Appendix VII

Uncertainty Analysis

Uncertainty analysis involves systematic procedures for calculating error estimates for experimental data. When estimating errors in heat engine experiments, it is usually assumed that data is gathered under fixed (known) conditions and detailed knowledge of all system components is available. Measurement errors arise from various sources, but they can be broadly classified as bias errors and precision (or random) errors. Bias errors remain constant during a set of measurements. They are often estimated from calibration procedures or past experience. Alternatively, different methods of estimating the same variable can be used, so that comparisons between those results would indicate the bias error. Elemental bias errors arise from calibration procedures or curve-fitting of calibrated data.

To quantify errors in experimental work, some calculations and estimation have to be applied on sensors, devices and machines that have been used to measure the experimental parameters. As the experiments performed as it need to express measurement uncertainty as

$$x' = x \pm u_x \qquad (P\%) \tag{VII.1}$$

where, x', x, u^x and P% are true value, tested value, uncertainty of the measurement and confidence respectively. To do this with assurance, total uncertainty of each component or portion of the experiment or procedure is determined. Total uncertainty is determined by finding error due to equipment (bias) and due to environment (precision). Wherever possible, uncertainty of each component or portion of experiment is found to determine where uncertainty may be minimized. Uncertainties are propagated in post-processing phase, to quantities that are non-linear functions of a measurement or functions of multiple measurements with uncertainties based upon the functional relationship.

Both bias and precision errors are present in an experiment. The precision is measured whereas the bias error is usually determined from equipment vendor specs. The total error is the vector sum of these errors and it is to be noted that errors in estimating each error affect the value of the total error.

$$u_X = (B_x^2 + P_x^2)^{1/2} \tag{VII.2}$$

where, B_x and P_x are bias and precision error respectively.

In case of several measurements of the same quantity like engine load, the uncertainty is estimated using statistical measures of spread. Several measurements of the same quantity are: $X_1,X_2,X_3,X_4,X_5,---,X_n$. Average load of the dynamometer is calculated as

$$\text{average} = (X1, X2, X3, X4, X5, ---, Xn)/n \qquad \text{(VII.3)}$$

Now, there are two ways to describe the scatter in these measurements. The mean deviation from the mean is the sum of the absolute values of the differences between each measurement and the average, divided by the number of measurements:

$$\text{mean deviation from mean} = \frac{\sum_{i=1}^{n}|X_i - \text{average}|}{n} \qquad \text{(VII.4)}$$

The standard deviation from the mean is the square root of the sum of the squares of the differences between each measurement and the average, divided by one less than the number of measurements:

$$\text{standard deviation from mean} = \frac{\sqrt{\sum_{i=1}^{n}(X_i - \text{average})^2}}{1-n} \qquad \text{(VII.5)}$$

Either the mean deviation from the mean, or the standard deviation from the mean, gives a reasonable description of the scatter of data around its mean value.

Tested load - mean deviation < true load < tested load + mean deviation (VII.6)

Tested load - mean deviation < true load < tested load + standard deviation (VII.7)

For parameter that have been evaluated depending on two or more independent parameters, propagation of uncertainty is carried out using

$$\frac{U_y}{y} = \sqrt{\left(\frac{u_{x1}}{x1}\right)^2 + \left(\frac{u_{x2}}{x2}\right)^2 + \ldots + \left(\frac{u_{xn}}{xn}\right)^2} \qquad \text{(VII.8)}$$

Where, U_y and y are uncertainty and the testing value of the evaluated parameter x1, x2,…., xn respectively.

The uncertainty analysis carried out in this Appendix is based on the lines suggested by Kline and McClintock [95]. It should be noted that the uncertainty analysis presented here considers only the errors that relate to the measurements made during testing. Δ is used here to symbolize the error in the quantity.

VII.1 Uncertainity Calculations

VII.1.1 Uncertainty in Thermal Performance Parameters

The uncertainty calculation shown here are carried out correspond to CR 18, IP 200bar and fuel as Diesel oil shown in Table III.1in Appendix III. The full load is taken as 12kg and low load is taken as 3kg.

VII.1.1.1 Uncertainty in Brake Power

$BP=2\pi NT/60*1000$, $T = W*R$

At Full Loading Condition (Load is 12kg)

$$\Delta BP/BP = \sqrt{[(\Delta N/N)^2 + (\Delta W/W)^2]}$$

$$= \sqrt{[(30/1530)^2 + (0.1/12)^2]}$$

$$= \sqrt{[0.0004 + 0.0000694]}$$

$$\mathbf{= 0.021 = 2.1\%}$$

At Low Loading Condition (Load is 3kg)

$$\Delta BP/BP = \sqrt{[(\Delta N/N)^2 + (\Delta W/W)^2]}$$

$$= \sqrt{[(30/1470)^2 + (0.1/3)^2]}$$

$$= \sqrt{[0.0004 + 0.0011]}$$

$$\mathbf{= 0.038 = 3.8\ \%}$$

VII.1.1.2 Uncertainty in BMEP

The BMEP is calculated by using the formula

$$BMEP = \frac{BP\ (KW) \times 60}{L \times A \times \left(\frac{N}{n}\right) \times No\ of\ cylinders \times 100}$$

At Full Loading Condition

$$\Delta BMEP/BMEP = \sqrt{[(\Delta BP/BP)^2 + (\Delta L/L)^2 + (\Delta D/D)^2]}$$

$$= \sqrt{[(0.021)^2 + (1/110)^2 + (1/87.5)^2]}$$

$$= 0.04413 = 4.413\%$$

At Low Loading Condition

$$\Delta BMEP/BMEP = \sqrt{[(\Delta BP/BP)^2 + (\Delta L/L)^2 + (\Delta D/D)^2]}$$

$$= \sqrt{[(0.038)^2 + (1/110)^2 + (1/87.5)^2]}$$

$$= 0.0407 = 4.07\%$$

VII.1.1.3 Uncertainty in BTHE

The BTHE is calculated by using the formula

$$\text{BTHE} = \frac{BP \times 3600 \times 100}{Fuel\ flow\ in\ \frac{kg}{hr} \times Calorific\ Value}$$

At Full Loading Condition

$$\Delta BTHE/BTHE = \sqrt{[(\Delta BP/BP)^2 + (\Delta m_f/m_f)^2]}$$

$$= \sqrt{[(0.021)^2 + (0.01/1.04)^2]}$$

$$\mathbf{= 0.023 = 2.3\%}$$

At Low Loading Condition

$$\Delta BTHE/BTHE = \sqrt{[(\Delta BP/BP)^2 + (\Delta m_f/m_f)^2]}$$

$$= \sqrt{[(0.038)^2 + (0.01/0.57)^2]}$$

$$\mathbf{= 0.041 = 4.1\%}$$

VII.1.1.4 Uncertainty in BSFC

The BSFC is calculated by using the formula

$$BSFC = \frac{Fuel\ flow\ in\ \frac{kg}{hr}}{BP}$$

At Full Loading Condition

$$\Delta BSFC/BSFC = \sqrt{[(\Delta m_f / m_f)^2 + (\Delta BP/BP)^2]}$$

$$= \sqrt{[(0.01/1.04)^2 + (0.02)^2]}$$

$$\mathbf{= 0.022 = 2.2\%}$$

At Low Loading Condition

$$\Delta BSFC/BSFC = \sqrt{[(\Delta m_f / m_f)^2 + (\Delta BP/BP)^2]}$$

$$= \sqrt{[(0.01/0.57)^2 + (0.038)^2]}$$

$$\mathbf{= 0.0418 = 4.18\ \%}$$

VII.1.1.5 Uncertainty in Volumetric Efficiency (η_{vol})

The η_{vol} is calculated by using the formula

$$\eta_{vol} = \frac{Airflow\ in\ kg/hr \times 100}{\left(\frac{\pi}{4}\right) \times D^2 \times L \times \left(\frac{N}{n}\right) \times 60 \times No\ of\ cylinders \times \rho_a}$$

At Full Loading Condition

$$(\Delta\eta_{vol}/\eta_{vol}) = \sqrt{[(\Delta m_a/m_a)^2 + (\Delta D/D)^2 + (\Delta L/L)^2 + (\Delta\rho_a/\rho_a)^2]}$$

$$= \sqrt{[(0.01/26.92)^2 + (1/87.5) + (1/110)^2]}$$

$$= 0.0146 = 1.46\%$$

At Low Loading Condition

$$(\Delta\eta_{vol}/\eta_{vol}) = \sqrt{[(\Delta m_a/m_a)^2 + (\Delta D/D)^2 + (\Delta L/L)^2 + (\Delta\rho_a/\rho_a)^2]}$$

$$= \sqrt{[(0.01/28.14)^2 + (1/87.5) + (1/110)^2]}$$

$$= 0.0146 = 1.46\%$$

VII.1.1.6 Uncertainty in HGas

$$HGas = (m_a + m_f) \times C_{pgas} \times (T_{exhaust} - T_{air})$$

At Full Loading Condition

$$\Delta HGas/HGas = \sqrt{[(\Delta m_a/m_a)^2 + (\Delta m_f/m_f)^2 + (\Delta EGT/EGT)^2]}$$

$$= \sqrt{[(0.01/26.92)^2 + (0.01/1.04)^2 + (0.01/423.71)^2]}$$

$$= 0.009622 = 0.96\%$$

At Low Loading Condition

$$\Delta HGas/HGas = \sqrt{[(\Delta m_a/m_a)^2 + (\Delta m_f/m_f)^2 + (\Delta EGT/EGT)^2]}$$

$$= \sqrt{[(0.01/28.14)^2 + (0.01/0.57)^2 + (0.01/196.27)^2]}$$

$$= 0.0175 = 1.75\%$$

VII.1.2 Uncertainty in Emission Constituents (Resolution/Range)

$\Delta CO/CO$ (%) = 0.001/15 = 0.00006 = **0.006%**

$\Delta CO/CO$ (ppm) = 1/4000 = 0.00025= **0.025%**

$\Delta CO_2/CO_2$ = 0.01/20 = 0.0005 = **0.05%**

$\Delta HC/HC$ = 1/30000 = 0.00003 = **0.003%**

$\Delta O_2/O_2$ = 0.01/25 = 0.0004 = **0.04%**

$\Delta NO_x / NO_x$ = 1 / 5000 = 0.0002 = **0.02%**

$\Delta SO_x / SO_x$ = 1/2000 = 0.0002 = **0.02%**

Table VII.1 Probable errors in the estimation of thermal performance of diesel engine running on diesel biodiesel blends

Quantity	Value	Probable error
Speed (N)	1500 rpm	30 rpm
Load (W)	12 Kg	0.1 kg
Fuel flow rate (m_f)	1.04 Kg/hr	0.01 kg/hr
Bore (D)	87.5mm	1mm
Stroke Length (L)	110mm	1mm
Air flow rate (m_a)	26.92 Kg/hr	0.01 Kg/hr

Table VII.2 Resolution and Range of Gas analyzer for the emission constituents

Quantity	Resolution	Range
Carbon Monoxide (CO)	0.001 %,	0%-15%, 0ppm-4000ppm
Carbon Dioxide (CO_2)	0.01%	0%-20%
Hydrocarbon (HC)	1 ppm	0ppm-30000ppm
Oxygen (O_2)	0.01%	0%-25%
Oxides of Nitrogen (NO_x)	1ppm	0ppm-5000ppm
Oxides of Sulphur (SO_x)	1ppm	0ppm-5000ppm