APPENDIX 1

SPECIFICATIONS OF PRESSURE TRANSDUCER

Table A1.1 Pressure transducer

<table>
<thead>
<tr>
<th>Model</th>
<th>Kistler, Switzerland 601A, water cooled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>0-250 bar</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>( \approx 14.80 \ \text{pC/bar} )</td>
</tr>
<tr>
<td>Linearity</td>
<td>0.1 (&lt;) % \text{Full Scale Output (FSO)}</td>
</tr>
<tr>
<td>Acceleration sensitivity</td>
<td>(&lt; 0.001 \ \text{bar/g} )</td>
</tr>
<tr>
<td>Operating temperature range</td>
<td>-19.6 to 200 ( \text{°C} )</td>
</tr>
<tr>
<td>Capacitance</td>
<td>5 PF</td>
</tr>
<tr>
<td>Weight</td>
<td>1.7 g</td>
</tr>
</tbody>
</table>
APPENDIX 2

EXHAUST GAS ANALYSER AND SMOKE METER

Table A2.1 Exhaust gas analyzer

<table>
<thead>
<tr>
<th>Type and make</th>
<th>AVL DiGas 444 exhaust gas analyzer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measurement Range</td>
</tr>
<tr>
<td>CO(% vol)</td>
<td>0-10</td>
</tr>
<tr>
<td>CO2(% vol)</td>
<td>0-20</td>
</tr>
<tr>
<td>HC(ppm)</td>
<td>0-20000</td>
</tr>
<tr>
<td>O2(% vol)</td>
<td>0-22</td>
</tr>
<tr>
<td>NO(ppm)</td>
<td>0-5000</td>
</tr>
<tr>
<td>Oil Temperature(C)</td>
<td>-30 to 125</td>
</tr>
<tr>
<td>Lambda</td>
<td>0-9.999</td>
</tr>
</tbody>
</table>

Figure A 2.1 Exhaust gas analyzer
Figure A 2.2 Smoke meter

Table A2.2 Smoke meter

<table>
<thead>
<tr>
<th>Type and make</th>
<th>AVL 437C smoke meter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measurement Range</td>
</tr>
<tr>
<td>Opacity (%)</td>
<td>0-100</td>
</tr>
<tr>
<td>Absorption (k) (m-1)</td>
<td>0-99.99</td>
</tr>
</tbody>
</table>
APPENDIX 3

THERMAL BARRIER COATING (TBC)

TBC helps to contain a higher quantity of heat inside the combustion chamber by minimising the heat loss. This coating acts as an insulator for the combustion chamber and it is applied on the inner surface of the cylinder head and piston crown. It has been done by an atmospheric plasma spray method using Aluminium oxide (Al₂O₃) + Molybdenum (Mo) + Titanium oxide (TiO₂) (40%+30%+30%), with a composition of (40%+30%+30%) over a thickness of 300μm. Generally, TBC is applied over a base coating existing on the metallic surface. The base coating is done by simple electro plating method using Nickel Chromium Alloy (Ni Cr) over a thickness of 150μm.

Figure A 3.1 Diagram showing the locations of thermal barrier coating
Figure A 3.2 TBC on cylinder head

Figure A 3.3 TBC on Piston head
APPENDIX 4

UNCERTAINTY ANALYSIS

All measurements of physical quantities are subject to uncertainties. Uncertainty analysis is needed to ensure and confirm the high level of confidence in the measurement results of the experiment. In order to have reasonable limits of uncertainty for a computed value an expression is derived which is as follows:

Let ‘R’ be the computed result function of the independent measured variables $x_1, x_2, x_3, \ldots \ldots \ldots x_n$, as per the relation.

$$R = f\{x_1, x_2, \ldots \ldots \ldots , x_n\}$$  \hspace{1cm} (A4.1)

and let error limits for the measured variables or parameters be

$$x_1 \pm \Delta x_1, x_2 \pm \Delta x_2, \ldots \ldots \ldots , x_n \pm \Delta x_n$$

and the error limits for the computed result be $R \pm \Delta R$

Hence to get the realistic error limits for the computed result, the principle of root-mean square method is used to get the magnitude of error given by Holman (2001) as

$$\Delta R = \left[ \left( \frac{\partial R}{\partial x_1} \Delta x_1 \right)^2 + \left( \frac{\partial R}{\partial x_2} \Delta x_2 \right)^2 + \ldots \ldots \ldots + \left( \frac{\partial R}{\partial x_n} \Delta x_n \right)^2 \right]^{1/2}$$ \hspace{1cm} (A4.2)
Using Equation (A4.2) the uncertainty in the compound values such as brake thermal efficiency and fuel flow measurements were estimated. The uncertainty value of speed, fuel time, voltage and current are estimated from their respective measured value based on the Gaussian distribution. For fuel time (t) the uncertainty (Δt) is taken as ± 0.2 sec.

A sample calculation is given below.

**Example:**

<table>
<thead>
<tr>
<th>Speed</th>
<th>N = 1500rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel volume</td>
<td>fx = 10cc</td>
</tr>
<tr>
<td>Brake power</td>
<td>BP = 4.4 kW</td>
</tr>
</tbody>
</table>

1. Total fuel consumption (TFC)

\[
TFC = \frac{(10 \times 3600 \times 0.83)}{(t \times 1000)}
\]

\[
TFC = \frac{(10 \times 3600 \times 0.83)}{(23.25 \times 1000)} = 1.28 \text{ kg/ h}
\]

\[
TFC = f (t)
\]

\[
\frac{\partial TFC}{\partial t} = \frac{-(10 \times 3600 \times 0.83)}{t^2 \times 1000}
\]

\[
\frac{\partial TFC}{\partial t} = \frac{-(10 \times 3600 \times 0.83)}{(23.25)^2 \times 1000} = -0.055 \text{ kg/ h}
\]

\[
\Delta TFC = \sqrt{\left(\frac{\partial TFC}{\partial t} \times (\Delta t)\right)^2}
\]  

(A4.3)
\[ \sqrt{(-0.055 \times 0.2)^2} = 0.011 \text{ kg/h} \]

The uncertainty in the TFC from equation (A4.3) is 0.011 kg/h and the limits of uncertainty are \((1.28 \pm 0.011) \text{ kg/h}\).

2. Brake thermal efficiency \((\eta)\)

\[ \eta = \frac{(BP \times 3600 \times 100)}{(TFC \times CV)} \]

\[ \eta = f(BP, TFC) \]

\[ \eta = \frac{3.7 \times 3600 \times 100}{(1.28 \times 42700)} = 28.98\% \]

\[ \frac{\partial \eta}{\partial BP} = \frac{(3600 \times 100)}{TFC \times 42700} \]

\[ = \frac{3600 \times 100}{1.28 \times 42700} = 6.58\% \]

The calculated uncertainty for the full load Brake Power \((\Delta BP)\) is \(=0.1929\text{kW}\)

\[ \frac{\partial \eta}{\partial TFC} = \frac{(BP \times 3600 \times 100)}{(TFC)^2 \times 42700} \]

\[ = \frac{(3.7 \times 3600 \times 100)}{(1.28 \times 42700)} = 22.64\% \]

\[ = 22.64\% \]
\[
\Delta \eta = \sqrt{\left(\frac{\partial \eta}{\partial BP} \times \Delta BP\right)^2 + \left(\frac{\partial \eta}{\partial TFC} \times \Delta TFC\right)^2}
\] 

(A4.4)

\[
\Delta \eta = \sqrt{(6.58 \times 0.1929)^2 + (22.64 \times 0.011)^2}
\]

= 1.3%

The uncertainty in the brake thermal efficiency from equation (A4.4) is ± 1.33% and the limits of uncertainty are 28.98 ± 1.3%.

3. Temperature Measurement

Uncertainty in temperature is:

± 1% (T > 150°C)

± 2% (150°C < T < 250°C)

± 3% (T > 250°C)

4. Percentage of uncertainty for the measurement of speed, mass flow rate, NO\textsubscript{x}, Hydrocarbon, Smoke and pressure are given below:

(i) Speed : 1.4
(ii) Mass flow rate of air : 1.3
(iii) Mass flow rate of diesel : 1.4
(iv) NO\textsubscript{x} : 2.7
(v) Hydrocarbon : 2.2
(vi) Smoke : 2.2
(vii) Pressure : 1.1
The following table provides the list of instruments used in the research work and its uncertainty level.

**Table A4.1 List of instruments used and its uncertainties**

<table>
<thead>
<tr>
<th>Instruments</th>
<th>Range</th>
<th>Accuracy</th>
<th>Measurement techniques</th>
<th>Percentage uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas analyzer</td>
<td>CO 0-10%</td>
<td>±0.01%</td>
<td>NDIR principle (Non depressive infra red sensor)</td>
<td>±0.2%</td>
</tr>
<tr>
<td></td>
<td>CO₂ 0-20%</td>
<td>±0.1%</td>
<td></td>
<td>±0.15%</td>
</tr>
<tr>
<td></td>
<td>HC 0-20,000ppm</td>
<td>±1ppm</td>
<td></td>
<td>±0.2%</td>
</tr>
<tr>
<td></td>
<td>No₂0-5000ppm</td>
<td>±1ppm</td>
<td>Electro chemical sensor.</td>
<td>±0.2%</td>
</tr>
<tr>
<td>Smoke level measuring instrument</td>
<td>Opacity (0-100%)</td>
<td>±0.1</td>
<td></td>
<td>±1%</td>
</tr>
<tr>
<td>EGT indicator</td>
<td>0-900°C</td>
<td>±1°C</td>
<td>k-type (Cr Al) thermocouple</td>
<td>±0.15%</td>
</tr>
<tr>
<td>Speed measuring unit</td>
<td>0-10,000 rpm</td>
<td>±10 rpm</td>
<td>Magnetic pick up type</td>
<td>±0.1%</td>
</tr>
<tr>
<td>Load indicator</td>
<td>0-100 kg</td>
<td>±0.1 kg</td>
<td>Strain gauge type load cell.</td>
<td>±0.2%</td>
</tr>
<tr>
<td>Burette for fuel measurement</td>
<td>±0.1cc</td>
<td></td>
<td></td>
<td>±1%</td>
</tr>
<tr>
<td>Digital stop watch</td>
<td>±0.6sec</td>
<td></td>
<td></td>
<td>±0.2%</td>
</tr>
<tr>
<td>Manometer</td>
<td>±1mm</td>
<td></td>
<td></td>
<td>±1%</td>
</tr>
<tr>
<td>Pressure pickup</td>
<td>0-110bar</td>
<td>±0.1kg</td>
<td></td>
<td>±0.1%</td>
</tr>
<tr>
<td>Crank angle encoder</td>
<td>±1Degree</td>
<td></td>
<td>Magnetic pick up type</td>
<td>±0.2%</td>
</tr>
</tbody>
</table>
APPENDIX 5

HEAT RELEASE ANALYSIS

Combustion duration and intensity are estimated from the heat release rate, which is the most valuable source of information for the combustion mechanism in diesel engines (Heywood 1998). The heat release rate diagram also provides the valuable information for the initial stage of combustion where the most NO\textsubscript{x} is formed. The heat release rate is determined by applying the first law of thermodynamics using the following equation.

\[dQ_{hr} = dU + dW + dQ_{ht}\]

\[dQ_{in} = C_v/R \left( PdV + VdP \right) + dW + dQ_{ht}\]  \hspace{1cm} (A5.1)

where

\[dQ_{hr} = \text{Instantaneous heat release modeled as heat transfer to the working fluid.}\]

\[dU = \text{Change in internal energy of the working fluid}\]

\[dW = \text{Work done by the working fluid.}\]

\[dQ_{ht} = \text{heat transmitted away from the working fluid (To the combustion chamber walls)}\]

\[R = \text{Gas constant}\]

Work done by the working fluid \(dW = PdV\)

Heat transfer rate to the wall can be written as

\[\frac{dQ_{in}}{dt} = hA_s(T_g - T_w)\]  \hspace{1cm} (A5.2)
T, P, V are Temperature, Pressure and Volume respectively,

\[ C_v = \text{Specific heat at constant volume} \]

\[ h = \text{Heat transfer coefficient} \]

\[ T_w = \text{Temperature of the wall: 400K} \]

The heat release was determined by a simplified analysis with the following assumptions.

- Combustion process is assumed as a single zone with uniform temperature, pressure, and composition
- Combustion gases are assumed as Ideal gas and its equation of state is, \( PV = mRT \) 
  \hspace{1cm} (A5.3)
- Dissociation of combustion products are neglected
- Assumed that the specific heat of gases are the function of temperature alone

From the equation the first law of thermodynamics can be written as follows with suitable assumptions:

\[
\frac{dQ_{hr}}{d\theta} = \frac{\gamma}{\gamma - 1} P \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dP}{d\theta} + (\text{Heat lost in cooling water})
\]

\[
\frac{dQ_{hr}}{d\theta} = \frac{\gamma}{\gamma - 1} P \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dP}{d\theta} + hA_s \left( T_g - T_w \right) \frac{dt}{d\theta}
\] 
  \hspace{1cm} (A5.4)

Where \( \theta \) is the crank angle in degrees, \( \gamma \) is the ratio of specific heats of the fuel and air, \( A_s \) is the area in m\(^3\) through which heat transfer from gas to combustion chamber walls takes place. A pressure value is obtained from the
cylinder pressure data corresponding crank angle. If the engine is air cooled
the heat lost in cooling water become zero then the equation becomes

\[
\frac{dQ_{hr}}{d\theta} = \frac{\gamma}{\gamma - 1} P \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dP}{d\theta}
\]  \hspace{1cm} (A5.5)

An analysis of this type has been shown to agree well with
calculations using complete equilibrium of the combustion products in diesel
engines.
APPENDIX 6

CALCULATIONS USED FOR CHANGING COMPRESSION RATIO

Figure A 6.1 Dimension of piston bowl

In the present work the compression ratio of the engine was changed by adding and removing material from the existing piston.

Existing compression ratio=17.5:1

Compression ratio= (Vs+Vc) / Vc

Where Vs=stroke volume Vc =clearance volume

Vs= (Π/4) *D²*L

D=87.5mm and L=110mm (Bore*stroke)

Vs= (3.14/4) x (0.0875)² x (0.110)
Vs=0. 000661 m³

Compression ratio = 17.5 : 1 = (Vs+Vc) / Vc

Vc = 0. 00004 m³

Let us consider the total clearance volume

Vc = Vc₁+Vc₂=0. 00004 m³

Vc₁ = clearance volume on the piston surface = 0.0000336 m³

Vc₂ = 0. 0000064m³ (bowl volume measurement by manual-hemisphere)

Vc₂ = (2/3) x π x r³ (volume of the hemisphere)

r = 0.025914m (existing bowl sphere radius)

**Modified compression ratio=18.5: 1**

If Compression ratio=18.5: 1= (Vs+Vc) / Vc

Where Vs = 0. 000661 m³ ,

Vc = 0. 000038m³

Vc₁ = 0. 0000336 m³

Vc = Vc₁+Vc₂

Therefore Vc₂ = 0. 000044 m³

Vc₂ = (2/3) x π x r³ (volume of the hemisphere)

When r = 0.025495m

**Modified compression ratio=19.5: 1**

If Compression ratio=19.5: 1= (Vs+Vc) / Vc

Where Vs = 0. 000661 m³ ,

Vc = 0. 000036m³

Vc₁ = 0. 0000336 m³

Vc = Vc₁+Vc₂

Therefore Vc₂ = 0. 000024 m³
\[ V_{c2} = \frac{2}{3} \pi r^3 \text{ (volume of the hemisphere)} \]

When \( r = 0.025023 \text{ m} \)

Compression ratio = 19.5: 1

hemisphere bowl radius \( r = 0.025023 \text{ m} \)

(0.00048m radius may reduce around the hemisphere bowl in the new piston - 2 by special machining process - material adding and machining).

Figure A6.2 and A6.3 shows the front and top view of the piston used in the work.

Figure A 6.2 Front view of the piston used in the work
Figure A 6.3 Top view of the piston used in the work
APPENDIX 7

TAGUCHI METHOD

Background

Most industrial experiments usually involve a significant number of factors, a full factorial design results in a large number of experiments. To reduce the number of experiments to a practical level, only a small set from all the possibilities is selected. The method of selecting a limited number of experiments which produces the most information is known as a partial fraction experiment. Although this method is well known, there are no general guidelines for its application or the analysis of the results obtained by performing the experiments. Taguchi constructed a special set of general design guidelines for factorial experiments that cover many applications.

Basic Concepts

Orthogonal array

Taguchi has envisaged a new method of conducting the design of experiments which are based on well defined guidelines. This method uses a special set of arrays called orthogonal arrays. These standard arrays stipulate the way of conducting the minimal number of experiments which could give the full information of all the factors that affect the performance parameter. The crux of the orthogonal arrays method lies in choosing the level combinations of the input design variables for each experiment. While there are many standard orthogonal arrays available, each of the arrays is meant for a specific number of independent design variables and levels.
Minimum number of experiments

The design of experiments using the orthogonal array is, in most cases, efficient when compared to many other statistical designs. The minimum number of experiments that are required to conduct the Taguchi method can be calculated based on the degrees of freedom approach.

\[ N_{\text{Taguchi}} = 1 + \sum_{i=1}^{N_V} (L_i - 1) \]  \hspace{1cm} (A7.1)

For example, in case of 8 independent variables study having 1 independent variable with 2 levels and remaining 7 independent variables with 3 levels (L18 orthogonal array), the minimum number of experiments required based on the above equation is 16. Because of the balancing property of the orthogonal arrays, the total number of experiments shall be multiple of 2 and 3. Hence the number of experiments for the above case is 18.

Assumptions of Taguchi method

The additive assumption implies that the individual or main effects of the independent variables on performance parameter are separable. Under this assumption, the effect of each factor can be linear, quadratic or of higher order, but the model assumes that there exists no cross product effects (interactions) among the individual factors. That means the effect of independent variable 1 on performance parameter does not depend on the different level settings of any other independent variables and vice versa. If at anytime, this assumption is violated, then the additivity of the main effects does not hold, and the variables interact.
Design of Experiment by Taguchi Method

The design of experiment by Taguchi Method involves the following steps

1. Selection of independent variables
2. Selection of number of level settings for each independent variable
3. Selection of orthogonal array
4. Assigning the independent variables to each column
5. Conducting the experiments
6. Analyzing the data
7. Inference

The details of the above steps are given below.

Selection of the independent variables

Before conducting the experiment, the knowledge of the product/process under investigation is of prime importance for identifying the factors likely to influence the outcome. In order to compile a comprehensive list of factors, the input to the experiment is generally obtained from all the people involved in the project.

Deciding the number of levels

Once the independent variables are decided, the number of levels for each variable is decided. The selection of number of levels depends on how the performance parameter is affected due to different level settings. If the performance parameter is a linear function of the independent variable, then the number of level setting shall be 2. However, if the independent variable is not linearly related, then one could go for 3, 4 or higher levels depending on whether the relationship is quadratic, cubic or higher order.
In the absence of exact nature of relationship between the independent variable and the performance parameter, one could choose 2 level settings. After analyzing the experimental data, one can decide whether the assumption of level setting is right or not based on the percent contribution and the error calculations.

**Selection of an orthogonal array**

Before selecting the orthogonal array, the minimum number of experiments to be conducted shall be fixed based on the total number of degrees of freedom present in the study. The minimum number of experiments that must be run to study the factors shall be more than the total degrees of freedom available.

Once the minimum number of experiments is decided, the further selection of orthogonal array is based on the number of independent variables and number of factor levels for each independent variable.

**Assigning the independent variables to columns**

The order in which the independent variables are assigned to the vertical column is very essential. In case of mixed level variables and interaction between variables, the variables are to be assigned at right columns as stipulated by the orthogonal array.

**Conducting the experiment**

Once the orthogonal array is selected, the experiments are conducted as per the level combinations. It is necessary that all the experiments be conducted. The interaction columns and dummy variable columns shall not be considered for conducting the experiment, but are needed while analyzing the
data to understand the interaction effect. The performance parameter under study is noted down for each experiment to conduct the sensitivity analysis.

**Analysis of the data**

Since each experiment is the combination of different factor levels, it is essential to segregate the individual effect of independent variables. This can be done by summing up the performance parameter values for the corresponding level settings.

Once the mean value of each level of a particular independent variable is calculated, the sum of square of deviation of each of the mean value from the grand mean value is calculated. This sum of square deviation of a particular variable indicates whether the performance parameter is sensitive to the change in level setting. If the sum of square deviation is close to zero or insignificant, one may conclude that the design variables are not influencing the performance of the process. In other words, by conducting the sensitivity analysis, and performing analysis of variance (ANOVA), one can decide which independent factor dominates over other and the percentage contribution of that particular independent variable.

**Inference**

From the above experimental analysis, it is clear that the higher the value of sum of square of an independent variable, the more it has influence on the performance parameter. One can also calculate the ratio of individual sum of square of a particular independent variable to the total sum of squares of all the variables. This ratio gives the percent contribution of the independent variable on the performance parameter.
In addition to above, one could find the near optimal solution to the problem. This near optimum value may not be the global optimal solution. However, the solution can be used as an initial / starting value for the standard optimization technique.

**Procedure for Taguchi-Grey-relational analysis**

1. Taguchi-Grey – used for optimising the operating parameters – producing more than one response parameters

2. Taguchi-Grey involves the following steps.
   a. Step-1: Fix parameters and its levels
   b. Select orthogonal array
   c. Conduct experiment as per the orthogonal layout
   d. Obtain response parameters (Example BTE, NO, Smoke and so on)
   e. Since, the experiment produces more than one response parameter use Grey relational approach for optimising process parameter.
   g. Convert all S/N ratios into normalized S/N ratios (Generation of Grey relations)
      i. Response parameter – equation for Larger the better
         
         \[ \text{Grey relation} = \frac{x - \min x}{\max x - \min x} \]
      a. Response parameter – equation for Smaller the better

Grey relation = (Max of x – x) / (Max of x – min of x)

h. Calculate Gray relational coefficient for all response parameters.

i. Grey Relation Coefficient

\[ \text{Grey Relation Coefficient} = \frac{\text{min of GR} + (\epsilon) \times \text{max of GR}}{[(1-x) + (\epsilon) \times \text{max of GR}]} \]

Epsilon = 0.5 Where \( \xi \) is the distinguishing coefficient, which is defined in the range \( 0 \leq \xi \leq 1 \). The WEDM process parameters are equally weighted in this study, and therefore \( \xi \) is 0.5[14].

i. Finally, form Grey relational grade by combining all three response parameters.

\[ \text{Grey Relational Grade} = \frac{(\text{GRC1}+\text{GRC2}+\text{GRC3})}{3} \]

j. Preparation of table for process parameter and mean Grey grade for all levels.

k. Draw a graph using the above Grey grade and the peak values of graphs are identified as optimum process parameter level.

3. ANOVA – using Grey grade values