TP, i_R, TL and ec are the period of the time of operation per year, interest rate, technical life and the unit cost of the energy respectively.

5. Illustrative example

As an example the following problem is considered. 63.77 kg/s of light oil enters the exchanger at 102 °C and is to be cooled down to 64 °C by 45 kg/s of water entering at 21 °C. A heat load of 5275.4 kW between the two fluids is found, which means that the water is leaving at 49 °C. Maximum allowable pressure drops of 20 kPa are imposed on both sides. Process condition and physical properties used for this problem have been given in Table 3.

6. Results and discussion

6.1. Sensitivity analysis results

Global sensitivity analysis is performed to assess the relative sensitivity of each model parameter. Through extensive Monte Carlo simulations, it is found that some geometric parameters of the STHX are rather insensitive. If the values of these insensitive parameters are fixed, a simplified model which reduces the complexity of the search space is obtained. The simplified model will be used to optimize the total cost of heat exchanger. For each heat exchanger geometries studied, the GSA of the total cost of the exchanger with respect to changes on the geometrical parameters of STHX is calculated. The results of the GSA have been summarized in Figs. 1 and 2.

In Fig. 1, the first-order sensitivity index for the total cost of the exchanger has been shown. It can be seen that the most sensitive parameter is D_s and the parameters like N_{tp},L_{bc}/D_s, and D_t have significant effect on exchanger cost. The total cost is less sensitive to parameters like B_c, L_{tp}/D_t and N_{ss}.

Fig. 2 shows the total sensitivity index for the total cost of the exchanger. It can be observed that N_{ss} does not have significant effect both on its own and in cooperation with others, so it can be considered as non-influential parameter and could be excluded in optimization step. Although the first-order sensitivity indexes of B_c and L_{tp}/D_t are small, cooperation of these parameters with other parameters is rather significant (more than 0.05) and can not be neglected.

Finally, it can be concluded that from the geometric parameters presented in Table 1 only N_{ss} could be excluded and the other parameters will be used in optimization step.

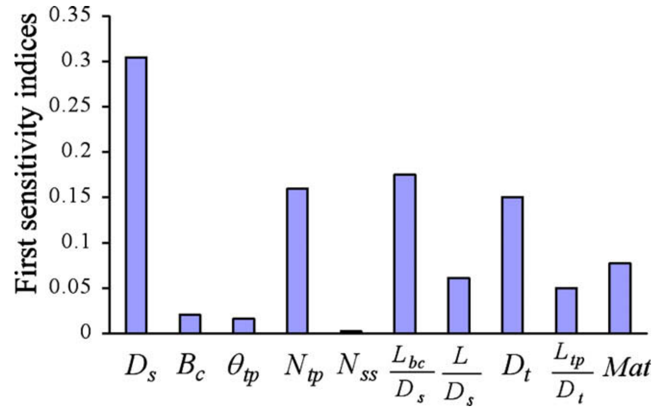

Fig. 1. First-order sensitivity indices of total cost.

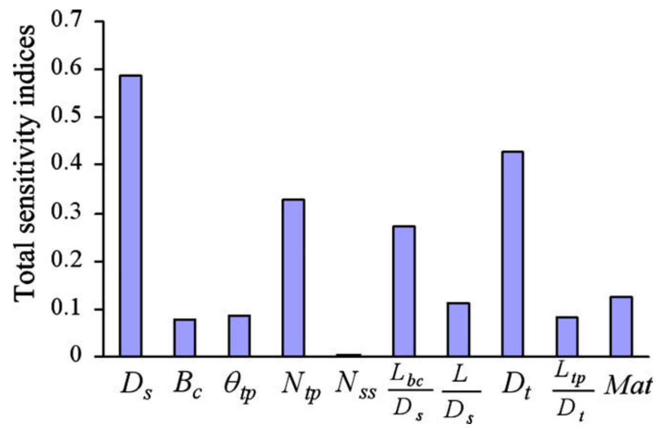

Fig. 2. Total sensitivity indices of total cost.

Table 3
The process requirements and physical properties

	Tube side (water)	Shell side (oil)
μ (kg/m s)	0.00072	0.00189
Cp (J/kg K)	4187	2177
λ (W/m K)	0.613	0.122
ρ (kg/m^3)	995	786.4
T (°C)	21/49	102/64
$\dot{m}$(kg/s)	45	63.77
ΔP_{allow} (kPa)	20	20

TP = 8000 h/yr, ec = 0.1 \$/kW h, TL = 10 years, i_R = 0.2, η = 0.85

6.2. Optimization results

For the given example with the process requirements, as shown in Table 3, the geometrical parameters are optimized using harmony search algorithm. To show the ability of the HAS, its performance is compared with genetic algorithm.

Although both GA and HSA have proven their abilities in finding near global solutions within a reasonable time, they are comparatively inefficient in finding the precise optimum solution. To evaluate the accuracy and precision of the obtained results, the global optimum solution is also calculated considering all possible exchanger geometries. Thus, first the continuous variables are divided to 100 equal sections in their range of variations, considering discrete variables a total number of 67,797,000,000 combinations are obtained. Then all the candidate solutions are examined to find the optimal solution.

The GA and HSA parameters as used in this study are listed in Table 4. The comparison between the results is shown in Table 5. Results reveal that both HSA and GA can converge to near optimal

Table 4
Genetic and harmony search parameters

Parameters/operators	Value/method
Genetic algorithm	
Population size	50
Population replacement	45
Probability of crossover	0.85
Probability of mutation	0.10
Crossover	Two-point crossover
Mutation	Permutation
Selection	Tournament
Harmony search algorithm	
Pitch adjusting rate	0.2–0.85
Memory considering rate	0.6
Harmony memory size	10
Bandwidth	0.01–4.0

Table 5
Optimal heat exchanger geometry

	Global optimum	GA	HSA
D_s (mm)	888	888	888
D_t (mm)	30	30	30
L_{tp} (mm)	37.8	37.50	37.75
θ_{tp} (deg)	90	45	90
L (mm)	3525.26	3670.92	3522.22
B_c (%)	15	17	14
L_{bc} (mm)	506.16	416.24	507.13
N_{tp}	4	4	4
Number of tubes	356	361	357
Material	CS	CS	CS
A_{total} (m^2)	118.27	124.89	118.51
ΔP_s (kPa)	17.96	14.51	18.04
ΔP_t (kPa)	8.10	8.27	8.10
$C_{operating}$ ($/yr)	1715.3	1459.3	1721.8
$C_{capital}$ ($/yr)	8838.2	9171.2	8850.2
C_{Total} ($/yr)	10553.4	10630.5	10572.0
Run-time (s)	591453	13.12	8.38

solutions in a reasonable time. The difference between the global optimum and those obtained using HSA is 0.2 percent. This difference becomes 0.7 percent for the GA. Note that the time required to find global optimal solution evaluating all possible combinations is about 164 hours on an Intel Pentium IV 2.4 GHz CPU while it takes only few seconds for GA or HSA to find the near optimal solutions.

7. Conclusions

This study demonstrates successful application of harmony search algorithm for the optimal design of shell and tube heat exchangers. The HSA is simple in concept, few in parameters and easy for implementation. Moreover, it does not require any derivative information. These features increase the applicability of the HSA, particularly in thermal systems design, where the problems are usually non-convex and have a large amount of discrete variables or discontinuity in the objective function. One of the features presented in this study is the use of global sensitivity analysis. The aim of the sensitivity analysis is to identify geometrical parameters that have the largest impact on total cost of STHXs. The GSA could successfully found the most important parameters. The algorithm ability was demonstrated using an illustrative example and the performance was compared with genetic algorithm. Results reveal that the proposed algorithm can converge to optimum solution with higher accuracy in comparison with genetic algorithm.

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