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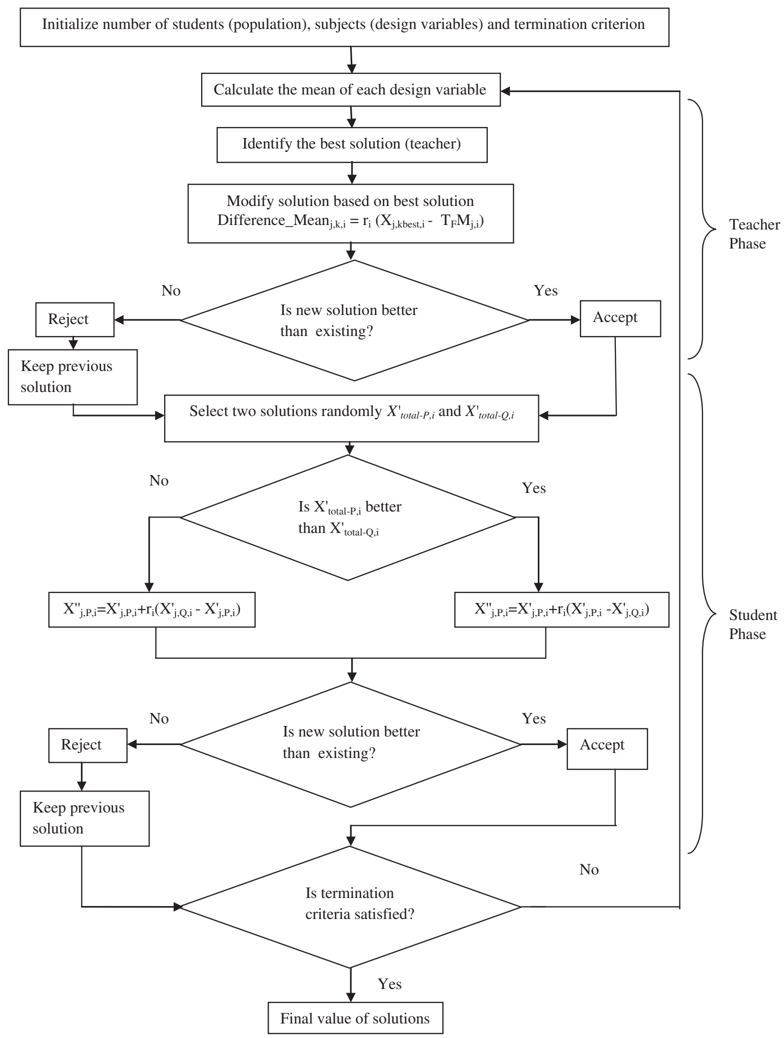

MECHANICAL ENGINEERING | RESEARCH ARTICLE

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Optimization of thermal performance of a smooth flat-plate solar air heater using teaching–learning-based optimization algorithm

R. Venkata Rao[1] and Gajanan Waghmare[1]*

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*Corresponding author: Gajanan Waghmare, Department of Mechanical Engineering, S.V. National Institute of Technology, Ichchanath, Surat, Gujarat 395 007, India
E-mail: waghmaregaju@yahoo.com

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Abstract: This paper presents the performance of teaching–learning-based optimization (TLBO) algorithm to obtain the optimum set of design and operating parameters for a smooth flat plate solar air heater (SFPSAH). The TLBO algorithm is a recently proposed population-based algorithm, which simulates the teaching–learning process of the classroom. Maximization of thermal efficiency is considered as an objective function for the thermal performance of SFPSAH. The number of glass plates, irradiance, and the Reynolds number are considered as the design parameters and wind velocity, tilt angle, ambient temperature, and emissivity of the plate are considered as the operating parameters to obtain the thermal performance of the SFPSAH using the TLBO algorithm. The computational results have shown that the TLBO algorithm is better or competitive to other optimization algorithms recently reported in the literature for the considered problem.

Subjects: Engineering Mathematics; Renewable Energy; Energy and Fuels

Keywords: smooth flat plate solar air heater; thermal efficiency; teaching–learning-based optimization algorithm

ABOUT THE AUTHOR

R. Venkata Rao is a professor in the Department of Mechanical Engineering of S.V. National Institute of Technology, Surat, Gujarat (India). He received his BTech degree from Nagarjuna University, his M.Tech degree from BHU, Varanasi, and his PhD degree from BITS, Pilani, India. He has about 23 years of teaching and research experience. He has authored about 260 research papers published in various reputed international journals and conference proceedings. He is also on the editorial boards of various international journals. His research interests include: advanced engineering optimization techniques and the applications, fuzzy multiple attribute decision-making, advanced manufacturing technology, automation and robotics.

PUBLIC INTEREST STATEMENT

Solar air heater is extensively used nowadays in various applications like space heating, seasoning of timber, curing of industrial products, etc. It consists of an absorbed plate with parallel plate below forming a small passage through which air is to be heated and flow. But the main drawback of solar air heater is low thermal efficiency, since the heat transfer coefficient is less between the absorber plate and air. Sometimes surfaces are roughed or longitudinal fines are used or geometrical parameters are changed to increase the thermal efficiency. In the present work, optimal set of operating parameters are investigated using the teaching–learning-based optimization algorithm, at which the thermal performance of a smooth flat plate solar air heater could be maximum. The computational results have shown that the TLBO algorithm is better or competitive to other optimization algorithms recently reported in the literature for the considered problem.

1. Introduction

Solar air heating is a solar thermal technology, in which the energy from sun is captured by an absorbing medium and used to heat air. Solar air heating is extensively used nowadays in commercial and industrial applications. Solar air heaters are simple in design and construction, but efficiency of flat plate solar air heater is low because of low convective heat transfer coefficient between the absorber plate and the flowing air that increases absorber plate temperature, leading to higher heat losses to environment. Low value of heat transfer coefficient is due to presence of laminar sublayer that can be broken by providing artificial roughness on heat transferring surface.

The use of flat-plate solar collectors to heat air to relatively low temperature has become a common practice in numerous applications from space heating to food dehydration industry (Hegazy, 1996). Hegazy (1996) optimized the flow channel depth for a conventional flat-plate solar air heater. The author had derived an expression for estimating the channel depth-to-length ratio that yields an outlet air temperature equal to the absorber plate mean temperature in terms of flow pumping power. This expression is of great importance for designers of this type of solar air heater. A parametric study was also carried out to investigate the effect of the channel depth on collector useful heat gain of collector over a wide range of D/L (depth of flow channel/length of absorber plate) ratios, and for different pumping power requirements.

Gupta, Solanki, and Saini (1997) explained that the systems operating in a specified range of Reynolds number show better thermohydraulic performance depending upon the insulation. Ammari (2003) presented a mathematical model for computing the thermal performance of a single-pass flat-plate solar air collector. The author had investigated the influence of the addition of the metal slats on the efficiency of solar collector with the help of the model developed. The effect of volume air flow rate, collector length, and spacing between the absorber and bottom plates on the thermal performance of the solar air heater was investigated.

Mittal and Varshney (2006) investigated thermohydraulic performance of a wire mesh-packed solar air heater having its duct packed with blackened wire screen matrices of different geometrical parameters (wire diameter and pitch). The authors had concluded that the Reynolds number was a strong parameter affecting the effective efficiency. Also, it was found that for higher values of the temperature rise, the effective efficiency values closely followed the thermal efficiency values, whereas there was an appreciable difference in the lower range of temperature rise values. The authors had also commented that merely the porosity of the bed does not govern the performance. Kalogirou (2006) used artificial neural networks (ANN) for the prediction of the performance parameters of flat-plate solar collectors. Six ANN models were developed for the prediction of the standard performance of collectors.

Layek, Saini, and Solanki (2007) optimized solar air heater having chamfered rib-groove roughness on absorber plate. The entropy generation in the duct of solar air heater having repeated transverse chamfered rib-groove roughness on one broad wall was studied numerically. The authors had concluded that the roughness parameters like relative roughness pitch, relative roughness height, relative groove position, chamfer angle, and flow Reynolds number had a combined effect on the heat transfer as well as fluid friction.

Improving the thermal performance by enhancing the heat transfer rate and reducing friction losses depends on the geometrical parameters of the solar air heater and hence, there is a need for optimization of design and operating parameters of the solar air heater. Varun and Siddhartha (2010) used genetic algorithm to investigate the thermal performance optimization of a flat-plate solar air heater. The authors considered different systems and operating parameters to obtain maximum thermal performance. Thermal performance was obtained for different Reynolds numbers, emissivity of the plate, tilt angle, and number of glass plate by using genetic algorithm.

Varun, Sharma, Bhat, and Grover (2011) implemented a stochastic iterative perturbation technique to obtain the optimum set of different system and operating parameters, such as the number of glass cover plate, emissivity of the plate, mean plate temperature, rise in temperature, tilt angle, and solar radiation intensity for different Reynolds numbers. El-Sebaii, Aboul-Enein, Ramadan, Shalaby, and Moharram (2011) presented an analytical model for the air heater with flat and V-corrugated plates. The authors had investigated the thermal performance of double-pass flat- and V-corrugated-plate solar air heaters theoretically and experimentally. The effect of mass flow rate of air on pressure drop, thermal and thermohydraulic efficiencies of the flat- and V-corrugated-plate solar air heater were also investigated.

Lanjewar, Bhagoria, and Sarviya (2011) presented experimental investigation of heat transfer and friction factor characteristics of a rectangular duct roughened with W-shaped ribs on its underside on one broad wall arranged at an inclination with respect to flow direction. The authors had compared the results of heat transfer and friction factor with those for a smooth duct under similar flow and thermal boundary conditions to determine the thermohydraulic performance. Correlations were also developed for heat transfer coefficient and friction factor for the roughened duct.

Tanda (2011) discussed the performance of solar air heater ducts with different types of ribs on the absorber plate. All the rib-roughened channels performed better than the reference smooth channel in the medium–low range of the investigated Reynolds number values. Gill, Singh, and Singh (2012) designed, fabricated, and tested two low-cost solar air heaters, i.e. single glazed and double glazed. The collector efficiency factor, heat-removal factor based on air outlet temperature, and air inlet temperature for solar air heaters were also determined.

There is an increasing interest among researchers in the design, development, and optimization of a smooth flat-plate solar air heater (SFPSAH) over past few decades. Siddhartha, Sharma, and Varun (2012) used particle swarm optimization algorithm for optimization of thermal performance of SFPSAH. The authors had carried out simulation for three different cases using the climatic condition data of Hamirpur city of India to investigate the thermal performance of SFPSAH. Maximization of thermal efficiency was set as an objective function. Siddhartha, Chauhan, Varun, and Sharma (2012) used simulated annealing algorithm to optimize the thermal performance of SFPSAH and predicted the optimum set of design and operating parameters.

Chamoli, Chauhan, Thakur, and Saini (2012) presented an extensive study of the research carried out on double-pass solar air heater. Karwa and Chitoshiya (2013) presented an experimental study of thermohydraulic performance of a solar air heater with 60° V-down discrete rib roughened on the airflow side of the absorber plate along with a smooth duct air heater. The authors claimed that the thermal efficiency was increased by 12.5–20% due to the roughness on the absorber plate depending on the airflow rate; higher enhancement was at the lower flow rate.

It has been observed that only few researches had attempted the optimization of flat-plate solar air heater by considering the different system and operating parameters to obtain maximum thermal performance (Varun & Siddhartha, 2010; Siddhartha, Chauhan, et al., 2012). Varun and Siddhartha (2010) used GA, Siddhartha, Chauhan, et al. (2012) used PSO and Siddhartha, Sharma, et al. (2012) used simulated annealing (SA) for optimization of thermal performance of a SFPSAH. However, the parameter setting of the GA, PSO, and SA algorithms is a serious problem which influences their efficiency and affects the performance of the algorithms, for example, GA requires the crossover probability, mutation rate, and selection method; PSO requires learning factors, the variation of weight, and the maximum value of velocity; SA requires temperature decrement. Similarly, the other advanced optimization algorithms like artificial bee colony (ABC) requires number of employed bees, onlooker bees, and value of limit; harmony search (HS) requires the harmony memory consideration rate, pitch adjusting rate, and number of improvisations. Unlike other optimization techniques, a recently developed optimization technique, namely teaching–learning-based optimization (TLBO) algorithm does not require any algorithm parameters to be tuned, thus making the implementation of TLBO algorithm simpler. This algorithm requires only the common control parameters and does not require any algorithm-specific control parameters. In the literature, it is observed that the TLBO algorithm is not yet used in the field of optimization of a SFPSAH. Hence, in this paper, TLBO algorithm is used to estimate the optimal performance of a SFPSAH, with various effective parameters. The next section presents the details of the TLBO algorithm.

2. TLBO algorithm

TLBO is a teaching–learning process-inspired algorithm proposed by Rao, Savsani, and Vakharia (2011a, 2011b) and Rao, Savsani, and Balic (2011) based on the effect of influence of a teacher on the output of learners in a class. The algorithm describes two basic modes of the learning: (1) through teacher (known as teacher phase) and (2) interacting with the other learners (known as learner phase). In this optimization algorithm, a group of learners is considered as population and different subjects offered to the learners are considered as different design variables of the optimization problem, and a learner's result is analogous to the "fitness" value of the optimization problem. The best solution in the entire population is considered as the teacher. The design variables are actually the parameters involved in the objective function of the given optimization problem and the best solution is the best value of the objective function. The working of TLBO is divided into two parts, "Teacher phase" and "Learner phase". The flow chart of TLBO algorithm is shown in Figure 1. Working of both these phases is explained below.

2.1. Teacher phase

It is the first part of the algorithm where learners learn through the teacher. During this phase, a teacher tries to increase the mean result of the class in the subject taught by him or her depending on his or her capability. At any iteration *i*, assume that there are "*m*" number of subjects (i.e. design variables), "*n*" number of learners (i.e. population size, $k = 1, 2, \ldots, n$), and $M_{j,i}$ be the mean result of the learners in a particular subject "*j*" ($j = 1, 2, \ldots, m$) The best overall result $X_{total\text{-}kbest,\,i}$ considering all the subjects together obtained in the entire population of learners can be considered as the result of best learner *kbest*. However, as the teacher is usually considered as a highly learned person who trains learners, so that they can have better results, the best learner identified is considered by the algorithm as the teacher. The difference between the existing mean result of each subject and the corresponding result of the teacher for each subject is given by,

$$\text{Difference\_Mean}_{j,k,i} = r_i \left(X_{j,kbest,i} - T_F \cdot M_{j,i} \right) \tag{1}$$

where, $X_{j,\,kbest,\,i}$ is the result of the best learner (i.e. teacher) in subject *j*. T_F is the teaching factor. It is important to note here that after conducting a number of computational experiments on various benchmark functions (Rao & Waghmare, 2014), it was observed that the best value of objective function can be achieved when T_F value is taken as 1. So, in the TLBO algorithm, the value of T_F is considered as 1 and the term "T_F" is removed in the TLBO algorithm. Hence, Equation 1 is rewritten as:

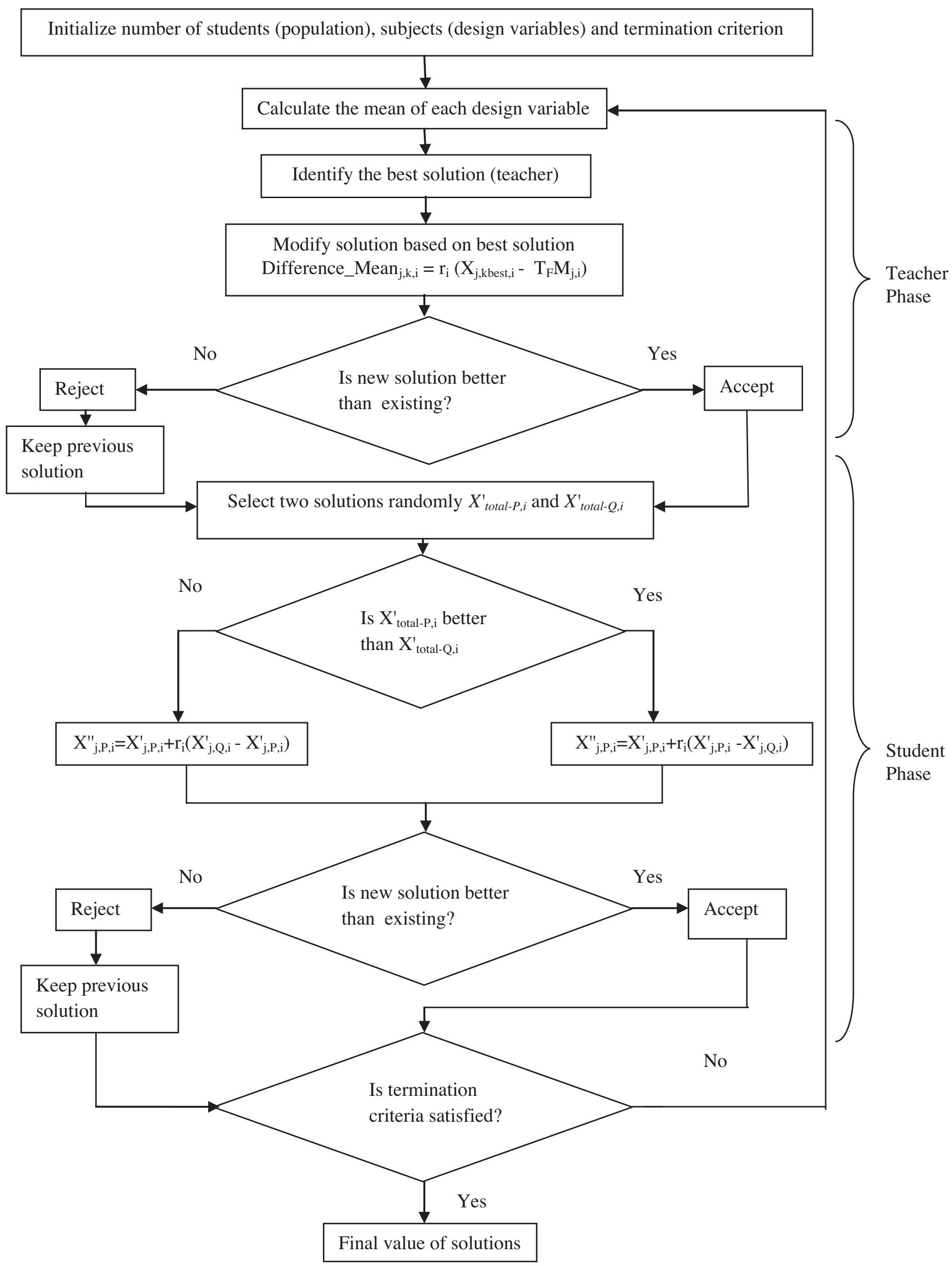
$$\text{Difference\_Mean}_{j,k,i} = r_i \left(X_{j,kbest,i} - M_{j,i} \right) \tag{2}$$

Based on the Difference_Mean$_{j,\,k,\,i}$, the existing solution is updated in the teacher phase according to the following expression.

$$X'_{j,k,i} = X_{j,k,i} + \text{Difference\_Mean}_{j,k,I} \tag{3}$$

where $X'_{j,k,i}$ is the updated value of $X_{j,\,k,\,i}$. $X'_{j,k,i}$ is accepted if it gives better function value. All the accepted function values at the end of the teacher phase are maintained and these values become the input to the learner phase. The learner phase depends upon the teacher phase.

Figure 1. The flow chart of TLBO algorithm (Rao et al., 2011a).



2.2. Learner phase

It is the second part of the algorithm where learners increase their knowledge by interaction among themselves. A learner interacts randomly with other learners for enhancing his or her knowledge. A learner learns new things if the other learner has more knowledge than him or her. Considering a population size of "*n*", the learning phenomenon of this phase is expressed below:

Randomly select two learners *P* and *Q*, such that $X'_{total-P,i} \neq X'_{total-Q,i}$ (where $X'_{total-P,i}$ and $X'_{total-Q,i}$ are the updated values of $X_{total\text{-}P,\,i}$ and $X_{total\text{-}Q,\,i}$, respectively, at the end of teacher phase)

$$X''_{j,P,i} = X'_{j,P,i} + r_i \left(X'_{j,P,i} - X'_{j,Q,i} \right), \quad \text{If } X'_{total-P,i} < X'_{total-Q,i} \tag{4a}$$

$$X''_{j,P,i} = X'_{j,P,i} + r_i \left(X'_{j,Q,i} - X'_{j,P,i} \right), \quad \text{If } X'_{total-Q,I} < X'_{total-P,i} \tag{4b}$$

$X''_{j,P,i}$ is accepted if it gives a better function value.

The TLBO algorithm has been already tested on several constrained and unconstrained benchmark functions and proved better than the other advanced optimization techniques (Rao & Patel, 2012, 2013; Rao & Waghmare, 2014) had evaluated the performance of the TLBO algorithm over a set of multi-objective unconstrained and constrained test functions and the results were compared against the other optimization algorithms. The TLBO algorithm was observed to outperform the other optimization algorithms for the multi-objective unconstrained and constrained benchmark problems.

Waghmare (2013) presented the correct understanding about the TLBO algorithm in an objective manner and comments were made on the note of Črepinšek, Liu, and Mernik (2012). Yu, Wang, and Wang (2014) used improved TLBO for numerical and engineering optimization problems. The authors mentioned that the claim made by Črepinšek, Liu, and Mernik (2014) that Waghmare (2013) used different success rates was unsuitable. The comparisons of evolutionary algorithms conducted by Veček, Mernik, and Črepinšek (2014) attempted to cast the TLBO algorithm in a poor light, although this attempt may also be seen as not meaningful. The findings were simply comparisons of the basic TLBO algorithm with different modified versions of DE and did not consider other important algorithms, such as the GA, SA, PSO, and ACO (Yu et al., 2014). It may be mentioned that various researchers like Niknam, Azizipanah-Abarghooee, and Rasoul Narimani (2012), Rao, Kalyankar, and Waghmare (2014), Baykasoğlu, Hamzadayi, and Köse (2014), Satapathy and Naik (2014), Medina, Das, and Coello (2014), Basu (2014), Zou, Wang, Hei, Chen, and Yang (2014), Camp and Farshchin (2014), Moghadam and Seifi (2014) and Sultana and Roy (2014) proved the better performance of the TLBO algorithm as compared to the other evolutionary algorithms. Hence, the TLBO algorithm is attempted in the present work for the optimization of thermal performance of SFPSAH.

3. Thermal performance of solar air heater

The thermal performance of SFPSAH is investigated using the TLBO algorithm based on heat transfer phenomena (ASHRAE Standards) and calculation of flat-plate collector loss coefficients (Klein, 1975).

Figure 2 presents the zenith angle, angle of incidence, tilts angle, and azimuth angle for a tilted surface (Twidell & Weir, 2005). The angle between the sun direction and the normal direction of a tilted surface can be represented as:

$$\cos\theta = \cos\theta_z \cos\beta + \sin\theta_z \sin\beta \cos(\gamma_s - \gamma) \tag{5}$$

where θ is the angle of incidence, θ_z is the solar zenith, β is the tilt angle, γ_s is the azimuth angles, and γ is the azimuth angle for a tilted surface.

The design parameters are: number of glass cover plates, irradiance, and Reynolds number and the operating parameters are: wind velocity, plate tilt angle, emissivity of the plate, and ambient temperature. The thermal performance of a SFPASH can be predicted on the basis of detailed considerations of heat transfer processes and correlations for heat transfer coefficient, heat removal factor, etc. The objective function for thermal performance of SFPSAH can be proposed as given by ASHRAE Standards (1997) and expressed by the following equation:

$$\text{Maximize } \eta_{\text{th}} = F_0 \left[\tau\alpha - \left(\frac{T_0 - T_i}{S} \right) U_0 \right] \tag{6}$$

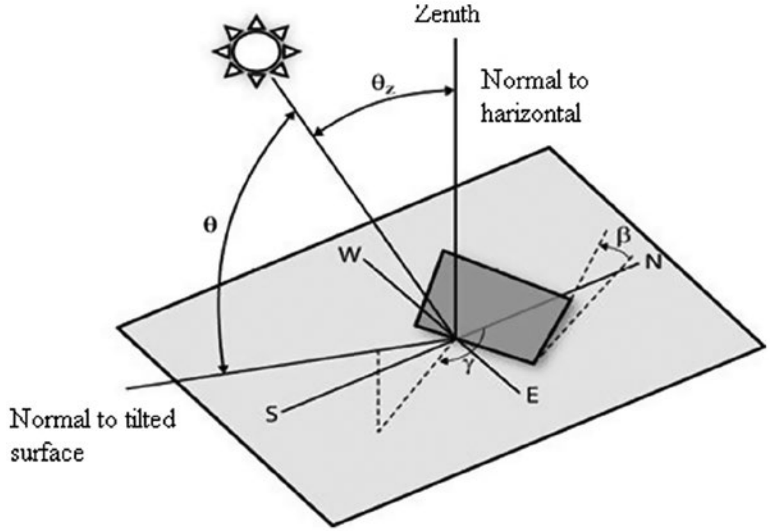


Figure 2. Zenith angle, angle of incidence, tilts angle, and azimuth angle for a tilted surface (Twidell & Weir, 2005).

The top loss coefficient is determined using relation (7) (Klein, 1975).

The different relations used for calculating overall loss coefficient (U_0), heat removal factor at outlet (F_0), and temperature rise (T_0 − T_i) are computed using relation (7), (11) and (13), respectively.

$$U_0=\left[\frac{N}{\left(C/t_p\right)\left[(t_p-t_a)/(N+f')\right]^e}+\frac{1}{h_w}\right]^{-1} + \frac{\sigma(T_p+T_a)(T_p^2+T_a^2)}{\left[\epsilon_p+0.00591Nh_w\right]^{-1}+\left[(2N+f'-1+-0.133\epsilon_p)/\epsilon_p\right]-N}+\frac{k_i}{t} \tag{7}$$

where

$$f'=\left(1+0.089h_w-0.11h_w\epsilon_p\right)(1+0.07866N) \tag{8}$$

$$C=520\left(1-0.000051\beta^2\right) \tag{9}$$

$$e=0.43\left(1-100T_p^{-1}\right) \tag{10}$$

Heat removal factor at outlet (F_0) can be expressed as:

$$F_0=\frac{Gc_p}{U_0}\left[1-\exp\left(\frac{-U_0F'}{GC_p}\right)\right] \tag{11}$$

where

$$F'=\frac{\left[0.024R_e^{0.8}P_r^{\,0.4}\frac{\lambda}{d}\right]}{\left[0.024R_e^{0.8}P_r^{\,0.4}\frac{\lambda}{d}+U_0\right]} \tag{12}$$

The temperature rise ($T_0 - T_i$) is computed by the following equation.

$$(T_0 - T_i) = \left[\frac{\left\{ (\tau\sigma)S - U_0(T_p - T_a) \right\}}{mc_p} \right] \cdot A_c \tag{13}$$

The constraints of the problem are:

- $1 \le N \le 3$; N is varied in steps of 1.
- $600 \le S \le 1{,}000$; S is varied in steps of 200.
- $2{,}000 \le Re \le 20{,}000$; Re is varied in steps of 2,000.

The computations were carried out using TLBO algorithm for three different cases using the climatic condition data of the city of Hamirpur, India, situated between 31°25′–31°52′ N (latitude) and 76°18′–76°44′ E (longitude).

The other climatic conditions of the city of Hamirpur, India, are as follows:

$$1 \le v \le 3$$

$$280 \le T_a \le 310$$

where v is the wind velocity (m/s) and T_a is ambient temperature.

The following three different cases are considered (Siddhartha, Chauhan, et al., 2012).

Case 1: Obtain the value of V and T_a through TLBO algorithm and generate ϵ_p (0.85–0.95) and β (0°–70°) randomly.

Case 2: Obtain the value of β and T_a through TLBO algorithm and generate ϵ_p (0.85–0.95) and v (1–3) randomly.

Case 3: Obtain the value of V and β through TLBO algorithm and generate ϵ_p (0.85–0.95) and T_a (280–310 K) randomly for a fixed value of N (1, 2 and 3) and fixed S (600, 800, and 1,000 W/m^2) and varying Re ranging from 2,000 to 20,000 in an incremental step of 2,000. The next section explains the detailed results and discussion.

4. Results and discussion

To check the effectiveness of the TLBO algorithm, extensive computational trials are conducted on a flat-plate solar air heater and results are compared with those obtained by the other optimization algorithms. For the fair comparison of the TLBO algorithm, the same number of function evaluations are used (Siddhartha, Chauhan, et al., 2012). Population size 30 and maximum number of generations 50 are considered. Like other optimization algorithms (e.g. PSO, ABC, ACO, etc.), TLBO algorithm also does not have any special mechanism to handle the constraints. So, for the constrained optimization problems, it is necessary to incorporate any constraint handling techniques with the TLBO algorithm. In the present experiments, Deb's heuristic constrained handling method (Deb, 2000) is used to handle the constraints with the TLBO algorithm. Deb's method uses a tournament selection operator, in which two solutions are selected and compared with each other. The TLBO code is written in MATLAB and implemented on a laptop having Intel core i3 2.53 GHz processor with 1.85 GB RAM.

Table 1 presents the typical parameter values of solar air heater system (Siddhartha, Sharma, et al., 2012). Table 2 shows the optimum results of thermal performance obtained using the TLBO algorithm and comparison is made with those obtained by the PSO algorithm at N = 3 and S = 600 W/m^2. The optimum results of thermal performance is also found at different values of N and S, but for the

Table 1. Typical values of solar air heater system parameters (Siddhartha, Chauhan, et al., 2012)

Collector parameters	Values
Length (L) (mm)	1,000
Width (wt) (mm)	200
Height (ht) (mm)	20
Transmittance–absorptance ($\tau\alpha$)	0.85
Emissivity of glass cover	0.88
Emissivity of glass plate	0.85–0.95
Tilt angle (β)	$0° \leq \beta \leq 70°$

Table 2. Set of optimal results at N = 3 and S = 600 W/m²

Cases	Algorithms	v	β	ϵ_p	T_a (K)	Temperature rise (K)	ηth (%)
Case 1	PSO (Siddhartha, Sharma, et al., 2012)	1	68.36°	0.89	280.43	10.68	72.42
	TLBO	1.23	59.58°	0.8835	293.93	2.1395	**76.6739**
Case 2	PSO (Siddhartha, Sharma, et al., 2012)	1.02	70.31°	0.94	291.46	10.64	72.19
	TLBO	1.84	69.46°	0.92	294.67	10.62	**76.3181**
Case 3	PSO (Siddhartha, Sharma, et al., 2012)	1.77	70°	0.90	280.01	10.66	72.31
	TLBO	1.98	69.89°	0.91	299.39	10.64	**76.4732**

comparison purpose, it is reported at N = 3 and S = 600 since the results for another settings are not available in Siddhartha, Chauhan, et al. (2012). From Table 2, it can be seen that the thermal efficiency is improved by 5.54% for case 1, 5.39% for case 2, and 5.44% for case 3 using the TLBO algorithm. The optimal thermal performance corresponding to the optimized set of values of velocity (v), tilt angle (β), emissivity of plate (ϵ_p), and ambient temperature (T_a) is determined using the TLBO algorithm as provided in Table 2.

Table 3 presents the range of thermal performance variation for different number of glass cover plates. In total, three sets of glass plates have been considered. Three cases are considered to evaluate the thermal performance of solar air heater using the TLBO algorithm and the results are compared with the PSO algorithm. From Table 3, it can be seen that the thermal efficiency increases as the number of glass cover plate increases. For case 1, the maximum thermal efficiency is obtained at S = 600 and Re = 20,000 and is improved by 8.70, 7.36, and 5.54% for N = 1, 2, and 3, respectively, using the TLBO algorithm. For case 2, the maximum thermal efficiency is obtained at S = 600 and Re = 20,000 and is improved by 8.89, 7.35, and 5.22% for N = 1, 2, and 3, respectively, using the TLBO algorithm. For case 3, the maximum thermal efficiency is obtained at S = 600 and Re = 20,000 and is improved by 8.88, 7.21, and 5.21% for N = 1, 2, and 3, respectively, using TLBO algorithm.

Table 4 presents a set of optimum results of thermal performance of solar air heater at different Reynolds numbers for N = 1 and S = 600 W/m² using the TLBO algorithm and the results are compared with those obtained by GA, PSO, and SA algorithms. The thermal performance in terms of thermal efficiency and different operating parameters for different Reynolds number varying from 2,000 to 20,000 with incremental step of 2,000 are estimated and included in Table 4. In Table 4, the symbol "–" indicates that the results are not available in the cited reference. From Table 4, it can be seen that the thermal efficiency of solar air heater obtained using the TLBO algorithm is better than that obtained using other optimization algorithms by the previous researchers.

Table 3. Range of thermal performance variation for different number of glass cover plates

Cases	Algorithms	N = 1		N = 2		N = 3	
		Min. ηth (%) (S = 1,000, Re = 2,000)	Max. ηth (%) (S = 600, Re = 20,000)	Min. ηth (%) (S = 1,000, Re = 2,000)	Max. ηth (%) (S = 600, Re = 20,000)	Min. ηth (%) (S = 1,000, Re = 2,000)	Max. ηth (%) (S = 600, Re = 20,000)
Case 1	PSO (Siddhartha, Sharma, et al., 2012)	17.24	63.88	22.95	69.08	26.36	72.42
	TLBO	**29.4882**	**69.9757**	**36.1047**	**74.5783**	**41.3158**	**76.6739**
Case 2	PSO (Siddhartha, Sharma, et al., 2012)	17.50	63.15	22.54	68.55	27.32	71.63
	TLBO	**31.1038**	**69.3214**	**35.8726**	**73.9923**	**42.6736**	**75.5839**
Case 3	PSO (Siddhartha, Sharma, et al., 2012)	17.65	62.89	22.91	68.88	27.10	72.31
	TLBO	**31.7482**	**69.0238**	**36.0827**	**74.2482**	**42.8113**	**76.2941**

Table 5 presents the set of optimum results at different Reynolds numbers, $N = 2$ and $S = 600$ W/m^2. It can be seen that the maximum thermal efficiency of 74.5783% is obtained using the TLBO algorithm at Reynolds number of 20,000, with v = 1.8635 m/s, T_a = 304.6286 K, β = 6.3283°, and ϵ_p = 0.8738. The set of optimum results at different Reynolds numbers, N = 3 and S = 600 W/m^2 are shown in Table 6. The maximum thermal efficiency obtained using TLBO algorithm is 76.6739%. It can be observed that for the same settings, the thermal performance of a SFPSAH obtained by the TLBO algorithm is better as compared to the other algorithms.

Table 7 presents the set of optimum results at different Reynolds numbers, $N = 1$ and $S = 800$ W/m^2. It can be seen that the maximum thermal efficiency of 69.8921% is obtained using the TLBO algorithm at Reynolds number of 20,000, with v = 2.3732 m/s, T_a = 305.8392 K, β = 43.4174°, and ϵ_p = 0.9146. The set of optimum results at different Reynolds numbers, N = 2 and S = 800 W/m^2 is shown in Table 8. The maximum thermal efficiency obtained using TLBO algorithm is 74.4992%. It can be observed that for the same settings, the thermal performance of a SFPSAH obtained by the TLBO algorithm is better as compared to the other algorithms.

A set of optimum results at different Reynolds numbers, N = 3 and S = 800 W/m^2 is shown in Table 9. The maximum thermal efficiency obtained using the TLBO algorithm is 76.5913%. It can be observed that for the same settings, the thermal performance of a SFPSAH is better for the TLBO algorithm as compared to that obtained by the other algorithms. Table 10 presents the set of optimum results at different Reynolds numbers, N = 1 and S = 1,000 W/m^2. It can be seen that the maximum thermal efficiency of 69.1102% is obtained using the TLBO algorithm at Reynolds number of 20,000 with v = 2.1194 m/s, T_a = 296.9633 K, β = 36.6728°, and ϵ_p = 0.9043.

Table 11 presents the set of optimum results at different Reynolds numbers, N = 2 and S = 1,000 W/m^2. It can be seen that the maximum thermal efficiency of 74.2392% is obtained using the TLBO algorithm at Reynolds number of 20,000, with v = 2.3991 m/s, T_a = 298.7654 K, β = 18.3877°, and ϵ_p = 0.9257. The set of optimum results at different Reynolds numbers, N = 3 and S = 1,000 W/m^2 is shown in Table 12. The maximum thermal efficiency obtained using TLBO algorithm is 76.4188%. It can be observed that for the same settings, the thermal performance of a SFPSAH obtained by the TLBO algorithm is better as compared to the other algorithms.

Set of optimum results at different Reynolds numbers, N = 1 and S = 1200 W/m^2 is shown in Table 13. The maximum thermal efficiency obtained using TLBO algorithm is 69.06378%. It can be observed that for the same settings, the thermal performance of a SFPSAH is better for the TLBO

Table 4. Set of optimum results at different Reynolds numbers (N = 1 and S = 600 W/m²)

S. No.		*Re*	v	T_a	β	ϵ_p	$T_o - T_i$	ηth (%)
1	GA	2,000	1.0392	301.6078	41.7255	0.8904	7.7582	29.2294
	PSO	2,000	–	–	–	–	–	–
	SA	2,000	–	–	–	–	–	19.5737
	TLBO	2,000	1.3412	293.3784	36.643	0.8826	6.4286	**31.7385**
2	GA	4,000	2.9686	295.1765	57.098	0.8806	5.6814	42.1749
	PSO	4,000	–	–	–	–	–	–
	SA	4,000	–	–	–	–	–	31.9158
	TLBO	4,000	2.3485	297.4782	41.3678	0.8698	5.4386	**43.5603**
3	GA	6,000	1.6745	299.8824	19.2157	0.8751	4.5364	49.7669
	PSO	6,000	–	–	–	–	–	–
	SA	6,000	–	–	–	–	–	40.3917
	TLBO	6,000	1.8692	303.7547	29.3782	0.9173	4.3298	**50.0247**
4	GA	8,000	2.2392	296.3529	25.8039	0.8798	3.7907	55.0673
	PSO	8,000	–	–	–	–	–	–
	SA	8,000	–	–	–	–	–	46.2107
	TLBO	8,000	2.1283	301.8377	45.8828	0.8745	3.7065	**55.9934**
5	GA	10,000	2.7569	302.2353	28	0.8684	3.2359	58.8518
	PSO	10,000	–	–	–	–	–	–
	SA	10,000	–	–	–	–	–	50.9748
	TLBO	10,000	2.2319	299.6739	14.2793	0.8835	3.0531	**60.4672**
6	GA	12,000	1.1412	290.7059	30.7451	0.8578	2.9532	61.7762
	PSO	12,000	–	–	–	–	–	–
	SA	12,000	–	–	–	–	–	54.8929
	TLBO	12,000	1.7835	299.4882	12.4825	0.8621	2.6854	**62.8964**
7	GA	14,000	2.8588	307.3333	42.8235	0.8669	2.5477	63.9401
	PSO	14,000	–	–	–	–	–	–
	SA	14,000	–	–	–	–	–	57.6921
	TLBO	14,000	2.5683	302.4248	48.3732	0.8754	2.4579	**64.7136**
8	GA	16,000	1.2588	302.1569	52.7059	0.8731	2.359	65.9159
	PSO	16,000	–	–	–	–	–	–
	SA	16,000	–	–	–	–	–	60.3319
	TLBO	16,000	1.6735	298.2994	49.3467	0.8634	2.2570	**66.4579**
9	GA	18,000	2.8902	308.3529	61.4902	0.8896	2.1111	67.461
	PSO	18,000	–	–	–	–	–	–
	SA	18,000	–	–	–	–	–	62.3207
	TLBO	18,000	1.9827	304.8321	52.3473	0.8739	2.0966	**68.7547**
10	GA	20,000	1.5725	305.451	39.8039	0.9382	1.9403	68.7416
	PSO	20,000	–	–	–	–	–	63.88
	SA	20,000	–	–	–	–	–	64.0582
	TLBO	20,000	2.1293	302.4858	53.9622	0.8734	1.8965	**69.9757**

Note: The symbol "–" indicates results are not available in the corresponding literature.

Source: The data of the GA, PSO, and SA are taken from Varun and Siddhartha (2010), Siddhartha, Sharma, et al. (2012) and Siddhartha, Chauhan, et al. (2012), respectively.

Table 5. Set of optimum results at different Reynolds numbers (N = 2 and S = 600 W/m²)

S. No.		Re	v	T_a	β	ϵ_p	$T_0 - T_i$	ηth (%)
1	GA	2,000	1.5725	293.3725	54.3529	0.8571	10.2868	36.8908
	PSO	2,000	–	–	–	–	–	–
	SA	2,000	–	–	–	–	–	25.6859
	TLBO	2,000	1.2965	297.9374	37.8745	0.8734	8.9456	**38.1378**
2	GA	4,000	1.3765	301.2157	3.5686	0.9461	6.8671	50.324
	PSO	4,000	–	–	–	–	–	–
	SA	4,000	–	–	–	–	–	39.8566
	TLBO	4,000	1.4385	304.7828	18.6564	0.8935	5.7835	**52.6885**
3	GA	6,000	2.4118	308.4313	31.5686	0.9492	5.239	57.6223
	PSO	6,000	–	–	–	–	–	–
	SA	6,000	–	–	–	–	–	48.6497
	TLBO	6,000	1.8937	305.8827	49.5543	0.9253	4.9831	**58.8843**
4	GA	8,000	1.4	310	56.549	0.8598	4.4204	62.4028
	PSO	8,000	–	–	–	–	–	–
	SA	8,000	–	–	–	–	–	54.6175
	TLBO	8,000	1.5735	309.8372	44.8761	0.9146	3.8736	**63.9765**
5	GA	10,000	2.098	300.5098	3.2941	0.8755	3.7091	65.5798
	PSO	10,000	–	–	–	–	–	–
	SA	10,000	–	–	–	–	–	58.9721
	TLBO	10,000	1.7732	303.4788	21.3567	0.8921	3.5787	**67.5684**
6	GA	12,000	1.8941	300.6667	9.3333	0.8606	3.2273	67.9671
	PSO	12,000	–	–	–	–	–	–
	SA	12,000	–	–	–	–	–	62.1944
	TLBO	12,000	1.3348	302.1784	16.7833	0.8846	3.0174	**68.8355**
7	GA	14,000	2.1843	290.3137	40.3529	0.9206	2.8679	69.6984
	PSO	14,000	–	–	–	–	–	–
	SA	14,000	–	–	–	–	–	64.709
	TLBO	14,000	2.4927	296.3229	34.2849	0.8953	2.6583	**70.3568**
8	GA	16,000	1.7294	298.7843	68.6257	0.8939	2.5842	71.3131
	PSO	16,000	–	–	–	–	–	–
	SA	16,000	–	–	–	–	–	66.7539
	TLBO	16,000	1.8943	301.1673	45.8392	0.8635	2.4846	**72.3462**
9	GA	18,000	1.0471	302	23.0588	0.8888	2.318	72.4333
	PSO	18,000	–	–	–	–	–	–
	SA	18,000	–	–	–	–	–	68.3109
	TLBO	18,000	1.7139	303.7845	11.2863	0.9265	2.2739	**73.1954**
10	GA	20,000	2.1608	299.8039	11.5294	0.8939	2.1088	73.4772
	PSO	20,000	–	–	–	–	–	69.08
	SA	20,000	–	–	–	–	–	69.7965
	TLBO	20,000	1.8635	304.6286	6.3283	0.8738	2.0683	**74.5783**

Note: The symbol "–" indicates results are not available in the corresponding literature.

Source: The data of the GA, PSO, and SA are taken from Varun and Siddhartha (2010), Siddhartha, Sharma, et al. (2012) and Siddhartha, Chauhan, et al. (2012), respectively.

Table 6. Set of optimum results at different Reynolds numbers (N = 3 and S = 600 W/m²)

S. No.		*Re*	*v*	T_a	β	ϵ_p	$T_o - T_i$	ηth (%)
1	GA	2,000	1.4	309.2941	41.1765	0.8708	11.35	41.7897
	PSO	2,000	1	282.76	14.4	0.92	41.69	28.38
	SA	2,000	–	–	–	–	–	19.5737
	TLBO	2,000	1.1265	301.3783	22.6394	0.8856	9.2992	**43.3532**
2	GA	4,000	2.2627	293.3725	48.8627	0.8908	7.8267	55.1325
	PSO	4,000	1	282.38	23.1	0.86	31.89	43.37
	SA	4,000	–	–	–	–	–	31.9158
	TLBO	4,000	1.4826	299.5738	36.8323	0.8912	7.2369	**56.7543**
3	GA	6,000	1.1961	292.7451	64.5098	0.9488	5.9713	61.852
	PSO	6,000	1	280.04	53.78	0.9	25.95	52.88
	SA	6,000	–	–	–	–	–	40.3917
	TLBO	6,000	1.6357	294.4782	45.2376	0.9243	4.9832	**63.4863**
4	GA	8,000	1.9725	292.2745	0	0.8633	4.7422	66.1788
	PSO	8,000	1.02	280.07	19.46	0.9	21.28	58.25
	SA	8,000	–	–	–	–	–	46.2107
	TLBO	8,000	1.3789	290.7489	31.5943	0.9074	4.1294	**67.6733**
5	GA	10,000	2.7098	295.5686	2.7451	0.8916	3.9458	68.8946
	PSO	10,000	1	280.11	30.79	0.93	18.23	61.95
	SA	10,000	–	–	–	–	–	50.9748
	TLBO	10,000	1.4937	291.7112	42.6582	0.9247	3.7836	**70.4711**
6	GA	12,000	1.1961	298.2353	49.9608	0.8516	3.4344	71.0254
	PSO	12,000	1	280.04	62.86	0.94	16.08	65.49
	SA	12,000	–	–	–	–	–	54.8929
	TLBO	12,000	1.7619	300.1388	57.9334	0.9376	3.2694	**72.2885**
7	GA	14,000	2.0275	292.2745	66.7059	0.9088	3.0221	72.5723
	PSO	14,000	1	280.02	20.45	0.93	14.13	67.72
	SA	14,000	–	–	–	–	–	57.6921
	TLBO	14,000	1.2834	295.7835	39.1178	0.9421	2.8479	**73.6319**
8	GA	16,000	2.3725	301.2157	65.6078	0.9461	2.6706	73.8123
	PSO	16,000	1.04	280.01	44.17	0.9	12.76	69.28
	SA	16,000	–	–	–	–	–	60.3319
	TLBO	16,000	1.7482	298.5294	61.9326	0.8995	2.5636	**74.3058**
9	GA	18,000	1.4038	297.6078	20.8627	0.879	2.4098	74.8367
	PSO	18,000	1	280.02	26.52	0.87	11.57	70.84
	SA	18,000	–	–	–	–	–	62.3207
	TLBO	18,000	1.1619	293.8943	21.8311	0.9105	2.3295	**75.9472**
10	GA	20,000	2.9529	296.1176	65.3333	0.8618	2.2047	75.6454
	PSO	20,000	1	280.43	68.36	0.89	10.68	72.42
	SA	20,000	–	–	–	–	–	64.0582
	TLBO	20,000	1.2729	293.9362	59.5832	0.8835	2.1395	**76.6739**

Note: The symbol "–" indicates results are not available in the corresponding literature.

Source: The data of the GA, PSO, and SA are taken from Varun and Siddhartha (2010), Siddhartha, Sharma, et al. (2012) and Siddhartha, Chauhan, et al. (2012), respectively.

Table 7. Set of optimum results at different Reynolds numbers (N = 1 and S = 800 W/m²)

S. No.		*Re*	*v*	T_a	β	ϵ_p	$T_o - T_i$	ηth (%)
1	GA	2,000	2.7725	292.0392	24.4314	0.9229	9.2733	28.2512
	PSO	2,000	–	–	–	–	–	–
	SA	2,000	–	–	–	–	–	18.7072
	TLBO	2,000	2.1139	297.3844	38.3772	0.8895	7.8746	**30.9532**
2	GA	4,000	1.2588	296.0392	53.5294	0.9237	7.5112	41.1115
	PSO	4,000	–	–	–	–	–	–
	SA	4,000	–	–	–	–	–	30.836
	TLBO	4,000	1.6726	294.5783	23.4788	0.8631	6.5937	**43.0947**
3	GA	6,000	2.098	294.2353	6.8627	0.9135	5.8441	48.9045
	PSO	6,000	–	–	–	–	–	–
	SA	6,000	–	–	–	–	–	39.2944
	TLBO	6,000	1.8371	290.1247	23.9984	0.8953	5.3693	**49.9363**
4	GA	8,000	2.7176	290.7059	59.0196	0.9331	4.9948	54.1312
	PSO	8,000	–	–	–	–	–	–
	SA	8,000	–	–	–	–	–	45.5684
	TLBO	8,000	2.2193	298.3667	47.2787	0.9256	4.6932	**55.3843**
5	GA	10,000	1.7294	301.451	57.098	0.881	4.3663	58.2862
	PSO	10,000	–	–	–	–	–	–
	SA	10,000	–	–	–	–	–	50.2908
	TLBO	10,000	1.5632	299.4882	34.5367	0.9173	4.1395	**59.6832**
6	GA	12,000	1.9176	300.3529	48.0392	0.9069	3.8012	61.0959
	PSO	12,000	–	–	–	–	–	–
	SA	12,000	–	–	–	–	–	54.1293
	TLBO	12,000	1.8936	302.4781	38.4673	0.9268	3.6395	**62.8734**
7	GA	14,000	1.7765	297.451	57.6471	0.8947	3.4416	63.5274
	PSO	14,000	–	–	–	–	–	–
	SA	14,000	–	–	–	–	–	57.1511
	TLBO	14,000	1.4423	299.4268	27.5764	0.8748	3.1957	**64.2154**
8	GA	16,000	3.0	291.6471	66.1569	0.9473	3.0741	65.3202
	PSO	16,000	–	–	–	–	–	–
	SA	16,000	–	–	–	–	–	59.6272
	TLBO	16,000	2.7394	295.3278	51.6478	0.9376	2.8643	**66.0115**
9	GA	18,000	2.5922	291.4118	67.7647	0.9214	2.8268	66.943
	PSO	18,000	–	–	–	–	–	–
	SA	18,000	–	–	–	–	–	61.4528
	TLBO	18,000	2.8846	298.2783	32.9754	0.9475	2.6493	**68.0364**
10	GA	20,000	2.0353	309.2941	14.2745	0.8606	2.5614	68.2924
	PSO	20,000	–	–	–	–	–	–
	SA	20,000	–	–	–	–	–	63.3172
	TLBO	20,000	2.3732	305.8392	43.4174	0.9146	2.4395	**69.8921**

Note: The symbol "–" indicates results are not available in the corresponding literature.

Source: The data of the GA, PSO, and SA are taken from Varun and Siddhartha (2010), Siddhartha, Sharma, et al. (2012) and Siddhartha, Chauhan, et al. (2012), respectively.

Table 8. Set of optimum results at different Reynolds numbers (N = 2 and S = 800 W/m^2)

S. No.		*Re*	*v*	T_a	β	ϵ_p	$T_o - T_i$	ηth (%)
1	GA	2,000	1.1098	308.7451	26.0784	0.9186	12.4267	35.6044
	PSO	2,000	–	–	–	–	–	–
	SA	2,000	–	–	–	–	–	24.5662
	TLBO	2,000	1.3847	301.2184	35.7628	0.8845	11.5783	**37.1049**
2	GA	4,000	2.2392	294.7843	34.3137	0.9229	9.0186	49.2273
	PSO	4,000	–	–	–	–	–	–
	SA	4,000	–	–	–	–	–	38.3891
	TLBO	4,000	2.8374	291.9345	52.8593	0.8936	8.3491	**50.6738**
3	GA	6,000	2.8039	297.7647	26.6275	0.9229	6.9579	56.7569
	PSO	6,000	–	–	–	–	–	–
	SA	6,000	–	–	–	–	–	47.5704
	TLBO	6,000	2.3948	301.8943	41.5675	0.8954	6.1103	**58.2194**
4	GA	8,000	2.5529	292.1176	1.098	0.8673	5.7996	61.6262
	PSO	8,000	–	–	–	–	–	–
	SA	8,000	–	–	–	–	–	53.7162
	TLBO	8,000	2.1284	296.3848	18.3573	0.8843	5.2295	**63.3042**
5	GA	10,000	2.6	290.4706	17.5686	0.8884	4.9222	65.0241
	PSO	10,000	–	–	–	–	–	–
	SA	10,000	–	–	–	–	–	58.1612
	TLBO	10,000	2.1839	297.8835	5.6884	0.9256	4.6402	**66.8211**
6	GA	12,000	1.5255	303.4902	48.3137	0.852	4.2986	67.4832
	PSO	12,000	–	–	–	–	–	–
	SA	12,000	–	–	–	–	–	61.3731
	TLBO	12,000	1.3111	298.7145	12.4678	0.8853	3.9836	**68.7343**
7	GA	14,000	1.1412	290.0784	11.2549	0.9488	3.7964	69.3503
	PSO	14,000	–	–	–	–	–	–
	SA	14,000	–	–	–	–	–	64.1098
	TLBO	14,000	1.7829	294.7883	21.4573	0.9145	3.5739	**70.2859**
8	GA	16,000	1.0314	294.7059	25.8039	0.8869	3.4103	70.8033
	PSO	16,000	–	–	–	–	–	–
	SA	16,000	–	–	–	–	–	66.1263
	TLBO	16,000	1.4388	290.8253	34.8754	0.9354	3.2954	**71.9348**
9	GA	18,000	1.7686	309.451	5.4902	0.8912	3.0433	72.1471
	PSO	18,000	–	–	–	–	–	–
	SA	18,000	–	–	–	–	–	67.8595
	TLBO	18,000	1.9999	302.7843	21.5784	0.9257	2.9184	**73.7721**
10	GA	20,000	1.0941	301.2157	21.1373	0.9382	2.8031	73.1107
	PSO	20,000	–	–	–	–	–	–
	SA	20,000	–	–	–	–	–	69.3062
	TLBO	20,000	1.6583	307.2738	7.8345	0.8853	2.6754	**74.4992**

Note: The symbol "–" indicates results are not available in the corresponding literature.

Source: The data of the GA, PSO, and SA are taken from Varun and Siddhartha (2010), Siddhartha, Sharma, et al. (2012) and Siddhartha, Chauhan, et al. (2012), respectively.

Table 9. Set of optimum results at different Reynolds numbers (N = 3 and S = 800 W/m²)

S. No.		*Re*	*v*	T_a	β	ϵ_p	$T_o - T_i$	ηth (%)
1	GA	2,000	2.3804	299.3333	12.902	0.9229	14.4294	40.3751
	PSO	2,000	–	–	–	–	–	–
	SA	2,000	–	–	–	–	–	18.7072
	TLBO	2,000	1.8947	293.8122	32.3632	0.8954	12.4839	**41.8493**
2	GA	4,000	1.8078	298.7059	49.6863	0.9088	10.1644	54.124
	PSO	4,000	–	–	–`	–	–	–
	SA	4,000	–	–	–	–	–	30.836
	TLBO	4,000	2.1378	293.7229	21.4673	0.8842	8.9937	**55.9932**
3	GA	6,000	2.7725	299.098	29.6471	0.8524	7.694	61.1521
	PSO	6,000	–	–	–	–	–	–
	SA	6,000	–	–	–	–	–	39.2944
	TLBO	6,000	2.4296	290.1283	36.9761	0.8824	6.8746	**62.4839**
4	GA	8,000	2.3412	307.098	70	0.939	6.2278	65.5463
	PSO	8,000	–	–	–	–	–	–
	SA	8,000	–	–	–	–	–	45.5684
	TLBO	8,000	2.6510	304.9392	58.3468	0.8964	5.7385	**67.2395**
5	GA	10,000	1.4863	293.5294	14.8235	0.8751	5.2581	68.485
	PSO	10,000	–	–	–	–	–	–
	SA	10,000	–	–	–	–	–	50.2908
	TLBO	10,000	1.5738	301.3935	34.4674	0.9365	4.8624	**69.8883**
6	GA	12,000	1.6039	296.4314	45.2941	0.941	4.5261	70.5836
	PSO	12,000	–	–	–	–	–	–
	SA	12,000	–	–	–	–	–	54.1293
	TLBO	12,000	1.2399	300.3782	25.2485	0.9156	4.3638	**72.0012**
7	GA	14,000	1.7059	309.6863	21.9608	0.8614	3.9446	72.2261
	PSO	14,000	–	–	–	–	–	–
	SA	14,000	–	–	–	–	–	57.1511
	TLBO	14,000	1.3911	304.5692	9.2474	0.8951	3.7953	**73.4924**
8	GA	16,000	1.4627	305.7647	61.2157	0.9124	3.5459	73.5504
	PSO	16,000	–	–	–	–	–	–
	SA	16,000	–	–	–	–	–	59.6272
	TLBO	16,000	1.6784	299.7832	48.3466	0.8627	3.3681	**74.1775**
9	GA	18,000	2.4824	296.2745	44.1961	0.9331	3.1948	74.5676
	PSO	18,000	–	–	–	–	–	–
	SA	18,000	–	–	–	–	–	61.4528
	TLBO	18,000	2.0384	291.5622	29.4673	0.8776	3.0193	**75.3221**
10	GA	20,000	1.2275	309.2157	51.8824	0.9422	2.9059	75.3931
	PSO	20,000	–	–	–	–	–	–
	SA	20,000	–	–	–	–	–	63.3172
	TLBO	20,000	1.6293	302.7223	32.4672	0.9189	2.7646	**76.5913**

Note: The symbol "–" indicates results are not available in the corresponding literature.

Source: The data of the GA, PSO, and SA are taken from Varun and Siddhartha (2010), Siddhartha, Sharma, et al. (2012) and Siddhartha, Chauhan, et al. (2012), respectively.

Table 10. Set of optimum results at different Reynolds numbers (N = 1 and S = 1,000 W/m²)

S. No.		*Re*	*v*	T_a	*β*	ϵ_p	$T_o - T_i$	*η*th (%)
1	GA	2,000	2.2471	298.9412	35.6863	0.8665	11.444	27.4864
	PSO	2,000	–	–	–	–	–	17.24
	SA	2,000	–	–	–	–	–	17.6966
	TLBO	2,000	1.8831	293.2967	47.3782	0.8965	10.3842	**29.4882**
2	GA	4,000	2.3176	291.4118	10.4314	0.8539	8.9379	40.1084
	PSO	4,000	–	–	–	–	–	–
	SA	4,000	–	–	–	–	–	30.0172
	TLBO	4,000	2.1293	295.2434	4.8932	0.8834	7.8343	**41.9837**
3	GA	6,000	2.6941	298.3137	4.3922	0.85	7.1593	48.1196
	PSO	6,000	–	–	–	–	–	–
	SA	6,000	–	–	–	–	–	38.1824
	TLBO	6,000	2.1934	299.8387	19.3893	0.8924	6.9837	**49.8212**
4	GA	8,000	1.2667	303.4902	1.9216	0.932	6.0706	53.5817
	PSO	8,000	–	–	–	–	–	–
	SA	8,000	–	–	–	–	–	44.6621
	TLBO	8,000	1.3847	297.3289	18.4923	0.8999	5.7184	**55.2149**
5	GA	10,000	1.8471	295.2549	26.3529	0.8633	5.3605	57.657
	PSO	10,000	–	–	–	–	–	–
	SA	10,000	–	–	–	–	–	49.3149
	TLBO	10,000	2.2389	299.5263	43.6722	0.9135	4.9285	**59.1038**
6	GA	12,000	1.3765	304.7451	22.2353	0.9484	4.6377	60.5783
	PSO	12,000	–	–	–	–	–	–
	SA	12,000	–	–	–	–	–	53.4182
	TLBO	12,000	1.2184	300.3784	11.3832	0.9145	4.3795	**62.4895**
7	GA	14,000	2.7725	309.2941	17.8431	0.9288	4.0572	63.0055
	PSO	14,000	–	–	–	–	–	–
	SA	14,000	–	–	–	–	–	56.5065
	TLBO	14,000	2.3495	303.5638	36.2781	0.8936	3.8947	**64.1783**
8	GA	16,000	2.1451	293.3725	5.2157	0.9371	3.7709	65.0191
	PSO	16,000	–	–	–	–	–	–
	SA	16,000	–	–	–	–	–	59.0541
	TLBO	16,000	2.4183	297.4567	23.6638	0.8954	3.6397	**65.9987**
9	GA	18,000	1.7529	291.2549	27.1765	0.9127	3.4971	66.6081
	PSO	18,000	–	–	–	–	–	–
	SA	18,000	–	–	–	–	–	61.1254
	TLBO	18,000	2.0847	290.8743	8.2563	0.8845	3.3865	**67.6341**
10	GA	20,000	2.4039	292.1961	55.7255	0.9182	3.2241	67.7749
	PSO	20,000	–	–	–	–	–	–
	SA	20,000	–	–	–	–	–	62.9629
	TLBO	20,000	2.1194	296.9633	36.6728	0.9043	3.1975	**69.1102**

Note: The symbol "–" indicates results are not available in the corresponding literature.

Source: The data of the GA, PSO, and SA are taken from Varun and Siddhartha (2010), Siddhartha, Sharma, et al. (2012) and Siddhartha, Chauhan, et al. (2012), respectively.

Table 11. Set of optimum results at different Reynolds numbers (N = 2 and S = 1,000 W/m²)

S. No.		*Re*	v	T_a	β	ϵ_p	$T_0 - T_i$	ηth (%)
1	GA	2,000	2.9294	308.8235	27.1765	0.9249	14.3719	34.5239
	PSO	2,000	–	–	–	–	–	22.95
	SA	2,000	–	–	–	–	–	23.5642
	TLBO	2,000	2.7839	302.5673	39.2781	0.9054	13.7954	**36.1047**
2	GA	4,000	2.0196	296.5098	11.5294	0.8696	11.0482	48.311
	PSO	4,000	–	–	–	–	–	–
	SA	4,000	–	–	–	–	–	37.5379
	TLBO	4,000	2.7329	301.3485	29.4882	0.8756	9.9535	**49.8348**
3	GA	6,000	2.6706	295.8824	67.2549	0.941	8.7547	56.0124
	PSO	6,000	–	–	–	–	–	–
	SA	6,000	–	–	–	–	–	46.5347
	TLBO	6,000	2.2937	300.3962	48.3257	0.8842	8.1482	**57.9234**
4	GA	8,000	1.5333	292.3529	9.6078	0.9245	7.1766	61.0463
	PSO	8,000	–	–	–	–	–	–
	SA	8,000	–	–	–	–	–	52.6971
	TLBO	8,000	1.6621	290.4852	27.6829	0.8944	6.8637	**62.8342**
5	GA	10,000	2.2627	303.4118	52.7059	0.8755	6.0997	64.3693
	PSO	10,000	–	–	–	–	–	–
	SA	10,000	–	–	–	–	–	57.3815
	TLBO	10,000	2.0382	297.3584	32.5710	0.8685	5.6786	**66.1038**
6	GA	12,000	2.5765	303.1961	67.2549	0.9429	5.2672	67.0317
	PSO	12,000	–	–	–	–	–	–
	SA	12,000	–	–	–	–	–	60.7765
	TLBO	12,000	2.2146	302.2468	53.2892	0.8821	4.8953	**68.8937**
7	GA	14,000	1.4549	303.6471	5.2157	0.9029	4.6683	69.0025
	PSO	14,000	–	–	–	–	–	–
	SA	14,000	–	–	–	–	–	63.3947
	TLBO	14,000	1.7816	294.6549	32.8267	0.9421	4.4168	**70.0127**
8	GA	16,000	2.1686	307.8824	56	0.8692	4.2096	70.5238
	PSO	16,000	–	–	–	–	–	–
	SA	16,000	–	–	–	–	–	65.6112
	TLBO	16,000	1.9725	302.3473	34.9392	0.9184	3.9994	**71.6739**
9	GA	18,000	1.7294	304.1961	65.0588	0.9375	3.8271	71.7789
	PSO	18,000	–	–	–	–	–	–
	SA	18,000	–	–	–	–	–	67.4154
	TLBO	18,000	1.6427	308.3697	47.1003	0.8756	3.6379	**72.5611**
10	GA	20,000	2.0196	302.4706	4.6667	0.9492	3.4616	72.8854
	PSO	20,000	–	–	–	–	–	–
	SA	20,000	–	–	–	–	–	68.8388
	TLBO	20,000	2.3991	298.7654	18.3877	0.9257	3.3982	**74.2392**

Note: The symbol "–" indicates results are not available in the corresponding literature.

Source: The data of the GA, PSO, and SA are taken from Varun and Siddhartha (2010), Siddhartha, Sharma, et al. (2012) and Siddhartha, Chauhan, et al. (2012), respectively.

Table 12. Set of optimum results at different Reynolds numbers (N = 3 and S = 1,000 W/m²)

S. No.		*Re*	*v*	T_a	β	ϵ_p	$T_0 - T_i$	ηth (%)
1	GA	2,000	2.2314	296.8235	69.451	0.9073	18.1867	39.2811
	PSO	2,000	–	–	–	–	–	26.36
	SA	2,000	–	–	–	–	–	17.6966
	TLBO	2,000	1.8366	299.3458	56.2886	0.9256	16.7855	**41.3158**
2	GA	4,000	1.5725	303.098	47.7647	0.8614	12.4564	53.1766
	PSO	4,000	–	–	–	–	–	–
	SA	4,000	–	–	–	–	–	30.0172
	TLBO	4,000	1.3857	300.4832	34.5673	0.8953	11.2398	**55.0012**
3	GA	6,000	2.1451	304.5882	29.098	0.888	9.4275	60.5002
	PSO	6,000	–	–	–	–	–	–
	SA	6,000	–	–	–	–	–	38.1824
	TLBO	6,000	1.8453	307.9765	16.4873	0.8745	8.6536	**62.2119**
4	GA	8,000	1.9333	301.1373	48.3137	0.8739	7.7438	64.9469
	PSO	8,000	–	–	–	–	–	–
	SA	8,000	–	–	–	–	–	44.6621
	TLBO	8,000	2.1183	296.3696	62.5893	0.8951	7.0964	**66.3957**
5	GA	10,000	2.4431	294.3922	24.9804	0.9175	6.4845	68.0499
	PSO	10,000	–	–	–	–	–	–
	SA	10,000	–	–	–	–	–	49.3149
	TLBO	10,000	2.1827	298.4594	8.3462	0.9054	5.996	**69.7367**
6	GA	12,000	2.1294	301.7647	33.4902	0.8904	5.5936	70.27
	PSO	12,000	–	–	–	–	–	–
	SA	12,000	–	–	–	–	–	53.4182
	TLBO	12,000	2.6748	297.2470	48.3672	0.8797	5.3478	**71.7732**
7	GA	14,000	1.0627	303.4118	3.0196	0.9014	4.9224	71.9223
	PSO	14,000	–	–	–	–	–	–
	SA	14,000	–	–	–	–	–	56.5065
	TLBO	14,000	1.3882	297.6738	23.6482	0.9262	4.6855	**73.3937**
8	GA	16,000	1.8	295.2549	7.1373	0.8782	4.4093	73.2418
	PSO	16,000	–	–	–	–	–	–
	SA	16,000	–	–	–	–	–	59.0541
	TLBO	16,000	1.5638	299.4537	19.3678	0.8963	4.2378	**74.1189**
9	GA	18,000	1.4941	290.7059	58.1961	0.8594	4.0209	74.2811
	PSO	18,000	–	–	–	–	–	–
	SA	18,000	–	–	–	–	–	61.1254
	TLBO	18,000	1.2811	293.2882	23.7748	0.8848	3.8267	**75.1932**
10	GA	20,000	1	291.3333	21.6863	0.9433	3.6408	75.2149
	PSO	20,000	–	–	–	–	–	–
	SA	20,000	–	–	–	–	–	62.3454
	TLBO	20,000	1.3294	294.9836	47.2782	0.9145	3.5796	**76.4188**

Note: The symbol "–" indicates results are not available in the corresponding literature.

Source: The data of the GA, PSO, and SA are taken from Varun and Siddhartha (2010), Siddhartha, Sharma, et al. (2012) and Siddhartha, Chauhan, et al. (2012), respectively.

Table 13. Set of optimum results at different Reynolds numbers (N = 1 and S = 1,200 W/m²)

S. No.		Re	v	T_a	β	ϵ_p	$T_o - T_i$	ηth (%)
1	GA	2,000	1.1098	298	12.0784	0.8524	13.7712	26.6961
	PSO	2,000	–	–	–	–	–	–
	SA	2,000	–	–	–	–	–	17.4604
	TLBO	2,000	1.5248	294.7832	23.3772	0.8738	12.7467	**28.3282**
2	GA	4,000	2.6784	301.8431	30.7451	0.8669	10.178	39.3842
	PSO	4,000	–	–	–	–	–	–
	SA	4,000	–	–	–	–	–	29.0595
	TLBO	4,000	2.4261	296.3782	49.2628	0.8634	9.4684	**41.6739**
3	GA	6,000	2.0431	304.4314	68.3529	0.9022	8.6299	47.2705
	PSO	6,000	–	–	–	–	–	–
	SA	6,000	–	–	–	–	–	37.6487
	TLBO	6,000	1.8131	301.7223	57.2837	0.8854	7.9854	**49.7638**
4	GA	8,000	1.7765	294.7843	58.7451	0.8947	7.4196	52.8345
	PSO	8,000	–	–	–	–	–	–
	SA	8,000	–	–	–	–	–	43.9187
	TLBO	8,000	1.3989	297.3629	62.4629	0.9252	6.8594	**54.7834**
5	GA	10,000	1.4941	297.2941	64.7843	0.8947	6.4737	57.0424
	PSO	10,000	–	–	–	–	–	–
	SA	10,000	–	–	–	–	–	48.8642
	TLBO	10,000	1.7712	301.8264	48.2563	0.9065	5.8832	**59.1021**
6	GA	12,000	1.9333	309.6863	53.2549	0.8653	5.5802	60.1529
	PSO	12,000	–	–	–	–	–	–
	SA	12,000	–	–	–	–	–	52.7259
	TLBO	12,000	2.2316	302.3782	35.2645	0.8812	5.2394	**61.8847**
7	GA	14,000	2.3333	300.2745	23.6078	0.8739	4.9692	62.4509
	PSO	14,000	–	–	–	–	–	–
	SA	14,000	–	–	–	–	–	55.7717
	TLBO	14,000	2.4712	298.3782	43.2842	0.8848	4.7183	**63.9456**
8	GA	16,000	1.3608	302.4706	21.9608	0.8598	4.5627	64.4455
	PSO	16,000	–	–	–	–	–	–
	SA	16,000	–	–	–	–	–	58.3572
	TLBO	16,000	1.7629	299.2774	36.6721	0.8932	4.3752	**65.7832**
9	GA	18,000	2.7255	300.5098	24.1569	0.8951	4.0956	66.2157
	PSO	18,000	–	–	–	–	–	–
	SA	18,000	–	–	–	–	–	60.3263
	TLBO	18,000	2.0527	303.2567	13.8288	0.9382	3.9611	**67.4527**
10	GA	20,000	1.1961	301.451	55.1765	0.9006	3.8724	67.5588
	PSO	20,000	–	–	–	–	–	–
	SA	20,000	–	–	–	–	–	62.3454
	TLBO	20,000	1.2836	304.8453	29.2752	0.9161	3.7923	**69.06378**

Note: The symbol "–" indicates results are not available in the corresponding literature.

Source: The data of the GA, PSO, and SA are taken from Varun and Siddhartha (2010), Siddhartha, Sharma, et al. (2012) and Siddhartha, Chauhan, et al. (2012), respectively.

Table 14. Set of optimum results at different Reynolds numbers (N = 2 and S = 1,200 W/m^2)

S. No.		*Re*	*v*	T_a	β	ϵ_p	$T_o - T_i$	ηth (%)
1	GA	2,000	1.0471	301.7647	33.4902	0.8873	17.796	33.6309
	PSO	2,000	–	–	–	–	–	–
	SA	2,000	–	–	–	–	–	22.6143
	TLBO	2,000	1.3772	298.5773	21.6737	0.8934	15.3859	**35.4562**
2	GA	4,000	2.1451	299.2549	24.9804	0.9339	12.7697	47.4312
	PSO	4,000	–	–	–	–	–	–
	SA	4,000	–	–	–	–	–	36.5246
	TLBO	4,000	2.4436	295.7382	42.8322	0.9132	11.6380	**49.4673**
3	GA	6,000	1.8392	293.8431	40.0784	0.8947	10.3696	55.2555
	PSO	6,000	–	–	–	–	–	–
	SA	6,000	–	–	–	–	–	45.6225
	TLBO	6,000	1.5263	290.3843	65.3738	0.9028	9.3496	**56.9932**
4	GA	8,000	2.0431	306.2353	61.2157	0.9233	8.4761	60.3607
	PSO	8,000	–	–	–	–	–	–
	SA	8,000	–	–	–	–	–	51.9252
	TLBO	8,000	1.8127	302.6325	52.4771	0.8992	7.8913	**62.6748**
5	GA	10,000	1.6431	302.3137	4.6667	0.9139	7.1846	64.0505
	PSO	10,000	–	–	–	–	–	–
	SA	10,000	–	–	–	–	–	56.4899
	TLBO	10,000	1.2328	297.1183	21.3392	0.8846	6.9964	**65.8992**
6	GA	12,000	1.0863	303.9608	56.549	0.8567	6.3845	66.5759
	PSO	12,000	–	–	–	–	–	–
	SA	12,000	–	–	–	–	–	60.0281
	TLBO	12,000	1.3823	299.7837	23.5732	0.8628	5.8732	**68.2184**
7	GA	14,000	2.8745	296.9804	59.8431	0.8547	5.6448	68.6168
	PSO	14,000	–	–	–	–	–	–
	SA	14,000	–	–	–	–	–	62.9441
	TLBO	14,000	2.6122	299.3822	47.2685	0.9163	5.3181	**69.9247**
8	GA	16,000	1.6118	295.9608	34.0392	0.879	5.0491	70.2132
	PSO	16,000	–	–	–	–	–	–
	SA	16,000	–	–	–	–	–	65.1525
	TLBO	16,000	1.2178	302.5732	21.4778	0.8927	4.8832	**71.4692**
9	GA	18,000	1.2353	301.6078	23.6078	0.8684	4.5681	71.4894
	PSO	18,000	–	–	–	–	–	–
	SA	18,000	–	–	–	–	–	67.0587
	TLBO	18,000	1.5721	304.9956	8.3772	0.9027	4.4616	**72.3785**
10	GA	20,000	1.5961	292.8235	21.9608	0.8547	4.1981	72.5851
	PSO	20,000	–	–	–	–	–	–
	SA	20,000	–	–	–	–	–	68.5195
	TLBO	20,000	1.8973	290.3753	16.4672	0.8623	4.1109	**74.1743**

Note: The symbol “–” indicates results are not available in the corresponding literature.

Source: The data of the GA, PSO, and SA are taken from Varun and Siddhartha (2010), Siddhartha, Sharma, et al. (2012) and Siddhartha, Chauhan, et al. (2012), respectively.

Table 15. Set of optimum results at different Reynolds numbers (N = 3 and S = 1,200 W/m²)

S. No.		*Re*	*v*	T_a	β	ϵ_p	$T_0 - T_i$	ηth (%)
1	GA	2,000	1.2431	297.0588	61.4902	0.8602	21.3196	38.1579
	PSO	2,000	–	–	–	–	–	–
	SA	2,000	–	–	–	–	–	17.4604
	TLBO	2,000	1.0151	294.3668	45.3568	0.8926	17.3942	**40.2748**
2	GA	4,000	1.8784	301.6078	12.6275	0.8645	14.505	52.4193
	PSO	4,000	–	–	–	–	–	–
	SA	4,000	–	–	–	–	–	29.0595
	TLBO	4,000	1.6714	297.6782	27.3564	0.8849	12.8242	**54.2748**
3	GA	6,000	1.3216	294.4706	64.2353	0.8594	11.5417	59.8554
	PSO	6,000	–	–	–	–	–	–
	SA	6,000	–	–	–	–	–	37.6487
	TLBO	6,000	1.7893	291.5683	56.7544	0.8941	10.5689	**61.4773**
4	GA	8,000	2.7725	294.6275	32.6667	0.9473	9.1277	64.5362
	PSO	8,000	–	–	–	–	–	–
	SA	8,000	–	–	–	–	–	43.9187
	TLBO	8,000	2.4844	298.4632	12.7348	0.9147	8.7635	**66.2726**
5	GA	10,000	2.5608	302.4706	58.1961	0.8825	7.7548	67.592
	PSO	10,000	–	–	–	–	–	–
	SA	10,000	–	–	–	–	–	48.8642
	TLBO	10,000	2.8637	298.3570	63.4563	0.9123	7.1074	**69.3674**
6	GA	12,000	2.9686	290.7059	43.9216	0.8908	6.7211	69.9637
	PSO	12,000	–	–	–	–	–	–
	SA	12,000	–	–	–	–	–	52.7259
	TLBO	12,000	2.8868	293.9874	56.7432	0.9038	6.3987	**71.2371**
7	GA	14,000	1.2118	293.7647	57.098	0.8986	5.9539	71.6221
	PSO	14,000	–	–	–	–	–	–
	SA	14,000	–	–	–	–	–	55.7717
	TLBO	14,000	1.6585	291.3683	34.8643	0.9142	5.5853	**72.6738**
8	GA	16,000	2.6314	309.2157	16.4706	0.8535	5.225	72.9702
	PSO	16,000	–	–	–	–	–	–
	SA	16,000	–	–	–	–	–	58.3572
	TLBO	16,000	2.8726	305.3783	31.4786	0.8736	4.9643	**73.9738**
9	GA	18,000	2.7647	299.098	44.1961	0.9025	4.7531	74.0904
	PSO	18,000	–	–	–	–	–	–
	SA	18,000	–	–	–	–	–	60.3263
	TLBO	18,000	2.2169	303.4577	29.8642	0.8856	4.5775	**74.8992**
10	GA	20,000	2.8353	306.7843	7.9608	0.9406	4.2964	74.969
	PSO	20,000	–	–	–	–	–	–
	SA	20,000	–	–	–	–	–	62.3454
	TLBO	20,000	2.7825	301.9751	24.5735	0.8821	4.2063	**76.0374**

Note: The symbol "–" indicates results are not available in the corresponding literature.

Source: The data of the GA, PSO, and SA are taken from Varun and Siddhartha (2010), Siddhartha, Sharma, et al. (2012) and Siddhartha, Chauhan, et al. (2012), respectively.

algorithm as compared to other algorithms. Table 14 presents the set of optimum results at different Reynolds numbers, $N = 2$ and $S = 1200$ W/m^2. It can be seen that the maximum thermal efficiency of 74.1743% is obtained using the TLBO algorithm at Reynolds number 20,000, with $v = 1.8973$ m/s, $T_a = 290.3753$ K, $\beta = 16.4672°$, and $\epsilon_p = 0.8623$. A set of optimum results at different Reynolds numbers, $N = 3$ and $S = 1200$ W/m^2 is shown in Table 15. The maximum thermal efficiency obtained using TLBO algorithm is 76.0374%. It can be observed that for the same settings, the thermal performance of a SFPSAH obtained by the TLBO algorithm is better as compared to the other algorithms.

In Tables 5–15, the symbol "–" indicates that the results are not available in the cited reference. From Tables 4–15, it can be seen that TLBO algorithm performed better than the other optimization algorithms considered by the previous researchers.

4.1. Effect of Reynolds number on thermal performance

In this section, the effect of Reynolds number on thermal performance of SFPSAH is analyzed with respect to the design and operating parameters. Figure 3 presents variation of thermal performance for different Reynolds number (*Re*) using TLBO algorithm. Figure 4 shows the comparison of different algorithms with Reynolds number. Figure 4 shows variation of thermal performance for different number of glass plates at $S = 600$ W/m^2 (using TLBO algorithm). The thermal performance of a flat-plate solar air heater increases with the increase in Reynolds number as seen in Figures 3–5. The thermal efficiency ranges from 31.7385 to 69.9757 with an increasing Reynolds number varying from 2,000 to 20,000 with single glass cover and irradiance of 600 W/m^2 as shown in Table 4. Similarly, the performance range is 38.1378–74.5783 and 43.3532–76.6739 for the same range of Reynolds number and irradiance having two and three glass covers, respectively. The maximum value of thermal efficiency is 76.67% and it is obtained with three glass cover plates and irradiance of 600 W/m^2 at Reynolds number of 20,000. The maximum value of efficiency is obtained at $V = 1.2729$ m/s, tilt angle = 59.5832°, emissivity of plate = 0.8835, ambient temperature = 293.9362 K, and temperature rise = 2.1395 K. Hence, it can be concluded from Tables 4–15 that the thermal performance of a flat-plate solar air heater increases with increase in Reynolds number.

Figure 3. Variation of thermal performance with Reynolds number (*Re*) (using TLBO algorithm).

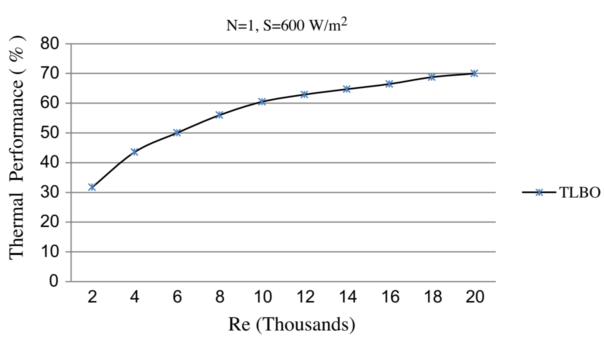
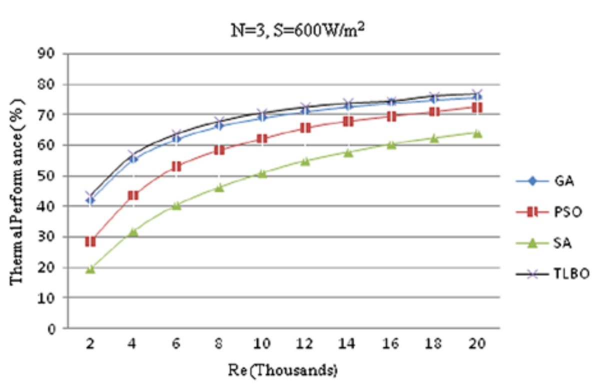


Figure 4. Comparison of thermal performance of different algorithms with Reynolds number.



4.2. Effect of number of glass plates on thermal performance

From Figure 4 and Tables 4–15, it can be seen that as the number of glass plates of solar air heater increases, the thermal efficiency of the solar air heater increases. The thermal performance of the solar air heater is investigated for different sets of glass plates varying from 1 to 3. The range of thermal performance for single glass cover varies from 28.3282% for I = 1200 W/m^2 and Re = 2,000 to 69.9757% for I = 600 W/m^2 and Re = 20,000. Similarly, for two glass covers, the thermal performance varies from 35.4562% for I = 1200 W/m^2 and Re = 2,000 to 74.7183% for I = 600 W/m^2 and Re = 20,000, and for three glass covers, the thermal performance varies from 40.2748% for I = 1200 W/m^2 and Re = 2,000 to 76.6739% for I = 600 W/m^2 and Re = 20,000.

4.3. Effect of solar radiation intensity on thermal performance

Figure 5 shows the effect of solar radiation intensity on thermal performance for N = 1. The maximum thermal performance is 76.6739, 76.5913, 76.4188, and 76.0374% for irradiance of 600 W/m^2, 800 W/m^2, 1,000 W/m^2, and 1200 W/m^2, respectively. Hence, it can be concluded that as the irradiance increases, the thermal performance slightly decreases as can be seen from Figure 5 and Tables 4–15.

5. Conclusions

In the present work, a recently developed optimization algorithm known as TLBO algorithm is used for investigating the thermal performance of a SFPSAH. Maximization of thermal efficiency of SFPSAH is considered as the objective function. The thermal performance is obtained for different Reynolds numbers, irradiance, and number of glass plates. The maximum value of thermal efficiency of 76.67% is obtained with wind velocity of 1.2729 m/s, tilt angle of 59.5832°, plate emissivity of 0.8835, ambient temperature of 3.9362 K, temperature rise of 2.1395 K, irradiance of 600, and Reynolds number of 20,000. The final results obtained by the TLBO algorithm are compared with other optimization algorithms like GA, PSO, and SA and found to be satisfactory. The results also show that the thermal performance increases with the Reynolds number and the number of glass cover plates, but slightly

Figure 5. Variation of thermal performance with Reynolds number (*Re*) for different number of glass plates at *S* = 600 W/m^2 (using TLBO algorithm).

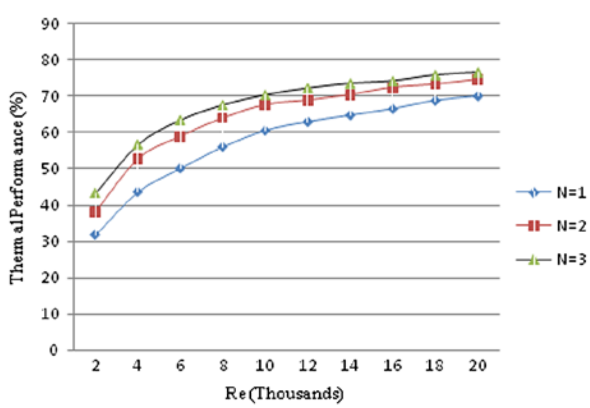
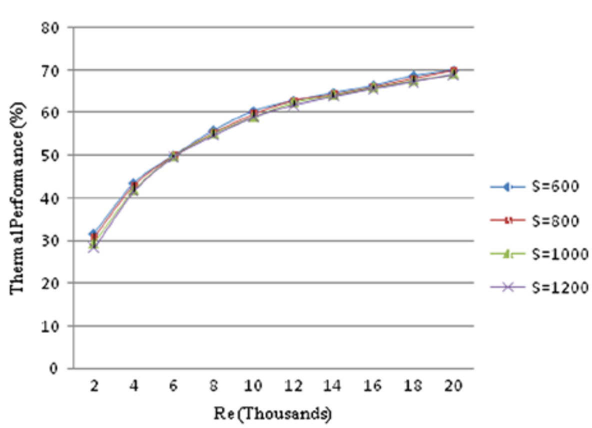


Figure 6. The effect of solar radiation intensity on thermal performance (*N* = 1).



decreases with the increase in irradiance. The TLBO algorithm is an effective algorithm and has potential for finding the optimal set of design and operating parameters at which the thermal performance of a SFPSAH is maximum. The TLBO algorithm may be tried on more complex problems in the near future.

Nomenclature

A_c	area of absorber plate (m^2)
c_p	specific heat of air (J/kg K)
d	hydraulic diameter of duct (m)
F_0	heat removal factor referred to outlet temperature (dimensionless)
G	mass velocity (kg/sm^2)
h	convective heat transfer coefficient (W/m^2K)
h_w	wind convection coefficient (W/m^2K)
S	irradiance (W/m^2)
k	index of iteration
k'	construction factor
k_{max}	maximum number of observations
$\dot{m}$	mass flow rate of air (kg/s)
N	number of glass covers (dimensionless)
p_k	position of *k*th iteration
p_r	Prandtl number (dimensionless)
Re	Reynolds number (dimensionless)
t	thickness of insulating material (m)
T_a	ambient temperature of air (K)
T_i	inlet temperature of air (K)
T_0	outlet temperature of air (K)
T_p	temperature of absorber plate (K)
U_0	overall loss coefficient (W/m^2K)
U_t	top loss coefficient (W/m^2K)
v	wind velocity (m/s)
x_i	experimental value at *i*th iteration
y_i	simulated value at *i*th iteration

Greek symbols

$(\tau\alpha)$	transmittance–absorptance product (dimensionless)
λ	thermal conductivity of air (W/mK)
λ_i	thermal conductivity of insulating material (W/mK)
ηth	thermal efficiency (dimensionless)
ϵ_p	emissivity of plate (dimensionless)
ϵ_g	emissivity of glass cover (dimensionless)
β	tilt angle (°)

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Author details
R. Venkata Rao[1]
E-mail: ravipudirao@gmail.com
Gajanan Waghmare[1]
E-mail: waghmaregaju@yahoo.com
[1] Department of Mechanical Engineering, S.V. National Institute of Technology, Ichchanath, Surat, Gujarat 395 007, India.

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References

Ammari, H. D. (2003). A mathematical model of thermal performance of a solar air heater with slats. *Renewable Energy, 28*, 1597–1615. http://dx.doi.org/10.1016/S0960-1481(02)00253-7

ASHRAE Standards. (1997). *Methods of testing to determine the thermal performance of solar collectors*. New York, NY: Author, 93–77.

Basu, M. (2014). Teaching–learning-based optimization algorithm for multi-area economic dispatch. *Energy*. Retrieved from http://dx.doi.org/10.1016/j.energy.2014

Baykasoğlu, A., Hamzadayi, A., & Köse, S. Y. (2014). Testing the performance of teaching–learning based optimization (TLBO) algorithm on combinatorial problems: Flow shop and job shop scheduling cases. *Information Sciences*. Retrieved from http://dx.doi.org/10.1016/j.ins.2014.02.056

Camp, C. V., & Farshchin, M. (2014). Design of space trusses using modified teaching–learning-based optimization. *Engineering Structures, 62–63*, 87–97. http://dx.doi.org/10.1016/j.engstruct.2014.01.020

Chamoli, S., Chauhan, R., Thakur, N. S., & Saini, J. S. (2012). A review of the performance of double pass solar air heater. *Renewable and Sustainable Energy Reviews, 16*, 481–492. http://dx.doi.org/10.1016/j.rser.2011.08.012

Črepinšek, M., Liu, S.-H., & Mernik, L. (2012). A note on teaching–learning-based optimization algorithm. *Information Sciences, 212*, 79–93.

Črepinšek, M., Liu, S.-H., & Mernik, M. (2014). Replication and comparison of computational experiments in applied evolutionary computing: Common pitfalls and guidelines to avoid them. *Applied Soft Computing, 19*, 161–170.

Deb, K. (2000). An efficient constraint handling method for genetic algorithms. *Computer Methods in Applied Mechanics and Engineering, 186*, 311–338. http://dx.doi.org/10.1016/S0045-7825(99)00389-8

El-Sebaii, A. A., Aboul-Enein, S., Ramadan, M. R. I., Shalaby, S. M., & Moharram, B. M. (2011). Investigation of thermal performance of-double pass-flat and v-corrugated plate solar air heaters. *Energy, 36*, 1076–1086. http://dx.doi.org/10.1016/j.energy.2010.11.042

Gill, R. S., Singh, S., & Singh, P. (2012). Low cost solar air heater. *Energy Conversion and Management, 57*, 131–142. http://dx.doi.org/10.1016/j.enconman.2011.12.019

Gupta, D., Solanki, S. C., & Saini, J. S. (1997). Thermohydraulic performance of solar air heaters with roughened absorber plates. *Solar Energy, 61*, 33–42. http://dx.doi.org/10.1016/S0038-092X(97)00005-4

Hegazy, A. A. (1996). Optimization of flow-channel depth for conventional flat plate solar air heaters. *Renewable Energy, 7*, 15–21. http://dx.doi.org/10.1016/0960-1481(95)00117-4

Kalogirou, S. A. (2006). Prediction of flat-plate collector performance parameters using artificial neural networks. *Solar Energy, 80*, 248–259. http://dx.doi.org/10.1016/j.solener.2005.03.003

Karwa, R., & Chitoshiya, G. (2013). Performance study of solar air heater having v-down discrete ribs on absorber plate. *Energy, 55*, 939–955. http://dx.doi.org/10.1016/j.energy.2013.03.068

Klein, S. A. (1975). Calculation of flat plate collector loss coefficients. *Solar Energy, 17*, 79–80. http://dx.doi.org/10.1016/0038-092X(75)90020-1

Lanjewar, A., Bhagoria, J. L., & Sarviya, R. M. (2011). Heat transfer and friction in solar air heater duct with W-shaped rib roughness on absorber plate. *Energy, 36*, 4531–4541. http://dx.doi.org/10.1016/j.energy.2011.03.054

Layek, A., Saini, J. S., & Solanki, S. C. (2007). Second law optimization of a solar air heater having chamfered rib-groove roughness on absorber plate. *Renewable Energy, 32*, 1967–1980. http://dx.doi.org/10.1016/j.renene.2006.11.005

Medina, M. A., Das, S., Coello Coello, C. A., & Ramírez, J. M. (2014). Decomposition-based modern metaheuristic algorithms for multi-objective optimal power flow—A comparative study. *Engineering Applications of Artificial Intelligence, 32*, 10–20. http://dx.doi.org/10.1016/j.engappai.2014.01.016

Mittal, M. K., & Varshney, L. (2006). Optimal thermohydraulic performance of a wire mesh packed solar air heater. *Solar Energy, 80*, 1112–1120. http://dx.doi.org/10.1016/j.solener.2005.10.004

Moghadam, A., & Seifi, A. R. (2014). Fuzzy-TLBO optimal reactive power control variables planning for energy loss minimization. *Energy Conversion and Management, 77*, 208–215. http://dx.doi.org/10.1016/j.enconman.2013.09.036

Niknam, T., Azizipanah-Abarghooee, R., & Rasoul Narimani, M. (2012). A new multi objective optimization approach based on TLBO for location of automatic voltage regulators in distribution systems. *Engineering Applications of Artificial Intelligence, 25*, 1577–1588. http://dx.doi.org/10.1016/j.engappai.2012.07.004

Rao, R. V., Kalyankar, V. D., & Waghmare, G. (2014). Parameters optimization of selected casting processes using teaching–learning based optimization algorithm. *Applied Mathematical Modelling, 38*, 5592–5608. http://dx.doi.org/10.1016/j.apm.2014.04.036

Rao, R. V., & Patel, V. (2012). An elitist teaching–learning-based optimization algorithm for solving complex constrained optimization problems. *International Journal of Industrial Engineering Computations, 3*, 535–560. http://dx.doi.org/10.5267/j.ijiec

Rao, R. V., & Patel, V. (2013). Comparative performance of an elitist teaching–learning-based optimization algorithm for solving unconstrained optimization problems. *International Journal of Industrial Engineering Computations, 4*, 29–50. http://dx.doi.org/10.5267/j.ijiec

Rao, R. V., Savsani, V. J., & Balic, J. (2011). 'Teaching–learning-based optimization algorithm for unconstrained and constrained real parameter optimization problems. *Engineering Optimization, 44*, 1447–1462.

Rao, R. V., Savsani, V. J., & Vakharia, D. P. (2011a). Teaching–learning-based optimization: A novel method for constrained mechanical design optimization problems. *Computer Aided Design, 43*, 303–315. http://dx.doi.org/10.1016/j.cad.2010.12.015

Rao, R. V., Savsani, V. J., & Vakharia, D. P. (2011b). 'Teaching–learning-based optimization: A novel optimization method for continuous non-linear large scale problems. *Information Sciences, 183*(1), 1–15.

Rao, R. V., & Waghmare, G. G. (2014). A comparative study of a teaching–learning-based optimization algorithm on multiobjective unconstrained and constrained functions. *Journal of King Saud University – Computer and Information Sciences, 26*, 332–346.

Satapathy, S. C., & Naik, A. (2014). Modified teaching–learning-based optimization algorithm for global numerical optimization—A comparative study. *Swarm and Evolutionary Computation, 16*, 28–37. http://dx.doi.org/10.1016/j.swevo.2013.12.005

Siddhartha, S., Chauhan, S. R., Varun, V., & Sharma, N. (2012). Thermal performance optimization of smooth flat plate solar air heater (SFPSAH) using simulated annealing: Evaluation and comparisons. *IEEE*, Copyright Notice: 978-1-4673-6008-1/11

Siddhartha, Sharma, N., & Varun (2012). A particle swarm optimization algorithm for optimization of thermal performance of a smooth flat plate solar air heater. *Energy, 38*, 406–413. http://dx.doi.org/10.1016/j.energy.2011.11.026

Sultana, S., & Roy, P. K. (2014). Optimal capacitor placement in radial distribution systems using teaching learning based optimization. *International Journal of Electrical Power & Energy Systems, 54*, 387–398.

Tanda, G. (2011). Performance of solar air heater ducts with different types of ribs on the absorber plate. *Energy, 36*, 6651–6660. http://dx.doi.org/10.1016/j.energy.2011.08.043
Twidell, J., & Weir, T. (2005). *Renewable energy resources* (2nd ed.). Taylor & Francis. ISBN-13:9780419253303
Varun, Sharma, N., Bhat, I. K., & Grover, D. (2011). Optimization of a smooth flat plate solar air heater using stochastic iterative perturbation technique. *Solar Energy, 85*, 2331–2337. http://dx.doi.org/10.1016/j.solener.2011.06.022
Varun, & Siddhartha (2010). Thermal performance optimization of a flat plate solar air heater using genetic algorithm. *Applied Energy, 87*, 1793–1799. http://dx.doi.org/10.1016/j.apenergy.2009.10.015
Veček, N., Mernik, M., & Črepinšek, M. (2014). A chess rating system for evolutionary algorithms: A new method for the comparison and ranking of evolutionary algorithms. *Information Sciences*. Retrieved from http://dx.doi.org/10.1016/j.ins.2014.02.154
Waghmare, G. (2013). Comments on ‘a note on teaching–learning-based optimization algorithm’. *Information Sciences, 229*, 159–169.
Yu, K., Wang, X., & Wang, Z. (2014). An improved teaching–learning-based optimization algorithm for numerical and engineering optimization problems. *Journal of Intelligent Manufacturing*. doi:10.1007/s5-014-0918-3
Zou, F., Wang, L., Hei, X., Chen, D., & Yang, D. (2014). Teaching–learning-based optimization with dynamic group strategy for global optimization. *Information Sciences, 273*, 112–131. http://dx.doi.org/ 10.1016/j.ins.2014.03.038