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Thermodynamic Analysis and Multi-Objective Optimization of Performance of Solar Dish Stirling Engine by the Centrality of Entransy and Entropy Generation

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Abstract: The current work is applied optimization process with multi objective on the solar-powered Stirling engine with high temperature differential. On the basis of finite – time thermodynamic, new mathematical approach was evolved. Furthermore, thermal efficiency of the solar Stirling system with rate of finite heat transfer, regenerative heat loss, the output power, finite regeneration process time and conductive thermal bridging loss are specified. The power output and thermal efficiency and entransy loss rate are specified at Maximum condition for a dish-Stirling system and entropy generation's rate in the engine Minimized by carrying out thermodynamic analysis and NSGAⅡ approach. Three well known decision making methods are carried out to indicate optimum values of outputs obtained with optimization process. Finally, with the aim of error analysis the error of the aforementioned results are determined.

Keywords: entransy loss rate; Stirling engine; Solar-Dish; entropy generation; NSGAⅡ; Decision making.

1. Introduction

One of the vital and straightforward standard air cycles for heat engines is addressed to Stirling cycle [1, 2]. With the aim of profits of the aforementioned cycle, an adequate efficiency can be specified and extend variety of fuels can be implemented for heating purposes. [2-4]. From theoretical point of view, at the Carnot efficiency, the Stirling engine can be a high performance engine to change heat into the mechanical work when the isothermal expansion and compression processes and ideal regeneration are involved. Working temperatures of the cooler and heater sides ply a crucial role on the thermal restriction for the operational condition of a Stirling engine. Through most cases, the operational temperatures of the aforementioned engine are 923K and 338K for heater and cooler temperature, correspondingly [5]. Efficiency of Engine changes from 30 to 40% that belongs to a general temperature boundary of 923-1073K, and span of the normal operating varies from 2000 to 4000 rpm [6,11]. Incorporation of solar concentrators and Stirling engines is a novel thought that facilitates changing the solar energy into the electric power. Through this instance, parabolic layers of the mirrors are utilized with a dish collector to concentrate the solar radiations throughout a central spot of the collector in which the absorber of heat is fixed.

Through the recent years, enormous efforts have been put forth to specify the optimal performance of solar-driven energy systems, with the aim of the analysis of the finite time thermodynamic (FTT) [12-37]. Solutions gained from the aforementioned thermodynamic analysis are more reliable than other thermodynamic approaches. Thanks to this fact, the upshots are highly discerned to improvise the real optimal solar energy systems draw in parallel with the previous approaches.
Yaqi and colleagues [13] performed finite-time thermodynamics to determine optimum values of parameters through a solar-powered Stirling heat engine. The primary regular operating conditions for a solar thermal power plant in expression of rate of finite heat transfer and a process with internally reversibility throughout illuminated a number of parametric formulas is specified by Lund [19]. The optimum operational statuses of a Carnot-type irreversible solar-powered heat engine with the radiation overcome heat transition between the source of heat and fluid of working as well as the convection overcome heat transition between the sink of heat and fluid of working are carried out by Tamer Yilmaz*et* and collaborators [20]. A finite-time factor as the proportion of the contact time of working fluid to the time constant of the engine which develops the heat transfer characteristics of the aforementioned Stirling engine project is specified by Ibrahim and Ladas [24]. They conducted a numerical investigation and schemed the variation of the power output against efficiency, the alteration of the power output against the finite-time factors and outcomes of the regeneration. Sieniutycz and von Spakovsky securitized the thermal exergy with the aim of the finite-time approach [28]. A smart thermo-economic research on the basis of the objective function stand for the power output per unit total cost is proposed by Kodal and Sahin [29]. A thought of the possible performance for an actual engine is illustrated by Blank and collaborators [32] throughout checking the optimization of power in the endoreversible Stirling cycle. The equivalence of energy of a self-determining solar power plant with a Stirling engine is thorough by Trukhow*et* and collaborators [33]. It is represented that the electric power output is depends on the direction of solar radiation. The size of engine restricts and

Chen and colleagues are investigated the efficiency of a solar driven Stirling heat engine at the maximum output power [34].

The entransy theory is recently progressed and is applied to heat transfer optimizations. Guo and colleagues [38] suggested the entransy concept from the comparison between the heat and electric conduction. According to this concept, Guo and colleagues established the extremum ED phenomenon and theory of the minimum entransy-dissipation on the basis of the thermal resistance. These origins are implemented to optimize heat transfer such as conduction and convection [39−43], thermal radiation [44, 45] and the design of the heat exchangers [46， 47].

For the concept of entransy dissipation (ED), researches show that it is not appropriate for optimizing the processes of heat-work conversion [48, 49]. However, efforts are made to extend the application of the entransy theory to the optimization of the heat-work conversion.

Cheng and colleagues [50-52] suggested the entransy loss (EL) concept, which is the sum of ED owing to the entransy variation thanks to the work output and the irreversible heat transfer. EL is the entransy that is employed in the heat-work conversion processes.

To indicate solution of the multi-objective optimization issues, huge amounts of efforts required to assure parallel and different objectives; however, may be conflict each other. Through previous decades evolutionary algorithms (EA) have been primarily utilized to stochastically unravel issues of this general category [53]. An appropriate outcome of a multi-objective issue is to specify an assortment of results, each of that assures the objectives at an adequate degree without being prevailed by any other result[54]. Optimizing Multi-objective issues in general depict a feasible countless assortment of outcomes known as frontier of Pareto, where examined vectors denote the best feasible trade-offs throughout the objective function region. Owing to this point, optimizing with multi-objective optimization of various energy systems and thermodynamic were carried out by different researchers [55-62]. Ahmadi et al [63-69] developed an intelligent approach to figure power of solar Stirling heat engine by implementation of evolutionary algorithms

This work includes two scenarios that, in the first scenario by executing multi-objective optimization approach, the Stirling engine's thermal efficiency and the output power and entransy loss rate of system are maximized. Also in the second scenario by utilizing multi-objective optimization approach output power and entransy losses rate of system are maximized and entropy generation's rate of the Solar-dish Stirling engine is minimized. Moreover, ultimate results of aforementioned processes have been drawing in parallel with Ref [13] data. Finally, analysis of error has been carried out to specify precision and robustness of ultimate outputs of each decision making techniques.

2. Thermodynamic Analysis of the System

As shown in Fig. 1, four different processes constitute the Stirling cycle. An isothermal process is addressed to Process 1-2, where the working fluid of compression at consistent temperature, T_c, releases the heat into the heat sink at fixed temperature, T_L. After that in an isochoric process 2-3, the fluid of working passes the regenerator and becomes warm to T_h. In next stage, the working fluid spreads out at a consistent temperature, T_h, and gains the heat from the source of heat at a consistent temperature T_H in process 3-4. Finally, through an isochoric process of cooling from 4 to 1, in which the regenerator obtains the heat from the fluid of working.

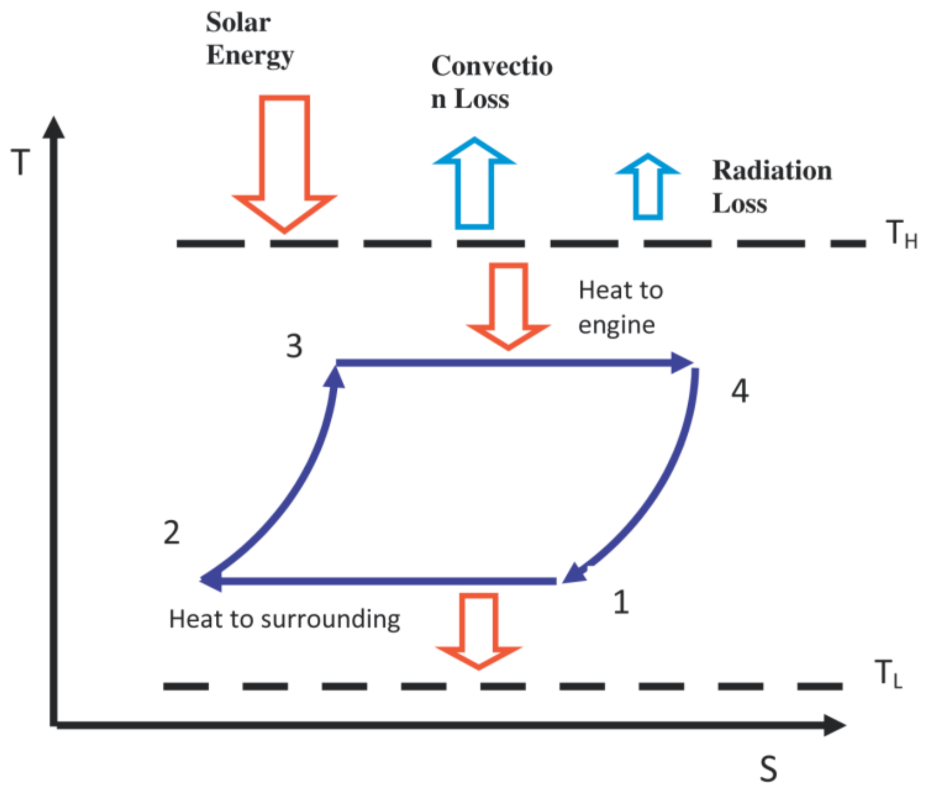


Figure. 1. Heat flows involved in a Stirling engine with solar collector [57].

In this section a thermal approach on the basis of the finite time thermodynamic for simulation of the Stirling cycle is developed as follows,

2.1. *Regenerative heat losses in the regenerator*

It should be point out here that through the regenerative heat transfer (Q_R) there also have a finite heat transfer. Q_R can be formulated as below equation [13, 25, 26, 34]:

$$Q_R = nC_V\varepsilon_R(\mathrm{T}_h - \mathrm{T}_c) \tag{1}$$

Where C_V stands for the working fluid's molar specific heat through the processes of regeneration, ε_R represents the regenerator's effectiveness and n denotes the working fluid's molar mass, correspondingly. Therefore, the heat loss of regeneration in two aforementioned processes of regeneration is determined as following equation [13, 25, 26, 35]:

$$\Delta Q_R = nC_V(1-\varepsilon_R)(\mathrm{T}_h - \mathrm{T}_c) \tag{2}$$

2.2.The amounts of heat released by the heat source and absorbed by the heat sink

The heat transferred between working fluid and the heat source (Q_h), and the heat transferred between the heat sink and the working fluid (Q_c) are calculated as below formulas [35,57]:

$$Q_h = nRT_h Ln\lambda \tag{3}$$

$$Q_c = nRT_c Ln\lambda \tag{4}$$

The net heat transferred by the heat source (Q_H) and the net heat gained by the heat sink (Q_L) are calculated as below equations [25,26,35]:

$$Q_H = Q_h + \Delta Q_R = nRT_h Ln\lambda + nC_v\left(1-\varepsilon_R\right)\left(T_h - T_c\right) \tag{5}$$

$$Q_L = Q_c + \Delta Q_R = nRT_c Ln\lambda + nC_v\left(1-\varepsilon_R\right)\left(T_h - T_c\right) \tag{6}$$

Assume that the thermal conductance's of the heat exchangers on the cold and hot sides are $(UA)_H$ and $(UA)_L$, correspondingly. The heat gained from the hot reservoir and that transferred to the cold reservoir with the aim of the fluid of working during each cycle are [35]

$$Q_H = \left(UA\right)_H \left(T_H - T_h\right)t_1 \tag{7}$$

$$Q_L = \left(UA\right)_L \left(T_c - T_L\right)t_2 \tag{8}$$

Thanks to the finite-rate's Irreversibility of heat transfer, the time of the processes of regeneration is significant draw in parallel with the two aforementioned isothermal processes [13,25,26,57]. To specify the processes of regeneration's time, the fluid of working's temperature throughout the processes of regenerations is presumed as a function of time that is recognized by [13,25,26,31,35,57]:

$$\frac{dT}{dt} = \pm M_i \tag{9}$$

Where M is the constant of proportionality that is not depends on the difference of temperatures and highly depends on the characteristic of the material of regeneration, known as time constant of regeneration and the $\pm$ sign referred to the cooling (i= 2) and heating (i=1) processes correspondingly [13,25,26,31,35,57].

$$t_3 = \frac{T_h - T_c}{M_1} \tag{10}$$

$$t_4 = \frac{T_h - T_c}{M_2} \tag{11}$$

2.3.*The cyclic period*

By executing Eqs. (5)-(11), the cyclic period t can be determined as following as:

$$t = t_1 + t_2 + t_3 + t_4 = \frac{nRT_h Ln\lambda + nC_v\left(1-\varepsilon_R\right)\left(T_h - T_c\right)}{\left(UA\right)_H\left(T_H - T_h\right)} \tag{12}$$
$$+\frac{nRT_c Ln\lambda + nC_v\left(1-\varepsilon_R\right)\left(T_h - T_c\right)}{\left(UA\right)_L\left(T_c - T_L\right)} + \left(\frac{1}{M_1} + \frac{1}{M_2}\right)\left(T_h - T_c\right)$$

Assume that the temperatures of working T_c and T_h and the heat reservoir temperatures T_H and T_L satisfy [35]:

$$\frac{T_c}{T_h} = \left(\frac{T_L}{T_H}\right)^r \tag{13}$$

Presuming the thermal efficiency, the power output, the cyclic period of the Stirling engine entransy loss and entropy generation’s rate of the engine are specified as following formulas [13, 14, 35]:

$$p = \frac{W}{t} = \frac{Q_H - Q_L}{t} \tag{14}$$

$$\eta_t = \frac{Q_H - Q_L}{Q_H} \tag{15}$$

$$\dot{G}_{loss} = \frac{\left(Q_H T_H - Q_L T_L\right)}{t} \tag{16}$$

$$\sigma = \frac{1}{t}\left(\frac{Q_L}{T_L} - \frac{Q_H}{T_H}\right) \tag{17}$$

By coupling Eq. (13) and Eqs. (14) and (15), following equation can be obtain:

$$P = \frac{1-\left(\frac{T_L}{T_H}\right)^r}{\left(\frac{1+M\left(1-\left(\frac{T_L}{T_H}\right)^r\right)}{(UA)_H\left(T_H - T_h\right)} + \frac{\left(\frac{T_L}{T_H}\right)^r + M\left(1-\left(\frac{T_L}{T_H}\right)^r\right)}{(UA)_L\left(T_h\left(\frac{T_L}{T_H}\right)^r - T_L\right)}\right) + \mathrm{F}_1\left(1-\left(\frac{T_L}{T_H}\right)^r\right)} \tag{18}$$

$$\eta_t = \frac{1-\left(\frac{T_L}{T_H}\right)^r}{1+M\left(1-\left(\frac{T_L}{T_H}\right)^r\right)} \tag{19}$$

$$\sigma = \frac{P\left[\left(1-\eta_t\right)T_H - T_L\right]}{\eta_t T_H T_L} \tag{20}$$

$$\dot{G}_{loss} = \frac{P\left[T_H - \left(1-\eta_t\right)T_L\right]}{\eta_t} \tag{21}$$

$$M = \frac{C_v\left(1-\varepsilon_R\right)}{RLn\lambda} \tag{22}$$

$$F_1 = \frac{1}{nRLn\lambda}\left(\frac{1}{M_1} + \frac{1}{M_2}\right) \tag{23}$$

Production of the optimal thermal efficiency of the Stirling engine and the thermal efficiency of the collector is assigned to the maximum thermal efficiency of the entire solar-dish Stirling engine [13,57] which can be determine as following as:

$$\eta_m = \left\{ \eta_0 - \frac{1}{IC}[h(T_H - T_0) + \varepsilon\delta(T_H^4 - T_0^4)] \right\} \times \frac{1 - \left(\frac{T_L}{T_H}\right)^r}{1 + M\left(1 - \left(\frac{T_L}{T_H}\right)^r\right)} \tag{24}$$

3. Multi-objective optimization with EAs

3.1. Optimization via EA

Throughout the present work, the frontier of Pareto is specified by executing Genetic Algorithm (GA) which is a chapter of evolutionary approach. John Holland in the 1960s is a first scientist that proposed and evolved the GA as a tool of numerical optimization with the inspiration of natural evolution of Darwin's theorem and converting it into computer program [55]. They are executed as a PC simulator approach where a population of digest illustrations (named chromosomes or the genotype of the genome) of volunteer outcomes (known as individuals, creatures, or pheno-types) to an optimization issue develops toward better outcomes. The evolution usually initiates from a population of randomly generated individuals and happens in generations. Throughout each creation, the fitness of every individual in the population is examined; multiple individuals are stochastically chosen from the present population (on the basis of their fitness), and adjusted (feasibly randomly mutated and recombined) to generate a new population. The new population is then implemented in the next repetition of the approach. Universally, the algorithm laid off when either, a proper fitness degree was met for the population or a maximum number of generations were created. If the algorithm has laid off thanks to a maximum number of generations, a proper outcome can or cannot been met. In genetic algorithms, a volunteer outcome to an issue is typically known as an individual, and the evolutionary livability of each individual is specified by a fitness function. This technique is a robust optimization approach for issue with high degree of nonlinearity [53, 56,57].

In addition, Multi-objective evolutionary algorithms (MOEAs) were evolved during the recent years by various researches that performed on complicated theoretical issues and on real-world industrial issue and have demonstrated that they can ignored the difficulties of traditional techniques [53, 56,57]. The framework of the MOEA executed in the current research is depicted in Fig.2 [55-57]. The actual magnitudes of decision factors are utilized in lieu of their binary coded.

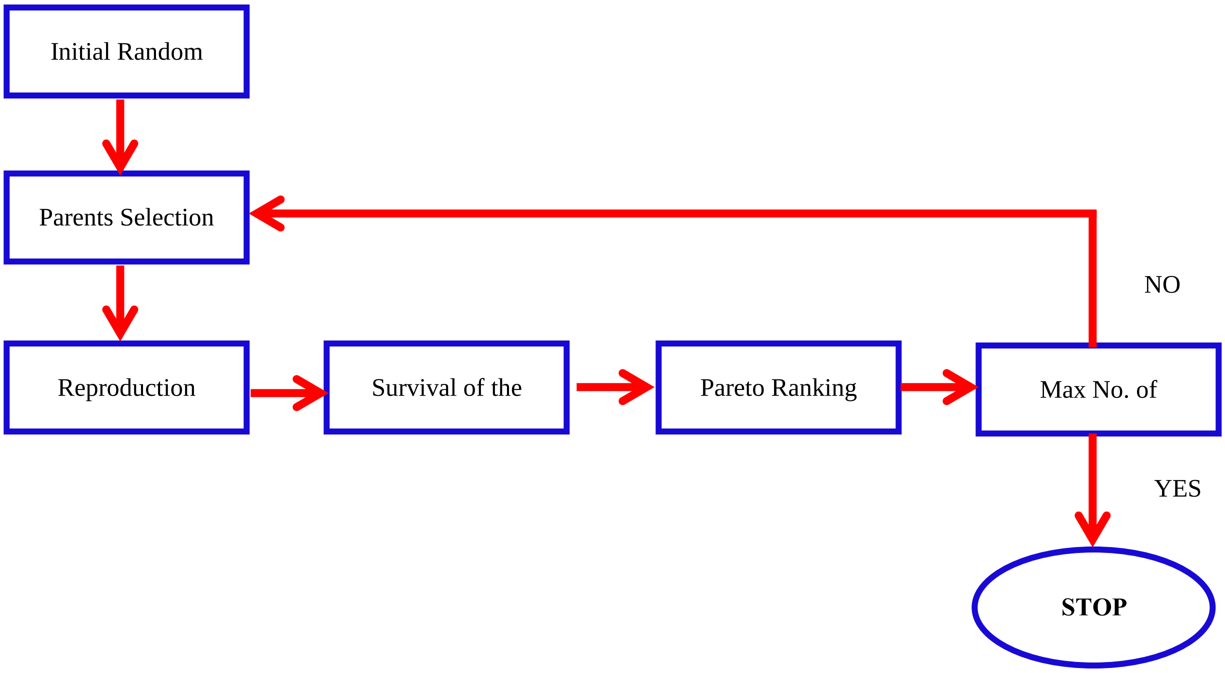


Figure.2. Scheme for the multi-objective evolutionary algorithm used in the present study [56-58,61,62].

3.2. *Objective functions, decision factors and restrictions*

The vital objective functions in first scenario for optimizing purpose are the thermal efficiency of Dish-Stirling engine system's, the output power and the system's entransy loss rate, denoted by Eqs.(18), Eqs.(24) and Eqs.(21), respectively.

The suggested objective functions in second scenario for optimizing purpose is the output power and the system's entropy production and the system's entransy loss rate, formulated by Eqs.(18), Eqs.(20) and Eqs.(21), correspondingly.

Throughout current research, two decision factors have been presumed as follow:

T_h : The working fluid's temperature in the isothermal process at the high temperature 3-4

T_H : Temperature of the heat source

The aforementioned objective functions with proportion to below restrictions were unraveled:

$$780 \leq T_h \leq 1000K \quad (25)$$

$$1100 \leq T_H \leq 1300K \quad (26)$$

A simulation program on the basis of genetic algorithm (GA) is evolved throughout Matlab software to determine the optimal magnitudes of design factors in the proposed system.

3.3. *Decision-making in the multi-objective optimization*

After optimization process with multi variables and objectives, selecting an ultimate optimum outcome from the results gained by evolutionary approach has a great importance. Thanks to this fact, numerous methods that known as decision making techniques can be execute to determine desire optimal variables from the frontier of Pareto that is previously gained. Throughout this research, three robust, high performance and well-known decision maker techniques including LINMAP, fuzzy Bellman-Zadeh and TOPSIS approaches are utilized. An ultimate optimum outcome was determined on the basis of the expert knowledge and indexes through results that proposed with the aim of decision maker approaches. Extensive description of three decision makers can be found in following references [56,57,70, 71].

4. Result and discussion

The dimensionless output power (P) and thermal efficiency of the solar-dish Stirling System (η_m) and entransy loss rate are maximized in parallel and entropy generation's rate of the engine are also minimized in parallel by executing the multi-objective optimization technique that developed on the basis of the NSGA-II process. Thanks to this fact, aforementioned approach is applied on the suggested functions that considered as objective functions which are formulated by Eqs. (18),(19),(20) and (21) and restrictions which are formulated with Eqs. (25)-(26).

Properties of the solar-dish Stirling engine are presumed as following as in order to have compromise with previous publications [13,57],

$(UA)_H = (UA)_L = 300W.K^{-1}, C = 1300$, $\delta = 5.67\times10^{-8}W.m^{-2}.K^{-4}$, $T_L = 320K$, $T_0 = 300K$,

$h = 20W.m^{-2}.K^{-1}$

, $I = 1000W.m^{-2}$, $\left(\frac{1}{\mathrm{M}_1}+\frac{1}{\mathrm{M}_2}\right) = 2\times10^{-5}\mathrm{s.K}^{-1}$, $R = 4.3J.mol^{-1}.K^{-1}$, $n = 1mol$, $\lambda = 2$, $\varepsilon = 0.9$, $\eta_0 = 0.85$

4.1. *Obtained Result of Scenario 1*

Fig 3 shows the optimum frontier of Pareto for considered objective functions such as output power of Stirling engine, system entransy losses rate and thermal efficiency of Stirling engines. As illustrated in Fig 3, the selected points on the basis of the decision making techniques are marked.

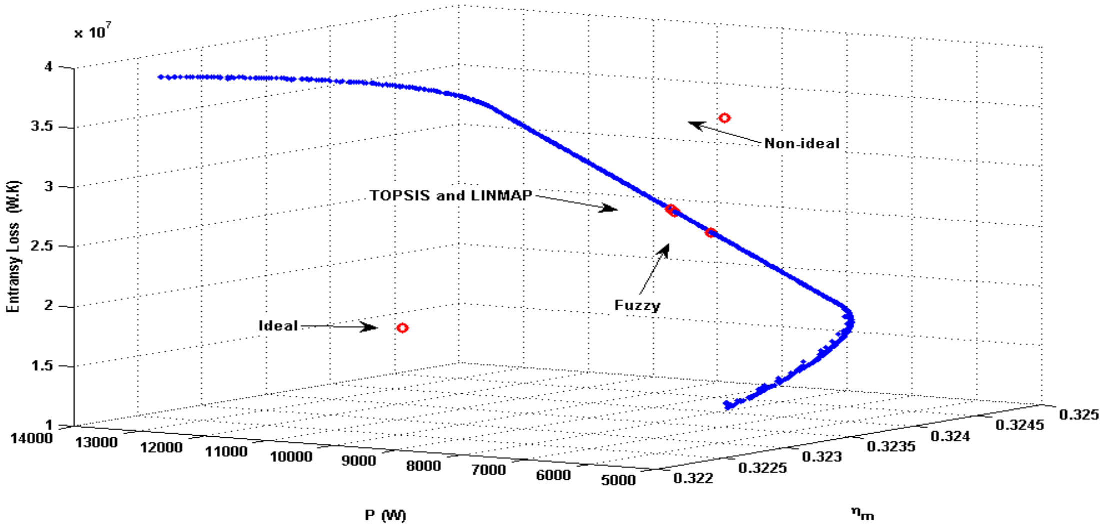


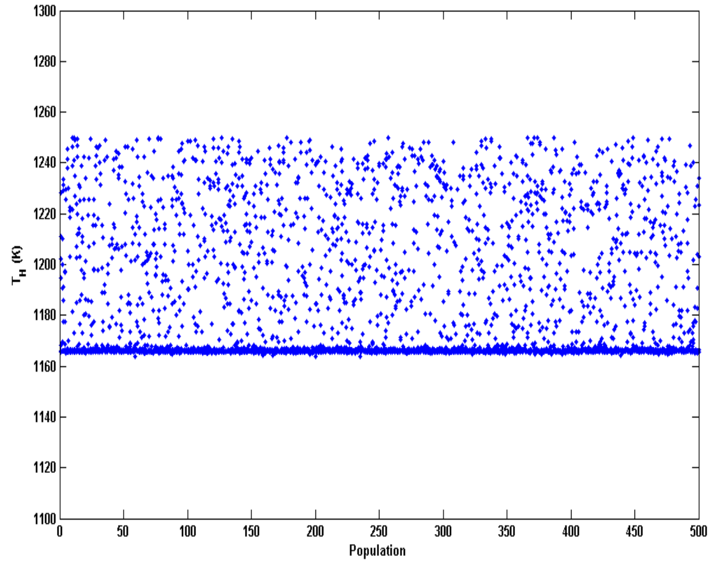
Fig.3. Pareto optimal frontier in objectives' space.

The optimum outcomes for objective functions and decision factors by executing aforementioned decision-making techniques are specified in Table 1.

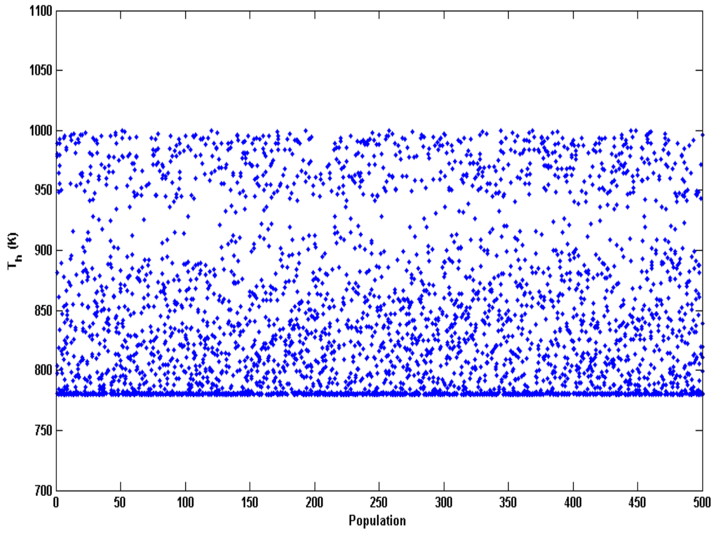
Table.1. Decision making of multi-objective optimal solutions for scenario 1

	Decision variables		***Objectives***		
Optimal solution	T_H ***(K)***	T_h ***(K)***	η_m	P ***(W)***	$\dot{G}_{loss}$ ***(W.K)***
TOPSIS	*1163*	*813*	*0.324428*	*8966.5*	*23928074*
LINMAP	*1165*	*825*	*0.324429*	*9523.3*	*25433699*
Fuzzy	*1165*	*827*	*0.324429*	*9596.9*	*25632885*
Ref. [13]	*1100*	*924*	*0.3081*	*10164.2*	*-*

Figures 4a to 4b demonstrate the scattered distribution of the design variables. These plots can provide better vision of variation of the design variables from the Pareto frontier.



(a)



(b)

Figure.4. (a)-(b) Scatter distribution of Decision variables with population in Pareto frontier for Scenario 1.

Magnitudes of the mean and maximum relative deviations for objective functions are demonstrated in Table 2. The aforementioned error investigation is performed for three aforementioned decision-making techniques.

Table.2. Error analysis based on the mean absolute percent error (MAPE) method for scenario1.

Decision Making Method	*Fuzzy*			*LINMAP*			*TOPSIS*		
Objectives	η_m	P	$\dot{G}_{loss}$	η_m	P	$\dot{G}_{loss}$	η_m	P	$\dot{G}_{loss}$
Max Error %	*0.0*	*1.7*	*1.8*	*0.0*	*1.1*	*1.1*	*0.0*	*0.5*	*0.6*
Average Error %	*0.0*	*1.5*	*1.6*	*0.0*	*0.4*	*0.4*	*0.0*	*0.2*	*0.2*

4.2.*Obtained Result of Scenario 2*

Fig 5 shows the optimum frontier of Pareto for suggested objective functions, output power of Stirling engine, generation of entropy in Stirling engines and system entransy losses rate. As illustrated in Fig.5 , the selected points on the basis of the decision making techniques are marked.

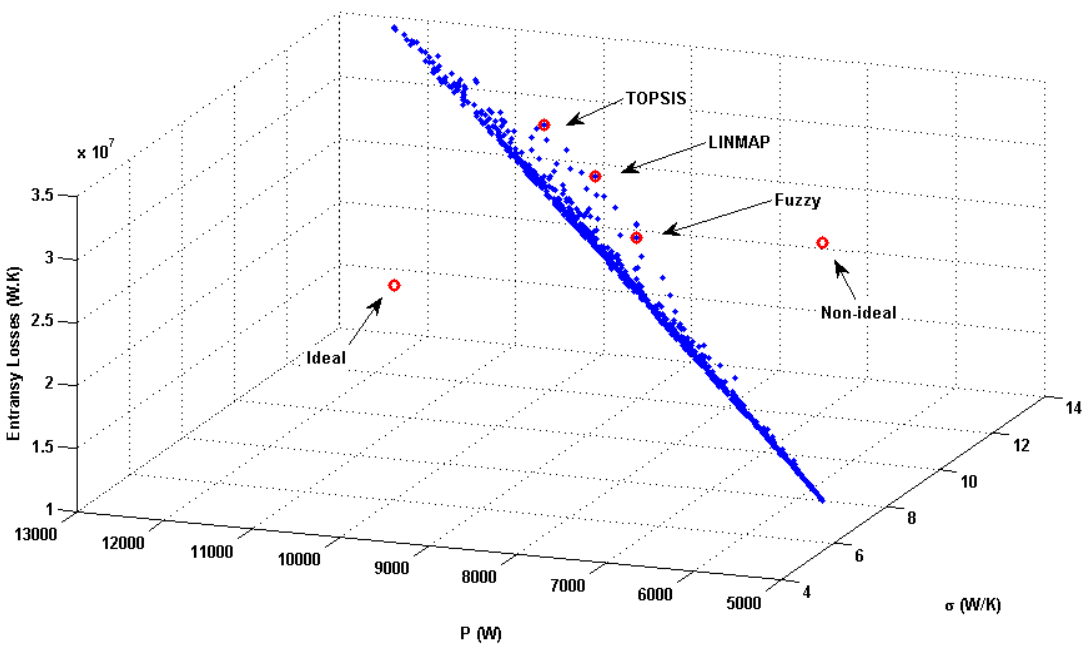


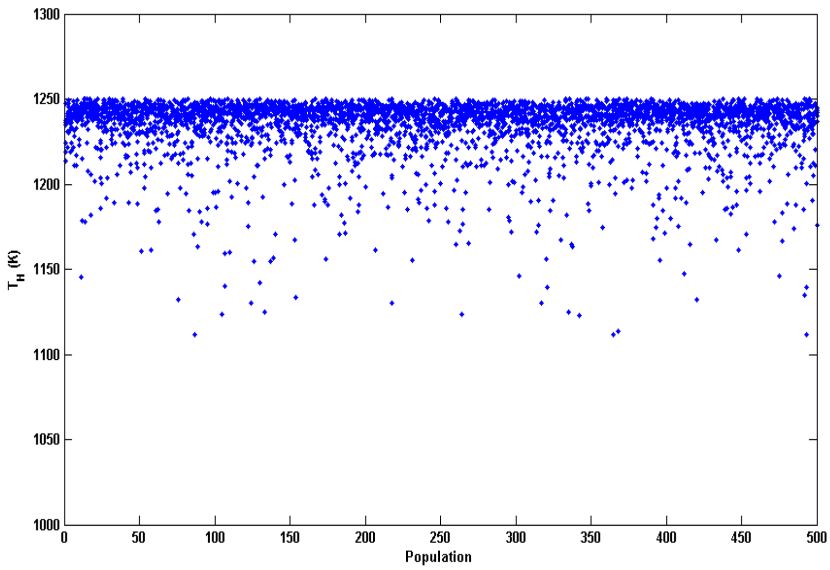
Figure.5. Pareto optimal frontier in objectives' space.

The optimum outcomes for objective functions and decision factors by executing aforementioned decision-making techniques are specified in Table 3.

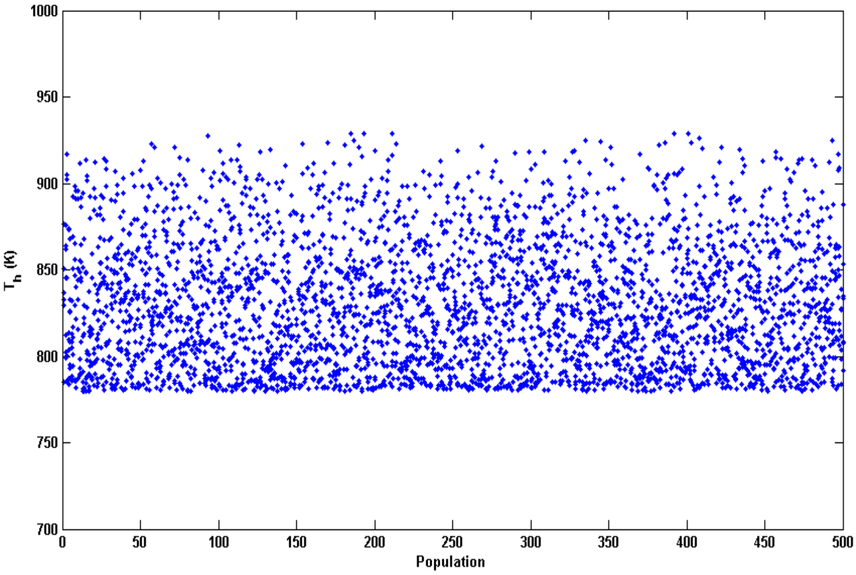
Table.3. Decision making of multi-objective optimal solutions for scenario 2

	Decision variables		*Objectives*		
Optimal solution	T_H *(K)*	T_h *(K)*	σ *(W/K)*	*P (W)*	$\dot{G}_{loss}$ *(W.K)*
Fuzzy	*1163.26*	*811.6594*	*11.45249*	*8874.768*	*23678473*
LINMAP	*1149.931*	*827.5145*	*12.89053*	*9764.618*	*25866585*
TOPSIS	*1163.245*	*850.9843*	*13.65205*	*10578.99*	*28225217*

Figures 6a to 6b demonstrate the scattered distribution of the design variables. These plots can provide better vision of variation of the design variables from the Pareto frontier.



(a)



(b)

Figure.6. (a)-(b) Scatter distribution of Decision variables with population in Pareto frontier for Scenario 2.

Magnitudes of the mean and maximum relative deviations for objective functions are demonstrated in Table 4. The aforementioned error investigation is performed for three aforementioned decision-making techniques.

Table.4. Decision making of multi-objective optimal solutions for scenario 2.

Decision Making Method	*Fuzzy*			*LINMAP*			*TOPSIS*		
Objectives	σ	P	$\dot{G}_{loss}$	σ	P	$\dot{G}_{loss}$	σ	P	$\dot{G}_{loss}$
Max Error %	*10.8*	*3.4*	*2.3*	*6.7*	*4.9*	*5.9*	*5.6*	*11.9*	*13.8*
Average Error %	*5.0*	*1.6*	*1.5*	*3.5*	*3.1*	*4.2*	*3.1*	*6.1*	*7.7*

5. Conclusion

Throughout the present work, to determine thermal efficiency, output power, entropy generation's rate of the system entransy losses rate and Solar Dish-Stirling engine, finite-time thermodynamics is carried out. Variables such as conductive heat transfer mechanism at source of heat, sink of heat throughout the engine and dish collector performance are included through our study. In the first scenario, the thermal efficiency, output power and entransy losses rate of the engine were involved in parallel for optimization process. Also, in the second scenario the output power and entransy losses rate of the engine are maximized also, entropy generation's rate is minimized as objective functions in this analysis to specify the optimal magnitudes of design variables for the system.

In both cases, following parameters have been picked up as decision factors: the heat source's temperature (T_H) and the working fluid's temperature throughout the isothermal process at high temperature (T_h). Optimum frontier of Pareto has been specified on the basis of the Multi objective optimization that evolved by implementing NSGA-II approach. Finally, an ultimate optimum solution has been chosen with the aim of effective decision making methods from outcomes of the frontier of Pareto.

Conflicts of Interest

The authors declare no conflict of interest.

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