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# Experimental Uncertainty Analysis on Diesel Fired Boiler for Steam Turbine Test Rig

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**Abstract —** *Any experimental results would have some magnitude of error. This error is collective result of biased error and unavoidable random variation which comes with instrumental limitations and repetitive experimental observations. In order to calculate the error in result of an experiment, we need a substantial amount of observations to find it. However, economic and time constrains make it unfeasible to repeat the experiment number of times. Hence, there are some mathematical models which are used to calculate 'expected error' of derived parameters of an experiment.*

*Using one such model by Kline and McClintock, we have done uncertainty analysis on findings of an experiment on a diesel fired boiler for steam turbine test rig. The observation and findings used for analysis is collected from an experiment on a steam turbine test rig commissioned at The Department of Mechanical Engineering of M. S. University [1]. We have used Wolfram Mathematica software for the purpose of calculation.*

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***Keywords***- *Air mass flow rate, Direct Thermal Efficiency, Fuel mass flow rate, Kline and McClintock Method, Water mass flow rate*

## I. INTRODUCTION.

*Kline and McClintock uncertainty analysis is used to calculate uncertainty or 'probable error' of derived parameters. By taking reference of the experiment [1], we have calculated the average of 17 observation of each parameter. This average values are used in formulas created in using Wolfram Mathematica to calculate the uncertainty in mass flow rate of air, water and fuel. Finally, uncertainty in direct thermal efficiency is calculated. During the analysis, uncertainty in enthalpy due to supposed uncertainty in measuring pressure and temperature is neglected while measuring uncertainty in direct thermal efficiency.*

## II. OVERVIEW OF KLINE AND MCCLINTOCK'S METHOD.

A mathematical method of estimating uncertainty in experimental results has been presented by Kline and McClintock. The method is based on a careful specification of the uncertainties in the various primary experimental measurements. For example, a certain pressure reading might be expressed as P= 100 kN/m2 ± 1 kN/m2, where the plus or minus notation is used to designate the uncertainty, the person making this designation is stating in very precise terms the degree of accuracy with which he believes the measurement has been made. It should be noted that this specification is in itself uncertain because the experimenter is naturally uncertain about the accuracy of these measurements.

To add a further specification of the uncertainty of a particular measurement, Kline and McClintock proposed that the experimenter specify certain odds for the uncertainty. The above equation for pressure might thus be written

$P = 100\ kN/m2 \pm 1\ kN/m^2$ (20 to 1)

In other words, the experimenter is willing to bet with 20 to 1 odds that the pressure measurement is within ± 1 $kN/m^2$. It is important to note that the specification of such odds can only be made by the experimenter based on his total laboratory experience.

Suppose a set of measurements is made and the uncertainty in each measurement may be expressed with the same odds. These measurements are then used to calculate some desired result of the experiments. We wish to estimate the uncertainty in the calculated result on the basis of the uncertainties in the primary measurements. The result R is given function of the independent variables $X_1, X_2, X_3,\ldots\ldots., X_n$
Thus,

$R = R(X_1, X_2, X_3,\ldots\ldots., X_n)$

Let $W_R$ be the uncertainty in the result and $W_1$, $W_2$, $W_3$,….., $W_4$ be the uncertainties in the independent variables. If the uncertainties in the independent variables are all given with the same odds, then the uncertainty in the result can be given as:

$$w_R = \sqrt{\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \left(\frac{\partial R}{\partial x_3} w_3\right)^2 + \ldots\ldots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2} \quad [2]$$

Based on the above method of uncertainty analysis, the uncertainty in mass flow rate of air, mass flow rate of water and fuel flow rate is worked and presented here. Similar prediction for direct thermal efficiency can also be worked out.

## III. SOURCE OF UNCERTAINITY.

The section presents the uncertainty involved by virtue of the instrumentation error which can influence the reliability in estimating parameters like mass flow rate of air, water and fuel which further affects thermal efficiency is given in the Table 3.1

***Table 3.1. Sources of Uncertainty.***

| Sr. No. | Parameter | Uncertainty |
|---|---|---|
| 1. | Linear dimensions, $U_{Lin}$ | 1 mm |
| 2. | Diameter, $U_{Dia}$ | 1 mm |
| 3. | Velocity of the flow on airside, $U_{Vel}$ | 0.2 m s-1 |
| 4. | Temperature, $U_{Temp}$ | 0.1 ºC |
| 5. | Monomeric Pressure difference, $U_{Pr}$ | 0.1 PSI (0.6894 kPa) |
| 6. | Time, $U_{Time}$ | 1 s |

## IV. PAREMETERS: DESIGNATION AND DESCRIPTION. [1]

***Table 4.1. Physical parameters at setup.***

| Parameter | Description | Remark/ Value |
|---|---|---|
| $D_w$ | Diameter of water tank (mm) | 1350 mm |
| $L_f$ | Width of square fuel tank (mm) | 735 mm |
| $D_a$ | Diameter of air inlet duct for boiler (mm) | 150 mm |

***Table 4.2. Inlet air parameters.***

| Parameter | Description | Remark/ Value |
|---|---|---|
| $P_{a,1}$ | Barometric pressure of ambient air (bar) | 1.013 bar |
| $T_{a,1}$ | Temperature of ambient air (ºC) | 32 ºC |
| $R_{a,1}$ | Gas constant for air (J/kg k) | 287.058 J/kg k |
| $\rho_{a,1}$ | Density of air at boiler inlet (kg/m3) | 1.156 kg/$m^3$ |
| $A_{a,1}$ | Cross section area of air duct at boiler inlet ($m^2$) | 0.0086590 $m^2$ |
| $V_{a,1}$ | Velocity of air at entry of boiler (m/s) | |
| $m_{a,1}$ | Mass flow rate of air at the inlet of boiler (kg/s) | |

***Table 4.3. Feed water parameters.***

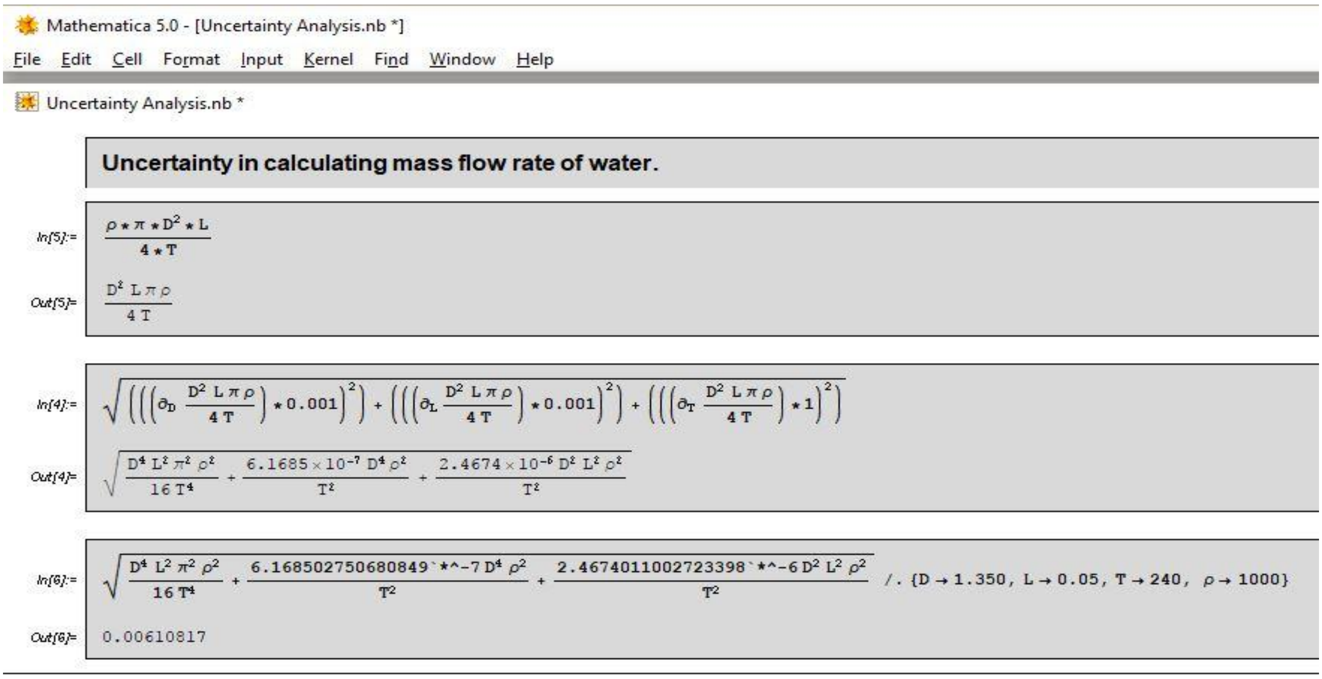
| Parameter | Description | Remark/ Value |
|---|---|---|
| $t_{w,1}$ | Time required to measure the change in the level of water tank (min) | |
| $\Delta L_{w,1}$ | Change of water level at the boiler feed water tank (cm) | |
| $m_{w,1}$ | Mass flow rate of feed water (kg/s) | |
| $\rho_{w,1}$ | Density of water (kg/m3) | 1000 kg/$m^3$ (Assumed) |

***Table 4.4. Fuel parameters.***

| **Parameter** | **Description** | **Remark/ Value** |
|---|---|---|
| $\Delta L_{f,1}$ | Change of fuel level at the boiler fuel feed tank (m) | |
| $t_{f,1}$ | Time required to measure the change in the level of fuel tank (min) | Same as $t_{w,1}$ |
| $m_{f,1}$ | Mass flow rate of fuel (kg/s) | |
| GC | Gross calorific value of fuel (kJ/kg) | 45,187 kJ/kg |
| $\rho_{f,1}$ | Density of fuel (kg/m$^3$) | 840 kg/m$^3$ (average.) |

## V. CALCULATIONS.

### 5.1. Sample calculation.



**Uncertainty in calculating mass flow rate of water.**

In[5]:= $\frac{\rho * \pi * D^2 * L}{4 * T}$

Out[5]= $\frac{D^2 L \pi \rho}{4 T}$

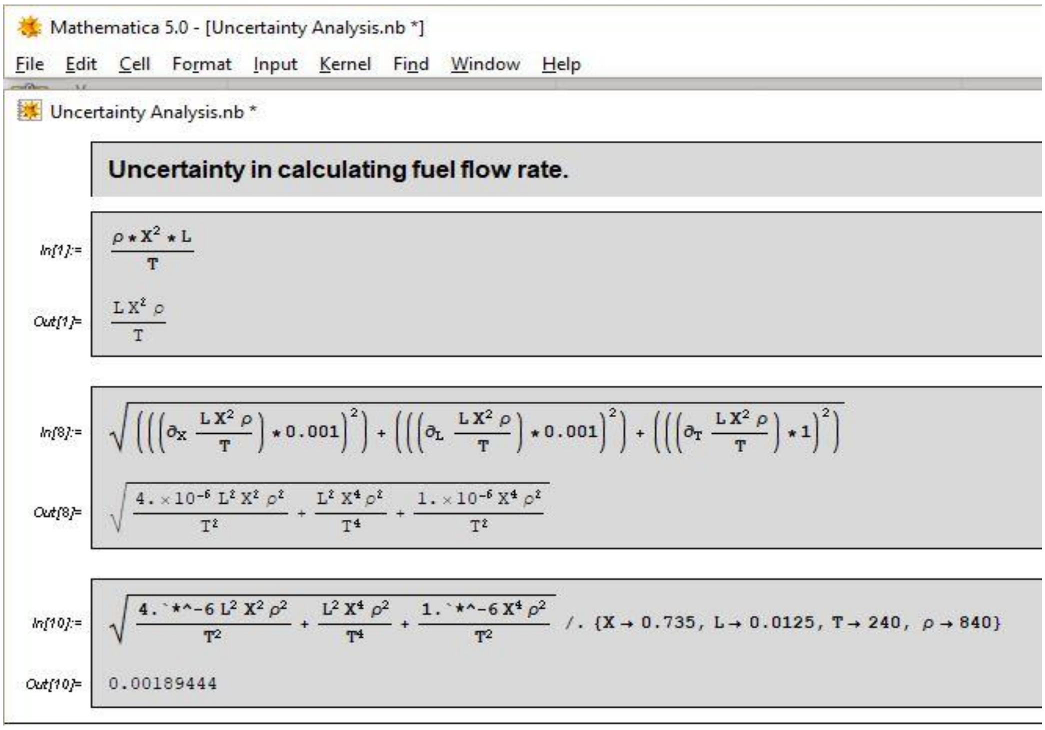
In[4]:= $\sqrt{\left(\left(\left(\partial_D \frac{D^2 L \pi \rho}{4 T}\right) * 0.001\right)^2\right) + \left(\left(\left(\partial_L \frac{D^2 L \pi \rho}{4 T}\right) * 0.001\right)^2\right) + \left(\left(\left(\partial_T \frac{D^2 L \pi \rho}{4 T}\right) * 1\right)^2\right)}$

Out[4]= $\sqrt{\frac{D^4 L^2 \pi^2 \rho^2}{16 T^4} + \frac{6.1685 \times 10^{-7} D^4 \rho^2}{T^2} + \frac{2.4674 \times 10^{-6} D^2 L^2 \rho^2}{T^2}}$

In[6]:= $\sqrt{\frac{D^4 L^2 \pi^2 \rho^2}{16 T^4} + \frac{6.168502750680849`*\hat{}-7 D^4 \rho^2}{T^2} + \frac{2.4674011002723398`*\hat{}-6 D^2 L^2 \rho^2}{T^2}}$ /. {D → 1.350, L → 0.05, T → 240, ρ → 1000}

Out[6]= 0.00610817

*Figure 5.1. Uncertainty in calculating mass flow rate of water.*



**Uncertainty in calculating fuel flow rate.**

In[1]:= $\frac{\rho * X^2 * L}{T}$

Out[1]= $\frac{L X^2 \rho}{T}$

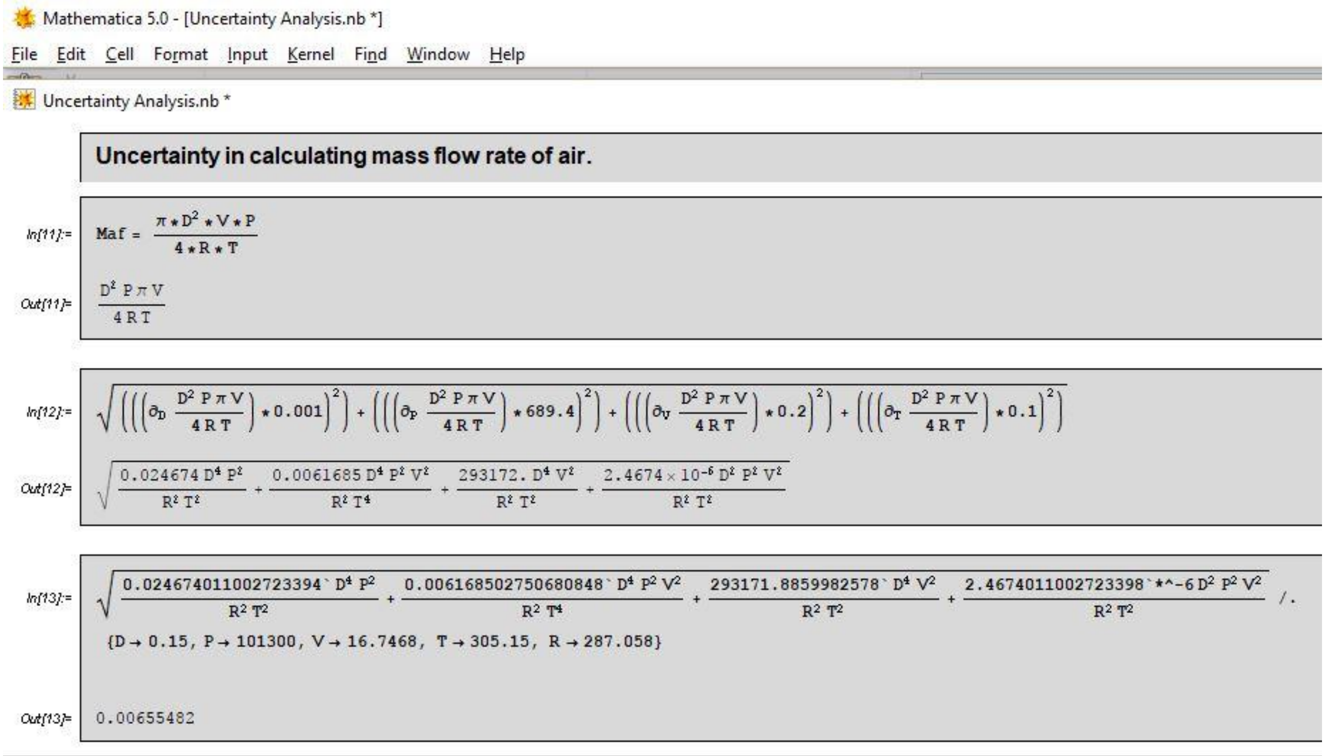
In[8]:= $\sqrt{\left(\left(\left(\partial_X \frac{L X^2 \rho}{T}\right) * 0.001\right)^2\right) + \left(\left(\left(\partial_L \frac{L X^2 \rho}{T}\right) * 0.001\right)^2\right) + \left(\left(\left(\partial_T \frac{L X^2 \rho}{T}\right) * 1\right)^2\right)}$

Out[8]= $\sqrt{\frac{4. \times 10^{-6} L^2 X^2 \rho^2}{T^2} + \frac{L^2 X^4 \rho^2}{T^4} + \frac{1. \times 10^{-6} X^4 \rho^2}{T^2}}$

In[10]:= $\sqrt{\frac{4.`*\hat{}-6 L^2 X^2 \rho^2}{T^2} + \frac{L^2 X^4 \rho^2}{T^4} + \frac{1.`*\hat{}-6 X^4 \rho^2}{T^2}}$ /. {X → 0.735, L → 0.0125, T → 240, ρ → 840}

Out[10]= 0.00189444

*Figure 5.2. Uncertainty in calculating fuel flow rate.*



**Uncertainty in calculating mass flow rate of air.**

In[11]:=
$$\text{Maf} = \frac{\pi * D^2 * V * P}{4 * R * T}$$

Out[11]=
$$\frac{D^2\, P\, \pi\, V}{4\, R\, T}$$

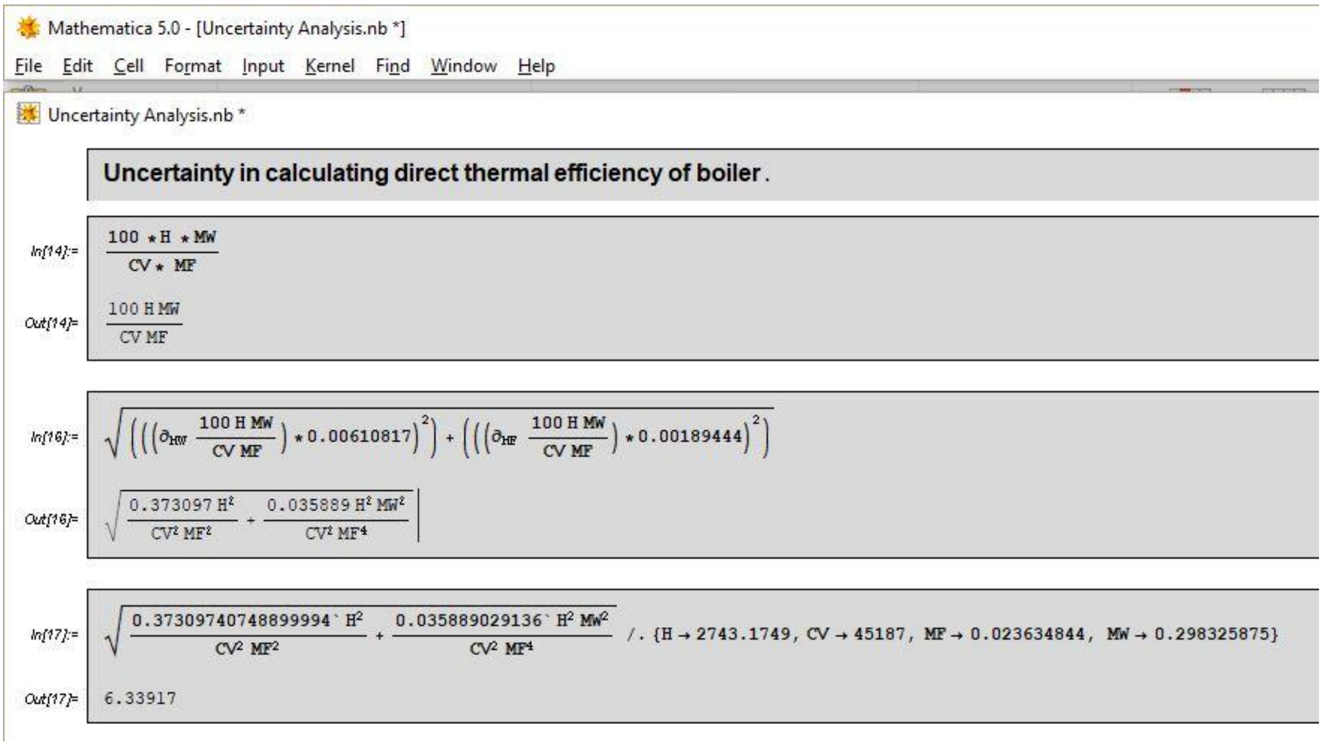
In[12]:=
$$\sqrt{\left(\left(\left(\partial_D \frac{D^2\, P\, \pi\, V}{4\, R\, T}\right) * 0.001\right)^2\right) + \left(\left(\left(\partial_P \frac{D^2\, P\, \pi\, V}{4\, R\, T}\right) * 689.4\right)^2\right) + \left(\left(\left(\partial_V \frac{D^2\, P\, \pi\, V}{4\, R\, T}\right) * 0.2\right)^2\right) + \left(\left(\left(\partial_T \frac{D^2\, P\, \pi\, V}{4\, R\, T}\right) * 0.1\right)^2\right)}$$

Out[12]=
$$\sqrt{\frac{0.024674\, D^4\, P^2}{R^2\, T^2} + \frac{0.0061685\, D^4\, P^2\, V^2}{R^2\, T^4} + \frac{293172.\, D^4\, V^2}{R^2\, T^2} + \frac{2.4674 \times 10^{-6}\, D^2\, P^2\, V^2}{R^2\, T^2}}$$

In[13]:=
$$\sqrt{\frac{0.024674011002723394`\, D^4\, P^2}{R^2\, T^2} + \frac{0.006168502750680848`\, D^4\, P^2\, V^2}{R^2\, T^4} + \frac{293171.8859982578`\, D^4\, V^2}{R^2\, T^2} + \frac{2.4674011002723398`{*}\text{^}{-6}\, D^2\, P^2\, V^2}{R^2\, T^2}}\ /.$$
$$\{D \to 0.15,\ P \to 101300,\ V \to 16.7468,\ T \to 305.15,\ R \to 287.058\}$$

Out[13]= 0.00655482

Figure 5.3. Uncertainty in calculating mass flow rate of air.



**Uncertainty in calculating direct thermal efficiency of boiler.**

In[14]:=
$$\frac{100 * H * MW}{CV * MF}$$

Out[14]=
$$\frac{100\, H\, MW}{CV\, MF}$$

In[16]:=
$$\sqrt{\left(\left(\left(\partial_{MW} \frac{100\, H\, MW}{CV\, MF}\right) * 0.00610817\right)^2\right) + \left(\left(\left(\partial_{MF} \frac{100\, H\, MW}{CV\, MF}\right) * 0.00189444\right)^2\right)}$$

Out[16]=
$$\sqrt{\frac{0.373097\, H^2}{CV^2\, MF^2} + \frac{0.035889\, H^2\, MW^2}{CV^2\, MF^4}}$$

In[17]:=
$$\sqrt{\frac{0.37309740748899994`\, H^2}{CV^2\, MF^2} + \frac{0.035889029136`\, H^2\, MW^2}{CV^2\, MF^4}}\ /.\ \{H \to 2743.1749,\ CV \to 45187,\ MF \to 0.023634844,\ MW \to 0.298325875\}$$

Out[17]= 6.33917

Figure 5.4. Uncertainty in calculating direct thermal efficiency of boiler.

## 5.2. Result Table.

***Table 5.1. Uncertainty in calculating mass flow rate of water.***

| **Uncertainty in Mass Flow Rate of Water - Mw (kg/s)** | | | |
|---|---|---|---|
| **Sr. No.** | **Calculated Value (kg/s)** | **Uncertainty (kg/s)** | **Probable Error (%)** |
| 1 | 0.298325875 | 0.00610817 | 2.047482472 |
| 2 | 0.298325875 | 0.00610817 | 2.047482472 |
| 3 | 0.35799105 | 0.00617049 | 1.72364365 |
| 4 | 0.2386607 | 0.00605671 | 2.537791098 |
| 5 | 0.298325875 | 0.00610817 | 2.047482472 |
| 6 | 0.298325875 | 0.00610817 | 2.047482472 |
| 7 | 0.2386607 | 0.00605671 | 2.537791098 |
| 8 | 0.35799105 | 0.00617049 | 1.72364365 |
| 9 | 0.298325875 | 0.00610817 | 2.047482472 |
| 10 | 0.298325875 | 0.00610817 | 2.047482472 |
| 11 | 0.298325875 | 0.00610817 | 2.047482472 |
| 12 | 0.298325875 | 0.00610817 | 2.047482472 |
| 13 | 0.298325875 | 0.00610817 | 2.047482472 |
| 14 | 0.298325875 | 0.00610817 | 2.047482472 |
| 15 | 0.298325875 | 0.00610817 | 2.047482472 |
| 16 | 0.298325875 | 0.00610817 | 2.047482472 |

***Table 5.2. Uncertainty in calculating fuel flow rate.***

| **Uncertainty in Mass Flow Rate of Fuel - Mf (kg/s)** | | | |
|---|---|---|---|
| **Sr. No.** | **Calculated Value (kg/s)** | **Uncertainty (kg/s)** | **Error (%)** |
| 1 | 0.024580238 | 0.00189474 | 7.708387683 |
| 2 | 0.026471025 | 0.00189537 | 7.160168524 |
| 3 | 0.024580238 | 0.00189474 | 7.708387683 |
| 4 | 0.02268945 | 0.00189416 | 8.34819707 |
| 5 | 0.028361813 | 0.00189605 | 6.685221546 |
| 6 | 0.02268945 | 0.00189416 | 8.34819707 |
| 7 | 0.024580238 | 0.00189474 | 7.708387683 |
| 8 | 0.026471025 | 0.00189537 | 7.160168524 |
| 9 | 0.026471025 | 0.00189537 | 7.160168524 |
| 10 | 0.0151263 | 0.00189229 | 12.50993303 |
| 11 | 0.0151263 | 0.00189229 | 12.50993303 |
| 12 | 0.026471025 | 0.00189537 | 7.160168524 |
| 13 | 0.024580238 | 0.00189474 | 7.708387683 |
| 14 | 0.026471025 | 0.00189537 | 7.160168524 |
| 15 | 0.02268945 | 0.00189416 | 8.34819707 |
| 16 | 0.020798663 | 0.00189362 | 9.104527755 |

***Table 5.3. Uncertainty in calculating mass flow rate of air.***

| **Uncertainty in Mass Flow Rate of Air - Ma (kg/s)** | | | |
|---|---|---|---|
| **Sr. No.** | **Calculated Value (kg/s)** | **Uncertainty (kg/s)** | **Error (%)** |
| 1 | 0.340266536 | 0.006531683 | 1.919578344 |
| 2 | 0.380117571 | 0.007007072 | 1.843395882 |
| 3 | 0.356615679 | 0.006724375 | 1.885608313 |
| 4 | 0.338222893 | 0.006507843 | 1.924128332 |
| 5 | 0.410976579 | 0.007387297 | 1.797498396 |
| 6 | 0.352528393 | 0.006675882 | 1.893714624 |
| 7 | 0.299393679 | 0.006066414 | 2.026233322 |
| 8 | 0.40198455 | 0.007275525 | 1.809901694 |
| 9 | 0.3805263 | 0.007012044 | 1.842722442 |
| 10 | 0.233997107 | 0.005383406 | 2.300629473 |
| 11 | 0.224800714 | 0.005294821 | 2.355339796 |
| 12 | 0.37909575 | 0.00699465 | 1.845087936 |
| 13 | 0.355593857 | 0.006712232 | 1.887611946 |
| 14 | 0.358659321 | 0.006748699 | 1.881646036 |
| 15 | 0.345375643 | 0.006591528 | 1.908509669 |
| 16 | 0.317786464 | 0.006272668 | 1.973862438 |

***Table 5.4. Uncertainty in calculating direct thermal efficiency of boiler.***

| **Uncertainty in Direct Thermal Efficiency (%)** | | | |
|---|---|---|---|
| **Sr. No.** | **Calculated Value (%)** | **Uncertainty (%)** | **Error (%)** |
| 1 | 68.41638988 | 5.092767322 | 7.443782596 |
| 2 | 88.41502692 | 6.97928217 | 7.893773731 |
| 3 | 63.85529722 | 5.576410022 | 8.732885547 |
| 4 | 63.85529722 | 4.461128017 | 6.986308437 |
| 5 | 79.81912152 | 6.861900142 | 8.596812406 |
| 6 | 58.94335128 | 4.78679231 | 8.121004669 |
| 7 | 82.09966785 | 6.040268053 | 7.357238112 |
| 8 | 68.41638988 | 5.092767322 | 7.443782596 |
| 9 | 119.7286823 | 15.19405692 | 12.69040687 |
| 10 | 119.7286823 | 15.19405692 | 12.69040687 |
| 11 | 68.41638988 | 5.092767322 | 7.443782596 |
| 12 | 73.6791891 | 5.875545095 | 7.974497503 |
| 13 | 68.41638988 | 5.092767322 | 7.443782596 |
| 14 | 79.81912152 | 6.861900142 | 8.596812406 |
| 15 | 87.0754053 | 8.129150816 | 9.335759952 |
| 16 | 76.62635666 | 6.339166767 | 8.272828101 |

## VI. CONCLUSION

Table 5.1. to table 5.4. shows the uncertainty observed in the experiment due to virtue of limitations of measurement techniques. Using Kline and McClintock model of uncertainty analysis, it is concluded that the average uncertainty in measurement of mass flow rate of water is 2.068%, that of fuel is 8.280% and that of air is 1.943%. Uncertainty in mass flow rate of water and fuel resulted into amplified uncertainty in measurement of direct thermal efficiency which is 8.56%.

Also, in table 5.2., it is observed that there is an abrupt rise of uncertainty in measurement of mass flow rate of fuel for observation 9th and 10th (marked red). This is the repercussion of heat inertia of boiler. This abnormity is reflected in corresponding calculation of uncertainty in measurement of direct thermal efficiency in table 5.4 (marked red).

## REFERENCES

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