Particulate Matter measurement of a Two-Stage Boiler

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Abstract

The goal of this project is to develop an technique to measure the PM produced by a two-stage wood based boiler in an inexpensive manner while still preserving high degree of accuracy. The general idea involved in the process involves sampling of the exhaust gas using a vacuum pump. A filter paper with a permeability of $2\mu m$ is used to capture $PM_{2.5}$ present in the exhaust. The sampled data is measured and PM content is presented in per million parts of the exhaust, at different intervals during the operation of the boiler. The results demonstrate the high water content of the flue gas, as is evident by the water dominates the mass of the residue immediately after the sampling. From dry samples, it can be inferred from that the highest PM production takes place during the initial few minutes of the exhaust while the least amount of PM is generated near the mid-point of the boiler run time.

I. Introduction

With the rising awareness of global climate change and the role emissions plays into it, measurement and reduction of all kinds of pollutants has become one of the most important issues of recent times. The automobile industry has been the front runner in emission control reforms for a long time but other industries are catching up as emission control becomes more stringent day by day. Soot is one of the most obvious and harmful products of most combustion processes. Etymologically, it means - that which sits on something i.e. a film that settles on a surface. In almost all cases, soot is product of some type of pyrolysis. Higher the soot content, more inefficient the combustion.

Epidemiological studies have proved that long term exposure to elevated levels of soot may lead to pulmonary diseases and is classified as highly carcinogenic. The general conclusion to be drawn from the health studies on ambient particle concentration is that fine particles, $PM_{2.5}$, (aerodynamic diameter$\leq 2.5\mu m$) are more harmful than larger ones [12][11]. Ultra-fine particles ($\leq 100nm$) would be most harmful fraction of particulate matter as the may penetrate deep into alveolar region of lungs and enter blood circulation. Apart from being an environmental pollutant and a health risk, emission of high amounts of soot from any combustion process indicates inefficient combustion and loss of useful energy.

Resident wood combustion (RWC), a collective term used to refer to the burning of wood in fireplaces, wood stoves, boilers at home, accounted for 7.0% of of the $PM_{2.5}$ emissions in US [14][5]. In rural New York, contribution of RWC to $PM_{2.5}$ is as high as 90% [1]. The major components of the wood smoke emitted by RWC are carbon monoxide (CO), $PM_{2.5}$, nitrogen oxides, sulfur oxides and other organic gases. Particulate Matter is primarily composed of Elemental Carbon (EC), solid or liquid organic compounds, traces of K, S, Cl and inorganic ash [14]. The soot and organic material are formed primarily because of incomplete combustion. The organic material is formed when organic vapors from the exhaust condense

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to particle phase. Soot particles, however are formed in the fool rich area of the flame through some complex mechanisms involving formation of soot nuclei from gaseous hydrocarbons and particle growth by surface reactions, coagulation and agglomeration [12] [2]. Amount of soot in the flue gas is generally lower in larger combustion appliances with long residence times. Also, secondary particle formation takes place in the atmosphere by the gaseous emissions such as SO_2 and NO_x. In pure wood combustion, the fine fly ash is primarily composed of potassium sulphates, chlorides and carbonates [12].

There have been numerous methods over the years that have been used to measure soot with varying degree of success and accuracy. Few methods that have been used in the past to measure soot are:

- **Aethalometer:** An aethalometer is an instrument which collects airborne particulate matter on a filter whilst continuously measuring its light transmission. The instrument generally involves a tape of filter paper through which the concerned gas is passed and the particulate matter is allowed to accumulate on a spot until a particular loading level or time is reached. The spot is then moved and a change in attenuation is observed due to black carbon deposit by passing a near infrared light through it. This data is then converted to black carbon concentration. Many studies have shown the results thus obtained to be in good agreement with the experimental data.[6]

- **Infrared (FT-IR) analysis:** It is one of the most common method used to measure soot level. The main criterion for using infrared is its low cost of operation and the ability to measure several other components in the same procedure. It is a relatively acceptable indicator of soot, provided that the soot content is $\leq 1.5\%$. Higher soot content can block out the soot transmission and reduce the detection range[16].

- **Thermogravimetric Analysis (TGA):** TGA measures the weight change of a material as a function of temperature. TGA basically measures carbon present in the sample. Since soot is primarily carbon, TGA was the most accurate representation for many years[16]. The complexity of the procedure and high cost of operation makes this process not a very popular choice in most circles.

- **Light Extinction Measurement(LEM):** In LEM, broadband white light is used. The white light is used to avoid molecular resonance Should a degree of resonance appear, the broad band eleminates any significant errors. The measurement of soot is accomplished directly within the sample, there is no need for separation of particulate matter. It also felicitates measurement of extreme soot content (with introduction of fresh dispersant additives). The accuracy of this method rivals that of TGA[16].

- **Laser Induced Incandescence (LII):** LII is a promising technology that is proving to be reliable in spatial and temporal measurement of soot volume fraction and soot particle size. The fundamental idea behind LII is that soot volume fraction can be determined if the absolute spectral intensity of he incandescence signal emitted bu from

the laser heated soot particles is measured and the temperature of the soot particles is known. In order to measure the LII intensity, the detection system must be calibrated by using a radiation source of known radiance[13].
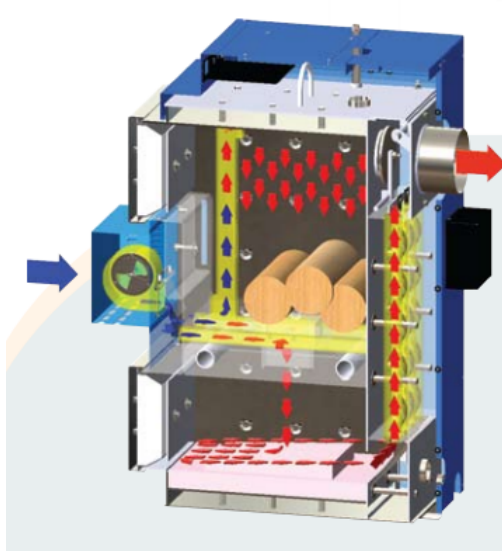

Figure 1: *EBW-200 boiler*

The system under observation is a Econoburn™EBW-200 boiler. It is a boiler with wood as the fuel, where the combustion takes place in two stages as demonstrated in fig. 1. As wood is burned in the firebox, fresh air is blown downward through the logs and coals. This hot smoke and air mixture is forced into the combustion chamber and mixed with a second jet of super-heated air creating a torch-like combustion of the retained gases - a process called wood gasification.
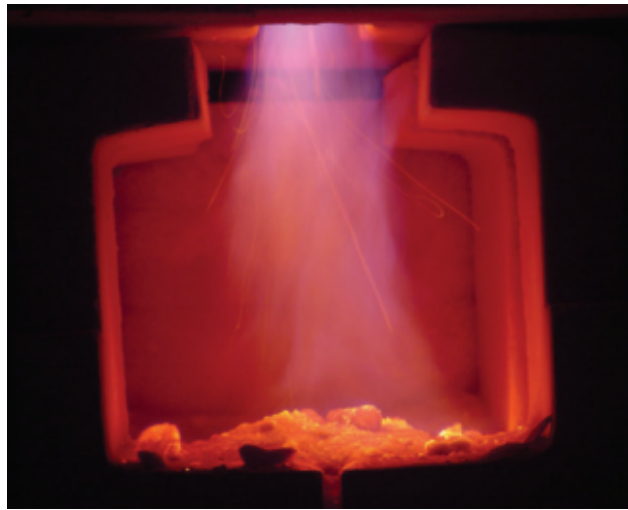

Figure 2: *Blow torch like flame produced in stage 2 of the boiler*

These boilers are started by using kindling and smaller pieces of firewood in the boiler's upper chamber with an upward draft. However, once the fire in the upper chamber is stable, the firebox is loaded to capacity, the upper damper is closed and a blower turns on to redirect the pyrolysis gases being emitted by the heated wood in a downward direction, as shown in fig. 1. These gases pass through a slot in a ceramic grate at the base of the combustion chamber. Air, pressurized by the blower, is also forced through holes in the side of this slot and mixes with the hot gases. The resulting combustion is intense, often reaching temperatures over 2000°F and having the appearance of a blow torch, as seen in fig. 2. This form of combustion results in very little residue[4].
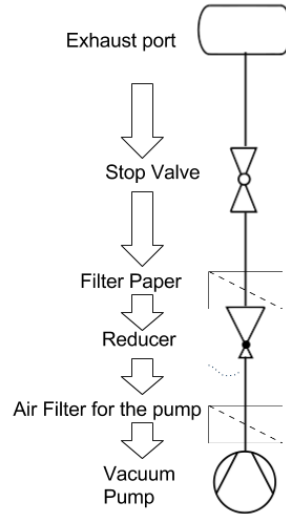
II.   Methodology

Figure 3: *Schematic of proposed process*

The general idea involved in this study is to physically extract the exhaust gases of the boiler by means of a vacuum pump. These gases would then be passed through a filter paper with porosity $\leq 2\mu m$. This will result in all $PM_{2.5}$ and larger particles would get trapped on the filter paper. The residue is then measured to determine the PM content of the exhaust. The process is demonstrated in fig. 3.
A CAD of the apparatus was prepared and is presented in fig. 4. The filter paper mount was designed in such way that it was secured by rubber-o rings. Special care was taken in order to make the design modular in order to felicitate quick filter change and more data collection during the course of a boiler run.
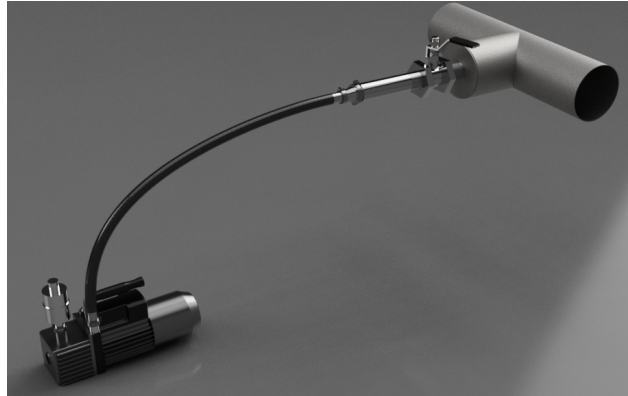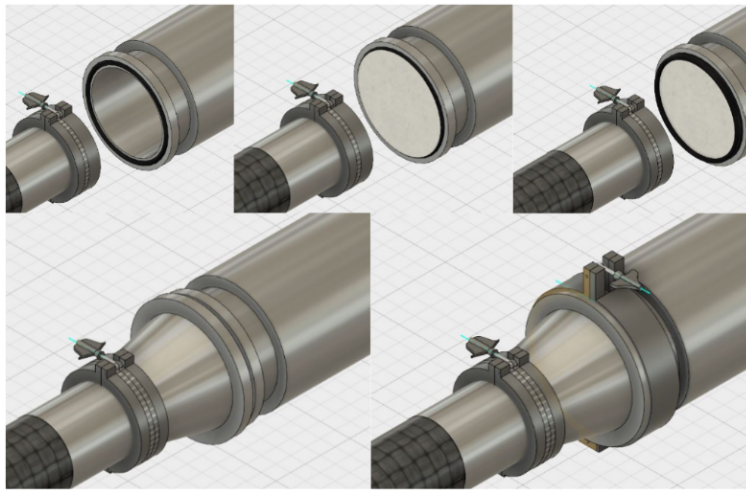
Figure 4: *CAD of the apparatus*

Figure 5: *Filter paper assembly*

Due to the high suction pressure of the vacuum pump, the cellulose based filter paper had to be supported with a metal wire mesh during experimentation. Since water vapor is one of the major constituents of the exhaust gas, the mass of the residue on the filter paper immediately after the sampling would be largely dominated by the water condensation. Also, carbon particles in soot also adsorb water molecules present in ambient air, the readings would again be skewed by the mass of water. Hence, it was imperative to fabricate a container where the filter paper would be suspended and dried completely before taking observations. For this purpose, an aluminum box was fabricated where the paper was suspended and heated to a temperature which was just below the upper limit of its temperature tolerance (150 ℃). Figure 6 shows the complete set up.
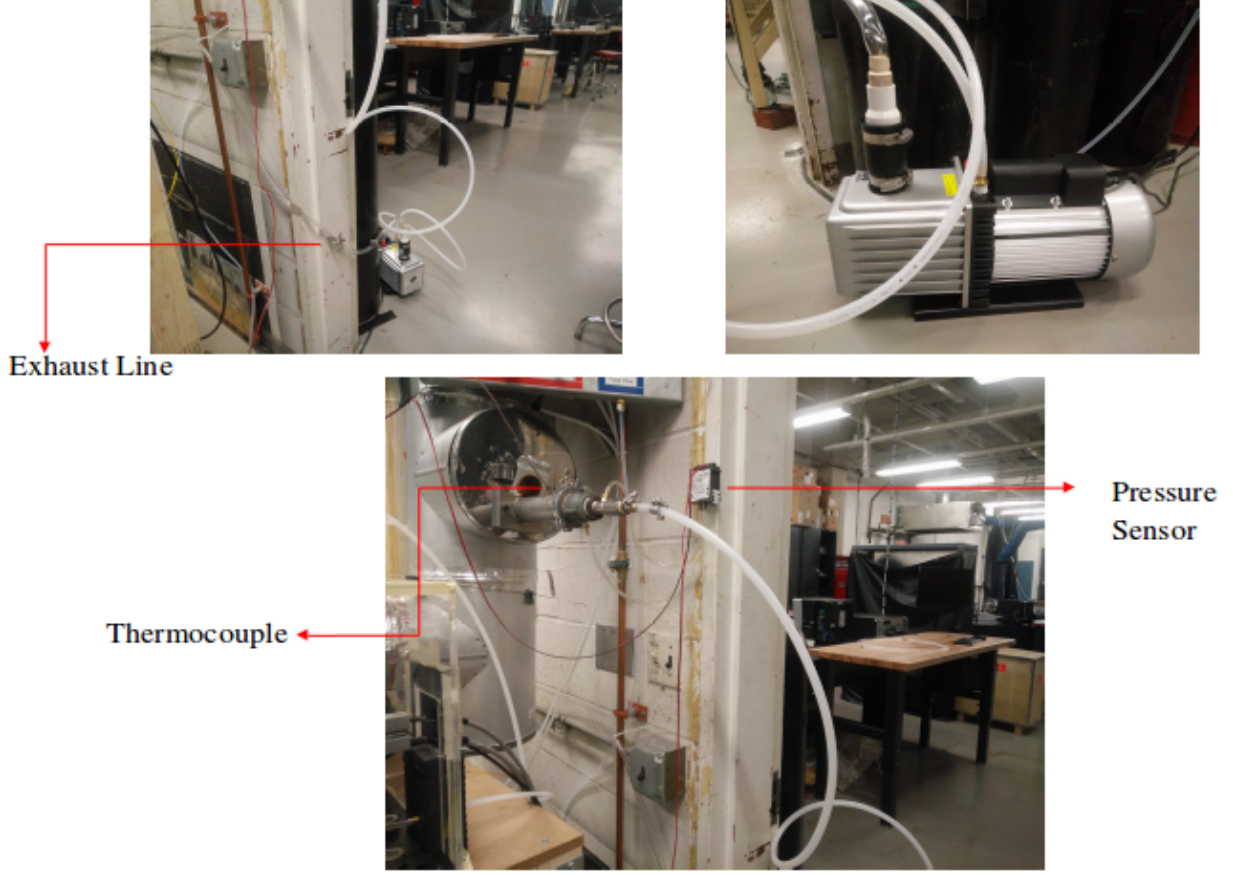
Figure 6: *Apparatus used to carry out the study*

I. Calibration

To determine the volume fraction of the soot content, we need to know the volumetric flow rate of the exhaust gas through the apparatus. The venturi section of the apparatus is not as per ASME standards hence, we had to calibrate it using a venturi that met the ASME standards. Determination of the exact flow rate from the pressure drop across the venturi is an iterative process because the Coefficient of discharge (C_D) is different at each flow rate. Hence, with the iterative process, we determine the C_D and that helps in determining the flow rate. Co-relating the flow rate, the pressure drop across the ASME venturi and the pressure drop across the venturi section of our apparatus, a calibration curve was obtained. The curve is presented in fig. 7 and it was used to accurately determine the flow rate of the exhaust gas passing through the apparatus. The formulae used for the calculations are given by eq. 1 - eq. 9 [8]:

$$x = RH\frac{6.112 \times e^{\frac{17.62t}{243.12 + t}}}{461.5T} \tag{1}$$

$$x_m = 1.61x; \tag{2}$$

$$\mu_a \times 10^6 = 0.40401 + 0.074582T - 5.7171 \times 10^{-5} \times T^2$$
$$+2.9928 \times 10^{-8} \times T^3 - 6.2524 \times 10^{-12} \times T^4 \tag{3}$$

$$\mu_v \times 10^6 = \frac{\sqrt{\frac{T}{647.27}}}{0.0181583 + 0.0177624 \times \frac{647.27}{T}}$$
$$+0.0105287 \times \left(\frac{647.27}{T}\right)^2 - 0.0036744 \times \left(\frac{647.27}{T}\right)^3 \tag{4}$$

$$\phi_{av} = \frac{\left[1 + \left(\frac{\mu_a}{\mu_v}\right)^{0.5} \times \left(\frac{m_v}{m_A}\right)^{0.25}\right]^2}{2\sqrt{2} \times \left(1 + \frac{m_A}{m_v}\right)^{0.5}} \tag{5}$$

$$\phi_{va} = \frac{\left[1 + \left(\frac{\mu_v}{\mu_a}\right)^{0.5} \times \left(\frac{m_A}{m_v}\right)^{0.25}\right]^2}{2\sqrt{2} \times \left(1 + \frac{m_v}{m_A}\right)^{0.5}} \tag{6}$$

$$\mu = \frac{\mu_a}{1 + \phi_{av} \times x_m} + \frac{\mu_v}{1 + \frac{\phi_{va}}{x_m}} \tag{7}$$

$$\rho = \frac{1 + x}{461.56 \times (0.62198 + x)} \times \frac{P}{T} \tag{8}$$

$$Re = \frac{D}{\mu}\sqrt{\frac{2\rho\Delta P}{1 - \beta^4}} \tag{9}$$

where,
RH = Relative Humidity,
x = Absolute Humidity,

t= Temperature (℃),
T= Temperature (K),
μ=Dynamic Viscosity,
ρ=Density,
Re=Reynolds Number,
D=Throat diameter,
ΔP=Pressure Drop from inlet to throat,
β=Ratio of throat to inlet diameter

Using the relationship between β and Re provided by Hollingshead *et. al* [7], the Coefficient of Discharge, C_D, was computed iteratively using eq. 10. With the final C_D, Re, Volumetric Flow Rate as well as mass flow rate relationships were established for the apparatus.

$$Re = \frac{C_D D}{\mu} \sqrt{\frac{2\rho\Delta P}{1 - \beta^4}} \tag{10}$$
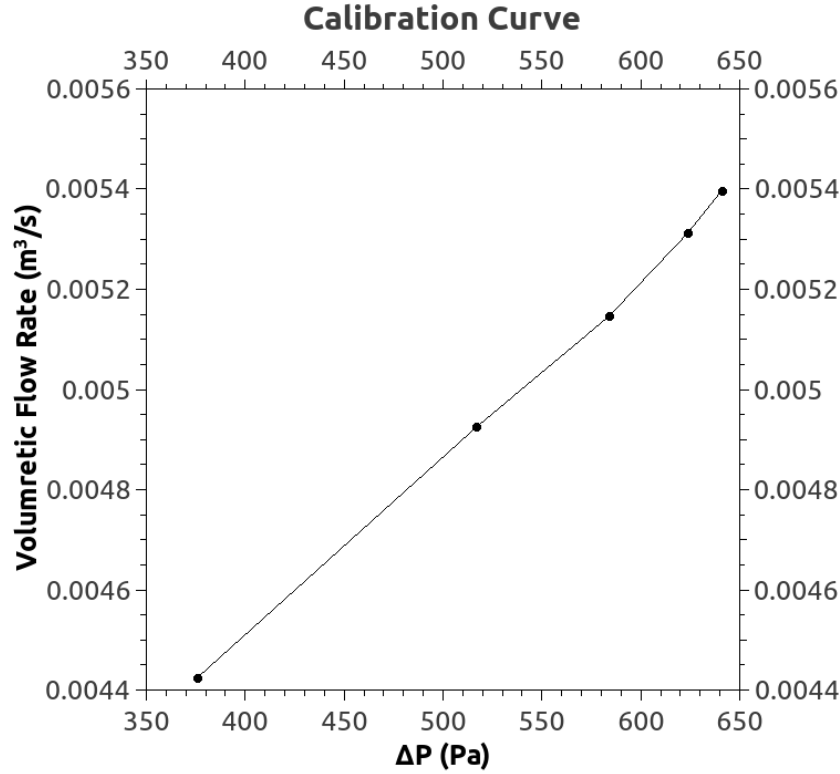

Figure 7: *Calibration curve*

II. Calculations

Immediately after the sampling, the mass of the filter paper was measured from which mass of the residue was computed by subtracting the mass of the filter paper prior to the sampling. Then using eq. 11, the mass fraction of the wet residue was computed. The filter paper was dried and the mass fraction of the dried residue was computed.

$$Mass\ Fraction\ of\ PM = \frac{Mass\ of\ PM}{Mass\ of\ Exhaust + Mass\ of\ PM} \tag{11}$$

The mole fractions, χ, of the components of the exhaust gas was used to compute the molecular weight of the exhaust using eq. 12:

$$MW = \Sigma \chi_i MW_i \tag{12}$$

Since, the mass of the residue is dominated by carbon, the molar mass of the residue is assumed to be 12 g/mole. Then, using eq. 13, moles of PM and moles of Exhaust gas were determined.

$$n = \frac{Total\ Mass}{MW} \tag{13}$$

Taking ratio of Moles of PM to Moles of exhaust gas, we obtained the PM content in parts per million parts of exhaust gas. The results are presented in the next section.

III. RESULTS

The measured mass of wet residue (M_{Wet}) and dry residue (M_{Dry}) are presented in Table 1. The respective Mass fractions are presented in Table 2 (Y_{Wet} and Y_{Dry} respectively), where T_{start} and T_{end} denote start and end time of the sampling period. The plot for the same is presented in fig. 8.

Table 1: *Mass of residue on the filter paper*

Sr No.	T_{start}(hr)	T_{end}(hr)	M_{Wet}(g)	M_{Dry}(g)
1	0.2	0.8	0.048	0.023
2	1.1	1.7	0.106	0.038
3	2.3	2.8	0.042	0.024
4	3.1	3.5	0.01	0.003
5	3.8	4.8	0.009	0.007
6	4.9	5.7	0.002	0.005

Table 2: *Mass Fraction of PM*

Sr No.	T_{start}(hr)	T_{end}(hr)	Y_{Wet}	Y_{Dry}
1	0.2	0.8	1.01×10^{-5}	4.9×10^{-6}
2	1.1	1.7	2.7×10^{-5}	9.9×10^{-6}
3	2.3	2.8	1.2×10^{-5}	6.6×10^{-6}
4	3.1	3.5	4.6×10^{-6}	1.3×10^{-6}
5	3.8	4.8	2.9×10^{-6}	2.3×10^{-6}
6	4.9	5.7	6.8×10^{-7}	1.7×10^{-6}

As is evident from the plot, water constitutes a major fraction of the mass of the wet residue. The plot of wet PM therefore shows the trend of water content more closely than that of PM content. The plot of dry PM presents a much more accurate trend of PM production by the boiler at the respective intervals during its operation. Table 3 presents the PM content in the exhaust gas and fig. 9 presents plot for the same.
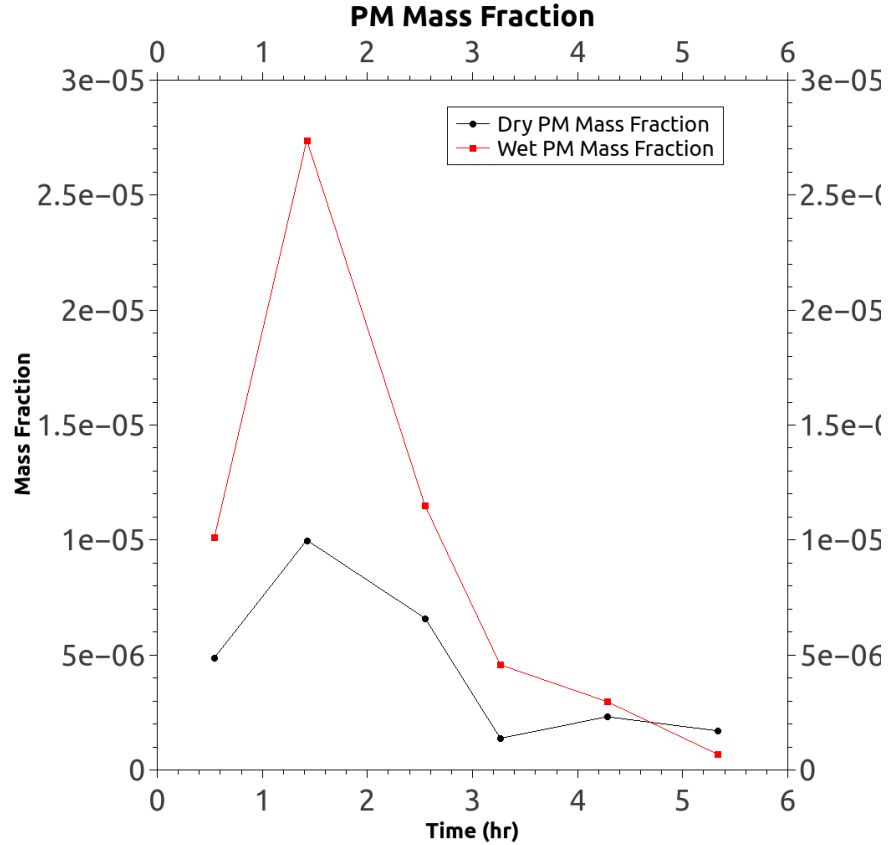

Figure 8: *Mass fraction of wet PM and dry PM deposit on filter paper*

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Table 3: *PM containt per million parts of exhaust gas*

Sr No.	T_{start}(hr)	T_{end}(hr)	Soot Content (ppm)
1	0.2	0.8	11.61
2	1.1	1.7	4.49
3	2.3	2.8	4.66
4	3.1	3.5	3.31
5	3.8	4.8	5.58
6	4.9	5.7	4.08

As fig. 9 shows, the soot production during the initial period of operation of the boiler is significantly higher than during the later periods, as expected. This can be attributed to the soot generation due the initial light up smoke and the fuel rich combustion during this period. The second data point in fig. 8 shows a sharp spike in the wet PM mass fraction plot. This was due to the high water content of the exhaust during that particular period, and was confirmed by the high mole fraction water in that interval. The lowest PM generation is observed during the halfway point of the runtime of the boiler which can be a result of lean combustion taking place during that period. The PM content thereafter is low yet higher than the mid point value. This can be attributed to the fly ash mixed with the exhaust gas after complete combustion of the fuel during that interval.
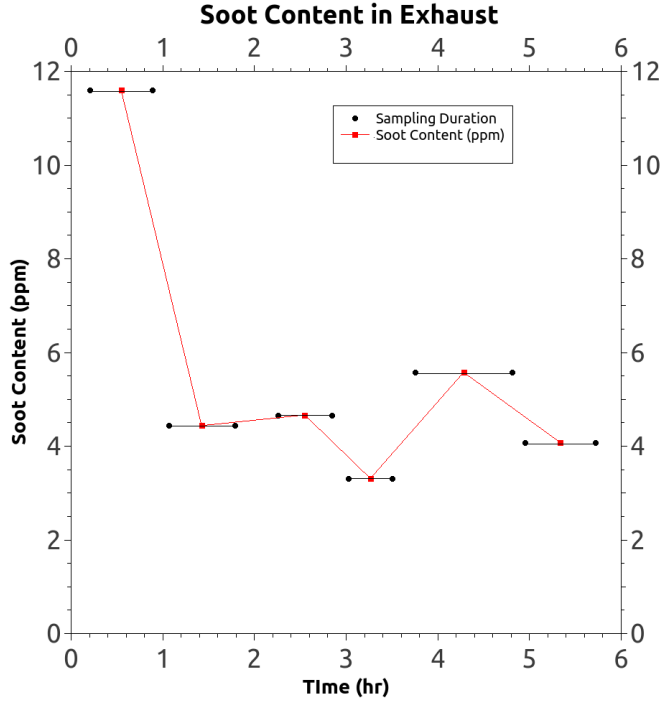

Figure 9: *Soot content in the exhaust gas expressed in parts per million*

IV. Conclusion

The experiments were carried out successfully and the data was presented in a form that gives a general idea of PM production during the operation of the boiler. From the data it can be inferred that maximum PM generation is observed during the first in the first few minutes of the boiler operation. The PM production the drops down significantly owing to a lean combustion of the wood. The lowest PM output is observed during the mid point of the boiler runtime. The PM content then increases slightly due to fly as mixed in with the exhaust. Overall, the results were satisfactory and show a trend that was expected for the process. The whole procedure demonstrated the ability to measure the PM content in an inexpensive manner while still preserving high degree of accuracy in the results.

I. Suggestions for Future Work

- Exhaustive trials with the apparatus to establish the repeatability of the results.

- Corroboration of results with results obtained with some other technique, say, by using a Tunable diode laser absorption spectroscopy (TDLAS) setup.

- Using a pure solvent (that leaves no residue) in order to include whatever minuscule amount of PM is deposited in the pipe section of the apparatus, while computing the total PM content. This additional step is not expected to influence the results in a significant manner but it should be performed in future studies in order to remove any uncertainties.

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