JOURNAL OF SCIENCE
SAKARYA UNIVERSITY

Sakarya University Journal of Science

ISSN 1301-4048 | e-ISSN 2147-835X | Period Bimonthly | Founded: 1997 | Publisher Sakarya University | http://www.saujs.sakarya.edu.tr/

Title: Application of Genetic Algorithm for Optimization of Heat-Transfer Parameters

Authors: Mustafa Akpınar
Recieved: 2018-12-21 16:49:36

Accepted: 2019-07-09 13:59:09

Article Type: Research Article
Volume: 23
Issue: 6
Month: December
Year: 2019
Pages: 1123-1130

How to cite
Mustafa Akpınar; (2019), Application of Genetic Algorithm for Optimization of Heat-Transfer Parameters. Sakarya University Journal of Science, 23(6), 1123-1130, DOI: 10.16984/saufenbilder.500643
Access link
http://www.saujs.sakarya.edu.tr/issue/44246/500643

New submission to SAUJS
http://dergipark.gov.tr/journal/1115/submission/start

Sakarya University Journal of Science 23(6), 1123-1130, 2019

Application of Genetic Algorithm for Optimization of Heat-Transfer Parameters

Mustafa Akpınar*[1]

Abstract

Nowadays, new materials are developed with the aim to reduce heat transfer and energy loss. Thus, energy can be reduced and heat energy can be transferred efficiently. Many researches on the field of heat transfer have been made in the literature. However, there are few studies on the determination of insulation material thickness using heuristic algorithms and there is no study on finding the thermal boundary layer thickness using heuristic algorithms. One of the heuristic algorithms used in the field of computer science is Genetic Algorithm (GA), which is frequently applied in optimization problems. We propose that GA could be used to solve heat transfer problems of insulation material selection and laminar thermal boundary layer thickness determination. The goal of the proposal is to estimate the optimal parameters using a GA. In the first case, the thickness of insulation material selection and the maximum amount of heat loss that can be caused by different thicknesses of the insulating material under the boundary conditions and assumptions are calculated using GAs. It is shown that, using the heat-transfer coefficient and unit length cylinder, GAs can be used in everyday problems, such as determining the thickness of the insulating material or the outer temperature of the insulating material. In the second case, the boundary layer thickness is determined using GA for air flow with a laminar flow, where its characteristics are constant, irradiation is neglected, and plate and air temperatures are constant in the continuous regime on the plate. For both cases, the GA results are repeated 5 times and it is observed that the results are very close to each other. The experimental results demonstrate that, for both cases GA gives optimal target, minimum and maximum values, thus, GAs are applicable in heat-transfer problems that require optimization.

Keywords: Heat transfer, genetic algorithm, optimization

1. INTRODUCTION

Heat transfer as a science studies to predict the energy transfer that may occur between material bodies as a result of temperature alterations [1]. The heat transfer researches seek not only to explain how heat energy may be transferred but also to estimate the amount of energy will be used under certain specified conditions [1]. Optimization must be determined under certain specified conditions of heat-transfer problems.

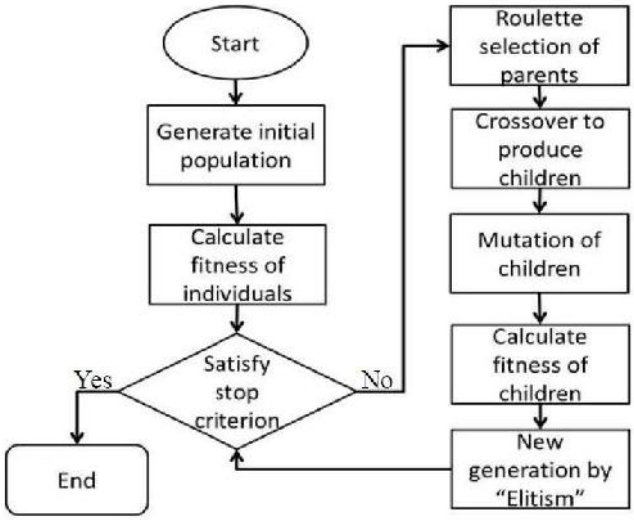
* Corresponding Author: akpinar@sakara.edu.tr
[1] Sakarya University, Software Engineering Department, Sakarya, Turkey. ORCID: 0000-0003-4926-3779

The growth of thermal systems, such as those related to material processing, energy conversion, pollution, aerospace, and automobiles, has caused the need to design and optimize thermal systems to grow as well [2]. Thus, optimization on heat transfer and thermal systems becomes more necessary.

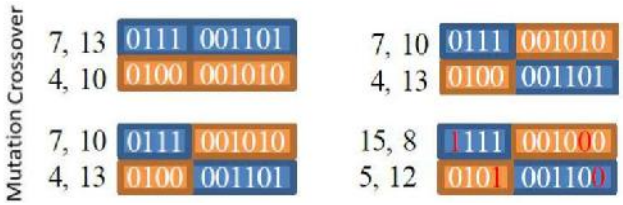
There are many studies on heat-transfer optimization. Hayati et al. studied an adaptive neuro-fuzzy inference system (ANFIS) model to estimate the heat-transfer rate of the wire-on-tube type of heat exchanger [3]. Stirling heat engine is applied for optimization with multiple criteria and genetic algorithm (GA) is used for optimization [4]. Shi et al. optimized the inlet part of a microchannel ceramic heat exchanger studying a surrogate model coupled with a GA [5]. Sadeghzadeh demonstrated the GA application in the design of techno-economically optimum shell-and-tube heat exchangers [6]. Anish and Krishnakumar optimized dimensionless parameters, such as the Reynolds number (*Re*), porosity (*p*), perforation perimeter factor (P_f), plate thickness to pore diameter ratio (*l/d*), and spacer thickness to plate thickness ratio (*s/l*) for the maximum Colburn factor and minimum friction factor using a GA [7]. Ge et al. optimized the structure of a minichannel heat sink using a multi-objective GA [8]. Maladi and Balaji applied artificial neural networks (ANNs) and GAs to determine optimal location of three discrete heat sources that could be placed anywhere inside a ventilated cavity and cooled by forced convection [9]. Saruhan and Uygur used genetic algorithm to optimize mechanical system design [10]. They used parameters of speed reducer design for optimization. The condenser heat transfer rate was maximized and pressure drop was minimized using GA in [11]. Another study using GA in heat transfer was optimization of total cost of heat exchanger. In this study, cost was reduced 13.16% and compactness was increased 254% [12]. Another study using GA in energy sector was the thermoelectric generators design [13]. Outpout power of the thermoelectric generators was increased about 51.9% using GA optimization. In another generator design (the heat recovery steam generator) using GA, it is concluded that their approach could be used in existing and new heat recovery steam generators [14]. As stated in the literature review above, heuristic algorithms can be used in heat-transfer problems. For this reason, the objective of this paper is that two sample heat-transfer studies are completed to determine the optimal parameters, using the GA, which is one of the heuristic algorithms used in computer science. The first study includes a heat source that is radially heated and wrapped for insulation purposes to protect the heat with minimum heat loss. In the second study, boundary layer thickness was determined using a GA for air flow with laminar flow.

2. GENETIC ALGORITHM

The GAs are first has applied into the field of neural networks, then into machine learning, and recently into what is now called "evolutionary computation" [15]. The main objective in all application fields was to evolve a population of candidate solutions to a given problem making calculations inspired by natural genetic variation and natural selection [15]. The GAs are approaches which try to find the optimal solution and are based on evolutionary methodologies such as evolutionary biology, which studies inheritance, learning, selection, and mutation [2], [16]. Figure 1a shows the process flow of a GA. As a first step, the initial population is generated, and the fitness for this population is calculated. The fitness is checked to determine whether it meets the stopping criterion. If the stopping criterion is not met, the selection algorithm is run to find the best solutions. The most commonly used selection algorithms are tournament, roulette wheel, proportionate, rank, and steady-state selection [15]–[17]. The next step is to create new children according to the selected parents. At this stage, a crossover is made and shown along with the process in Figure 1. Crossover is a matter of replacing some of the genes in one parent with the corresponding genes of the other [17]. After the crossover phase, a mutation is made. Mutations consist of flipping the bit at a randomly chosen locus [15]. After this process, the fitness of the generated children is calculated, and the best is selected according to the “Elitism” approach. The error criterion is checked again, and this process is repeated until the desired point is reached.



(a)



(b)

Figure 1. (a) Genetic algorithm process flow (b) Genetic algorithm crossover and mutation.

Genetic algorithms have a target based on the fitness function. Constraints and design variables are used while the target is found. Constraints are variables that include formulas and ranges and only affect the target function. Design variables are found in a certain range of values, and they are explored by the GA. They are effective on the constraints and target function. The target is the fitness value for which the maximum, minimum, and target values are to be determined

3. CASE STUDIES

In this paper, two sample studies have been defined for optimization. The first of these is the heat transfer in cylindrical surfaces. In this problem, an insulation material surrounds the heat source. The optimization problem is to determine the thickness of the insulation material and the material that will provide the lowest heat loss.

The first study includes a heat source (Figure 2) that is radially heated with a constant/continuous regime and has constant characteristics with no heat generation and is wrapped for insulation purposes to protect the heat with minimum heat loss.

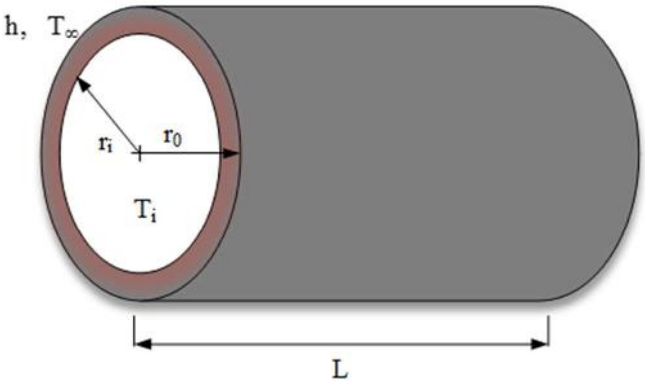


Figure 2. Insulation of a cylinder problem

In the continuous regime and absence of heat generation, the energy balance is equal, and the heat transfer is shown in Eq. (1) [1], [18].

$$Q = 2\pi L\left(T_i - T_\infty\right)\Big/\left(\left(\ln\left(r_o/r_i\right)/k\right) + \left(1/\left(r_o h\right)\right)\right) \quad (1)$$

where Q is the heat flow (heat-transfer amount), T_i is the inner temperature of insulation, T_∞ is the outer surface of insulation, r_o and r_i are the outer and inner radius of insulation, k is the thermal conductivity constant of the material, h is the convection heat transfer coefficients, and L is the length of the cylinder. By taking the derivative of Q according to r_o and equating to zero, the value of r_o, maximizing the heat transfer, is found and given in Eq. (2):

$$\begin{aligned} dQ/dr_o &= 0 \\ &= F\Big/\left(\ln\left(r_o/r_i\right)/k + 1/r_o h\right)^2 \ where \\ F &= -2\pi L\left(T_i - T_\infty\right)\left[\left(1/\left(kr_o\right)\right) - \left(1/\left(kr_o^2\right)\right)\right] \end{aligned} \quad (2)$$

In the second case study, the thermal boundary layer thickness was determined for air flow with the laminar flow, where its characteristics are constant, irradiation is neglected, and plate and air temperatures are constant in the continuous regime on the plate. There are three types of flow

regions on a flat plate [1], [18]. These are laminar, transition, and turbulent regions (Figure 3).

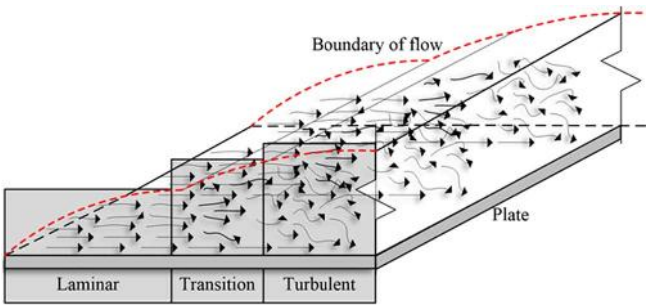


Figure 3. Thermal boundary layer problem

The transition from laminar to turbulent flow occurs when Eq. (3) represented:

$$Re = u_\infty x/v = \rho u_\infty x/\mu > 5 \cdot 10^5 \quad (3)$$

In this equation, u_∞ is the free-stream velocity, x is the distance from leading edge, v is the kinematic viscosity. Kinematic viscosity (v) is dynamic viscosity (μ) divided by the density (ρ) [1]. The Nusselt number, Nu, is the dimensionless variable that identifies the convective heat transfer [18], [19]. In the case in which the flow is laminar ($Re<5\cdot10^5$), the Nusselt number is expressed as:

$$Nu_x = 0.332 Re^{1/2} Pr^{1/3} \quad (4)$$

Where Pr is the Prandtl number, which is a dimensionless parameter representing the ratio of the diffusion of momentum to the diffusion of heat in a fluid [20] and is given in Eq. (5):

$$Pr = v/\alpha = v/\left(k/\rho c_p\right) \quad (5)$$

where c_p is the specific heat at a constant pressure (kJ/kg°C), k is the thermal conductivity (kW/m°C), α is the thermal diffusivity, and v is the kinematic viscosity [1]. Equation (6) shows the heat-transfer coefficient:

$$h = Nu_x k/x \quad (6)$$

Equation (7) gives the average value of the heat-transfer coefficient.

$$\bar{h} = 2h \quad (7)$$

The heat flow is calculated in Eq. (8):

$$Q = \bar{h} A (T_w - T_\infty) \quad (8)$$

where T_∞ is the temperature of the fluid outside the thermal boundary, T_w is the temperature of the wall, and A is the area of the plate [1]. Before finding the thermal boundary layer thickness, the hydrodynamic boundary layer thickness should be calculated as follows:

$$\delta = \left(4.64/\sqrt{Re_x}\right) x \quad (9)$$

Equation (10) shows the thermal boundary layer thickness:

$$\delta_t = \left(0.977/Pr^{1/3}\right)\delta \quad (10)$$

4. RESULTS

The results of two different studies are shown in this section. The first of these problems is the cylindrical insulating that has two cases. The first of these two cases is to find the insulation material that is to be used at a predetermined thickness for the allowed maximum heat loss. In the second case, we determine the thickness, given the maximum thermal conductivity constant and insulation material, for the highest heat loss allowed. In both cases, the heat loss (Q) is taken as a constraint. Inner and outer temperature of insulation cylinder is 500°C and 75°C, respectively. Heat sources radius is 30mm. In the first case, Q is a maximum of 100 W and in the second case; Q is a maximum of 120 W. For all tests in both cases, optimization started with k = 1 W/m°C and t = 1 mm. In the first case, optimization was initiated as a design variable at a maximum of 200 mm and a minimum of 25 mm t, and k was determined. In the second case, k is taken as a design variable so that a maximum 0.084 W/m°C and the lowest t-thickness are determined. The main reason why k is different, is that Q is increased from 100W to 120W. Q and k are directly proportional. The fitness function of the cases is given in formula (1). In the case that

the first fitness function is found with t left alone in the equation and, the second fitness function is when k is left alone. The chromosome structure has five values that are t, k and three random generated numbers. Table 1 shows the results and the processing times for the five tests of the two cases.

In the two cases, the following parameters (max 100 generations) were used for optimization: 16 chromosomes in the population, 0.9 crossover probability, 0.1 chromosome mutation probability, and 0.1 random selection probability. The average of the optimization process was performed in approximately one minute. Process steps of the GA optimization is given in Figure 4. Although the GA is a heuristic approach, there are different results, but these values are very close to each other. The results of evolving for each different generation and chromosome are getting close in each iteration. We tried to figure out two situations of the same problem could be solved using GA. Thus, we tried to change design variable and target (k and t) in both model and numeric values and it is clearly seen that GA finds nearly optimum values.

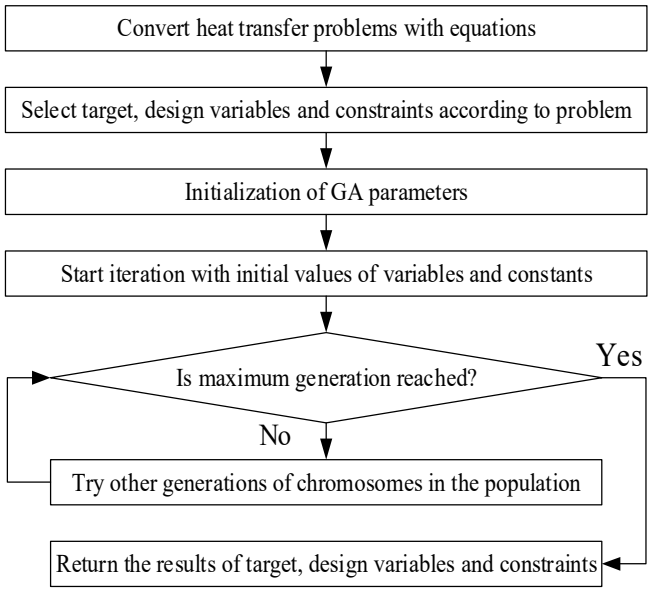


Figure 4. Process steps of the GA optimization

We found that cellulose cotton material (k = 0.071 W/ m°C) could be used as insulation material for the first case, where the material is unknown. In the second case, window glass material (k = 0.078 W/m°C) can be used, and the lowest thickness of insulation material is found to be 137.1 mm.

Table 1. Insulation material and thickness problem results

	Target: Material Type (k - W/m°C)				**Target: Thickness of Insulation (t - mm)**			
Test	***k* (kW/m°C)**	***t* (mm)**	***Q* (W)**	**time (s)**	***k* (kW/m°C)**	***t* (mm)**	***Q* (W)**	**time (s)**
1	0.082	200	99.948	75	0.084	145	117.016	36
2	0.080	200	97.226	59	0.084	137.1	119.994	58
3	0.077	200	93.802	51	0.084	150	115.272	55
4	0.076	200	92.365	57	0.084	137.2	119.955	54
5	0.080	200	97.226	52	0.084	137.1	119.994	59
Avg.	0.079	200	96.113	58.8	0.084	141.28	118.446	52.4

Table 2. Constraints and design variables of different targets with different cases

Case	**Type**	**Goal - Range**
Case 1	Goal	Maximum, minimum, and target (19.6 mm) values of thermal boundary layer thickness (δt)
	Constraints	$Re < 50 \times 10^3$, 140 W $\leq Q \leq$ 190 W
	Design Variables	0.2 m $\leq x \leq$ 1 m, 80°C $\leq T \leq$ 130°C
Case 2	Goal	Maximum, minimum, and target (160.43 W) values of heat flow (Q)
	Constraints	$Re < 50 \times 10^3$
	Design Variables	0.2 m $\leq x \leq$ 1 m, 80°C $\leq T \leq$ 130°C, 0.01 mm $\leq \delta t \leq$ 20 mm
Case 3	Goal	Maximum, minimum, and target (0.61 m) values of distance from leading edge (x)
	Constraints	140 W $\leq Q \leq$ 190 W, 0.01 mm $\leq \delta t \leq$ 20 mm
	Design Variables	$0.01 \leq Re \leq 50 \times 10^3$, 80°C $\leq T \leq$ 130°C

The second study is a problem regarding laminar flow on a hot plate. In this problem, the air at a certain speed flows over the plate, which is hotter than the air. It is aimed so that the flowing air is laminar. In the problem with the laminar boundary layer, three different target variables were determined. Targeted variables for three different cases and relations of these cases with constraints and design variables are given in Table 2. For these three cases, the problems were studied at the minimum, maximum, and target values. Each study was repeated five times, and the average results are shown in Table 3. In all cases of the second study, the temperature of the air is 65.6°C. The temperature in the region of the heat flow is taken as the average of the temperature of the plate and air. The properties of air at atmospheric pressure, given in the table in [1], are used to calculate variables such as the density (ρ), thermal conductivity (k), specific heat at constant pressure (c_p), and velocity of the air (u_∞) in the flow area, which vary according to the plate temperature in the optimization program.

The design variables in the models in Case 1 started at x = 1 m and T = 1°C. In the models in Case 2, the design variables x = 1 m, T = 1°C and δt = 1 mm were initiated. In Case 3, the initial values of the design variables were Re = 1 and T = 1°C. The fitness function of the cases is given in formula (10). In three cases, three fitness functions are evaluated using Eq. (3) to (10). The chromosome structure has five values which are x, T and three random generated numbers for the first case; x, T, δt and two random generated numbers for the second case; Re, T and three random generated numbers for the third case. In all three cases, the following parameters were used for optimization: 16 chromosomes in population, 0.9 crossover probability, 0.1 chromosome mutation probability, 0.1 random selection probability, max 100 generations, and the average of the optimization time is under 85 seconds. The average results for each case are shown in Table 3. In these results, all values in the target rows in the goal column are close when the target values, design variables, and constraints in Cases 1 and 3 are examined. This shows that, while the target variable is found, even though the effect parameters are different in the constraint and design variable states, the results can be found correctly in the global environment. The processing times for the cases were changing an average of 25% (Table 3, t(s) column).

5. CONCLUSION

Parametric equations used in heat transfer are frequently used in the solution of problems. In this study, we attempted to find the most suitable solution in the problems selection of insulation material and determination of laminar boundary layer thickness, which are two different situations used in everyday life. To find the most suitable solution, we proved that the calculations can find the optimum result in the solution space with the help of GA but it does not guarantee to find best solution. It was also found that GAs can be used in more complex problems of heat transfer. As the future work, heuristic algorithms such as simulated annealing, artificial bee colony, ant colony optimization and particle swarm optimization will be applied to determine parameters.

Table 3. Thermal boundary layer problem results

Cases	Goal	x (m)	T_w (°C)	Re	δt (mm)	Q (W)	t (s)
1 - Thermal boundary layer (δt in mm)	Minimum	0.38	128.03	15,189	**15.57**	140.95	77.00
	Target	0.60	123.45	24,507	**19.60**	165.73	94.00
	Maximum	1.00	116.64	41,368	**25.12**	189.60	93.00
2 - Heat flow from plate to air (Q in Watt)	Minimum	0.20	80.00	9,070	20.00	**13.44**	63.20
	Target	0.63	101.11	27,126	13.50	**160.45**	80.60
	Maximum	1.00	130.00	40,084	0.01	**600,936**	77.20
3 - Distance from leading edge (x in m)	Minimum	**0.36**	130.00	14,232	15.14	140.97	78.20
	Target	**0.61**	127.03	24,553	19.76	176.39	92.20
	Maximum	**0.63**	123.33	25,479	19.98	168.54	106.40

6. REFERENCES

[1] J. P. Holman, Heat Transfer, 10th ed. New York, NY: McGraw-Hill, 2010.

[2] Y. Jaluria, Design and Optimization of Thermal Systems, Second Edition, vol. 20071213. CRC Press, 2007.

[3] M. Hayati, A. Rezaei, and M. Seifi, "Prediction of the heat transfer rate of a single layer wire-on-tube type heat exchanger using ANFIS," Int. J. Refrig., vol. 32, no. 8, pp. 1914–1917, Dec. 2009.

[4] R. V. Rao, K. C. More, J. Taler, and P. Ocłoń, "Optimal design of Stirling heat engine using an advanced optimization algorithm," Sādhanā, vol. 41, no. 11, pp. 1321–1331, 2016.

[5] H. Shi, T. Ma, W. Chu, and Q. Wang, "Optimization of inlet part of a microchannel ceramic heat exchanger using surrogate model coupled with genetic algorithm," Energy Convers. Manag., vol. 149, pp. 988–996, Oct. 2017.

[6] H. Sadeghzadeh, M. A. Ehyaei, and M. A. Rosen, "Techno-economic optimization of a shell and tube heat exchanger by genetic and particle swarm algorithms," Energy Convers. Manag., vol. 93, pp. 84–91, Mar. 2015.

[7] A. K. John and K. Krishnakumar, "Performing multiobjective optimization on perforated plate matrix heat exchanger surfaces using genetic algorithm," Int. J. Simul. Multidiscip. Des. Optim., vol. 8, p. A3, Jan. 2017.

[8] Y. Ge, F. Shan, Z. Liu, and W. Liu, "Optimal Structural Design of a Heat Sink With Laminar Single-Phase Flow Using Computational Fluid Dynamics-Based Multi-Objective Genetic Algorithm," J. Heat Transfer, vol. 140, no. 2, p. 022803, Sep. 2017.

[9] R. R. Madadi and C. Balaji, "Optimization of the location of multiple discrete heat sources in a ventilated cavity using artificial neural networks and micro genetic algorithm," Int. J. Heat Mass Transf., vol. 51, no. 9–10, pp. 2299–2312, May 2008.

[10] H. Saruhan and İ. Uygur, "Design Optimization of Mechanical Systems Using Genetic Algorithms," Sak. Univ. J. Sci., vol. 7, no. 2, pp. 77–84, 2003.

[11] S. Sanaye and M. Dehghandokht, "Modeling and multi-objective optimization of parallel flow condenser using evolutionary algorithm," Appl. Energy, vol. 88, no. 5, pp. 1568–1577, May 2011.

[12] K. Baadache and C. Bougriou, "Optimisation of the design of shell and double concentric tubes heat exchanger using the Genetic Algorithm," Heat Mass Transf., vol. 51, no. 10, pp. 1371–1381, Oct. 2015.

[13] W.-H. Chen, P.-H. Wu, and Y.-L. Lin, "Performance optimization of thermoelectric generators designed by multi-objective genetic algorithm," Appl. Energy, vol. 209, pp. 211–223, Jan. 2018.

[14] A. Rezaie, G. Tsatsaronis, and U. Hellwig, "Thermal design and optimization of a heat recovery steam generator in a combined-cycle power plant by applying a genetic algorithm," Energy, vol. 168, pp. 346–357, Feb. 2019.

[15] M. Melanie, An Introduction to Genetic Algorithms, 5th ed. London: MIT Press, 1999.

[16] R. L. Haupt and S. E. Haupt, Practical Genetic Algorithms, 2nd ed. New York, NY, USA: Wiley, 2004.

[17] F. Glover and G. A. Kochenberger, Eds., Handbook of Metaheuristics, vol. 57. Boston: Kluwer Academic Publishers, 2003.

[18] F. Kreith, R. M. Manglik, and S. B. Mark, Principles of Heat Transfer, 7th ed. Stamford, CT: Cengage learning, 2011.

[19] G. L. Shires, "Nusselt Number," in A-to-Z Guide to Thermodynamics, Heat and Mass Transfer, and Fluids Engineering, Begellhouse.

[20] G. L. Shires, "Prandtl Number," in A-to-Z Guide to Thermodynamics, Heat and Mass Transfer, and Fluids Engineering, Begellhouse.