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Design Optimization of a cross flow plate fin Heat Exchanger using TLBO algorithm

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Abstract- Various types of heat exchangers are widely in use as process equipments for different industrial applications and one of the important types is the plate fin heat exchanger. This study explores basics of plate fin heat exchanger along with its thermal modeling. ε -NTU method is presented to determine heat exchanger pressure drop and effectiveness.

Because of its superior thermal performance at the expense of higher pressure drop, there is need to have balance between these two. Different objectives to optimize plate fin heat exchanger design are presented in this study. Literatures review is presented which mainly focus on plate fin heat exchanger's design was optimized earlier using different types of optimization techniques. This study also presents a meta-heuristic optimization algorithm TLBO (Teaching Learning Based Optimization) along with detailed description of its component.

Various techniques such as particle swarm optimization, genetic algorithm, non-dominated sorting genetic algorithm etc. were used in the past to get optimum objectives and optimum design variables of plate fin heat exchanger. In this work, a TLBO optimization technique is applied for the design optimization of plate fin heat exchanger.

The present work are solved through TLBO algorithm and its results are compared with the results of other methods previously reported in the literature. The results show how previously reported designs can be improved through the use of TLBO algorithm.

Keywords- ***Heat Exchanger, TLBO algorithm, Optimization, cross flow plate fin.***

I. INTRODUCTION

Heat Exchanger is process equipment designed for the effective transfer of heat energy between two or more fluids; a hot fluid and a coolant. The purpose may be either to remove heat from a fluid or to add heat to a fluid. In heat exchangers, there are usually no external heat and work interactions. Typical applications involve heating or cooling of a fluid stream of concern and evaporation or condensation of single or multicomponent fluid streams. The heat transferred in the heat exchanger may be in the form of latent heat (e.g. in boilers and condensers), or sensible heat (in heaters and coolers)

variety of different internal constructions are used in shell and tube exchangers, depending on the desired heat transfer and pressure drop performance and the methods employed to reduce thermal stresses, to prevent leakages, to provide for ease of cleaning, to contain operating pressures and temperatures, to control corrosion, to accommodate highly asymmetric flows, and so on. Shell and tube exchangers are classified and constructed in accordance with the widely used TEMA (Tubular Exchanger Manufacturers Association) standards (TEMA, 1999), other standards in Europe and elsewhere, and ASME (American Society of Mechanical Engineers) boiler and pressure vessel codes. (Edwards, 2008). Fig. 1 shows the schematic diagram of a Shell and Tube heat exchanger.

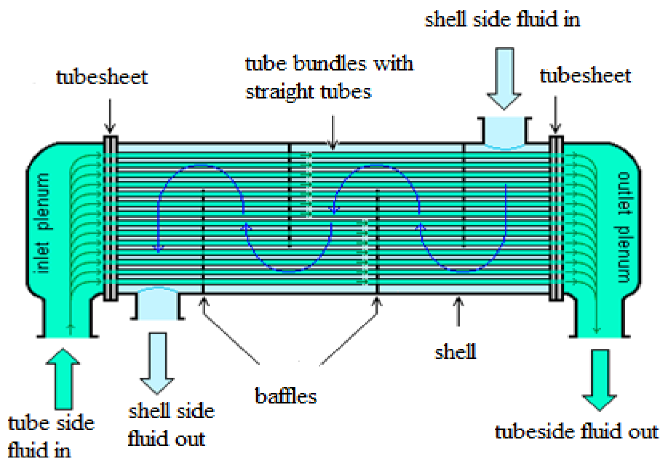

Figure 1 A Shell and Tube heat exchanger (Incropera and DeWitt ,1996)

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There are many previous studies on the optimization of heat exchanger. Several investigators had used different optimization techniques considering different objective functions to optimize heat exchanger design.

Ravagnani et al. (2003) proposed a new methodology to include features like pressure drop and fouling effects which were usually neglected in grassroots as in retrofit designs. Pariyani et al. (2006) presented randomized algorithm with stream splitting for design of heat exchanger networks in this work. Babu and Munawar (2007) applied Differential evolution (DE) and its various strategies for the optimal design of shell and tube heat exchangers. Minimum heat transfer area was main objective in heat exchanger design.

Ravagnani and Caballero (2007) presented an optimisation model for the synthesis of heat exchanger networks (HEN) including the detailed design of the equipments formulated as a decomposition method. Fakheri (2007) proposed methodology for Optimization of Shell and Tube Heat Exchangers in Series. For a given total rate of heat transfer and the known inlet and exit temperatures of the hot and cold fluids, the total area of the heat exchanger network was minimized. Gholap and Khan (2007) proposed a detailed thermodynamic model for a refrigerator based on an irreversible Carnot cycle is developed with the focus on forced air heat exchangers. Caputo et al. (2008) proposed a procedure for optimal design of shell and tube heat exchangers, which utilized a genetic algorithm to minimize the total cost of the equipment including capital investment and the sum of discounted annual energy expenditures related to pumping. Soltan et al. (2008) proposed a computer program enables designers to determine the optimum baffle spacing for segmentally baffled shell and tube condensers.

Costa and Queiroz (2008) formulated problem on design optimization of shell and tube heat exchangers which consists of the minimization of the thermal surface area for a certain service, involving discrete decision variables. Thirumarimurugan et al. (2008) investigated on comparative heat transfer study on a solvent and solutions were made using 1-1 Shell and Tube Heat Exchanger. Steam is the hot fluid; whereas Water and Acetic acid-Water miscible solution serves as cold fluid. Ponce et al. (2009) presented an approach based on genetic algorithms for the optimal design of shell and tube heat exchangers. Patel and Rao (2010) proposed the use of a non-traditional optimization technique; called particle swarm optimization (PSO), for design optimization of shell and tube heat exchangers from economic view point.

Turgut et al. (2014) achieved the economic optimization of the STHE design using intelligent tuned harmony search (ITHS) algorithm and improved ITHS (IITHS) algorithm. Kang et al. (2015) used a multi-objective optimization method of heat exchanger network (HEN) on the basis of partition of minimum approach temperature intervals to minimize the total annual cost and accumulated CO2 emissions in construction and operation phases. Cavazzuti et al. (2015) presented in which a finned concentric pipes heat exchanger simulated by using CFD, and optimized by the Nelder and Mead simplex downhill optimization algorithm. Mohanty (2015) had used Firefly algorithm for economic optimization of shell-and-tube heat exchanger.

Turgut (2016) investigated the thermal design of PFHE by using Hybrid Chaotic Quantum behaved Particle Swarm Optimization (HCQPSO) algorithm. Wen et al. (2016) proposed a hybrid genetic algorithm based on the Kriging response surface method for optimization of plate-fin heat exchanger with serrated fins. Wong et al. (2016) used Excel-based multi-objective optimization (EMOO) program, based on the elitist non dominated sorting genetic algorithm with different termination criterion for design and optimization of STHEs. Caputo et al. (2016) presented a detailed manufacturing cost estimation method for shell and tube heat exchangers. Wang and Li (2016) reviewed the layer pattern thermal design and optimization of the multi-stream PFHE. Rosa and Zamora (2016) optimized heat exchanger networks by using NLP model and stochastic multi-start optimization approach.

It has been observed from the literature review that some of the researchers had used traditional optimization techniques like Taguchi method, sequential quadratic programming, Lagrange multiplier method, Nelder-Mead simplex method, mixed-integer non-linear programming method, etc. for design optimization of selected thermal devices. However, these approaches suffer from some drawbacks as following: (i) these traditional techniques may be relevant only for simple cost functions and may not be relevant for complicated cost functions. (ii) the traditional techniques may not give global optimum solution. In order to overcome these drawbacks of traditional optimization techniques, few researchers had used the advanced optimization techniques such as GA, SA, NSGA-II, PSO, ABC, GEO, GEM, ICA, BBO, CSA, FFA, ITHS, I-ITHS, CI, MODE and MOPSO algorithms. All the evolutionary and swarm intelligence based algorithms are probabilistic algorithms and required common controlling parameters like population size and number of generations. Beside the common control parameters, different algorithms require their own algorithm-specific control parameters. The improper tuning of algorithm-specific parameters either increases the computational effort or yields the local optimal solution.

In this paper recently developed algorithm-specific parameter-less algorithms known as TLBO algorithm is proposed for design optimization of selected thermal devices. TLBO algorithm requires only the common controlling parameters like population size and number of generations for their working (Just like any other

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population-based optimization algorithms). In this thesis the performance evaluation of the proposed algorithm is carried out for the design optimization of selected Heat exchanger. From this literature survey it is clear that shell and tube heat exchanger optimization was attempted by many non-traditional optimization algorithms like GA, PSO, DE and ACO in the past. So in this dissertation work an attempt is made to implement a new algorithm called shuffled TLBO algorithm to achieve shell and tube heat exchanger optimization.

II. TEACHING-LEARNING-BASED OPTIMIZATION ALGORITHM

Teaching-learning-based optimization algorithm (TLBO) is a teaching-learning process inspired algorithm proposed by Rao et al. (2011) based on the effect of influence of a teacher on the output of learners in a class. The algorithm mimics the teaching - learning ability of teachers and learners in a classroom. Teacher and learners are the two vital components of the algorithm and describe two basic modes of the learning, through teacher (known as teacher phase) and interacting with the other learners (known as learner phase).

The output in TLBO algorithm is considered in terms of results or grades of the learners which depend on the quality of teacher. So, teacher is usually considered as a highly learned person who trains learners so that they can have better results in terms of their marks or grades. Moreover, learners also learn from the interaction among themselves which also helps in improving their results. TLBO is a population based method and a group of learners is considered as population and different design variables are considered as different subjects offered to the learners and learners' result is analogous to the 'fitness' value of the optimization problem. In the entire population, the best solution is considered as the teacher. The flowchart of TLBO algorithm is shown in Fig. 2. The working of TLBO is divided into two parts, 'teacher phase' and 'learner phase'. Working of both the phases is explained below.

In the teacher phase, each independent variables in each candidate solution x is modified according to Eqs. (1) and (3) .

$$x_i'(s) \leftarrow x_i(s) + r(x_t(s) - \bar{x}(s)) \qquad (1)$$

where,

$$\bar{x}(s) = \frac{1}{N}\sum_{i=1}^{N} x_i(s) \qquad (2)$$

for i ∈ [1, N] and independent variable s ∈ [1, n], where N is the population size, n is the total number of independent variables, x_t is the best individual in the population (i.e. the teacher), r is the random number taken from a uniform distribution on [0, 1]. The new solution obtained after the teacher phase x_i' replaces the previous solution x_i if it is better than x_i.

The learner phase mimics the act of knowledge sharing among two randomly selected learners. The learner phase entails updating each learner based on another randomly selected learner as follows:

$$x_i''(s) \leftarrow \begin{cases} x_i'(s) + r(x_i'(s) - x_k'(s)) \text{ if } x_i' \text{ is better than } x_k' \\ x_i'(s) + r(x_k'(s) - x_i'(s)) \text{ otherwise} \end{cases} \qquad (3)$$

Case Study1

The present application example is taken from the previous work of Peng and Ling (2008). In this case study a cross flow plate fin heat exchanger with offset-strip fins on both sides is considered. The given core geometry with its design configuration is as shown in Fig. 3.

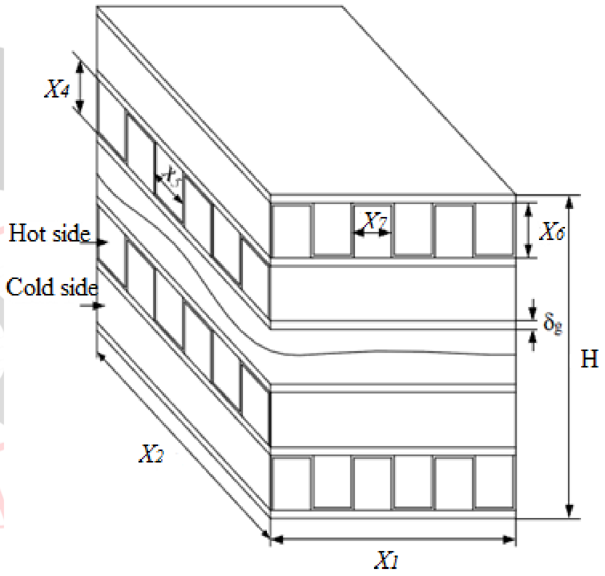

Figure 3 The design configuration of PFHE for case study 1 (Peng and Ling, 2008).

Length of PFHE core (X_1), width of PFHE core (X_2), number of fin layers on hot side (X_3), fin height at hot side (X_4), fin pitch at hot side (X_5), fin height at cold side (X_6) and fin pitch at cold side (X_7) were considered as geometric parameters to be optimized and there ranges are given in Table 1.

Table 1 Geometric parameters for case study 1.

Parameters	Specified ranges
Length of PFHE core, X_1 (m)	0.15 – 0.25
Width of PFHE core, X_2 (m)	0.15 – 0.5
Number of fin layers on hot side, X_3	15 – 35
Fin height at hot side, X_4 (mm)	5 – 10
Fin pitch at hot side, X_5 (mm)	2 – 3.5
Fin height at cold side, X_6 (mm)	8 – 10
Fin pitch at cold side, X_7 (mm)	2 – 3.5

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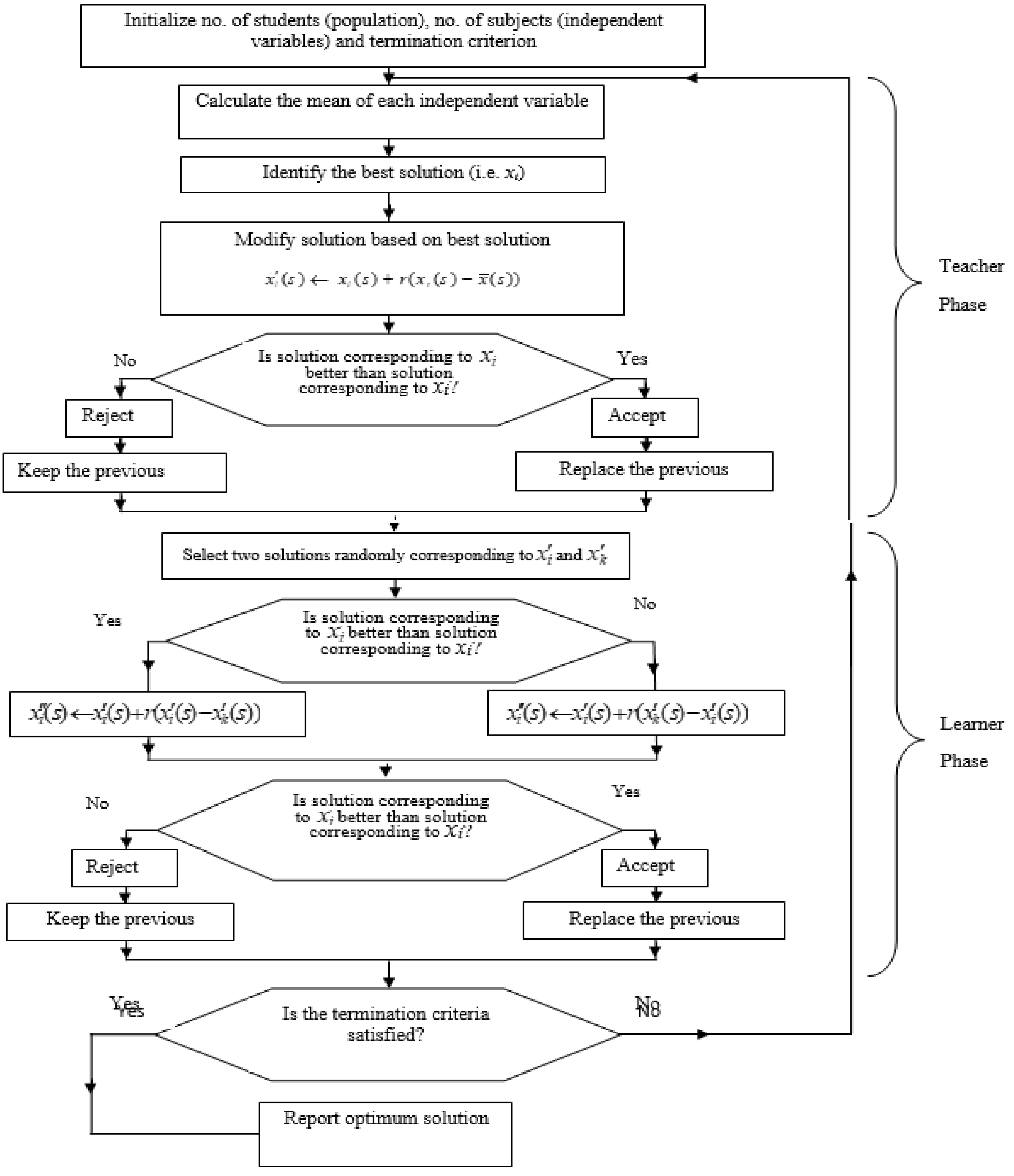

Figure 2 Flowchart of teaching-learning-based optimization algorithm (Rao, 2015)

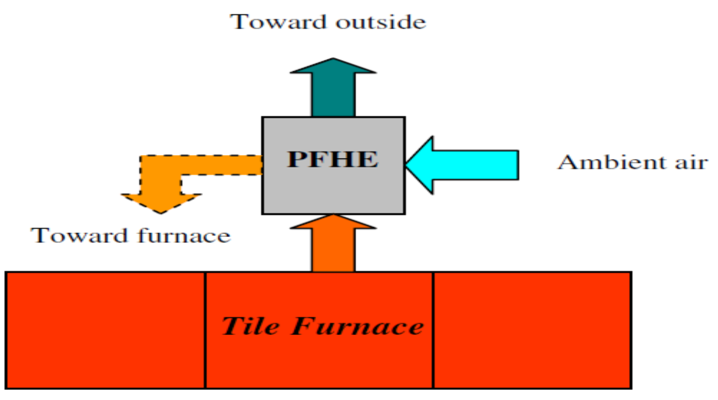

Fig. 4 A schematic diagram of a tile furnace with a PFHE (Sanaye and Hajabdollahi, 2010).

The operating parameters values considered for the two fluids and economic data are shown in Table 2

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Table 2 Operating parameters and economic data for case study.

Operating parameters	Hot fluid	Cold fluid
Mass flow rate, *m* (kg/s)	1	1.25
Inlet temperature, T_1 (K)	423	303
Outlet temperature, T_2 (K)	373	343
Inlet pressure, P (kPa)	120	120
Maximum pressure drop, ΔP_{max}	6.5	2.5
Economic data		
Annual operating period, *AH* (second/year)	21,600,000	
Rate of increase of energy cost, *ec* (%)	30	
Fixed cost, *fc* ($)	187.5	
Electric cost, *fe* ($/kWh)	0.065	
Interest rate, *i* (%)	40	
Total operating period, *tp* (year)	5	
Unit cost of heat exchanger per unit area, *uc* ($/m^2)	25	
Density of aluminum, ρ_{Al}(kg/m^3)	2707	

For the consistency of the comparison, the same objective function i.e. to minimize total weight, considered by Peng and Ling (2008) is used in the present work.

Minimize

$$W = [\, (X_3+(X_3+1)+1)\times X_1\times X_2\times \delta_g + X_3\times(X_4+X_5-t)\times X_1\times t\times(X_2/X_5)$$

$$+ (X_3+1)\times(X_6+X_7-t)\times X_2\times t\times(X_1/X_7)\,] \times \rho_{Al} \quad (5.13)$$

Design constraints:

$$\Delta P_h - \Delta P_{h,max} \leq 0 \quad (5.14)$$

$$\Delta P_c - \Delta P_{c,max} \leq 0 \quad (5.15)$$

$X_i^L \leq X_i \leq X_i^U$ for all i= 1 to 7.

In the present work, the above design optimization problem is attempted using the TLBO algorithm. The number of populations considered 50 and the program run for 100 iterations. Table 3 shows the optimized values of the design variables of the considered example using TLBO algorithm and the comparison with the results obtained by Peng and Ling (2008) using GA combined with back propagation neural network (BP) approach.

Table 3 Comparison of results generated by TLBO algorithm with GA with BP

Parameters	GA with BP (Peng and Ling, 2008)	GA Algorithm	TLBO algorithm
Length of PFHE core, X_1 (m)	0.23	0.234	0.200
Width of PFHE core, X_2 (m)	0.40	0.195	0.152983
Number of fin layers on hot side, X_3	17	20	20
Fin height at hot side, X_4 (mm)	7.0	7.0	9.23
Fin pitch at hot side, X_5 (mm)	2.4	3.405	3.0
Fin height at cold side, X_6 (mm)	8.7	9.0	9.093
Fin pitch at cold side, X_7 (mm)	2.5	3.0	3.0
Hot side pressure drop, ΔP_h (kPa)	6.10	5.797	4.806
Cold side pressure drop, ΔP_c (kPa)	2.00	2.48	2.495
Total weight, W (kg)	7.47	4.37	**3.1044**

The best solution obtained by TLBO algorithm shows **41.5%** decrease in the total weight when compared with the results given by Peng and Ling (2008) using GA combined

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with back propagation neural network (BP) approach. Fig 5 shows the convergence graph of TLBO algorithm.

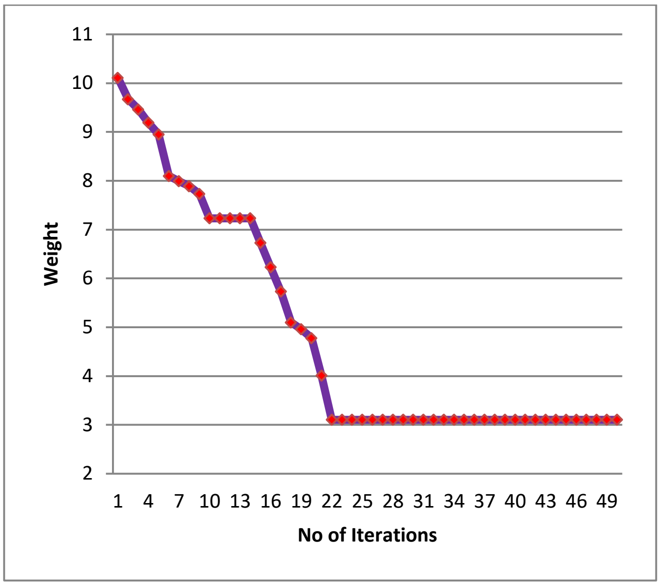

Fig 5- Convergence of TLBO algorithm for minimizing the weight of Heat exchanger.

III. Conclusion

Shell and tube heat exchangers are the most common type of thermal equipment employed in many chemical process industries. The optimization problems related to heat exchanger design are considered in this work which includes optimizing the objectives of minimization of operating and overhead costs and overall weight. Heat exchanger design is a complex task, and advanced optimization tools are useful to identify the best and cheapest heat exchanger for a specific duty. The present study demonstrates the successful application of TLBO Algorithm for the optimal design of a shell and tube heat exchanger from economic view point.

The TLBO algorithm will develop in MATLAB environment and four case studies from the literature are solved by this code. The presented Jaya algorithm is simple in concept, few in parameters and easy for implementation. These features boost the applicability of the TLBO algorithm particularly in heat exchanger design like problems, where the problems are usually complex and have a large number of variables and discontinuity in the objective function. Also TLBO algorithm has good ability for the global exploration and it is easy to realize. The presented TLBO algorithm ability is demonstrated using different literature case studies and the performance results are compared with those obtained by the previous researchers. Comparatively better results are obtained by using the TLBO algorithm.

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