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ORIGINAL PAPER

Design Optimization of Heat Exchangers with Advanced Optimization Techniques: A Review

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Abstract
This literature review presents the extensive literature survey of various heat exchangers (HEs) for the design optimization using advanced optimization techniques concerning with various aspects. The chief objective of this work is to focus on the parametric design optimization of different types of HEs using advanced optimization algorithms and therefore only the research works associated with advanced optimization techniques are considered. This is the first paper which exclusively summaries the research works concerning with the parameter optimization of HEs using advanced optimization techniques. Various types of HEs considered in this review paper are shell-and-tube HEs, plate-fin HEs, fin-tube HEs and various configurations of HE networks etc. The parametric design optimization of HEs is associated with number of structural and physical parameters having highly complexity. Trial and error method is used in the general design approaches and this becomes tediously and time consuming and not having the guarantee of getting an optimum design. Therefore, for the design of HEs advanced optimization techniques are preferred. The review work on parametric design optimization was not attempted previously by taking into consideration various types of HEs therefore this review paper may turn into the complete information at one place and it may be very useful to the industrial design and successive researchers to choose the direction of their research work in the field of parameter optimization of HEs using advanced optimization algorithm.

1 Introduction

A heat exchanger (HE) is a device which is used for recovering the thermal energy between two or more fluids kept at different temperature. Various types of heat exchangers are available in the industry i.e. shell-and-tube heat exchangers (STHE), plate-fin heat exchangers (PFHE), fin-and-tube heat exchanger (FTHE), gasket heat exchanger, and various configurations of heat exchanger networks (HENs) etc. The design of these HEs is based on various geometric and operational parameters while meeting with certain specified objective(s) such as minimum total cost, maximum heat transfer rate, minimized weight etc. with certain specified constraint(s) such as constrained associated with maximum pressure drop, minimum and maximum fluid flow velocity, structural constraint etc. These HEs are used in various industries as process equipment e.g. heats recovery, refrigeration, cryogenics, food processing and many other industries.

PFHEs and STHEs are the widely used heat exchangers for industrial and as well as commercial applications. The STHE is the HE in which on fluid is carried by tube and the other fluid is carried by shell. The heat transfer takes place by mean mutual heat transfer between the tube and shell side fluid. The design of STHE depends upon many geometrical parameters i.e. shell diameter, tube diameter, number tubes, baffle spacing, number of tube passes, tube length, tube layout etc. and operational parameters i.e. specification of heat pump, fluid flow velocity inside the tube and shell, fouling resistance etc. PFHEs are the HE in which transfer of heat takes place between two fluids by means of plates and finned chambers. The design of PFHE depends upon many structural parameters i.e. fin height, length and thickness, length of fluids flow, no flow length, number of fins, fin frequency etc. and many operational parameters. Similarly, the design of other HEs depends upon many structural and operational parameters.

The HENs design uses a detailed analysis for the optimum design of heat exchangers. It employs three concepts:

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the composite curves, the grid diagram of process stream and the pinch point; and these are applied to minimize the energy use in the process. This process takes the necessary streams information from the user and decides the best arrangement of heat exchangers, heaters and coolers so that the amount of utilities needed such as cooling water and steam is minimized.

It is clear from the above discussion that the design of heat exchangers is based upon many geometrical and operational parameters with high complexity. Hence, the design of a cheap and effective HE becomes a complicated task. To ensure the finest performance, usage and low cost of the HE, the design optimization techniques are applied in the product development stage. In the process of design optimization of HEs various studies are carried out with different objectives. This work summarises these studies.

Traditional techniques such as steepest decent, linear programming and dynamic programming usually fail to solve such as non-linear large-scale problems. Most of the traditional techniques require gradient information and hence it is not possible to solve non-differentiable functions with the help of such traditional techniques. Moreover, such techniques often fail to solve optimization problems that have many local optima. To overcome these problems, advanced optimization algorithm are developed which are gradient free.

During the last two decades, many advanced optimization techniques such as genetic algorithm (GA), non-nominated sorting GA (NSGA-II), simulated annealing (SA), artificial bee colony (ABC), imperialist completive algorithm (ICA), bio-geography based optimization (BBO), cuckoo search algorithm (CSA), firefly algorithm (FFA), ant colony optimization (ACO), particle swarm optimization (PSO), teaching–learning-based optimization (TLBO), Jaya algorithm, etc. had been used for the design optimization heat exchangers. These algorithms are having their own merits and demerits i.e. GA can solve every optimization problem which can be described with the chromosome encoding and solves problems with multiple solutions but GA requires tuning of many algorithmic-specific parameters such as mutation probability, selection operator, crossover probability, etc. NSGA-II is having explicit diversity preservation mechanism and elitism does not allow an already found Pareto optimal solution to be deleted but crowded comparison can restrict the convergence and it requires the tuning of algorithmic-specific parameters such as mutation probability, crossover probability etc. BBO is an efficient algorithm for optimization and it prevents the degradation of the solutions but BBO is poor in exploiting the solutions. There is no provision for selecting the best members from each generation and it requires the tuning of many algorithmic-specific parameters. PSO is a derivative-free technique just like as other heuristic and it is having the character of memory but it requires the tuning of algorithmic specific parameters and multiplicity of population is not enough to reach the global optimal solution. Similarly, other advanced optimization algorithms needs the tuning of their own algorithmic specific parameters expect TLBO and Jaya algorithms which are algorithmic-specific parameter-less algorithms.

Figure 1 shows the publication statistics for the design optimization of HEs using advanced optimization techniques. These algorithms have already proved their significance in the field of design optimization of various types of heat exchanger designs. Design optimization of heat exchangers through advanced optimization techniques is now proving as a milestone for the heat exchanger design and hence various researchers are trying to make use of these advanced optimization techniques for the heat exchangers design. This paper makes an efforts to identify all such works in which the use of various advanced optimization techniques are involved till now for the design optimization of different types of heat exchangers. The next section summarizes the applications of advanced optimization techniques for the design optimization of heat exchangers.

2 Review of the Applications of Advanced Optimization Algorithms for Design Optimization of Heat Exchangers

The literature review of the design optimization of HEs using advanced optimization is organized into three parts:

(a) Design optimization of plate-fin heat exchangers.
(b) Design optimization of shell-and-tube heat exchangers.
(c) Design optimization related to some miscellaneous heat exchangers i.e. fin-and-tube, heat exchanger networks (HENs), printed circuit heat exchanger (PCHE), vertical U-tube ground heat exchanger, wavy-fined-and-

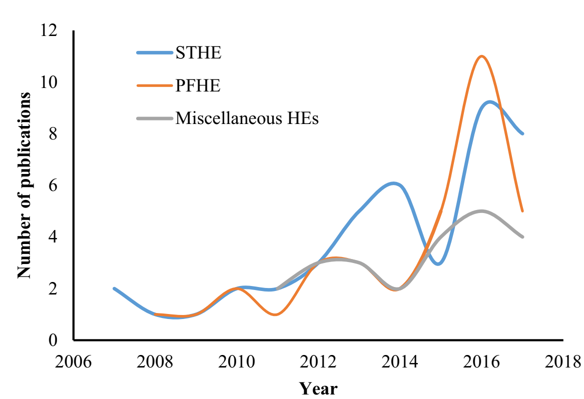

Fig. 1 Publication statistics for the design optimization of HEs using advanced optimization techniques

elliptical tube heat exchanger and U-shaped square duct heat exchanger.

The next section presents the application of advanced optimization algorithms for the design optimization of PFHEs.

2.1 Review of the Application of Advanced Optimization Algorithms for Design Optimization of Plate-Fin Heat Exchangers

Table 1 presents the summary of the applications of advanced optimization algorithms for the design optimization of PFHEs with design variables, constraints and objective function(s) [1–35]. The PFHEs are widely used in the industries of chemical, petroleum, petrochemical and power generation. In this extended surfaces are added for enhancing the heat transfer rate. The major design parameters of PFHE are: hot and cold fluid flow length, no-flow length, fin thickness, fin height, fin pitch, fin frequency etc. The selection criterion of suitable combination of these parameters for a particular application depends upon allowable pressure drops, ranges of the temperatures, thermal stress of fluid and heat exchanger material and dynamic properties of fluids.

In the recent years, the application of advanced optimization algorithms for the design optimization of PFHEs has got much momentum since the last decade [11–35]. It can be observed from the literature review that the various algorithms has been applied for the design optimization PFHEs and these are: GA, SA, PSO and its variants, NSGA-II, ICA, HSA, Bees algorithm, DE algorithm and its variants, BBO algorithm, TLBO algorithm and Jaya algorithm and its variants. The research has been carried by aiming various objectives i.e. minimization of total annual cost [1, 3–6, 8, 9, 12–19, 22, 23, 28, 29, 34], maximization of effectiveness [3, 7, 12, 13, 16, 19, 29, 31, 34], minimization of pressure drop [7, 17, 25, 27, 34], maximization of heat transfer rate [5, 6, 14, 17, 22, 26], minimization of entropy generation units [2, 4, 8, 13, 23, 32, 33], minimization of total weight or volume of the PFHE [1, 4, 8, 9, 15], minimization of heat transfer area [4, 27, 34], layer pattern optimization [10, 20, 21] and optimization of friction factor and Colburn factor [24, 30, 35]. Manny researchers had carried out multi-objective optimization [3, 5, 6, 12, 28, 29, 34] by considering the different combination of the above mentioned objectives.

It can be observed from the above literature review that the advanced optimization algorithms have been applied mainly aiming the minimization of total cost and maximization of effectiveness. Furthermore, very few researchers have applied multi-objective optimization [3, 5, 6, 12, 28, 29, 34] for the design optimization of the PFHE. It can also be observed from Table 1 that few researchers have integrated surrogate models along with the advanced optimization algorithms [3, 23, 24] and few researchers have used computational fluid dynamics with advanced optimization algorithms [6, 35]. Moreover, the analytical models used in design optimization of PFHE contain many assumptions such as thermal and physical properties are independent of temperature gradient, steady state analysis, constant heat transfer coefficient etc. while developing the models which may lead errors as compared to the actual situations.

2.2 Review of the Application of Advanced Optimization Algorithms for Design Optimization of Shell-and-Tube Heat Exchangers

Table 2 presents the summary of the applications of advanced optimization algorithms for design optimization of STHEs with design variables, constraints and objective function(s) [12, 28, 29, 36–74]. The STHEs are widely used in the process industries, steam generators in pressurized and water reactor plants, feed water heaters, in conventional and nuclear power stations as condenser etc. In this, one fluid flows through the tube and other fluid flow through the shell and the mutual heat transfer takes place between the fluids. The major design parameters of STHEs are: shell diameter, tube diameter, tube length, number tubes, number of tube passes, tube layout pattern, tube pitch, baffle spacing, etc. The selection criteria of the suitable combination of these parameters for a particular application depends upon allowable pressure drops, ranges of the temperatures, thermal stress of fluid and heat exchanger material, dynamic properties of fluids, fouling factor, maintenance cost and clean ability.

In the recent years, the application of advanced optimization algorithms for the design optimization of STHEs has got much momentum [12, 28, 29, 43–75]. It can be observed from the literature review that the various advanced optimization algorithms have been applied for the design optimization STHEs and these are: GA, SA, PSO and it variants, NSGA-II, ICA, HSA, Bees algorithm, DE algorithm and its variants, BBO TLBO, ABC, FFA, GSA, I-ITHS algorithms and Jaya algorithm and its variants. The research has been carried by aiming various objectives i.e. minimization of total annual cost [12, 28, 36–39, 41–45, 48, 49, 52, 53, 55, 57, 60–67, 69–73, 75], maximization of effectiveness [12, 28, 42, 62, 71], minimization of pumping power [50, 54, 68], maximization of heat transfer rate [54, 56, 57, 64, 68], minimization of pressure loss [56], minimization of entropy generation units [47, 51, 68], minimization of total weight or volume of the STHE [59, 74], minimization of heat transfer area [50] and maximization of thermal efficiency [46, 58]. Manny researchers had carried out multi-objective optimization [12, 28, 42, 46, 47, 50, 51, 56, 57, 62, 64, 68, 71] by considering the different combination of the above mentioned objectives.

Table 1 Review of the applications of advanced optimization algorithm for PFHE design

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Xie et al. [1]	Compact heat exchanger (PFHE)	Cold and hot fluid flow length and no-flow length	Pressure drop	Total annual cost Total volume	GA	GA had provided 15% lesser total cost and 15% lesser total volume when pressure drop was considered as constraint About 49% decrement in total volume and 16% decrement in total cost were obtained without considering imposing the constraint of the pressure drop
Mishra et al. [2]	PFHE with offset-strip fins	Fin height and pitch, hot and cold fluid flow length	Specified heat duty and given space restrictions	Entropy generation	GA	Application second law of thermodynamics for the design optimization HEs along with the capability of GA for the optimization of complicated design problem
Sanaye and Hajabdollahi [3]	Compact heat exchanger (PFHE)	Fin offset length, fin height and pitch, hot and cold fluid flow length and no-flow length	Specified heat duty and given space restrictions	Total annual cost Effectiveness	NSGA-II	A set of Pareto-optimal solution were generated ANN was used in order to get the optimal system design along with allowable precision
Rao and Patel [4]	Cross flow PFHE	Fin offset length, fin height and pitch, hot and cold fluid flow length, no-flow length, number of fin layers and fin frequency	Heat duty requirement, geometrical constraints and pressure drop	Total cost, Number of entropy generation units Total volume	PSO	Single and multi-objective optimization was carried out and found improvement as compared to results of GA Effect of HE design parameters and PSO parameters on objective function was carried out

Table 1 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Najafi et al. [5]	Cross flow PFHE	Numbers of fin layers, fin height and thickness, hot and cold fluid flow length, Fin frequency, lance length of fin	Geometrical constraints, pressure drop	Total cost Heat transfer rate	MOGA	A set 25 Pareto optimal solutions were developed. MOGA optimization MOGA was applied for Sensitivity analysis was carried for getting the effect of process parameters on the optimal solution
Hajabdollahi et al. [6]	Compact heat exchanger (PFHE)	Fin height and pitch, cold and hot fluid flow length and no-flow length	Geometrical constraints	Effectiveness Total pressure	NSGA-II	A set of non-dominated solutions were generated Sensitivity analysis was also carried which reveals that increment in heat transfer area essentially does not increase the pressure loss and it was found to be case sensitive
Yousefi et al. [7]	PFHE	Fin height and pitch, hot and cold fluid flow length and no-flow length	Heat transfer rat, pressure drop	Heat transfer rate Pressure drop	GA hybrid with PSO	In case of maximization of heat transfer rate, result produced by GAHPSO algorithm is increased by 17.5% and 9.5% as compared to the design of respectively GA and PSO In case minimization of pressure drop, result obtained by GAHPSO algorithm is decreased by 5.0% and 12.5% as compared to the design of respectively GA and PSO

Table 1 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Yousefi et al. [8]	Compact heat exchanger (PFHE)	Cold fluid and hot fluid flow length, height and frequency, strip length, thickness of fin and fin layers	Heat transfer rate and pressure drop	Total cost Total weight Entropy generation units	Learning automata based particle swarm optimization (LAPSO)	A new constraint handling method based on self-adaptive penalty was employed The optimum configuration obtained with superior success rate and a superior accuracy in comparison to PSO and GA
Yousefi et al. [9]	PFHE	Length of hot and cold fluid flow, layers of hot side, fin thickness, frequency and height, and length of strip of fins.	Operational geometric constraint	Total cost Total weight	ICA	Results were compared with GA It was found that ICA was able to find better values of the objective function with less computational cost
Zao and Li [10]	Multistream PFHE	Ratio of the total number of hot layers to cold layers and spacing layers between cold and hot streams	Pressure drop and effectiveness	Layer pattern	GA	The GA had achieved a significant improvement thermal efficiency of HE had been increased from 92.4% up to 98% and some even close to 99%
Yousefi et al. [11]	PFHE	Fin height and pitch, hot and cold fluid flow length	Structural constraints, heat duty	Heat transfer area Pressure drop	Improved HSA	A new constraint handling method based on self-adaptive penalty was employed The results showed the superiority of improved HSA over GA, PSO and hybrid of GA and PSO
Rao and Patel [12]	PFHE	Lengths for hot and cold fluids, no flow length, fin length, fin height, fin pitch	Geometrical and space restriction	Total cost Effectiveness	Modified TLBO	Multi-objective optimization was carried and the results were found better in comparison to the design suggested by GA

Table 1 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Zarera et al. [13]	Cross flow PFHE	Length of cold and hot fluid flow, fin frequency, height and thickness, fin strip length	Pressure drop, specific heat duty, and space restriction	Effectiveness Entropy generation units	Bees algorithm	The results obtained BA were compared with GA, PSO, ICA and preliminary design and found optimum construction with higher precision in comparison with other algorithms
Guo et al. [14]	PFHE	Length and width of column, number of grids and columns	Working temperature	Maximum heat transfer	GA with Monte Carlo algorithm	GA algorithm was applied to get the optimum column distributions and hence to get maximum heat transfer performance The design suggested by using GA and Monte Carlo algorithm had provided guidelines for the optimal designs of PFHE
Guo et al. [15]	Counter-current PFHE	Plate spacing, fin length, fin thickness, fin type, and fin pitch	Geometrical constraints, pressure drop	Total volume of heat exchanger	CONOPT solver in GAMS	The design variables were first considered as continuous variable later for the optimum solution these were rounded towards the standard size Pressure drop sensitivity analysis was carried out
Hajabdollahi [16]	PFHE	Fin height and pitch, flow length of hot and cold fluid and no-flow length	Geometrical constraints	Effectiveness Total annual cost	MOPSO	Analysed the influence of similar and non-similar fins in on PFHE Effectiveness and total annual cost were improved by 0.95% and 10.17%, with the different fin compared with similar fin

Table 1 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Hadidi [17]	PFHE	Hot and flow length, height And thickness of fin, fin frequency, fin offset length, number of hot side layers	No flow length, pressure drop, fluid velocity, geometrical constraints	Total cost, Pressure drop Teat transfer rate	BBO	BBO has improved the results of all the objectives with feasible designs Parameters influence were analysed to estimate the sensitivity of the BBO to the cost and geometrical parameters
Wang and Li [18]	PFHE	Fin height and pitch, length of hot and cold fluid flow length	Structural, constraints, heat duty	Pumping power Efficiency, Total annual	Improved multi-objective cuckoo search (IMOCS) algorithm	The IMOCS had obtained optimum solutions of the objective functions with higher accuracy and lower irreversibility It requires less function evaluations in comparison to the PSO and GA
Yousefi et al. [19]	Compact heat exchanger	Fin height and pitch, hot and cold fluid flow length	Structural constraints, heat duty	Effectiveness Total cost	Learning automata based particle swarm optimization (LAPSO)	Multiple-step design of heat PFHE was proposed A feasibility based ranking strategy was introduced to handle the constraints Results obtained by LAPSO are found better as compared to the results of GA and PSO
Wang and Li [20]	Multistream PFHE	Fin height and pitch, hot and cold fluid flow length	Geometrical constraints	Layer pattern design	GA, PSO and HS algorithm	The energy consumption of the PFHE was reduced
Wang and Li [21]	Multistream PFHE	Hot and cold fluid flow length, fin thickness, flow length, fin offset length Mass flow rate of each layer, fin height and fin frequency	Effectiveness and pressure drop	Layer pattern optimization Surface selection	Hybrid GA and CSA	Two case studies were analysed with 4 streams and 7 streams of fluid 98% effectiveness of MPPFHE was obtained which better as compared to general design of industry

Table 1 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Zhang et al. [22]	PFHE networks	Temperatures ranges of the hot and cold fluid	Heat balance of each stream, single heat exchanger and utility load	Total cost Total heat flow rate	Chaotic ant swarm (CAS) algorithm	Two case studies were analysed and results obtained by this study had reduced the total cost significantly as compared to the previous studies
Wen et al. [23]	PFHE with serrated fin	Fin height, space and thickness, interrupted length of serrated fin and Reynolds number of channel inlet	Space and geometrical constraints	Number of entropy generation Total annual cost	Geometrical constraints with Kriging response surface	The computational experiment shows that under the same effectiveness, the annual cost of the obtained NSGA-II was about 10% less as compared to previous design
Wen et al. [24]	PFHE with serrated fin	Fin height, fin thickness, fin space and interrupted length of serrated fins	Geometrical constraints and heat duty	f factor, j factor, JF factor	Geometrical constraints with Kriging response surface	The power consumption was decreased by 48.5% The sensitivity of the parameters on the optimum design was also analysed
Juan et al. [25]	PFHE with offset fins	Fin wrinkling angle, fin height and fin length	–	Total pressure drop Heat transfer rate	GA	Total heat transfer rate of the optimized structure is improved by about 6.2% Pressure drop decreases by about 40% volume was reduced by about 2.7% as compared original design
Peng et al. [26]	Multistream PFHE	Length, width of heat exchanger, fin frequency, height, thickness of fins	Mass flow rate, inlet and outlet temperatures	Heat transfer rate	Hybrid PSO	The total heat transfer rate was increased by 2.50% and 4.52% under different inlet flow misdistributions of single fluid flow and increased by 2.58–3.98% under different inlet flow misdistributions of flow of two fluid simultaneously

Table 1 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Turgut [27]	PFHE	Length of hot and cold fluid flow, fin frequency, fin thickness, lance length of the fin and fin layers	Space restrictions and specified heat duty and	Total cost Heat transfer area Pressure drop	HCQPSO	An Automatic Dynamic Penalization method was integrated with algorithm for handling the constraints The proposed HCQPSO algorithm had successfully converged towards optimum configuration with a higher accuracy
Rao and Saroj [28]	PFHE	Lengths for hot and cold fluids, no flow length, fin length, fin height, fin pitch	Geometrical and space restriction	Total cost Effectiveness	Elitist-Jaya algorithm	For same effectiveness of PFHE total cost of PFHE obtained by elitist-Jaya is much less as compared to GA and modified TLBO
Ayala et al. [29]	PFHE	Fin pitch, height and length, fluid flow length of hot and cold fluid, no-fluid flow length, ratio of fin pitch to fin height.	Operational constraints	Total cost Effectiveness	Multi-objective Differential evolution and free search (MOFSDE)	The advantage of this algorithm that it does not need the tuning of population size and the number of generations The Pareto optimal solutions obtained by MOFSDE algorithm has dominated 76% of the solutions obtain by NSGA-II
Salviano et al. [30]	Plate fin compact heat exchanger	Longitudinal vortex generator position in x–y directions, attack angle, and roll angle	Structural and operational constraint	Colburn factor Friction factor	GA	Position of winglet-type vortex generator positions and angles used in plate-fin compact heat exchanger is optimized with help RSM
Gupta et al. [31]	PFHE	Mass flow rate, outlet and inlet temperatures of the cold and hot fluid pressure of cold and hot fluid,	Operational constraints and heat duty	Effectiveness	GA and SA	ANN with GA and SA was used to optimize the experimental model of effectiveness PFHE

Table 1 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
de Vasconcelos Segundo et al. [32]	PFHE	Lengths for hot and cold fluids, height of the fin, fin frequency, fin thickness, lance length and number of fin layers for the hot fluid	Specified heat duty and Geometrical constraints	Entropy generation units	Tsallis JADE	Two case studies were analysed The entropy generation units were reduced by 9.60%, 24.30% and 9.30% in comparison ton to GA, BA and PSO algorithm respectively for the first case study and (Bees Algorithm) methods, respectively, were obtained for the first case study and reductions about 15.96%, 13.39 and 11.26% in comparison to the results obtained with GA, ICA and BA methods were obtained for the second case study
Rao and Saroj [33]	PFHE	Flow length of hot and cold fluid, Fin height, fin thickness, frequency of fin, offset length, fin layers number	Heat duty, geometrical and space restriction	Entropy generation units	SAMP-Jaya algorithm	The SAMP-Jaya had obtained better design as compared to the GA, PSO and CSA algorithms with lesser function evaluations
Rao et al. [34]	PFHE	Flow length of hot and cold fluid, fin height, thickness and frequency, offset length, fin layers number	Heat duty, geometrical, space restriction and no-flow length	Heat transfer area Total cost Pressure drop	Jaya algorithm	Single and multi-objective optimizations were carried out The design suggested by this study was found better as compared to ICA, BBO, hybrid-GA, IHSA and TLBO algorithms
Liu et al. [35]	PFHE for the hydraulic retarder	Height, pitch, spacing and thickness of the fin	Heat duty, geometrical, space restriction and no-flow length	Colburn factor Friction factor	NSGA-II	CFD simulation and NSGA-II were combined for improving the performances of the HE Colburn factor was enhanced by 12.83% And the friction factor was reduced by 26.91%

Table 2 Review of the applications of advanced optimization algorithm for STHE design

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Özçelik [36]	STHE	Tube length, pitch type, outer diameter of tube, pitch ratio, tube passes and pitch layout angle,	Geometrical constraints	Annual capital cost Exergetic cost	GA	STHE's optimization with exergetic optimization was proposed that can evaluate the optimal values of the discrete as well as continuous variables
Wildi-Tremblay and Gosselin [37]	STHE	Diameter of shell, tube outer diameter and pitch of, layout angle of tube, tube passes, baffle cut, baffle spacing at centre, outer diameter of tube bundle	Pressure of tube and shell side, fluid velocity inside the tube and ratio of tube length to diameter of shell	Total cost	GA	Two case studies were attempted with and without maintenance considerations Heat exchanger was over designed for avoiding the HE breakdown Design was better as compared to previous design
Caputo et al. [38]	STHE	Shell diameter, baffle spacing and tube inner diameter	Heat duty and operational constraint	Total annual cost	GA	Three case studies with different heat duty and working fluid were analysed Results were found better as compared to original design and up to 50% reductions in total annual cost were obtained
Fesanghary [39]	STHE	Diameters of shell and tube, tube arrangement, number of tube passes, material of shell and tube and baffle cut	Heat duty and pressure drop	Total cost	HSA	The HSA along with the global sensitivity analysis was used design optimization of STHE from the economic point of view The HSA was used to optimize the influential geometrical parameters on STHE design

Table 2 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Guo et al. [40]	STHE	Tube outer diameter, quantity of tubes, ratio baffle spacing to shell diameter, baffle cut angle, temperature of cold fluid at outlet	Length-diameter ratio, baffle spacing, tube and shell side pressure drop	Entropy generation number	GA	Second law of thermodynamics was integrated with GA to develop a new design optimization approach for STHEs design Three case studies of HE design were presented The optimized design had increased the heat exchanger rate significantly, and had reduced the total cost
Patel and Rao [41]	STHE	Diameter of shell, tube outer diameter, tube layout and baffle spacing	Heat duty, geometrical and operational constraints	Total cost	PSO	Four case studies with different heat duty and working fluid were attempted PSO was able to obtain better design as compared to GA with less computational cost
Sanaye and Hajabdollahi [42]	STHE	Arrangement of tubes, outer diameter of tube, pitch of tube, baffle spacing ratio length of tube, baffle cut ratio and number of tubes	Structural and operational constraints	Effectiveness Total cost	Elitist-NSGA-II	A set of Pareto optimal solutions were generated A closed relation between the total cost and effectiveness was developed Sensitivity analysis of the parameters on the optimum value was performed
Şahin et al. [43]	STHE	Tube length, outer diameter of tube, tube pitch size, and baffle spacing,	Heat duty and operational constraints	Total cost	ABC	Three case studies with different heat duty and working fluid were attempted Results were found better as compared to the results original design and GA

Table 2 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Rao and Patel [44]	STHE	Diameter of shell, outer diameter of tube, pitch of tubes, layout angle of tube, passes of tube, percentage baffle cut, baffle spacing at centre, outer diameter of tube bundle	Pressure of tube and shell side, fluid velocity inside the tube and ratio of tube length of tube to diameter of shell	Total cost	Civilized swarm optimization (CSO) and PSO	Two case studies were attempted with and without maintenance considerations Heat exchanger was over designed for avoiding the HE breakdown Design obtained by CSO was better as compared to designs suggested by GA and PSO with less computational cost
Mariani et al. [45]	STHE	Tube diameter, baffle spacing and shell diameter	Heat duty, pressure drop	Total cost	QPSOZ	Two case studies were attempted for which reduction in total cost was 30% and 27% respectively for the first and second case study respectively as compared to PSO
Hajabdollahi et al. [46]	STHE	Arrangement of tube, tube inner diameter, pitch ratio, length, tube number, baffle cut ratio and baffle spacing	Ratio of tube length to shell internal diameter	Exergy efficiency Cost	NSAG-II	Pareto optimal solutions were generated which showed the confliction between exergy efficiency and cost Exergy analysis was also carried out which had showed that irreversibility like high temperature differences and pressure drop between the hot and cold stream having a crucial role
Guo and Xu [47]	STHE	Outer diameter of tube, tubes number, central angle of baffle cut and ratio of baffle spacing to shell diameter	Length to shell diameter ratio, baffle spacing, shell and tube side pressure drop	Entransy dissipation Fluid friction	GA	Single and multi-objective optimization was carried out A set of Pareto optimal solution were generated

Table 2 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Hadidi et al. [48]	STHE	Length of tube, outer diameter of tube, size of pitch and baffle spacing	Heat duty and pressure drop	Total cost	ICA	Two case studies were attempted with different heat duty and results obtained by ICA were found better as compared to original design GA with higher accuracy with less computational cost
Hadidi and Nazari [49]	STHE	Length of tube, outer diameter of tube, size of pitch and baffle spacing	Heat duty and fluid velocity	Total cost	BBO	Three case studies with different heat duty and working fluids were attempted Results obtained in this study were found better as compared to GA, PSO and ABC algorithms
Fettaka et al. [50].	STHE	Pattern of tube layout, baffle spacing, baffle cut, tube passes, clearance between tube-to-baffle, clearance between shell-to baffle, length of tube, outer diameter of tube and thickness of tube wall	Pressure drop and heat duty	Heat transfer area Pumping power	NSGA-II	Two different case studies with logarithmic cost function were attempted The influence of continuous parameters of the tube diameter, thickness and length rather than using discrete values for obtaining the optimal heat transfer area and pumping power are analysed using the algorithm A set of Pareto optimal solutions were generated with continuous as well as discrete variables

Table 2 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Guo et al. [51]	STHE	Tube outer diameter, tubes number, ratio Baffle spacing to the shell diameter, central baffle angle, Outlet temperature of helium gas, inlet temperature of liquid LBE	Shell side fluid velocity, length of heat exchanger tube, baffle spacing, pressure drop, ratio of tube length to shell diameter and heat duty	Entransy dissipation numbers Fluid friction	NSGA-II	Based on the entransy dissipation multi-objective optimization of STHE used in an irreversible Brayton cycle system was done A set of Pareto optimal solutions were generated The diversity of Pareto the design patterns were very suitable for the users to choose the most suitable design pattern as per the real needs
Rao and Patel [12]	STHE	Internal diameter of tube, ratio of tube pitch to tube outer diameter, length of tube, number of tubes	Ratio of baffle spacing to shell diameter, ratio of tube length to shell diameter	Total cost Effectiveness	Modified-TLBO	Multi-objective optimization was carried and the results were found better in comparison to the design suggested by GA
Asadi et al. [52]	STHE	Tube outer diameter, internal diameter of shell and baffle spacing	Heat duty, geometrical and operational constraints	Total annual cost	CSA	Two case studies with different heat duty and working fluid were attempted Designs were found better as compared to the designs obtained by GA and PSO
Turgut et al. [53]	STHE	Baffle spacing, diameter of shell, number of tube passes and outer diameter of tube	Heat duty and operational constraints	Total cost	Improved intelligence tuned HSA	Search mechanism of the ITHS algorithm is enhanced by using random numbers with chaotic sequences Three case studies with different heat duty and working fluid were analysed and results were found better as compared to GA, PSO, ABC, BBO and ITHS algorithm

Table 2 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Yang et al. [54]	STHE	Tube and shell diameters, tube length, tube wall thickness and tube arrangement	Heat duty and pressure drop	Total cost	GA with constructal theory confirming TEMA standard	Three cases studies were studied using this approach Total cost was significantly decreased in comparison to the designs of original design method and general GA
Yang et al. [55]	STHE network	Tube and shell diameters, tube length, tube wall thickness and tube arrangement	Heat duty and pressure drop	Total cost	GA with constructal theory	Three cases studies were studied using this approach Total cost was significantly deceased in comparison to the original design method and general GA
Daróczy et al. [56]	Cross-flow tube bank heat exchanger	Seven coordinates of cylinder	Volume of cylinder	Pressure loss Heat transfer rate	NSGA-II	A set of Pareto optimal solutions are generated The results compared with the results of CFD
Amini and Bazargan [57]	STHE	Tube outer diameter, tubes number, central angle of baffle cut, ratio of baffle spacing to shell diameter, etc.	Velocity of fluid pressure drop and TEMA standards	Heat transfer rate Total cost	NSGA-II	Two case studies with different heat duty and working fluid were attempted A set of Pareto optimal solutions were generated using Sensitivity analysis of the parameters on the optimal solution is also carried out
Khosravi et al. [58]	STHE	Tube arrangement, inside diameter of tube, ratio of tube pitch to tube outer diameter, baffle spacing ratio, number of tubes, baffle cut ratio, tube length	Heat duty, geometrical and operational constraints	Thermal efficiency	GA, FFA and cuckoo search (CS) method	GA was not able to get the allowable and optimum design in the many of cases Design obtained by FAA and CS always tends to maximum efficiency of STHE The computational costs of the CS algorithm were significantly less as compared to FFA

Table 2 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Caputo et al. [59]	STHE	Diameter of shell, baffle spacing, inner diameter of tube, baffle cut, layout angle of tube	Structural and operational constraints	Weight	GA	The design obtained by GA and with commercial software was compared Four case studied are analysed and significant weight savings were obtained through GA optimizer tool
Sadeghzadeh et al. [60]	STHE	Central baffles spacing, diameter of tube, and shell	Heat duty and operational constraints	Total cost	GA and PSO	Two cases were studied with different heat duty and working fluids were attempted PSO has obtained betters results as compared to GA for both case studies
Azad and Azad [61]	STHE	Tube diameter, length of tube, baffle spacing, shell diameter, tube pitch	Heat duty, fluid velocity	Total cost	GA	Alumina nano-fluid was used for improving the efficiency of STHE with reduction in energy consumption and overall cost The pressure drop and total cost of the STHE were reduced by 94% and 55% in comparison to the previous design
Ayala et al. [29]	STHE	Tube inner diameter, length of tube, tube number, ratio of baffle cut to shell diameter, ratio of baffle spacing to shell diameter and ratio of tube length to shell diameter and ratio of tube pitch to outer diameter	Pressure drop and working fluid velocity	Effectiveness Total cost	Multi-objective differential evolution and free search (MOFSDE)	The advantage of this algorithm that it does not need the tuning of number of populations and maximum iterations The Pareto optimal solutions developed by MOFSDE algorithm has dominated 68% of the solutions obtained by NSGA-II

Table 2 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Wong et al. [62]	STHE	Tube diameter, tube passes, pitch type and head type, tube length, ratio of baffle spacing to shell diameter	Length of tube to shell diameter ratio, baffle spacing, tube and shell side fluid velocity, pressure drop of tube and shell side	Pumping cost Capital cost	Elitist NSGA-II	Continuous as well as discrete parameter optimization was carried out for getting the advantage of standard available part Two cases were studied with different heat duty and working fluids were attempted and results were found better as compared to the results of PSO
Wen et al. [63]	STHE with helical baffle	Helical angles, baffle overlap proportion, and volume flow rate at inlet	Geometrical and operational constraints	Total cost Heat transfer rate	MOGA	MOGA combined with Kriging response was proposed for overcoming the dependency upon empirical correlations and to get accurate design for the design optimization of STHE The optimized results had showed a noble agreement within ± 3% error as compared with CFD results
Mohanty [64]	STHE	Shell diameter, baffle spacing and tube inner diameter	Heat duty and operational constraint	Total annual cost	FFA	Two case studies with different heat duty and working fluid were analysed Results were compared with GA, PSO, ICA, BBO and CSA and it was found that results of this study were better with less computational cost

Table 2 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Mohanty [65]	STHE	Shell diameter, baffle spacing and tube inner diameter	Heat duty and operational constraint	Total annual cost	GSA	Two case studies with different heat duty and working fluid were analysed Results were compared with GA, PSO, ICA, BBO, FFA and CSA and it was found that results of this study were better with less computational cost
Caputo et al. [66]	STHE	Shell diameter, tube inside diameter, baffle spacing and number of tube passes,	Heat duty, manufacturing and operational constraints	Total cost	GA	Misappropriation of parametric costing approaches for optimal equipment design was revealed Model was developed based on initial cost, manufacturing cost and operational cost GA was applied to optimize the design based on the developed model
Yin et al. [67]	STHE	Tube outer diameter, tubes number, length of tube and mass flow rate	Tube bundles, air velocity, pressure drop of shell and tube side fluid	Pressure drop Heat transfer rate, Entropy generation number	NSGA-II	The structural parameters of water tubes and the coiled pipes are optimized independently Single and multi-objective optimization is applied to get the optimized structural parameters of the heat exchanger
Rao and Saroj [28]	STHE	Tube internal diameter, ratio of tube pitch to tube outer diameter, length of tube, number of tubes	Ratio of baffle spacing to shell diameter, ratio of tube length to shell diameter	Total cost Effectiveness	Elitist-Jaya algorithm	Multi-objective optimization was carried out with a priori approach Set of Pareto optimal solutions were generated Results were found better as compared to GA and modified-TLBO

Table 2 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
de Segundo et al. [68]	STHE	Shell internal diameter, tube outer diameter, baffles spacing	Heat duty and operational constraints	Total cost	Tsallis DE	A variant of DE was proposed the design optimization of STHE Results were found better as compared to GA, PSO, BBO, CSA and DE
Rao and Saroj [69]	STHE	Diameter of shell, outer diameter of tube, pitch of tube, tube passes, baffle cut, baffle spacing at centre, outer diameter of tube bundle and tube layout angle	Pressure of tube and shell side, fluid velocity inside the tube and ratio of tube length to shell diameter	Total cost	Jaya algorithm	Two case studies were attempted with and without maintenance considerations Heat exchanger was over designed for avoiding the HE breakdown Design obtained by was better as compared to designs suggested by GA, CSO and PSO with less computational cost
Rao and Saroj [70]	STHE	Tube outer diameter, length of tube, tube passes, layout of tube, head type, ratio of baffle spacing to shell diameter, etc.	Ratio of tube length to shell diameter ratio, baffle spacing, fluid velocity and pressure drop	Total cost	Elitist-Jaya algorithm	Five different case studies were analysed Three case studies with different heat duty and fluid were analysed with discrete as well as continues variables Results were found better as compared to GA, PSO, BBO, FFA, CSA, ITHS, GSA etc.
Hajabdollahi et al. [71]	STHE	Tube pass, tube pattern, tube inner diameter, tube length and number of tubes	Fluid velocity and allowable pressure drop	Total cost Effectiveness	GA with constructal theory	A set of Pareto optimal solutions were generated Efficiency of HE had been improved by 28%
Saldanha et al. [72]	STHE	Layout pattern of tube, tube passes, length of tubes, thickness of tube wall, outer diameter of tube, baffle spacing etc.	Maximum pressure drop and maximum heat transfer area	Setup cost Operational cost	NSGA II, Predator–Prey, and MOPSO algorithms	Pareto optimal solutions were found by using evolutionary algorithms The PROMETHEE method applied to get the best evolutionary algorithm MOPSO algorithm was the most robust algorithm

Table 2 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Pham et al. [73]	STHE for a binary geothermal power plant	Tube diameter tube passes number, baffle spacing and tube length	Heat duty and operational constraints	Setup cost Operational cost	GA	The results showed that total cost for both preheater and evaporator decreased by 46.1% and 56.4%, in comparison to traditional approach without optimization
Roy et al. [74]	STHE for Organic Rankine cycles	Tube passes and diameter, baffle spacing and tube length etc.	Heat duty and operational constraints	Tube configuration Optimal weight	BBO	Optimized configuration was obtained with minimum error as compared to other algorithms
Rao and Saroj [75]	STHE	Tube outer diameter, length of tube and baffle spacing	Ratio of tube length to shell diameter ratio, baffle spacing, fluid velocity and pressure drop	Total cost	SAMPE-Jaya	Three different case studies were analysed Results were compared with GA, PSO, BBO, ICA, GSA etc. and found better as compared to these algorithms

It can be observed from above literature review that the advanced optimization algorithms have been applied mainly aiming the minimization of total cost. Furthermore, few researchers had applied multi-objective optimization for the design optimization of the STHE. It can also be observed from Table 2 that few researchers have used discrete parameter optimization [36, 50, 63, 70] in order to get the advantage of standard sizes available for STHE parts. A few researchers had used computational fluid dynamics (CFD) with advanced optimization algorithms [56, 64]. A Kriging response model was integrated with MOGA [64]. Furthermore, PROMETHEE (preference ranking organization method) method [72] was used to select the best optimal solution among the Pareto optimal solutions. A misappropriation of parametric costing approaches for optimal equipment design was revealed [67]. Moreover, the analytical models used in design optimization of STHEs contain many assumptions while developing the models which may lead errors as compared to the actual situations.

2.3 Review of the Application of Advanced Optimization Algorithms for Design Optimization of Some Miscellaneous Heat Exchangers

Table 3 presents the applications of advanced optimization algorithms for the design optimization of heat exchanger networks (HEN) [76–78, 80, 87, 92, 93, 95, 98], fin-and-tube heat exchangers (FTHEs) [6, 79, 81, 82, 85, 91, 94], printed circuit heat exchangers (PCHEs) [83, 89], vertical U-tube ground HE [96], wavy fined-and-elliptical tube HE [96] and U-shaped square duct HE [97]. The algorithms used for the design optimization of these heat exchangers [75–98] includes: GA, SA, NSGA-II, PSO, ABC, DE and CSO algorithms. The objectives of these heat exchangers were: total cost (HENs); effectiveness, total cost, heat transfer rate and thermal resistance (FTHEs); effectiveness and pressure drop (PCHE); heat transfer rate, pressure drop and entropy generation (vertical U-tube ground heat exchanger), size of bore hole HE [90]; Colburn and friction factor of wavy fined-and-elliptical tube heat exchanger [96] and pressure drop and heat transfer rate (U-shaped square duct HE). A few researchers had applied multi-objective optimization of HEs [77, 82, 83, 86, 96]. The CFD was used with advanced optimization algorithm [96]. In [97] several surrogate models were integrated with the advanced optimization algorithms. It can be seen from this literature survey [76–98] that there is still a lot of scope for the application of advanced optimization algorithms for the design optimization of these heat exchangers. There are many efficient and most power algorithms such as biogeography-based optimization (BBO), gravitational search algorithm (GSA), firefly algorithm (FFA), cuckoo search (CS), bat algorithm (BA),

Table 3 Review of the applications of advanced optimization algorithm for some miscellaneous heat exchanger design

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Luo et al. [76]	Synthesis of HE networks	Hot utility and a cold utility, cold and hot process streams, etc.	Target temperatures	Total cost	GA hybrid with SA	The examples presented had shown special search abilities of hybrid GA–SA in both structure space and continuous variable space
Gorji-Bandpy et al. [77]	HE network	Initial temperature, final temperature and temperature length	Energy balance, areas constraints	Total cost	GA	HE networks was found better in all cases as compared to the results found using traditional optimization
Hajabdollahi et al. [6]	Fin-and-tube HE	Transversal and longitudinal pitch, pitch of fin, tube pass, diameter of tube, flow length of cold fluid, no-flow length, and stream flow length of hot fluid	Structural and operation constraint	Effectiveness Total cost	NSGA-II	The results of optimal designs were presented in a set of non-dominated solutions Sensitivity analysis of change in design parameter on optimum effectiveness and total annual cost was also carried out
Wang et al. [78]	Heat exchanger network Retrofit	Variables related to areas and split ratios	Augmentation ratio	Total cost	SA	HEN retrofit optimization was done by enhancing the heat transfer Retrofit process had become simpler and required lower cost
Ghazi et al. [79]	Fin-and-elliptical tube HE	High and low drum pressures, duct burner fuel consumption, flow pinch point temperature differences and steam mass flow rates	Energy balance	Total cost	GA	It was observed that with increase in the exergy unit cost, the optimum values of design parameters were designated such that to decrease the objective function Sensitivity analysis of design variables on the objective function was also done

Table 3 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Ahmad et al. [80]	HE networks	Heat duty change, repipe heat exchanger, splitter flow, fractions change etc.	–	Total annualized Cost	SA	Results obtained by deterministic optimization based design approaches were compared with present design and found better as compared to previous
Kashani et al. [81]	Fin-tube heat exchanger	Length of tube, outer and inner diameter of tube, tube rows, tubes per row, fin density, fin height, thickness etc.	Fluid flow velocity, Reynolds number, tube bundle length to width ratio, fan diameter and pressure drop	Temperature approach Total annual cost	NSGA-II	No-dominated set of solutions were generated between two objectives Sensitivity analysis of design variables on objective function is carried out A decision-making method was used to get the final optimum design point
Qian et al. [82]	Fin-and-tube HE	Tube length, tube outer diameter, horizontal and vertical spacing, number of tubes etc.	–	Heat transfer rate Total cost Thermal resistance	MOGA	Four different case studies were presented with different objectives and variables A set of Pareto optimal solutions were generated for the each case
Lee et al. [83]	Printed circuit HE	Ratios of the fillet radius, wavelength, and wave height to the hydraulic diameter of the channels	–	Non-dimensional pressure drop Effectiveness	NSGA-II	The response surface model was used as a surrogate model Four optimal designs were obtained on the Pareto-optimal front by using K-means clustering
Huang et al. [84]	Vertical U-tube ground HE	Boreholes, depth of borehole, distance among borehole, radius of borehole, radius of pipe diameter	Material properties and operational condition	Heat transfer Pressure drop	GA	It was found that the total cost of the system optimized by GA optimization was 5.5% lesser than that of using the original design parameters

Table 3 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Juan and Qin [85]	Fin-and-tube HE	Fin pitch, tube outside diameter, tube transverse and longitudinal pitch, fin thickness, number of tube rows	Structural and operation constraint	Heat transfer rate total pressure drop	MOGA	The heat transfer of the optimized HE was increased by 2.1–9.2% as compared with the original design and total pressure drop was decreased by about 4.4–8%
Huang et al. [86]	Vertical U-tube ground heat exchangers	Number of bore hole, depth of borehole, radius of borehole, fluid mass flow rate and outer radius of U-tube	Structural and operational constraints	System cost Entropy	NSGA-II	Two case studies were analysed validating the effectiveness of the method System cost was reduced by 5.2% as compared to the total system cost of the original design
Sreepathi and Rangaiah [87]	Retrofitting of heat exchanger networks	60 structural (integer) variables and 27 corresponding to areas and split ratios	Maximum additional area, approach temperature	Total annual cost Utility cost separately	Elitist-NSGA-II	Heat exchanger network retrofitting was with variable heat capacities of steam was studied Better and practical solutions were produced for heat exchanger network retrofitting in process plants
Biyanto et al. [88]	HE network Cleaning Schedule	Variables related to areas and split ratios	Augmentation ratio	Cost of cleaning	ICA	The result of HE network cleaning schedule obtained by using ICA has saved heat transfer loss about 44.83 in a period of 44 months
Lee and Kim [89]	Printed circuit HE	Ratio of the pitch and depth of the ribs to the hydraulic diameter of the channel	–	Heat transfer Pressure drop	NSGA-II	Pareto optimal curve was generated Ten design points has been chosen in the design space with the help of Latin hypercube sampling To approximate the objective functions Surrogate models were developed

Table 3 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Schulte et al. [90]	Borehole heat exchanger array	Borehole diameters, pipe diameters, shank space, Length of insulation, Pipe thermal conductivities etc.	Heat duty and operational constraints	Size of a BHE	Global optimization toolbox	It had finished competence gaps of presently existing simulators like the consideration of borehole insulation and unrestricted bore path geometries
Sajedi et al. [91]	Fin-tube heat exchanger	Total number of tube, fin thickness, array, tube pitch, number of column, outer diameter		Exergy efficiency Total cost	GA	Four different nano-fluid were considered as working fluid For all nano-fluid working system, the total cost of the system grows much more than an exergy efficiency enhancement In all cases the optimal working point has approached towards the zero nano-fluid concentration
Diaby et al. [92]	Heat exchanger network	Gel layer resistance, and coke layer resistance of heat exchanger	Input and output temperature	Cleaning Schedule	GA	Significant savings was gained by the application of preset cleaning schedules for all the ageing settings in comparison to with and without optimized cleaning or no cleaning performed in the case study having the 14-unit crude oil refinery

Table 3 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Deka and Datta [93]	Scheduling of a heat exchanger network	Operational status, Steam temperature at the outlet, Milk temperature at the outlet etc.	Thickness of mass deposition, maximum heating duration, minimum residence time etc.	Total cleaning cost, Excess energy consumed in overheating Flow rate of heating steam	GA, PSO and DE	Optimal cleaning schedule is presented under milk fouling Single as well as multi-objective optimization is carried out Both the DE and PSO had significantly reduced the energy loss and steam flow rate as compared to GA The PSO had not achieved enhancement up to the level of none of the GA and DE
Rao [94]	Fin-and-tube	Outer tube diameter, transverse pitch, longitudinal pitch, number of tube rows, fin pitch etc.	Maximum allowable pressure, ratio of correction section to hollow section	Total weight Total annual cost	Modified TLBO, ABC and CSO	Both the objectives were optimized separately Results obtained by modified-TLBO shows that this algorithm perforce achieves good results in comparison to the other advanced algorithms with less computational cost
Zhang et al. [95]	Heat exchanger network synthesis	Number of hot steam and cold steam, number of stages, target temperature, supply temperature etc.	Space and operational constraint	Total annual cost	Random walking algorithm	Four different cases were considered which showed the effectiveness of algorithm Simpler and economic networks were found with less computational cost
Damavandi et al. [96]	Wavy fin-and-elliptical tube heat exchangers	Aspect ratio of elliptical tube, ratio of transverse tube pitch to the semi-major axis, wavy angle of fin and the ratio of wavy fin pitch to the semi-major axis of elliptical tube	Structural and operational constraints	Friction factor Colburn factor	NSGA-II algorithm with CFD	Combining and simultaneously using the CFD, neural network and NSGA-II algorithm was found very convenient and had produced valuable results A set of Pareto optimal solutions were generated and were validated through CFD

Table 3 (continued)

References	Heat exchanger	Design variables	Constraint(s)	Objective function(s)	Optimization technique(s)	Key findings
Wansaseub et al. [97]	U-shaped baffle square-duct heat exchanger	Baffle radii and heights	Overall length of duct, duct height	Pressure loss HE Heat transfer rate	Self-adaptive DE with neighbourhood search	Several surrogate models were used for objective function approximation The simultaneous use of multiple surrogate models with DE provided better results
Pavão et al. [98]	Heat exchanger network synthesis	Initial temperature, final temperature and temperature length	Energy balance, areas constraints	Total annual costs	SA and PSO	SA was proposed for topology optimization PSO was used to handle the continuous heat load variables Four different cases were considered

TLBO, Jaya etc. are available in the literature which can be used. Furthermore, the cost model used for FTHE is very old and contains many assumptions.

3 Conclusions

This work presents the optimization aspects of the widely used heat exchangers such as shell-and-tube heat exchangers, plate-fin heat exchangers, fin-and-tube heat exchangers, heat exchangers network and some other heat exchangers such as printed circuit heat exchanger, vertical U-tube ground heat exchanger, bore hole heat exchanger, wavy fin-and-elliptical tube heat exchanger and U-shaped square duct heat exchanger. A thorough literature review related to design optimization of these heat exchangers are made and summarised. The objective function(s), design variables and constrained imposed to the design are listed. A critical remark on various research works is also presented. The following observations are made based on this review work:

- A lot of work is conducted on the parameter optimization of STHEs and PFHEs as compared to the other heat exchangers.
- The objective function(s) considered in most of the cases was total cost and effectiveness in case of PFHE and total cost in case of STHEs.
- A few multi-objective optimization algorithms were applied to STHEs PFHEs.
- A few researches had used surrogate models along with advanced optimization algorithms in order to minimize the error of empirical relations.
- A few researchers had used computational fluid dynamics along with advanced optimization algorithms.
- The cost models used for the optimization are old and do not include the direct relation with the heat exchanger parts and maintenance aspects in most of works were not included.
- The cost models used were developed from the vendor point of view. The accurate cost models from vendor as well as manufacturing point of view are not available.
- In most of the research works, the design optimization of HEs (STHE and PFHE) were carried out by considering the design variables as continuous variables or semi-discrete variables. A few works were carried out by considering all the design variables as discrete variables (standard size of the parts).
- The application of advanced fluid such as nano-fluid and smart fluid along with the optimization were taken up.
- A very few research work was carried out in the field of design optimization of fin-and-tube heat exchangers. Application many powerful and more advanced optimi-

zation algorithms are missing which may provide good designs as compared to the others.

- In case of design optimization of heat exchanger networks, the application of advanced optimization is limited which needs to explore this field.
- Similarly, the application of the advanced optimization algorithms to other heat exchangers such as printed circuit heat exchanger (PCHE), vertical U-tube ground heat exchanger, wavy-fined-and-elliptical tube heat exchanger and U-shaped square duct heat exchanger is limited. The field of design optimization of these heat exchangers using advanced optimization still needs to be explored from the point of view of application of various advanced optimization algorithm, objectives as well as mathematical models.

Compliance with Ethical Standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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