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Design of Experiment Technique for Improving the Performance of Stirling Engine

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Abstract - *The aim of this design is to improve the performance of Stirling engine. Stirling engine performance is mainly identified by its efficiency. The efficiency of Stirling engine is affected by many parameters such as total swept volume, temperature of the hot source, the dead volume ratio, the temperature ratio, and phase angle, area of the displacer section, exchanger piston conductivity, and regenerator effectiveness. Among all these parameters, the ones which critically influence the efficiency of Stirling engine is identified and is optimized with the help of design of experiment technique. The obtained results show that the optimal values of identified parameters increases the efficiency of engine by 2% comparing to other optimal values. A new design is proposed relating to the obtained optimal values and a prototype is fabricated.*

Key Words: Stirling engine, Performance, Parameters, Design of experiment, Taguchi

1. INTRODUCTION

Stirling engine is a simple external combustion engine which uses the heat to produce work. A simple Stirling engine consists of a heat source, displacer cylinder, power cylinder, displacer, power piston, transfer tubes and a flywheel with connecting rods connected to displacer and the power piston. The working fluid can be air, hydrogen or helium. The concept is that the thermal heat from heat source is used to heat air in the displacer cylinder. Due to thermal expansion the pressure of air increases. This increasing pressure of air pushes the displacer forward and gets transferred to power cylinder through the transfer tubes and in turn the power piston in the power cylinder is also pushed forward. In the compression area of the cylinders the pressure of air decreases, gets compressed and is again retarded back to the expansion area of the cylinders. This concept makes the displacer and power piston to move in and out of the engine and a mechanical motion is produced. This mechanical motion is used to produce the desired work. This is how a simple Stirling engine works.

An ideal Stirling cycle consists of four thermodynamic processes: Isothermal compression process, constant volume process with heat addition, isothermal expansion process and constant volume process with heat rejection. Based on different mechanical configurations Stirling engine is classified into three types [1]. They are alpha type Stirling engine, beta type Stirling engine, and gamma type Stirling engine. Alpha type Stirling engine consists of two power pistons whereas beta and gamma type Stirling engines consists of one displacer and one power piston.

1.1 Study of Various Parameters of Stirling Engine

The performance of the Stirling engine depends on many thermal and geometrical parameters. These parameters differs by their influence on the efficiency of Stirling engine, therefore a detailed study is carried out to identify the parameters which have critical results over the efficiency of the Stirling engine. According to Cheng and Yang [2] an optimal combination of phase angle and swept volume ratio increases the shaft work of the engine. Effects of the dead volume ratio, temperature ratio to increase the efficiency of the engine are studied. According to Cheng and Yang [2] the shaft work of the engine increases only when the swept volume ratio is in the region of low temperature ratio. In the swept volume region there lies a critical value. Over this critical value of swept volume ratio the shaft work of the engine begins to vary inversely. On increasing the swept volume ratio the shaft work of the engine increases till the critical value. After this critical value of swept volume ratio the shaft work of the engine decreases. This indicates that an optimal value of swept volume ratio is needed to increase the performance of Stirling engine.

The effect of phase angle result in the variation of the shaft work. Therefore an optimal phase angle is needed for getting the optimal shaft work. The values of the optimal phase angle mentioned [2] are 30° for α-type, 80° for β-type and 100° for γ-type, these optimal values can also be referred to the values according to the results given by Kirkley [3] and Senft [4]. It is stated [2] that the shaft work attains a peak value for the β-type Stirling engine and for γ-type Stirling engine the shaft work is the least. The parameter temperature ratio vary the performance of Stirling engine. The temperature difference between the regions of expansion and compression gets decreased as the temperature ratio is elevated. As the temperature ratio attains a critical value the shaft work of engine suddenly decreases, drops to zero and even gets vanished as it progresses. This critical value of temperature ratio is low. With this low temperature ratio only the γ-type engine is most suitable to produce the shaft work comparing to other types α- and β-type engines [2]. The temperature ratio represents the ratio of the temperature in compression region to the expansion region [2]. Actually the temperature ratio depends on engine speed, regenerator effectiveness, mass of working fluid, and thermal resistance of compression and expansion regions [2], [5].

Dead volume ratio also has some enhancing characteristic over the efficiency of engine. It is seen that when the dead volume ratio increases the output work of the engine also increases [2]. Optimization to find out an optimal value for the dead volume ratio is also to be carried over to improve the performance of Stirling engine. From the above discussion it can be seen that the shaft work of engine gets increased when the temperature ratio and dead volume ratio gets decreased. Similarly the shaft work of the engine get vary depending on the values of phase angle and swept volume ratio. So an optimization for all these parameters is to be done to increase the performance of Stirling engine.

1.2 Identified problems

Stirling engine is an external combustion engine producing work with high efficiency. The efficiency of engine is influenced by many parameters such as clearance volume, swept volume, piston conductivity, piston stroke, phase angle, temperature ratios, mass of working fluid and even more. From the literature survey it is learnt that not every parameter bias the efficiency of engine to a greater extent. So the parameters which have more influence are to be identified. Efficiency of Stirling engine can increase or decrease depending on the values of identified parameters. So the values of these parameters are to be optimised. Optimization is carried out with the help design of experiment technique and the resultant is fabricated as a working prototype.

2. MATERIALS AND METHODOLOGY

Performance of Stirling engine is influenced by many parameters, but not all the parameters have an equal importance. They differ by their influence on the effectiveness of performance on Stirling engine. On studying about the roles of these parameters only four parameters are identified to have major bias on the performance of Stirling engine. Namely the parameters are phase angle (α), swept volume ratio (κ), dead volume ratio (χ), and temperature ratio (τ). The behaviour of Stirling engine is identified by its efficiency. Two standard outcomes are calculated to single out the efficiency of Stirling engine. They are:

- Dimensionless indicated work
- Dimensionless heat input.

These consequences for all the three types of engines are given as:

$$\bar{w} = \frac{2\pi\tau k(1-\tau)\sin\alpha}{a^2+b^2}\left(\frac{\beta-\sqrt{\beta^2-(a^2+b^2)}}{\sqrt{\beta^2-(a^2+b^2)}}\right) \qquad (1)$$

$$\bar{Q}_{in} = \frac{2\pi\tau k\sin\alpha}{a^2+b^2}\left(\frac{\beta-\sqrt{\beta^2-(a^2+b^2)}}{\sqrt{\beta^2-(a^2+b^2)}}\right) \qquad (2)$$

Moreover,

$$a = -(1-\tau)\sin\alpha \qquad (3)$$

$$b = k-(1-\tau)\cos\alpha \qquad (4)$$

$$\beta = \frac{4\tau\chi}{(1+\tau)} + \tau + \sqrt{1-2k\cos\alpha+k^2} \qquad (5)$$

For improving the performance of the Stirling engine, the design of experiment technique is used. In this design of experiment technique, taguchi design analysis method is used [6]. In taguchi design four parameters and three levels design is selected for generating the L9 orthogonal array. The selected four parameters and three levels of each parameter are shown in table I. By this three level taguchi design the L9 orthogonal array was generated using minitab software[7]. The generated L9 orthogonal arrays for identified four parameters are shown in table II.

Table 1
Three level Taguchi design

Parameters	Level 1	Level 2	Level 3
Phase angle	30	31	32
Temperature ratio	0.3	0.4	0.5
Swept volume ratio	0.1	0.2	0.3
Dead volume ratio	1.5	1.6	1.7

Table 2
L9 Taguchi Design Worksheet

Phase angle (α)	Temperature ratio (τ)	Swept volume ratio (k)	Dead volume ratio (χ)
30	0.3	1.5	0.1
30	0.4	1.6	0.2
30	0.5	1.7	0.3
31	0.3	1.6	0.3
31	0.4	1.7	0.1
31	0.5	1.5	0.2
32	0.3	1.7	0.2
32	0.4	1.5	0.3
32	0.5	1.6	0.1

2.1 Design Calculations

After forming the L9 orthogonal array, the efficiency of the Stirling engine was calculated using each combinations of that four parameters by using the equations 1,2,3,4, & 5 [2]. Than the larger is better option is selected for calculating the signal to noise ratio from taguchi design for getting the optimized value. Then from this optimized new four parameters again the efficiency of the striling engine is calculated. The obtained efficiency of this new parameter is high compare to existing design. By this new design parameter values the stirling engine was fabricated.

Table 3
Taguchi Design Work Sheet with Efficiency

Phase angle (α)	**Temperature ratio (τ)**	**Swept volume ratio (k)**	**Dead volume ratio (χ)**	**Efficiency (η)**
30	0.3	1.5	0.1	70.00
30	0.4	1.6	0.2	60.00
30	0.5	1.7	0.3	50.50
31	0.3	1.6	0.3	70.00
31	0.4	1.7	0.1	60.00
31	0.5	1.5	0.2	50.00
32	0.3	1.7	0.2	70.00
32	0.4	1.5	0.3	59.97
32	0.5	1.6	0.1	50.00

2.2 Fabrication of New Design

With the help of optimal values selected from the generated graph a new design for Stirling engine is proposed. The proposed design of Stirling engine consists of two cylinders; one cylinder with a displacer and the other cylinder with a power piston, connecting rods and a flywheel. Sheet metal SS 304 is used to make the two cylinders; displacer cylinder and the power cylinder. Copper tube is used as transfer tubes; to transfer the hot air between displacer cylinder and power cylinder. The displacer and the power piston is made up of SS 304. Simple connecting rods with linkages are used to transfer the reciprocating motion of displacer and power piston to flywheel as rotary motion. Processes such as cutting, drilling, tig welding, brazing and buffing are used to fabricate the new design of Stirling engine. The layout of new design is shown in fig 1.

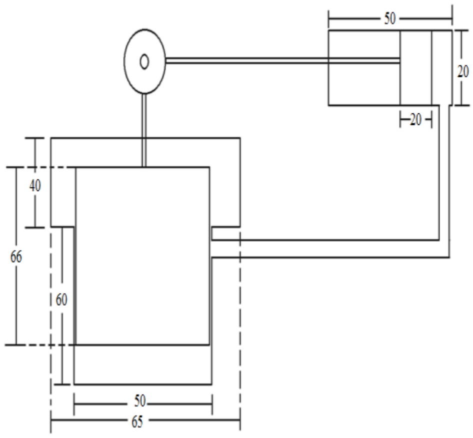

Fig. 1. Layout of new design

2.3 Assembly of Stirling Engine

Fig.2. New design of Stirling Engine

3. RESULTS AND DISCUSSIONS

After simulating the L9 orthogonal array by taguchi design, the optimized new parameter value is selected by generating the graph. The graph was generated by using larger is better option. The graph was plotted against signal to noise ratio vs four design parameters. The graph was shown in fig 3. From this graph the optimized new design parameters are tabulated which is shown in table IV.These values are used for the fabrication of the new model of the Stirling engine. This new design gives the efficiency of 72%, which is more than the existing design [2] efficiency value which is around 70%. The fabricated new design was shown in fig 2.

Table 4
Values of Optimized Parameters

S.No.	Parameters	Optimized
1.	α - Phase angle (°)	32°
2.	τ - Temperature ratio (T_c/T_e)	0.3
3.	χ - Dead volume ratio (V_d/V_e)	1.7
4.	κ - Swept volume ratio (V_{cs}/V_{es})	0.3
5.	η – Resulting Efficiency	72%

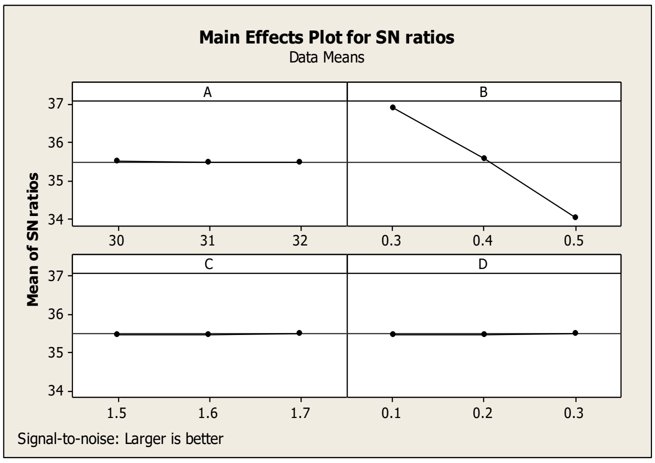

Fig 3. Generated graph

4. CONCLUSION

Thus the parameter value of existing design like phase angle, temperature ratio, swept volume ratio & dead volume ratio was modified with the help of design of experiment technique like taguchi method. This optimized new design gives the high efficiency compare to existing design. The new design gives the 72% efficiency which is 2% high as compare to the existing design. By this modified new design parameters the stirling engine was fabricated.

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