Application of Symbiotic Organisms search technique for design optimization of shell and tube heat exchanger from economic point of view

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Abstract. Refineries and process plants are the industries having wide use of shell and tube heat exchangers. Being a key component of the industry the cost optimization is the main concern of the designer and the end user. The design of shell and tube heat exchanger is a complex procedure involving several geometric parameters and operating parameters. For a given heat duty there are several possible combinations of geometric and operating parameters with typical geometrical constraints. Traditional designs are time consuming and do not assure an optimal design. The present study explores the application of a newly developed metaheuristic symbiotic organisms search (SOS) for the optimization of shell and tube heat exchanger. The overall cost comprising of the initial cost and operating cost is considered as the objective function and baffle spacing, shell internal diameter and tube outer diameter are the design variables considered. A benchmark shell and tube heat exchanger design problem is solved using above technique and result are compared for the same problem being solved using other metaheuristics like Genetic Algorithm and Particle Swarm Optimization.

Keywords: Shell and tube heat exchanger (STHX), Optimization, Symbiotic organisms search.

1. Introduction

Heat exchange between two fluids is the prime reason for using heat exchangers. Being simple in manufacturing and versatile in having different operating characteristics STHX are being extensively operated in industrial process and refineries. Several design methodologies are proposed by various researchers, however being versatile and most commonly used, Kern's and Bel Delaware formulation is being used for present work. Initial design is done using fixed set of geometric parameters and maximum allowable pressure drop. The other design variables taken are considered to provide a heat transfer coefficient which gives best utilization of the surface area. Furthermore, in the optimization procedure various iterations are carried out using proposed technique ultimately providing a most optimum set of design variables. Investigators and researchers have been using several metaheuristics for above purpose.

2. Literature Review

Prosenjit Chaudhari and Urmila Diwekar [1] used simulated annealing technique for heat exchanger optimization. Fabio T mizutani [2] utilized MINLP to minimize the operational cost providing best set of design variables. J M P Ortega et al [3] utilized GA (genetic algorithm) for optimum configuration of STHX, same team also used MINLP programming for lower initial cost design of multiple STHX. Dogan Eryener [4] used thermo economic optimization method for optimal baffle spacing which is now widely used. Y A kara and O Guararas [5] developed software code for the design of STHX. Optimization procedure can be easily utilized along with their developed computer code. R Selbas, O Kizilkan [6] used GA for the optimization of STHX. The geometric parameters considered were tube passes, sequential baffle space, tube outer diameter, baffle cut and diameter of shell. Several instance of using GA have been found thereafter [7-10]. Maintenance aspects [7] along with other design variables were taken into account taking fouling as a main consideration. However the maintenance consideration converged to higher costs for the equipment. Here the consideration of a network of heat exchanger in series or furthermore the effect of fouling can be taken as transient (time dependent) to converge to a more realistic solution of a design problem [11]. Using a set of initial given values, the required geometry was calculated using Genetic Algorithm, the author suggested that pressure drop and NTU should be in conjunction to achieve the best possible configuration of the heat exchanger [12]. Multi Objective optimization was the next big research in this area. The compact formulation of Bell delaware design was used for predicting the shell side parameters along with Genetic Algorithm [13].

M.Fesanghary et al [14] performed analysis using harmony search. On close examination of the results the HAS proved to be better than GA and converges to better optimal solution with higher accuracy. M A S S Ravagnani [15] used the Particle Swarm Optimization method for optimization of STHX. It was shown that the PSO provides optimum results avoiding local minima. Patel and Rao [16] utilized the PSO for optimum solution of a STHX design problem. The cost optimization was considered as the objective function. A S Sahin et al [17] used the artificial bee colony algorithm for the optimum design of STHX. H Hajabdollahi et al [18] used particle swarm and genetic algorithm for design optimization of STHX. Rao and Patel [19] performed the analysis using modifications in basic teaching learning based optimization technique. This algorithm simulates the learning outcomes in class room. TLBO is the latest development in the field of meta-heuristics algorithms and it's a parameter free algorithm. A Hadidi and A Nazari [20] used the Bio geography based algorithm [BBO] and Imperialist competitive algorithm [ICA] for STHX. A VAzad and M Amidpour [21] used the constructional theory for optimization of STHX. S Fettaka et al [22] used the NSGA-II for multi objective optimization of STHX. Masoud Asadi et al [23] applied the cuckoo search algorithm for the same purpose. The results were superior as compared to PSO and GA. H. Sadeghzadeh et al [24] recently applied the GA and PSO for the techno economic optimization of STHX.

3. Mathematical modelling and objective function formulation for STHX

Nomenclature

	Subscripts	Re	Reynolds number
i	Inner	N_s	number of shells in series
o	Outer	L_{bc}	central baffles spacing [m]
s	Shell side	L	Tube length [m]
t	Tube side	d_i	Tube diameter inside [m]
w	Tube wall	d_o	Tube diameter outside [m]
	Greek Symbols	Pr	Prandtl number
μ	dynamic viscosity [Pa s]	P	Pumping power [W]
ΔT_{lm}	logarithmic mean temperature difference	Pt	tube pitch
τ	Operational hours per year [hr/yr]	Q	heat transfer rate [W]
η	Overall pump efficiency	$A_{o, cr}$	flow area at or near the shell centreline for one cross flow section [m2]
Δp	Pressure drop [Pa]	$A_{o, sb}$	Leakage flow area shell to baffle [m^2]
		C_{in}	Total investment cost [INR]
N_b	number of baffles	C_o	Annual operating cost [INR/yr]
n_p	number of tube passes	C_{op}	Total Operating cost [INR]
n_y	Life of equipment [yr]	C_p	Specific heat at constant pressure [KJ/kg K]
D_{otl}	Tube bundle outer diameter [m]	C_{total}	Total cost [INR]
h_i	tube side heat transfer coefficient [W/m^2 K]	k_{el}	price of electrical energy [INR/Kwh]
h_o	shell side heat transfer coefficient [W/m^2 K]	N_t	number of tubes
m	mass flow rate [kg/s]	d_s	shell diameter [m]
$R_{i,f}$	Inner fouling resistance [m^2K/W]	F	correction factor for the number of tube passes
$R_{o,f}$	Outer fouling resistance [m^2K/W]	λ	annual discount rate [%]
k	thermal conductivity [W/m K]	J	correction factor for shell side heat transfer
U_0	overall heat transfer coefficient [W/m^2 K]	S	heat transfer surface area [m^2]

The surface area A of the STHX can be determined by [25, 26]:

$$A = \frac{Q}{U_o \Delta T_{lm} F} \quad (1)$$

The notations carry the meaning as written in the nomenclature.

The U_0 can be calculated from [6]:

$$U_o = \left[\frac{1}{h_o} + R_{o,f} + \frac{d_o}{d_i}(R_{i,f} + \frac{1}{h_i}) \right]^{-1} \quad (2)$$

Where

$$d_i = 0.8 d_o \tag{3}$$

The notations carry their usual meaning as given in the nomenclature. The LMTD can be calculated from the below equation:

$$\Delta T_{lm} = \frac{(T_{h1} - t_{c2}) - (T_{h2} - t_{c1})}{\ln \frac{(T_{h1} - t_{c1})}{(T_{h2} - t_{c2})}} \tag{4}$$

It is common practice to calculate correction factor using temperature and shell and tube passes to simulate the original exchanger. [27,28].

$$F = \frac{\left(\sqrt{1+R^2}\ln\left(\frac{1-P}{1-RP}\right)\right)}{(R-1)\ln\left(\frac{2-P\left(R+1-\sqrt{1+R^2}\right)}{2-P\left(R+1+\sqrt{1+R^2}\right)}\right)} \tag{5}$$

R and P are function of temperature and can be determined from:

$$R = \frac{T_{h1} - T_{h2}}{t_{c2} - t_{c1}} \tag{6}$$

$$P = \frac{t_{c2} - t_{c1}}{T_{h1} - t_{c1}} \tag{7}$$

Tube Side design,

Tube side coefficient for heat transfer is given by: [29,30,31]:

$$h_i = \left(\frac{k_t}{d_i}\right) 0.116\left(\mathrm{Re}_t^{\,2/3} - 125\right)\mathrm{Pr}_t^{1/3}\left(1+\frac{d_i}{L}\right)^{2/3}\left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{8}$$

For $2100 < \mathrm{Re}_t < 10^4$

$$h_i = \left(\frac{k_t}{d_i}\right) 0.027\,\mathrm{Re}_t^{\,0.8}\,\mathrm{Pr}_t^{\,0.4}\left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{9}$$

For $\mathrm{Re}_t < 10^4$

And

$$h_i = \left(\frac{k_t}{d_i}\right) 1.86\left(\frac{\mathrm{Re}_t\,\mathrm{Pr}_t\,d_i}{L}\right)^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{10}$$

For $\mathrm{Re}_t < 2100$

The above equations are valid for $\left(\frac{\mathrm{Re}_t\,\mathrm{Pr}_t\,d_i}{L}\right)^{1/3}\left(\frac{\mu}{\mu_s}\right)^{0.14} > 2$

Whereas for $\left(\frac{\mathrm{Re}_t\,\mathrm{Pr}_t\,d_i}{L}\right)^{1/3}\left(\frac{\mu}{\mu_s}\right)^{0.14} < 2$, the relation used is:[29]

$$h_i = 3.66\frac{k_t}{d_i} \tag{11}$$

The required properties are taken from the mean temperature property tables. Tube side Reynolds number is evaluated from the basic equation: [29]

$$\mathrm{Re}_t = \frac{m_t d_i}{\mu_t A_{ot}} \tag{12}$$

For one tube pass, the flow cross sectional area is evaluated from: [32]

$$A_{o,t} = \frac{\pi d_i^2 N_t}{4 n_p} \tag{13}$$

The number of tubes is estimated by [33,6,34,16]

$$N_t = k_1 \left(\frac{D_{otl}}{d_o} \right)^{n_1} \quad 14$$

The coefficient values k_1 and n_1 are determined from the literature[27].

The pressure drop along the tube flow is given by: [26,35]

$$\Delta P_t = \frac{v_t^2}{2} \left(\frac{f_t.L}{d_i} + y \right).n_p \quad 15$$

Researchers have been using different values of *y*. Kern suggested y = 4 whereas sinnot et al used y = 2.5. While referring to the benchmark problem appropriate value will be taken. Turbulent flow friction factor is calculated as: [25]

$$f_t = 0.046 \left(\mathrm{Re}_t \right)^{-0.25} \quad 16$$

Shell side design:

Bell and Delaware suggested the below correlation having different correction factors for determination of heat transfer coefficient for shell flow: [26].

$$h_o = h_{id} J_c J_l J_b J_s J_r \quad 17$$

Where h_{id} denotes the ideal heat transfer coefficient. Here the J with different subscripts represents various correction factors for real time design.

The ideal heat transfer coefficient is calculated as: [25]

$$h_{id} = J_{id} C_p \left(\frac{m_s}{A_{o,cr}} \right) \left(\frac{k_s}{C_p \mu_s} \right)^{2/3} \left(\frac{\mu_s}{\mu_{s,w}} \right)^{0.14} \quad 18$$

The notation carry their usual meaning and J_{id} is the colburn coefficient, which is expressed as: [25,7]

$$J_{id} = a_1 \left(\frac{1.33}{\frac{p_t}{d_o}} \right)^a \left(\mathrm{Re}_s \right)^{a_2} \quad 19$$

Where:

$$a = \frac{a_3}{1 + (0.14 \mathrm{Re}_s^{a_4})} \quad 20$$

$$\frac{p_t}{d_o} = 1.25 \quad 21$$

The empirical value of coefficients a and b are taken from [25].

Here $A_{o,cr}$ is given by:

$$A_{o,cr} = L_{b,c} \left[d_s - D_{otl} + 2 \frac{D_{ctl}}{X_t} \left(P_t - d_o \right) \right] \quad 22$$

Where $A_{o,cr}$ is the cross flow area for the fluid flow at the shell centreline and between baffles. The other notations carry their usual meaning.

Here D_{ctl} (circle diameter of outermost tubes centre) is: [25]

$$D_{ctl} = D_{otl} - d_o \quad 23$$

The corresponding drop of pressure at shell inlet and outlet section as given by Delaware is given by: [25]:

$$\Delta p_s = \left[\left(N_b - 1 \right) \Delta P_{b,id} R_b + N_b \Delta p_{w,id} \right] R_l + 2 \Delta p_{b,id} \left(1 + \frac{N_{r,cw}}{N_{r,cc}} \right) R_b R_s \quad 24$$

Here $N_{r,cc}$ is the amount of tube rows passed during flow through one cross flow and $N_{r,cw}$ is the effective tube rows crossed during flow through one window in segmentally baffled heat exchanger. The pressure drop for flow between two baffles is given as:

$$\Delta p_{b,id} = 4 f_{id} \frac{G_s^2}{2\rho_s}\left(\frac{\mu_{s,w}}{\mu_s}\right)^{0.14} N_{r,cc} \quad 25$$

f_{id} is the friction factor and function of shell side Reynold's number. This corresponds for ideal tube bank.

$$f_{id} = b_1\left(\frac{1.33}{\frac{p_t}{d_o}}\right)^{b}\left(\mathrm{Re}_s\right)^{b_2} \quad 26$$

$$b = \frac{b_3}{1+(0.14\,\mathrm{Re}_s^{b_4})} \quad 27$$

Values for coefficient b_1, b_2, b_3 and b_4 are taken from literature. For window cross section the corresponding pressure drop is:

$$\Delta p_{w,id} = (2+0.6N_{r,cw})\frac{G_s^2}{2\rho_s} \quad 28$$

Moreover, the equations for correction coefficients are taken from [25]

Cost Function (primary objective)

The corresponding cost functions of STHX is given by [37]:

$$C_{op} = \sum_{k=1}^{n_y}\frac{C_o}{(1+\lambda)^k} \quad 29$$

$$C_{in} = 8000 + 259.2A^{0.91} \quad 30$$

Where $C_o = P.k_{el}.\tau$ 31

Is the annual current cost [38], the notations carry their usual meaning. The corresponding pumping power is given by:

$$P = \left(\frac{m_t\Delta p_t}{\rho_t}+\frac{m_s\Delta p_s}{\rho_s}\right).\frac{1}{\eta} \quad 32$$

Henceforth the overall cost is given by:

$$C_{total} = C_{in} + C_{op} \quad 33$$

4. Symbiotic organisms search technique

Cheng and prayogo proposed the SOS algorithm. The SOS mimics the behaviour of natural way of living beings. Mutualism, commensalism and parasitism are the three common behaviour of organisms on which this algorithm is based upon. Like other nature inspired meta heuristics an initial population called the ecosystem is used. Each organism in the ecosystem is having association with a certain fitness value which correlates the degree of adaptation with the objective function [39].

As mentioned the algorithm consists of three phases. The mutualism denotes benefits to both the sides, the commensalism indicates benefits to one and neutral or no effect to another and parasitism indicates benefit to one and harm to other. Each organism randomly interacts with another organism through all phases. This process is repeated through iterations until a stipulated termination criterion is met.

The mathematical representation of all three phases of SOS algorithm can be represented as below.

Mutualism phase:

Let X_i and X_j be randomly selected from the population to interact with each other. Since it is a mutual relation the goal for both is to mutually survive in best possible manner. New candidate solutions can be hence devised as [39]:
$X_{inew} = X_i + random\ (0,1) * (X_{best} – mutual\ vector * BF_1)$
$X_{jnew} = X_j + random\ (0,1) * (X_{best} – mutual\ vector * BF_2)$
$Mutual\ vector = (X_i + X_j)/2$
The benefit factor indicates the random benefit to the concerned organism, either chosen as 1 or 2. It indicated whether the organism benefits fully or partially.
$(X_{best} – mutual\ vector * BF_1)$ indicates the effort to achieve the goal of overall advantage. X_{best} indicates the highest degree of adaptation and hence the target point. The solution is only adapted if their new solution is better than the pre interaction value.

Commensalism phase:

In this phase, again X_i and X_j are randomly selected from the population to interact among themselves. However in this phase X_i is the only beneficiary and X_j will not have any impact on the interaction. Henceforth this phase will give a new fitness value of X_i only if better than pre interaction. This phase can be mathematically represented as below[39]:
$X_{inew} = X_i + random\ (-1,1) * (X_{best} – X_j)$

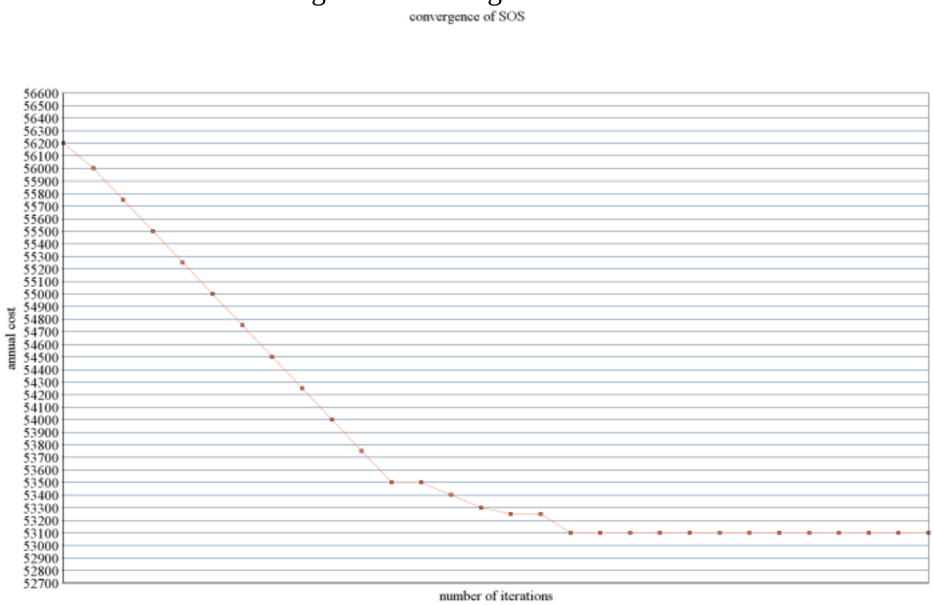
Parasitism phase:

As mentioned this phase will be advantageous to only one organism and other will suffer harm. An artificial parasite vector is created by using organism X_i given the role of a parasite. Parasites generally harm other organism causing their own benefit. Organism X_j will behave as a host to X_i. X_i tries to replace X_j in the population if it has a better fitness value. However if X_j is not affected from $X_{i,}$ it will survive and X_i will not be able to survive in the ecosystem.
Based on the mathematical model of heat exchanger, the total cost is deduced. The procedure is repeated considering new value of area, length and new dimensions of the heat exchanger meeting the specifications. The values of design variables changes as and when the iteration is repeated.
The method used the below approach for calculations:
Step 1: assuming an initial set of geometric variables and calculation of heat transfer area based on given heat duty and other specified properties.
Step 2: calculation of different cost and and hence objective function.
Step 3: subjecting the calculation to SOS technique.
Step 4: Iterative calculation until termination criterion is met.

5. Case Study:
A benchmark heat exchanger design problem is solved using the above methodology. This problem have been used by several researchers mainly Caputo et al [36], hence the solution can be comparatively validated with that of the previously obtained results.
The heat exchanger is to be designed using Methanol and Brackish water as the heat exchanging fluids with 4.34 MW heat duty.
For the design variables, the below upper and lower bounds are imposed so as to have a meaningful design.

$0.1 < D_s < 1.5$, $0.015 < d_o < 0.051$, $0.05 < B < 0.5$
All dimensions are in meters. All values of costs are considered using equipment life of 10 years, annual discount rate of 10%, annual working hours as 7000 hours/year and energy cost of 0.12 €/Kwh. To obtain optimum solution using SOS, the following algorithm parameters are chosen.
No. of organisms (ecosystem/population size) = 50
No. of iterations = 70

Figure 1: Convergence of SOS



The initial population is set considering upper and lower values of design variables.
The design proposed assumed an exchanger of 2-1 configuration.
The increase in the number of tubes decreased the tube side flow velocity and ultimately decreases heat transfer coefficient of tube flow by 1.2% as compared to the literature. The shell side flow heat transfer coefficient is increased by 11.2% because of reduction in shell diameter. The overall heat transfer coefficient increases by an approximate value of 8%.

Table 1: Results obtained using SOS algorithm

Parameter	GA	PSO	SOS (present work)	Parameter	GA	PSO	SOS (present work)
L (m)	3.379	3.115	3.112	d_e ***(m)***	0.011	0.0107	0.01
Do (m)	0.016	0.015	0.015	v_s ***(m/s)***	0.44	0.53	0.63
B (m)	0.5	0.424	0.423	Re_s	11075	12678	13124
D_s ***(m)***	0.83	0.81	0.8	Pr_s	5.1	5.1	5.1
S_t ***(m)***	0.02	0.0187	0.019	h_s ***(W/m²K)***	1740	1950.8	2038
cl (m)	0.004	0.0037	0.0038	f_s	0.357	0.349	0.34
N_t	1567	1658	1642	ΔP_s ***(Pa)***	13267	20551	21136
v_t ***(m/s)***	0.69	0.67	0.66	***U (W/m²K)***	660	713.9	794
Re_t	10936	10503	10492	***A*** (m^2)	262.8	243.2	239
Pr_t	5.7	5.7	5.7	C_i ***(€)***	49259	46453	46125
h_t (w/m^2K)	3762	3721	3715	C_o ***(€/yr)***	947	1038.7	1102
f_t	0.031	0.0311	0.03	C_{od} ***(€)***	5818	6778.2	6988
ΔP_t ***(Pa)***	4298	4171	4156	C_{total} ***(€)***	55077	53231.1	53011
a_s (m^2)	0.0831	0.0687	0.059				

Graph above shows the convergence attained with the number of generations. The analysis has been performed on the scientific computing environment MATLAB.

6. Conclusion

This paper presents the applicability of recently developed optimization metaheuristic symbiotic organism search (SOS) in solving the problem of heat exchanger design. Shell and tube heat exchanger are the most versatile and widely used heat exchanger in process industry, henceforth the demand for geometric and economic optimization keeping the requisite heat duty in mind. SOS algorithm requires simple mathematical coding thereby enhancing performance stability. The algorithm is robust and easy to implement in thermal system design and able to solve optimization problems using less control parameters. A benchmark heat exchanger design problem is solved using the algorithm. An 8% rise in overall heat transfer coefficient is observed using this methodology eventually reducing the surface area and overall costs. The results obtained are compared with that of the same problem solved using Genetic and Particle Swarm Optimization. This method can be used as a suitable and reliable method for heat exchanger design in industrial applications.

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