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TECHNICAL NOTE

Multi-objective Optimization of Stirling Heat Engine Using Gray Wolf Optimization Algorithm

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ABSTRACT

The use of meta-heuristic optimization methods have become quite generic in the past two decades. This paper provides a theoretical investigation to find optimum design parameters of the Stirling heat engines using a recently presented nature-inspired method namely the gray wolf optimization (GWO). This algorithm is utilized for the maximization of the output power/thermal efficiency as well as minimization of the pressure loss. The linear programming technique is employed for analyzing the multi-objective problem and the result is compared with the three individually computed costs of the aforementioned cost functions. The results show that the new meta-heuristic algorithm (i.e. GWO) yields acceptable results in quality compared to the other presented methods such as TOPSIS and Bellman-Zadeh.

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NOMENCLATURE

n_r	Engines rotation speed	N_R	Number of gauzes of the matrix
s	Stroke	D_c	Piston diameter
p_m	Mean effective pressure	D_R	Regenerator diameter
T_H	Heat source temperature	L	Regenerator's length
T_L	Heat sink temperature	Δp_{throut}	The pressure drop due to the internal friction produced by the regenerator
ΔT_L	The temperature difference between the working fluid and the heat source	Δp_f	The pressure drop due to the mechanical resistance of engine parts
ΔT_H	The temperature difference between the working fluid and the heat sink	Δp_w	The pressure drop due to the piston speed
R	Gas constant	Δp_i	Total pressure loss
τ	Ratio of the extreme temperatures	ρ_{st}	Density
γ	Specific heat ratio	λ	Ratio of volume during the regenerative processes (compression ratio)
μ'	Defined parameter in the text	Q_h	The heat transfer between the working fluid and the heat source
m_g	Mass of the gas	ΔQ_R	The heat loss through the two regenerators
f	Coefficient related to the friction contribution	Q_H	The total released heat from the heat source
X	Vector of decision variables	$\dot{Q}_H$	Heat transfer rate
X_1	Optimistic evaluations related to regeneration losses	C_{vg}	Specific volumetric heat of the gas
X_2	Pessimistic evaluations related to regeneration losses	η	Efficiency

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y	Second adjusting coefficient	η_c	Carnot efficiency
M	Defined parameter in the text	$\eta_{II,irr}$	Second law irreversible efficiency
m_R	Defined parameter in the text	$\eta_{II,irr(X)}$	Deficient regenerating
d	Wire diameter	$\eta_{II,irr(\Delta p)}$	The effect of mechanical friction, piston speed and pressure drop in regenerator
b	Coefficient value between 0 and 2	η'	Defined parameter in the text
B	Defined parameter in the text	h	Heat transfer coefficient
A_R	Regenerator area	v	Viscosity of the working gas
C_p	Specific pressure heat	Pr	Prandtl number

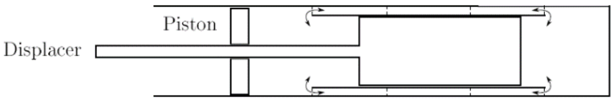
1. INTRODUCTION

Due to the dramatic consumption of fossil fuels, significant attention is devoted to the renewable energy and energy-efficient conversion systems. The researchers have found that the world needs a clean energy in order to break the dependency to fossil fuels. Accordingly, the Stirling engines are invented as one of the most promising sustainable energy technologies in recent years [1]. The Stirling engines are external combustion engines that convert heat into mechanical energy by means of the expansion and contraction of a contained working fluid, usually a gas. The first Stirling engine was invented in 1816 by Robert Stirling [2].

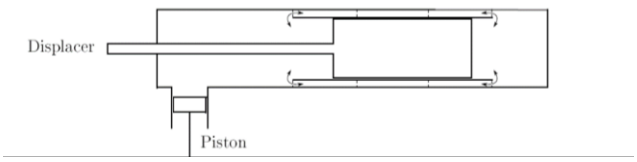
The Stirling engines can be classified into three categories namely alpha, beta and gamma configurations. The alpha type consists of two separate cylinders, each containing its own power piston. This configuration is a conventional design as demonstrated in Figure 1. This structure requires more seals because it has two pistons instead of just a single one. With the additional seals, there is more chance of leakage losses which can degrade engine performance [3-5]. The beta configuration invented by Robert Stirling, has been widely employed ever since. The beta type have a power piston and a displacer in the same cylinder where the compression space of the engine is placed between the top side of the power piston and the bottom side of the displacer [6-8]. The beta configuration of the Stirling engine is shown in Figure 1. The gamma type Stirling engines are similar to the beta types, differing only in that the power piston and the displacer piston are placed in separate chambers (Figure 1**).** Furthermore, there are two compression spaces in both power and displacer cylinders [9-11].

So far, several mathematical models have been provided for the analysis of the Stirling engine behavior. In recent years, researchers attempted to propose methods in order to optimize performance of the Stirling engines. Accordingly, they applied the Meta-heuristic optimization techniques to obtain the design parameters of Stirling engine in order to optimize the performance of these engines. Meta-heuristic optimization techniques have become very popular over the last two decades. Kraitong and Mahkamov [12] studied the optimal design parameters of a desired Stirling engine using genetic algorithm (GA). The governing thermodynamic equations of the desired Stirling engine were first determined and then, four engine parameters including bores and strokes of the power and displacer pistons were extracted using a GA. Ahmadi et al. [13] applied NSGA-II technique for optimization of desired Stirling engine. Maximization of output power, overall thermal efficiency, and minimization of the pressure loss were intended as objective functions in his study.

Alpha configuration



Beta configuration



Gamma configuration

Figure 1. Stirling engine configurations. (a) Alpha configuration, (b) Beta configuration, (c) Gamma configuration

Ahmadi et al. [14] studied the optimal output power of a reversible Stirling cycle including a perfect regeneration. Genetic algorithm (GA) was employed for the optimization of this reversible desired Stirling engine. Ahmadi et al. [15] used NSGA-II algorithm for dimensionless thermo-economic optimization of solar dish-Stirling engine. Later, Ahmadi et al. [16] proposed the NSGA-II algorithm for optimization of solar dish-Stirling engine.

Based on the outlined literature, to the best of our knowledge, only a few advanced optimization algorithms like GA and NSAGII have been employed by the researchers for the optimization of Stirling engines. But, these techniques require tuning of several parameters. In other words, the proper tuning of the specific parameters of the algorithms is an essential issue which affects the performance of the optimization procedure. The improper tuning of algorithms' parameters either increases the computational endeavor or yields the local optimal solution [17]. Furthermore, the specific parameters of an algorithm, such as population size and the number of iterations are to be intended. The burden on the designer will be reduced if there is no need to tune at least some of the parameters needed by the algorithm. Thus, to overcome the problem of tuning the algorithm parameters, a recently accomplished parameter-less algorithm known as Grey Wolf Optimizer (GWO) algorithm [17] is employed in the present research for the multi-objective optimization of desired Stirling engine. However, there is a question here: why GWO is applied to obtain design parameters of desired Stirling engines? The answer to this question can be summarized into three main factors: this method is simple, flexible and local optima avoidance [17].

In this research, maximization of output power, overall thermal efficiency and minimization of the pressure loss are addressed. Accordingly, an attempt is made to see if there is any improvement possible in the design of Stirling engines by applying an advanced optimization algorithm known as GWO technique. The reason for selection of the GWO algorithm is that it is robust, simple, flexible, parameter-less and gives optimal solutions with less number of function evaluations and less computational endeavor. The GWO technique is employed in the present research for simultaneously optimizing the three objectives considered by Ahmadi et al. [13] for the design of desired Stirling engines.

2. GENERAL PRINCIPLES

A Stirling engine is a closed-cycle regenerative heat engine that operates by cyclic compression and expansion of the working fluid at different temperatures, such that there is a net conversion of heat energy to mechanical work. A great deal of inventions based on the very first proposed Stirling engine [18], were presented in variable shapes and sizes.

2. 1. Stirling Cycle

There are four main thermal processes in the Stirling cycles as illustrated in Figure 2. In this figure, both the *p*-*V* and *T*-*S* diagrams are demonstrated. The thermal efficiency of the Stirling engine is equal to the Carnot cycle utilizing an ideal regenerator. Heat transfer from the working fluid to the external sink at constant temperature T_C occurs at process 1-2 which is an isothermal compression process. By pushing the working fluid to the cold area of the cylinder, the power piston changes its position from the bottom dead center (BDC) to the top dead center (TDC), producing work equal to the area under process 1-2. Another main features of the Stirling cycle is the heat transfer from the regenerator to the working fluid in a constant volume heating process 2-3. Pushing the working fluid to the regenerator is the result of shifting the displacer from the TDC to the BDC. This causes an increase in temperature of the working fluid while keeping the volume at a constant value. In the next process, the heat is added to the working fluid at high temperature from an external source. In this process, the working fluid is expanded achieving the pressure at state 4 while the temperature is held at a constant value. The work exerted by the working fluid can be found by computing the area under process 3-4. At the final stage, the power piston travels from BDC to TDC resulting in pressure and temperature drops by moving throughout the regenerator. The heat is then transferred to the regenerator in the process 4-1 and the cycle will continue to the stage 1-2 [19-21].

2. 2. Mathematical Model of the Stirling Heat Engine

2. 2. 1. Pressure Evaluation

Due to the incomplete regeneration processes, additional external heat is required in order to have an ideal Stirling cycle. Moreover, an equivalent heat exists due to the incomplete heat rejection of regenerator to the working fluid.

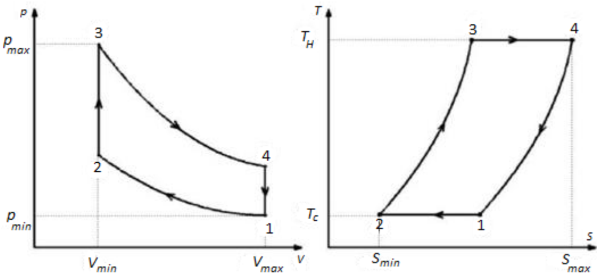


Figure 2. Four main processes of every Stirling cycles

These two irreversibilities plus the working fluid friction passing through the regenerator cause the pressure loss in the thermodynamic cycle. The pressure loss is mathematically modeled here as previously presented by Ahmadi et al. [13]. Thus, one can define the pressure loss terms introduced in literatures [22-25] as:

$$\sum \Delta P_i = \Delta P_{throut} + \Delta P_f + \Delta P_w \tag{1}$$

The terms ΔP_{throut}, ΔP_f and ΔP_w are defined as the pressure drops due to the internal friction produced by the regenerator, mechanical resistance of engine parts and piston speed, respectively which are individually defined as:

$$\Delta P_{throut} = \frac{15}{\gamma}\left[\frac{p_m}{2R(\tau+1)(T_L+\Delta T_L)}.\left(\frac{(s.n_r)^2}{900}\right)\right].N.\left(\frac{{D_c}^2}{N_R {D_R}^2}\right)^2 \tag{2}$$

$$\Delta P_f = (0.94 + 0.0015 s n_r).\frac{10^5}{3\mu'}.\left(1-\frac{1}{\lambda}\right) \; where \; \mu' = 1-\frac{1}{3\lambda} \tag{3}$$

$$\Delta P_w = \left(\frac{s n_r}{60}\right).\frac{4p_m}{(1+\lambda).(1+\tau)}.\left(\frac{\lambda ln\lambda}{\lambda-1}\right).\sqrt{\frac{\gamma}{R}}.\left(\frac{1}{\sqrt{T_L+\Delta T_L}}\right) \times \left[1+\sqrt{\frac{T_H-\Delta T_H}{T_L+\Delta T_L}}\right] \tag{4}$$

2. 2. 2. Output Power and Thermal Efficiency Evaluation

The heat loss through the two regenerators (ΔQ_R) is presented as:

$$\Delta Q_R = m_g C_{vg} X(T_H - \Delta T_H - T_L - \Delta T_L) \tag{5}$$

The heat transfer between the working fluid and the heat source can be calculated as:

$$Q_h = m_g\left(1-\Delta p_w.\frac{(\lambda+1)(\tau+1)}{4p_m}\right) - \frac{b\Delta p_{throut}}{2p_m} - \frac{f\Delta p_f}{p_m}) \times R(T_H - \Delta T_H) ln\lambda \tag{6}$$

Thus, one can obtain the total released heat from the heat source in the following way:

$$Q_H = Q_h + \Delta Q_R \tag{7}$$

The net heat flux ($\dot{Q}_H$) can then be determined by multiplying Equation (7) with the term $\frac{n_r}{60}$. The output power can then be easily computed as:

$$power = \eta \dot{Q}_H = \eta_c . \eta_{II,irr} . \dot{Q}_H \tag{8}$$

where

$$\eta_c = \left(1 - \frac{T_L+\Delta T_L}{T_H-\Delta T_H}\right) \tag{9}$$

$$\eta_{II,irr} = \eta_{II,irr(X)} . \eta_{II,irr(\Delta p)} \tag{10}$$

And the terms η_c and $\eta_{II,irr}$ are the Carnot efficiency and the second law efficiency, respectively. It is worth noting that the second law efficiency is calculated by multiplying the two parts including the deficient regenerating ($\eta_{II,irr(X)}$) and mechanical friction, piston speed and pressure drop in regenerator ($\eta_{II,irr(\Delta p)}$), respectively. More details about the efficiency terms can be found below.

The term $\eta_{II,irr(\Delta p)}$ due to the mechanical friction, pressure drop in the regenerator and the speed of piston is calculated as:

$$\eta_{II,irr(\Delta p)} = 1 - \frac{3\mu' . \sum \frac{\Delta p_i}{p_i}}{\eta' . \left(\frac{T_H-\Delta T_H}{T_L+\Delta T_L}\right) . ln\lambda} \tag{11}$$

where:

$$\eta' = \eta_{II,irr(X)} . \eta_c \tag{12}$$

$$p_1 = \frac{4p_m}{1+\lambda}.(1+\tau) \tag{13}$$

As can be seen in these equations, the term $\eta_{II,irr(\Delta p)}$, is related to the deficient regenerating term that can be evaluated as:

$$\eta_{II,irr(X)} = \frac{1}{1+\left(\frac{X}{(\gamma-1)ln\lambda}\right).\eta_c} \tag{14}$$

where:

$$X = yX_1 + (1-y)X_2 \tag{15}$$

The parameters X_1 and X_2 are the optimistic and pessimistic evaluations related to regeneration losses and y is the second regulating factor which is assigned as $y = 0.72$ for the better adaption of the experimental and analytical conclusions [22-25]. One can find calculation of the aforementioned parameters in details as follows:

$$X_1 = \frac{1+2M+e^{-B}}{2(1+M)} \tag{16}$$

$$X_2 = \frac{M+e^{-B}}{1+M} \tag{17}$$

where:

$$M = \frac{m_g C_{vg}}{m_R C_R} \tag{18}$$

$$B = (1+M).\frac{hA_R}{m_R C_R}.\frac{30}{n_r} \tag{19}$$

$$m_R = \frac{\pi^2 D_R^2 L d \rho_{st}}{16(b+d)} \tag{20}$$

$$h = \frac{0.295.\left(\frac{4p_m}{RT_L}\right).\left(s.\frac{n_r}{30}\right)^{0.424} C_p v^{0.576}}{(1+\tau).\left(1-\frac{\pi}{4\left(\frac{b}{a}+1\right)}\right).D_R^{0.576}.Pr^{0.667}} \tag{21}$$

$$A_R = \frac{\pi^2 D_R^2 L}{4(b+d)} \tag{22}$$

As stated earlier, this paper aims to maximize both the output power and thermal efficiency and minimize the pressure loss of the Stirling engine. Thus, three cost functions are to be optimized. The parameters with their corresponding ranges are defined in Table 1. The ranges of the parameters are selected according to the restriction of the available materials. It is worth noting that these ranges are chosen close to the values selected by Ahmadi et al. [13], thus making the current work fairly comparable.

2. 2. 3. Optimization Method In the past two decades, the use of meta-heuristic optimization methods has become quite generic. In this study, an interesting method inspired by the nature living behavior of gray wolf packs is utilized, which is called the gray wolf optimizer (GWO). This algorithm is based on the employment of the leadership hierarchy of the gray wolfs, including four groups naming as alphas, betas, deltas and omegas in the order of obedience. The leaders could be male or female called the alphas. Alphas are mostly responsible for making decisions about hunting, sleeping, time to wake and etc. The decisions received by alphas are then dictated to the wolf pack. It is worth noting that the alphas are not necessarily the strongest in the pack, indeed they are best in terms of management. The second level in the hierarchy is called the betas. They help the alphas in the decision making and they are the best candidate in case the alphas die. Plus, they can command the lower level in the hierarchy group. Followed by the betas are deltas and omegas with lower ranking in the management class.

Three major steps almost always occur in every group hunting of the gray wolfs which is converted to mathematical model stated as chasing and approaching the prey, encircling the prey and finally the attacking phase. The structure of the GWO method of the Stirling heat engine is represented in Figure 3.

The GWO algorithm requires several input parameters analogous to the population based algorithms proposed to date. Accordingly, the population size, the numbers of iteration plus the inherent GWO parameters A and D, which are declared at the Table 2.

The parameters r_1 and r_2 are random vectors in the ranges of [0, 1].

TABLE 1. The parameters employed with their corresponding ranges

Individuals	Range	Range	Individuals
p_m (MPa)	[.69,6.89]	[0.06,0.1]	S (m)
T_L (K)	[288,360]	[1200,3000	n_r (Rpm)
ΔT_L (K)	[5,25]	[800,1300]	T_H (K)
D_c (m)	[0.05,0.14]	[64.2,237.6	ΔT_H (K)
D_R (m)	[0.02,0.06]	[0.006,0.00	L
N_R	[250,400]		

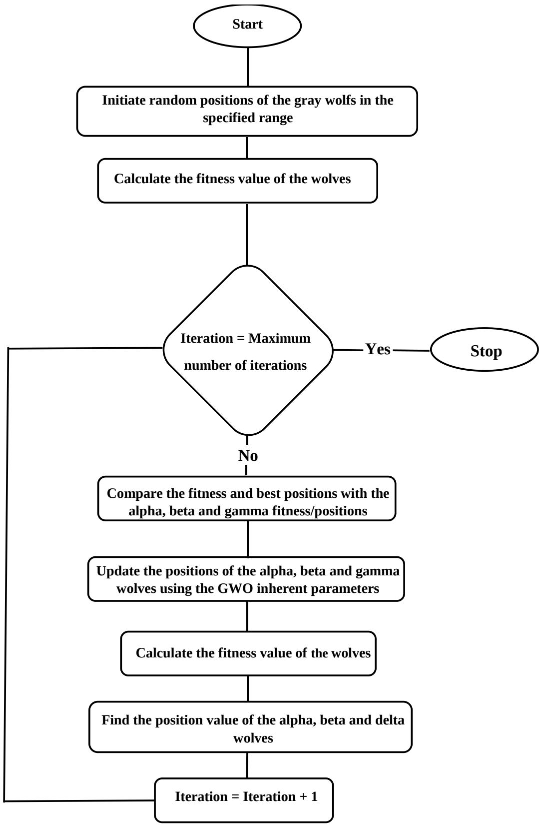


Figure 3. The Structure of the GWO algorithm

TABLE 2. Values of GWO parameters

Population size	50
Numbers of iteration	2000
A	$2a.r_1$
D	$2r_2$

It is worth noting that the improper selection of the population size and numbers of iteration would result the non-scientific values of the fitness function because of trapping the final values in the local answers not the global one. Thus, the trial and error process is conducted to achieve the best selection of the population size and iteration number comparing with the results of Ahmadi et al. [13]. The position updating of the gray wolf packs mentioned above is illustrated in Figure 4. The prey position or simply the global answer of the problem is estimated by the positions of the three groups of alpha, beta and delta of the gray wolfs.

In order to find the maximum values of power and efficiency and minimum values of the pressure loss simultaneously, linear programmable decision-making technique is applied and the resulting value is compared with the multi-objective function employed by other authors.

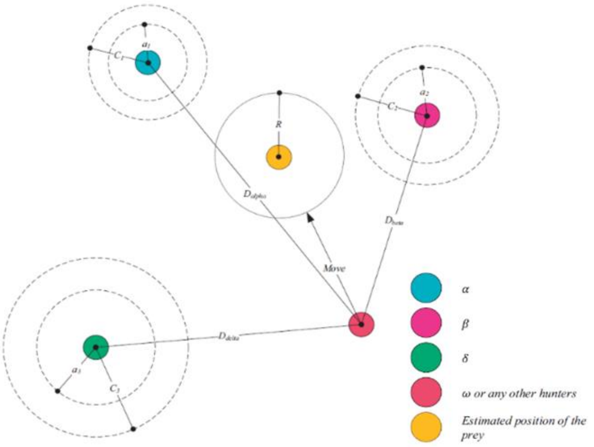


Figure 4. The Gray Wolf Optimizer Position updating scheme [17]

To do this, several weight vectors are chosen in a way that their sum equals to 1. Choosing the values of weight vectors strongly depend on the designer's idea about which of the objective functions are in a great matter. For convenience, identical importance of the cost functions are assumed, resulting $w_1 = w_2 = w_3 = 1/3$.

The extreme and minima values of $X_{1,max}$, $X_{2,max}$ and $X_{3,min}$ are the maximum values of power, Stirling engine efficiency and the minimum value of pressure loss, respectively in which they are obtained individually. One can compute the resulting parameters of the three objective functions by solving them simultaneously as below:

$$X = w_1 \times \frac{X_1}{X_{1,max}} + w_2 \times \frac{X_2}{X_{2,max}} - w_3 \times \frac{X_3}{X_{3,min}} \tag{23}$$

3. RESULTS

As stated earlier, the parameters utilized in this paper are based on the extracted values from Ahmadi et al. [13]. Besides, the ranges of parameters defined in the previous section and several constant values are also defined that can be observed in Table 3 [13].

Three different popular decision making procedure including the Bellman-Zadeh, TOPSIS and LINMAP were employed by Ahmadi et al. [13], in order to obtain the best solution from three dependent objective functions using NSGA-II algorithm. It is worth noting that the first procedure mentioned above executes the fuzzy non-dimensionalization while the other two procedures implement the Euclidian non-dimensionalization. The GWO algorithm is now implemented acquiring the best solution of the three objective functions naming the output power, Stirling engine efficiency and the power loss.

TABLE 3. Constant variables utilized in reference [13]

Parameter	Value	Parameter	Value
N	8	C_{pg}	5193 $(Jkg^{-1}K^{-1})$
C_v	3115.6 $(Jkg^{-1}K^{-1})$	b	6.88×10^{-5}
ρ_{st}	8030 (kgm^{-3})	γ	1.667
λ	1.2	m_g	0.001135 (kg)
d	4×10^{-5} (m)	C_R	502.48 $(Jkg^{-1}K^{-1})$
v	3.249×10^{-5} (m^2/s)	f	0.556
P_r	0.71		

All of the aforementioned equations plus the defined parameters have been coded into the MATLAB software. The individually obtained extreme and minima values of power, Stirling engine efficiency and the minimum value of pressure loss are reported in Table 4. In order to have a better understanding of solving the three objective functions simultaneously, their corresponding results are also presented in the same table.

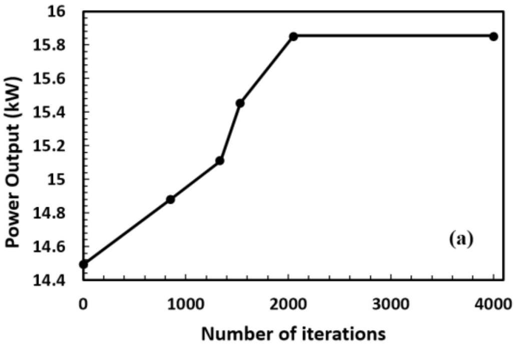
The convergence curve of the individual and multi-objective functions are illustrated in the Figures 5 and 6, respectively. It is obvious that the output results converge to the value reported in Table 4 when the iteration number reaches 4000.

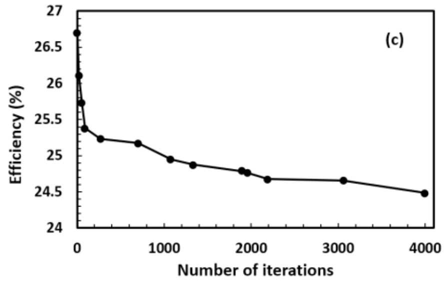
More details about the 11 individual parameters discussed earlier are presented in Table 5 comparing the results from this paper with the outcomes of the three techniques naming TOPSIS, LINMAP and the Bellman-Zadeh.

It is worth noting that the results gathered from GWO approach was obtained from computing the mean values of the 10 times repetition of the problem. It is evident from Table 5 that although the terminal results from the multi-objective functions are very close, but the individual values of the parameters differs as will be discussed shortly. The values of the mean effective pressure, stoke, regenerator's length and temperature of the heat sink are quite the same.

TABLE 4. Optimum results obtained by the use of GWO technique

Cost Function	Individually calculated cost function	Optimum value of the cost function attempted simultaneously
Minimization of pressure loss	11.57 kPa	17.5 kPa
Maximization of Stirling engine efficiency	24.55 %	14.2 %
Maximization of power output	16.49 kW	6.06 kW





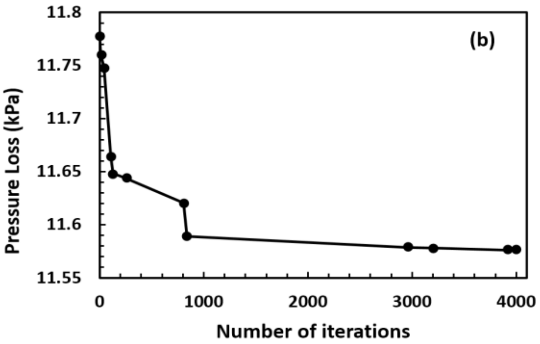


Figure. 5. The convergence curve for the analysis of the three objective functions individually using the GWO algorithm. a) Power output b) Pressure loss c) Efficiency

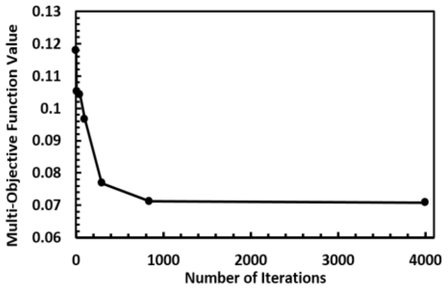


Figure. 6. The convergence curve of the multi-objective function versus the number of iterations

TABLE 5. Comparison of the optimization results from various methods including GWO [13]

	p_m (kPa)	T_L (K)	ΔT_L (K)	D_c (mm)	D_R (mm)	N_R	s (mm)	n_r (rpm)	T_H (K)	ΔT_H (K)	L (mm)	Power (kW)	η (%)	P_{loss} (kPa)
LINMAP	2550.3	298.4	11.8	101.6	59.5	339	60.5	2120	989.6	74.4	70	6.076	14.56	19.69
TOPSIS	2550.3	298.4	11.8	101.6	59.5	339	60.5	2120	989.6	74.4	70	6.076	14.56	19.69
Bellman-Zadeh	2437	299.5	12.1	106.1	58.9	338	60.5	2056	989.3	76.4	76.4	5.84	14.51	18.82
GWO	2514.19	298.4	14.04	99.12	29.39	317.28	60.0	1200	1070.2	220.73	67.6	6.06	14.2	17.5

The value of the heat sink's temperature, temperature difference between heat source and working fluid and temperature difference between heat sink and working fluid are estimated higher than those reported by other authors while the remaining parameters are evaluated lower values than the ones referenced.

4. CONCLUSION

Due to the compulsion of the need of humanity to energy, numerous engines have been invented producing power. Stirling engines are a reciprocating, external combustion engines that convert heat into mechanical energy by means of the expansion and contraction of a contained working fluid, usually a gas.

The development of the three output power, engines efficiency and pressure loss functions are discussed in this paper. In order to capture the optimized values of the three aforementioned objective functions individually, the new meta-heuristic algorithm inspired by the nature of gray wolf's living is utilized naming as the Gray Wolf Optimizer (GWO) technique. This simple algorithm is a population based algorithm requiring few initial parameters for use.

Solving multi-objective function on the other hand, has become a very important field of research in the analysis of engineering problems. This paper employs the linear decision-making method for multi-dimensional analysis (LINMAP). The optimized solutions for both the individual and the three cost functions altogether, displays the ability of using the GWO as a powerful algorithm solving single and multi-objective functions in engineering problems.

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Multi-objective Optimization of Stirling Heat Engine Using Gray Wolf Optimization Algorithm

TECHNICAL NOTE

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چکیده

استفاده از روش‌های بهینه‌سازی فراابتکاری در دو دهه گذشته بسیار فراگیر شده است. در این مقاله یک تحقیق نظری برای پیدا کردن پارامترهای طراحی بهینه موتورهای حرارتی استرلینگ، با استفاده از روشی الهام گرفته از طبیعت که به تازگی ارائه شده است، یعنی بهینه‌سازی گرگ خاکستری (GWO)، صورت گرفته است. این الگوریتم برای به حداکثر رساندن قدرت خروجی، بازده حرارتی و همچنین به حداقل رساندن افت فشار استفاده شده است. در این مقاله، تکنیک خطی‌سازی برای تحلیل مساله چندهدفه به کار گرفته شده است. به عبارت دیگر، به کمک سه تابع هدف به صورت جداگانه و به کمک تکنیک خطی‌سازی، مساله حاوی سه تابع هدف به صورت هم‌زمان حل شده است . نتایج نشان می‌دهد که الگوریتم گرگ‌های خاکستری استفاده شده در این مقاله، خروجی قابل قبولی از لحاظ کیفیت در مقایسه به سایر روش‌های مطرح همچون TOPSIS و Bellman-Zadeh دارد.

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