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Application of Taguchi Method for Optimization of Physical Parameters Affecting the Performance of Pulse Detonation Engine

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Abstract: **Pulse detonation Engine technology is a next generation propulsion technology which utilizes detonation of fuel instead of deflagration to produce thrust more efficiently than the conventional internal combustion engines. Pulse detonation engine technology is mechanically simple design, low cost, high thrust to weight ratio and thermodynamically more efficient. Even though the pulse detonation engine technology looks simple but the development and attaining successive detonations and sustaining the detonations is a very difficult phenomenon until the parameters affecting the performance (detonations) are understood and optimized thoroughly. The various parameters affecting the PDE performance are PDE diameter of tube (D), length of tube (L), Schelkin Spiral length (l), Spiral wire diameter (d) and Spiral pitch (p). In this paper Taguchi method of experimentation is used for optimization of physical parameters affecting the performance of pulse detonation engine. A L50 array, Signal to Noise (S/N) ratio and Analysis of Variance are applied to study the performance characteristics of Pulse detonation engine parameters (PDE diameter of tube (D),length of tube (L) ,Schelkin Spiral length (l) ,Spiral wire diameter (d) and Spiral pitch (p) with consideration of output as Thrust. Results obtained by Taguchi method match closely with ANOVA.**

Keywords: Pulse detonation engine, Taguchi method, Schelkin spiral, S/N ratio, ANOVA

NOMENCLATURE

DDT =deflagration to detonation transition
PDE =Pulse detonation Engine
D =PDE tube diameter
L =PDE tube length
l =Schelkin Spiral length
d =Spiral wire diameter
I =Impulse
V =Volume of detonation tube
T =Thrust
E initiation=Initiation energy
C2H2 =Acetylene
O2 =Oxygen
R =Tube mean radius
t =tube wall thickness
ΔP3 =Over pressure
U_{CJ} =Chapman-Jouguet (CJ) velocity
C3 =Speed of sound
K =Kilo
g_o =Standard acceleration due to gravity
ρ =initial mixture mass density
f =cycle repetition frequency
p =Spiral pitch
P_3 =Plateau pressure
Iv =impulse per unit volume
Isp = impulse per unit mass or specific impulse
α =Non dimensional parameter characteristic of constant and decaying part of pressure signal
β = Non dimensional parameter characteristic of constant and decaying part of pressure signal
P_{CJP} = Chapman-Jouguet (CJ) pressure
P_{CJ} = Chapman-Jouguet (CJ) pressure
S/N =Signal to Noise
ANOVA=Analysis of variance

1. INTRODUCTION

A Pulse Detonation Engine (PDE) is a type of propulsion system that uses detonation waves to combust the fuel and oxidizer mixture. The engine is pulsed because the fuel oxidiser mixture must be renewed in the combustion chamber between each detonation wave initiated by an ignition source (1).PDEs are future propulsion systems based on principle of successive detonations to produce significant thrust or power.

The detonation has an advantage over deflagration as the former follows the constant volume combustion process. The idea of PDE is to successfully repeat the detonation combustion in the tube at a faster rate in order to achieve almost constant thrust generation. The constant thrust generation is really important in propulsion applications. The thrust produced during Pulse detonation engine PDE PEC setup is around 280 Kgf or 2746.8 N (2). Pulse detonation Engine (PDE) works on the constant volume combustion process. Constant volume process has higher thermodynamic efficiency and release higher energy compared to constant pressure combustion (3). PDE offers the potential to provide increased performance while simultaneously reducing the engine weight, cost and complexity relative to conventional propulsion systems currently in service (4). Even the design is very simple PDE still produces high power that is significant for the propulsion purposes. The rate of energy release in detonation mode normally in the magnitude of three compared to deflagration combustion (5). The major difficulty with a PDE is starting the detonation, while it is possible to start a detonation directly with a large spark; the amount of energy input is very large and is not practical for an engine. The typical solution is to use a deflagration to detonation transition (DDT) that is ,start a high energy deflagration and have it accelerate down a tube to the point where it becomes fast enough to become a detonation(6).

The objective of this paper is to optimize the physical parameters affecting the performance of Pulse Detonation Engine (PDE) like detonation Tube diameter (D), tube length (L), schelkin spiral length (l), Spiral wire diameter (d) and Spiral pitch (p) to obtain maximum thrust by using Taguchi method of experimentation, based on the S/N analysis and ANOVA.

2. TAGUCHI METHOD: OPTIMIZATION OF PHYSICAL PARAMETERS OF PDE.

Optimization of physical parameters is the key step in the Taguchi method to achieve high quality without increasing cost. This is because optimization of physical parameters can improve quality and optimal physical parameters obtained from Taguchi method are insensitive to the variation of environmental conditions and other noise factors (7). An advantage of Taguchi method is that it emphasizes a mean performance characteristic value close to the target value rather than a value within certain specification limits, thus improving the product quality. Additionally Taguchi's method for experimental design is straight forward and easy to apply to many engineering situations making it a powerful yet simple tool. It can be used to quickly narrow the slope of a research product or to identify problems in a process from data already in existence.

A large number of experiments have to be carried out when the number of parameters to optimize are increases. To overcome this problem Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments. Using an orthogonal array to design the experiment could help designers to study the influence of multiple controllable factors on the average of quality characteristics and variation in the fast and economic way. While using signal to noise (S/N) ratio to analyse the experimental data could help designers of product to easily find out the optimal parametric combinations.

A loss function is then defined to calculate the deviation between the experimental value and the desired value. Taguchi recommends the use of the loss function to measure the deviation of the quality characteristic from the desired value. The value of overall loss function is further transformed into a signal to noise (S/N) ratio. Usually there are three categories of quality characteristics in the analysis Of S/N ratio. i.e "the lower the better "the larger the better and the Nominal the better .The S/N ratio for each level of parameter is computed based on the S/N analysis. Regardless of the category of quality characteristic a larger S/N ratio corresponds to a better quality characteristic Therefore the optimal level of the physical parameter is the level within the highest S/N ratio. Furthermore a statistical analysis of variance (ANOVA) is performed to see which physical parameters are statistically more significant.

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Finally a confirmation experiment is conducted to verify the optimal physical parameters obtained from the parameter design.

3. 3. EXPERIMENTATION PULSE DETONATION ENGINE

Fig.1. Pulse Detonation Engine PEC Setup

A single tube valve less PDE is developed by the research team conducting thesis research. The engine consists of a combustion tube, fuel injector system and ignition system. The engine capable of burning both Acetylene/Oxygen and acetylene/air mixture. A schelkin Spiral is incorporated for deflagration to detonation transition (DDT). A thrust stand is incorporated to measure axial thrust data and new data acquisition software created for high speed data capture. The details of the Pulse detonation engine can be easily understood by using simplified schematic layout of PDE system.

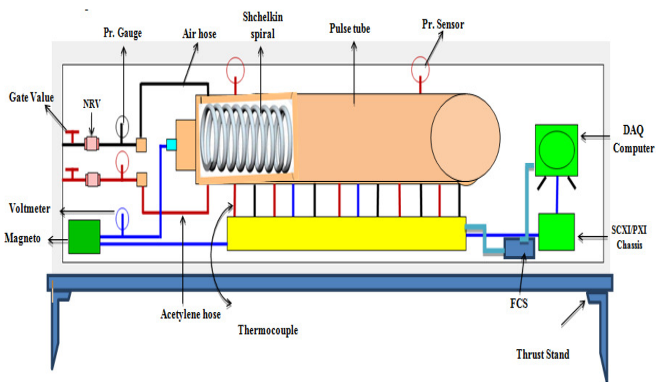

Fig.2. Simplified schematic layout of PDE system.

4. SELECTION OF PARAMETERS FOR OPTIMIZATION

In this section the physical parameters affecting the performance of Pulse detonation engine (PDE) like Pulse detonation engine Tube diameter (D), tube length (L),Schelkin spiral .length (l),Spiral wire diameter (d) and

Spiral pitches (p) are selected for optimization and to obtain max thrust as output.

4.1 SELECTION OF ORTHOGONAL ARRAY

In this present study five level parameters i.e. Tube diameter (D), tube length (L), Schelkin spiral length (l), Spiral wire diameter (d) and spiral pitch (p) are considered. Knowing the number of parameters and the number of levels the proper orthogonal array can be selected. Using the array selector table shown below the name of appropriate array can be found by looking at the column and row corresponding to the number of parameters and number of levels. The arrays were created using an algorithm Taguchi developed, and allows for each variable and setting to be tested equally. In this study we have selected seven parameters (five active parameters and two optional parameters frequency, mass flow rate) and five levels it can be seen the proper array is L_{50}.

Number of Levels	Number of Parameters (P)																													
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2	L4	L4	L8	L8	L8	L8	L12	L12	L12	L12	L16	L16	L16	L16	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32
3	L9	L9	L9	L18	L18	L18	L18	L27	L27	L27	L27	L27	L36	L36	L36	L36	L36	L36	L36	L36	L36	L36								
4	L'16	L'16	L'16	L'16	L'32	L'32	L'32	L'32	L'32																					
5	L25	L25	L25	L25	L25	L50	L50	L50	L50	L50	L50																			

Table: Array Selector

Taguchi's L50 array

Experiment	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3	3	3	3	3
4	1	1	4	4	4	4	4	4	4	4	4	4
5	1	1	5	5	5	5	5	5	5	5	5	5
6	1	2	1	2	3	4	5	1	2	3	4	5
7	1	2	2	3	4	5	1	2	3	4	5	1
8	1	2	3	4	5	1	2	3	4	5	1	2
9	1	2	4	5	1	2	3	4	5	1	2	3
10	1	2	5	1	2	3	4	5	1	2	3	4
11	1	3	1	3	5	2	4	4	1	3	5	2
12	1	3	2	4	1	3	5	5	2	4	1	3
13	1	3	3	5	2	4	1	1	3	5	2	4
14	1	3	4	1	3	5	2	2	4	1	3	5
15	1	3	5	2	4	1	3	3	5	2	4	1
16	1	4	1	4	2	5	3	5	3	1	4	2
17	1	4	2	5	3	1	4	1	4	2	5	3
18	1	4	3	1	4	2	5	2	5	3	1	4
19	1	4	4	2	5	3	1	3	1	4	2	5
20	1	4	5	3	1	4	2	4	2	5	3	1
21	1	5	1	5	4	3	2	4	3	2	1	5
22	1	5	2	1	5	4	3	5	4	3	2	1
23	1	5	3	2	1	5	4	1	5	4	3	2
24	1	5	4	3	2	1	5	2	1	5	4	3
25	1	5	5	4	3	2	1	3	2	1	5	4
26	2	1	1	1	4	5	4	3	2	5	2	3
27	2	1	2	2	5	1	5	4	3	1	3	4
28	2	1	3	3	1	2	1	5	4	2	4	5
29	2	1	4	4	2	3	2	1	5	3	5	1
30	2	1	5	5	3	4	3	2	1	4	1	2
31	2	2	1	2	1	3	3	2	4	5	5	4
32	2	2	2	3	2	4	4	3	5	1	1	5
33	2	2	3	4	3	5	5	4	1	2	2	1
34	2	2	4	5	4	1	1	5	2	3	3	2
35	2	2	5	1	5	2	2	1	3	4	4	3
36	2	3	1	3	3	1	2	5	5	4	2	4
37	2	3	1	3	3	1	2	5	5	4	2	4
38	2	3	3	5	5	3	4	2	2	1	4	1
39	2	3	4	1	1	4	5	3	3	2	5	2
40	2	3	5	2	2	5	1	4	4	3	1	3
41	2	4	1	4	5	4	1	2	5	2	3	3
42	2	4	2	5	1	5	2	3	1	3	4	4
43	2	4	3	1	2	1	3	4	2	4	5	5
44	2	4	4	2	3	2	4	5	3	5	1	1
45	2	4	5	3	4	3	5	1	4	1	2	3
46	2	5	1	5	2	2	5	3	4	4	3	1
47	2	5	2	1	3	3	1	4	5	5	4	2
48	2	5	3	2	4	4	2	5	1	1	5	3
49	2	5	4	3	5	5	3	1	2	2	1	4
50	2	5	5	4	1	1	4	2	3	3	2	5

Table:Orthogonal array is L50

Generalised L50 array will have 12 parameters and in our experimentation we have only 5 parameters to be optimized so the L 50 orthogonal array as per our experiment will have five parameters and fifty experiments. The five levels of five physical parameters are

Tube diameter (D):	30, 40, 50, 60, 70 mm
Tube length (L):	75,150,190,250,350 cm
Schelkin Spiral length (l):	20, 30,40,50,60 cm
Spiral Wire diameter (d):	4, 6, 8, 10, 12 mm
Spiral Pitch (p):	5, 6,7,8,9 mm

When the number of parameters increases a large number of experiments have to be carried out. Taguchi method of experiments enables us to reduce the number of experiments with the help of special design of orthogonal arrays. In this study we have taken five physical parameters and five levels for which L50 orthogonal array is suitable for experimentation. In this fifty experiments are required to study the entire Pulse Detonation Engine parameters space. The experimental layout of Pulse detonation Engine (PDE) physical parameters using the L50 array is shown in table.

EXPERIMENT	Spiral Pitch P mm	Tube Dia D mm	Tube Length L cm	Spiral length l cm	Wire Dia D mm
1	5	30	75	20	4
2	5	30	150	30	6
3	5	30	190	40	8
4	5	30	250	50	10
5	5	30	350	60	12
6	5	40	75	30	8
7	5	40	150	40	10
8	5	40	190	50	12
9	5	40	250	60	4
10	5	40	350	20	6
11	5	50	75	40	12
12	5	50	150	50	4
13	5	50	190	60	6
14	5	50	250	20	8
15	5	50	350	30	10
16	5	60	75	50	6
17	5	60	150	60	8
18	5	60	190	20	10
19	5	60	250	30	12
20	5	60	350	40	4
21	5	70	75	60	10
22	5	70	150	20	12
23	5	70	190	30	4
24	5	70	250	40	6
25	5	70	350	50	8
26	6	30	75	20	10
27	6	30	150	30	12
28	6	30	190	40	4
29	6	30	250	50	6
30	6	30	350	60	8
31	6	40	75	30	4
32	6	40	150	40	6
33	6	40	190	50	8
34	6	40	250	60	10
35	6	40	350	20	12
36	6	50	75	40	8
37	6	50	150	40	8
38	6	50	190	60	12
39	6	50	250	20	4
40	6	50	350	30	6
41	6	60	75	50	12
42	6	60	150	60	4
43	6	60	190	20	6
44	6	60	250	30	8
45	6	60	350	40	10
46	6	70	75	60	6
47	6	70	150	20	8
48	6	70	190	30	10
49	6	70	250	40	12
50	6	70	350	50	4

4.2 OVERALL LOSS FUNCTION AND S/N RATIO

Thrust of the Pulse detonation engine belongs to the "larger the better quality characteristics. The loss function of the larger the better quality characteristics be expressed as

Experiment	P1	P2	P3	P4	P5	SN
1	1	1	1	1	1	SN1
2	1	1	2	2	2	SN2
3	1	1	3	3	3	SN3
4	1	1	4	4	4	SN4
5	1	1	5	5	5	SN5
6	1	2	1	2	3	SN6
7	1	2	2	3	4	SN7
8	1	2	3	4	5	SN8
9	1	2	4	5	1	SN9
10	1	2	5	1	2	SN10
11	1	3	1	3	5	SN11
12	1	3	2	4	1	SN12
13	1	3	3	5	2	SN13
14	1	3	4	1	3	SN14
15	1	3	5	2	4	SN15
16	1	4	1	4	2	SN16
17	1	4	2	5	3	SN17
18	1	4	3	1	4	SN18
19	1	4	4	2	5	SN19
20	1	4	5	3	1	SN20
21	1	5	1	5	4	SN21
22	1	5	2	1	5	SN22
23	1	5	3	2	1	SN23
24	1	5	4	3	2	SN24
25	1	5	5	4	3	SN25
26	2	1	1	1	4	SN26
27	2	1	2	2	5	SN27
28	2	1	3	3	1	SN28
29	2	1	4	4	2	SN29
30	2	1	5	5	3	SN30
31	2	2	1	2	1	SN31
32	2	2	2	3	2	SN32
33	2	2	3	4	3	SN33
34	2	2	4	5	4	SN34
35	2	2	5	1	5	SN35
36	2	3	1	3	3	SN36
37	2	3	1	3	3	SN37
38	2	3	3	5	5	SN38
39	2	3	4	1	1	SN39
40	2	3	5	2	2	SN40
41	2	4	1	4	5	SN41
42	2	4	2	5	1	SN42
43	2	4	3	1	2	SN43
44	2	4	4	2	3	SN44
45	2	4	5	3	4	SN45
46	2	5	1	5	2	SN46
47	2	5	2	1	3	SN47
48	2	5	3	2	4	SN48
49	2	5	4	3	5	SN49
50	2	5	5	4	1	SN50

SN Ratio: L50 Orthogonal array

$$L_j = 1/n \sum_{K=1}^{n} 1/y_i^2 \quad \text{------} \qquad (1)$$

$$\eta_j = -10 \log L_j \text{ -----------} \qquad (2)$$

When n is the number of tests y_i is the experiment value of ith Quality characteristic, Lj Overall loss function and η_j is the S/N ratio. By applying equations 1-2 the η_j corresponding to the overall loss function for each experiment of L50 is to be calculated. Basically the larger the S/N ratio, the better the quality characteristics of Thrust of Pulse Detonation Engine.

After calculating the SN ratio for each experiment, the average SN value is calculated for each factor and level. This is done as shown below for parameter 3 (P3) in the array.

Once these SN ratio values are calculated for each factor and level, they are tabulated as shown below and the range R (R=high SN-Low SN) of the SN for each parameter is calculated and entered into the table. The larger the R value for a parameter, the larger the effect the variable has on the process. This is because the same change in signal causes a larger effect on the output variable being measured.

Once these SN ratio values are calculated for each factor and level, they are tabulated as shown below and the range R (R=high SN-Low SN) of the SN for each parameter is calculated and entered into the table. The larger the R value for a parameter, the larger the effect the variable has on the process. This is because the same change in signal causes a larger effect on the output variable being measured.

5. OF VARIANCE (ANOVA)

The relative effect of the different physical parameters on the thrust is obtained by decomposition of variance, which is called Analysis of variance (ANOVA). The relative importance of physical parameters with respect to thrust is investigated to determine more accurately the optimum combinations of physical parameters by using ANOVA.

The result of ANOVA for the thrust (output) is to be presented in table. Statistically F-test provides a decision at some confidence level as to whether these estimates are significantly different (9-12). Larger F-Value indicates that the variation of the physical parameters makes a big change on the performance. According to this analysis, the most effective physical parameter with respect to thrust is the percent contribution indicates the relative power of a factor to reduce variation. For a factor with high percent contribution, a small variation will have a great influence on the performance.

6. CONFIRMATION TEST:

The confirmation experiment is the final step in the first iteration of the design of experimentation process. The purpose of confirmation experiment is to validate the conclusions drawn during the analysis phase. The confirmation experiment is performed by conducting a test with a specific combination of the factors and levels previously evaluated. In this study after determining the optimum conditions and predicting the response under these conditions, a new experiment was designed and conducted with optimum levels of the physical parameters.

The final step is to predict and verify the improvement of the performance characteristics. The predicted S/N ratio η_j using the optimal level of the physical parameters can be calculated as

$$\eta = \eta_m + \sum_{i=1}^{n} (ni - nm)$$

Where η_m is the total mean of S/N ratio, ηi is the mean of S/N ratio at the optimum level and n is the number of main parameters that significantly affect the performance.

7. CONCLUSIONS

This paper has presented an investigation into the optimization of physical parameters affecting the performance of the Pulse detonation engine. The level of importance of physical parameters on the thrust is determined by using Taguchi L50 array method and ANOVA. Based on the ANOVA the highly effective physical parameter on thrust is found. This method is most effective and less time consuming when a large number of parameters to be optimized, the confirmation test indicate that it is possible to increase thrust significantly by using the proposed statistical technique. This is the procedure of "Taguchi method for enhancing the thrust and optimizing the physical parameters of Pulse Detonation Engine.

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