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Investigation of Optimal Dilution Ratio from a Dilution Tunnel Using in Particulate Matter Measurement

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Abstract- Combustion of fuels leads to the formation of gaseous and particulate matter pollutants that have an impact on air quality and the environment. Comparison to the gaseous emissions from stack, measuring of particulate matter (PM) needs extra attention because particles do not behave as a continuum. Dilution tunnels are used with the PM measuring instruments to dilute the hot exhaust gases leaving from the stack. The main focus of this study was to investigate the dilution ratio results obtained from a partial flow dilution tunnel. The partial flow dilution system consists of a porous tube diluter, an ejector diluter and an air heater. The dilution air flow settings into the porous tube diluter and ejector diluter are selected for a wide range of dilution ratios. Two mass flow controllers were used to regulate the flow of dilution air into the diluters. The experiments were conducted at the Renewable Energy Laboratory of the Vrije Universiteit Brussel (VUB).There were a total of fifteen experiments with four flow settings conducted. Dilution ratio (DR) is evaluated based on the ratio of the CO_2 (dry) concentration in the raw sample to the diluted sample. The results obtained from the experiments with the partial flow diluters are limited between 34 and 110. The experimental results are also compared with other works and found quite similar.

Indexed Terms- Dilution ratio, porous tube diluter, ejector diluter, air flow, dilution tunnel

I. INTRODUCTION

Energy is present in nature in various forms. The energy is supplied for the mankind uses through the combustion of different fuels such as natural gas, coal, diesel, biomass etc. The combustion of fuels leads to the formation of gaseous and particulate matter pollutants that have an impact on air quality and the environment. Several studies have shown that increased particle concentrations in the ambient air correlate with adverse health effects in the exposed population, including respiratory and cardiovascular illnesses as well as increased mortality human health [1-7]. Traditionally, particle emission measurements from the small scale biomass combustion technologies are performed in undiluted hot flue gases at temperatures of about 120-280 °C. However, sampling in raw hot flue gases may suffer from transient conditions with varying flue gas flows, or from the condensable nature of many of the semi-volatile organic compounds. This may lead to erroneous results and incorrect conclusions. In the case of particulate matter (PM) in particular, interactions between particles and walls must be limited, and appropriate quenching should be done in order to preserve particle size distributions. Dilution of the exhaust gas decreases the temperature and partial vapour pressures. This causes some of the semi-volatile compounds to condense on the particles. If particles are sampled from a hot and undiluted exhaust, many organic species remain in the gas phase whereas by using dilution, a fraction of the organics condenses and is collected [8-11]. Therefore, sampling at lower temperature is desirable and dilution of the hot exhaust gases is a suitable alternative method. There are two types of dilution tunnels in use. Using a dilution tunnel in particle sampling leads to [8-10, 12];

- Cooling of the sample gas

- Keeping the concentration within the measuring range
- Providing possibility for long term measurements
- Keeping particle size distribution as unchanged as possible

Full flow dilution: In this tunnel, all the exhaust gases from the combustion appliance are drawn by a constant volume pump through a collection hood and are mixed with ambient dilution air. Next, the diluted exhaust gas sample passes through the filters and measuring instruments to prepare for PM sampling. With this sampling method, the size of the dilution tunnel is dependent on the volume flow of the exhaust gas. Therefore, the greater the volume flow of the exhaust gas from the combustion test unit, the larger the dilution system must be. The full flow system is quite large in size and expensive. This tunnel is steady state and not suitable for field measurements.

Partial flow dilution: In the partial flow system, only a small part of the exhaust gas from the combustion appliance is drawn to a dilution tunnel and is mixed with dilution air. The diluted sample passes through the analyzer for particle analysis. A number of partial flow dilution tunnels are available, including a combination of porous tube diluter (PRD) and ejector diluter (ED), ejector diluter only, two stage of ejector diluters.

A wide range of instruments can be used for the particle measurement and the selection and combination of instruments depends on the objectives. Measurements of particles are conducted in terms of mass concentrations, number concentrations and their size distributions[5, 11]. Electrical Low Pressure Impactor Plus (ELPI+) is one of the widely used for measurements of particles in real time. Adding to this the fact that the Electrical Low Pressure Impactor Plus (ELPI+) cannot withstand the hot and humid flue gas for direct analysis, the use of a dilution system is unavoidable in the particle measurement setup. A dilution system is required upstream of the ELPI+ for the particulate matter (PM) measurements. A partial flow dilution system with a combination of a porous tube diluter and an ejector diluter was chosen for conducting experiments, because this combination is believed to be the best in preserving the particle distribution. This combination yields very stable conditions, which allows for the possibility to add or remove objects downstream without affecting the dilution ratio. Flow control is therefore more easy and an advantage in field measurements. After the porous tube diluter, the sample is mixed efficiently in the ejector diluter. Higher dilution ratios are possible due to additional dilution by the ejector diluter [13]. The one stage ejector diluter in combination with heated dilution air was not chosen in the present study because it gives a low dilution ratio. The drawback of using only ED is that the dilution ratio is more or less fixed and the sample is subject to considerable particle losses due to temperature difference of thermophoresis and condensation of vapors. In addition, the ejector nozzle starts to accumulate particle deposits which affects the flow rates and sometimes also gets blocked [13]. A combination of two ejectors can be rather unstable with changing dilution ratios.

The study investigates for the appropriate dilution air flow settings into the porous tube diluter and ejector diluter in order to have a wide range of dilution ratios. The dilution ratios are calculated from CO_2 measurements, being the most practical reference gas to be measured. The experiments were conducted at the Renewable Energy Laboratory of the Vrije Universiteit Brussel (VUB), Belgium.

II. MATERIALS AND METHODS

The following sections briefly illustrate the experimental setup, the description of the dilution tunnel, the instruments used for the measurements of the CO_2 concentration and the air filtering system.

2.1 Experimental setup

The schematic of the test setup used in this study is presented in Figures 1 and 2. As can be seen from this schematic, the ELPI+ instrument and the vacuum pump were part of the experimental setup to mimic the real combustion tests. The combination of two stage dilution tunnel (PRD and ED) is less sensitive to add or remove instruments downstream of the tunnel without affecting the dilution ratio [13].

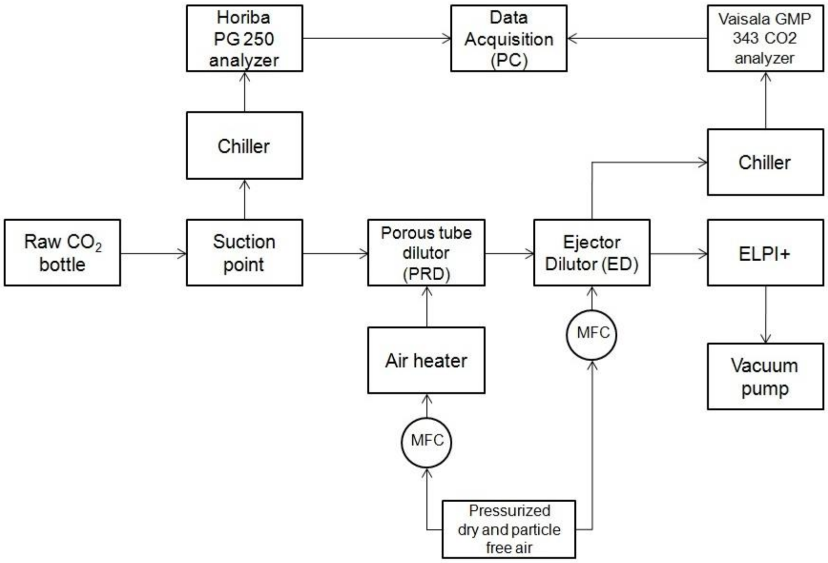


Figure 1: Schematic of the experimental setup for all tests

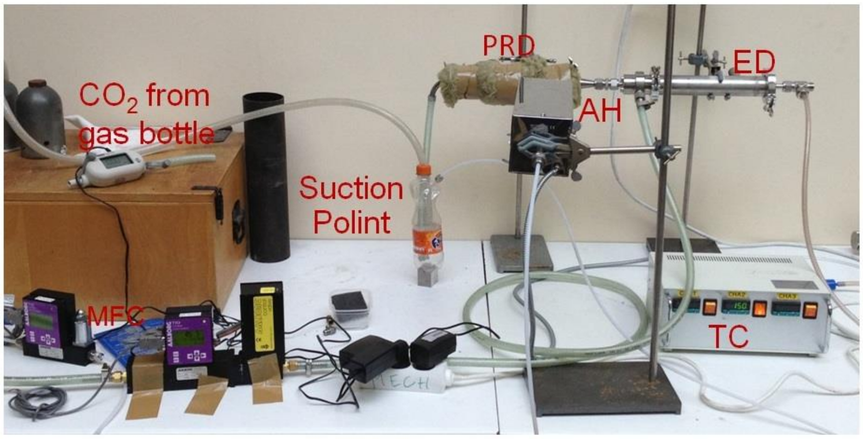
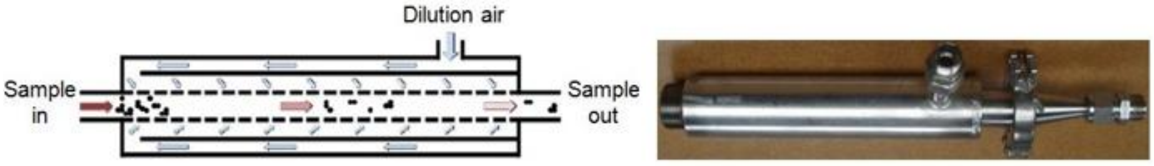


Figure 2: A photo of the test setup for all the measurements, PRD=Porous tube diluter, ED = Ejector diluter, AH = Air heater, MFC = Mass flow controller, TC = Temperature controller

2.2 Description of the dilutors

Two stage dilution system with a combination of a porous tube diluter, an ejector diluter and an air heater was chosen for conducting experiments. Brief description of the dilutors is given as follows.

Porous tube diluter (PRD): The target of the optimum particle dilution system is to dilute and cool the sample to make it suitable for the used analyzers and to preserve the particle size distribution as unchanged as possible. In the porous tube diluter, the sample is drawn through a porous tube, while the dilution gas is introduced through the pores of the porous tube wall to prevent thermophoresis particle losses and vapor condensation on walls as shown in Figure 3. The PRD is 250 mm long and the inner diameter of the porous tube is 12 mm and the dilution zone length is 200 mm. The PDR material is AISI 316L stainless steel.



(a) (b)

Figure 3: (a) Schematic diagram and (b) Photo of the porous tube diluter used in the experiments

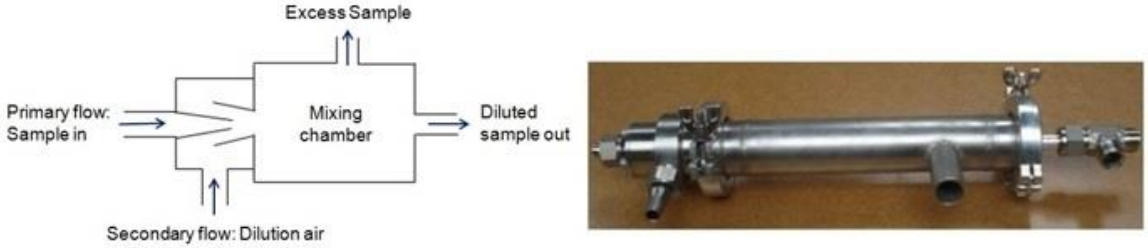
The balancing of the dilution flow and suction in the diluter outlet is used to get the desired sample flow into the diluter. This allows a wide range of dilution ratios. However, care must be taken that the flows are stable. Thus, for the dilution gas supply, a mass flow controller is used to control the flow. In addition, the suction at the diluter should remain stable to achieve a constant dilution ratio.

Air heater with the temperature controller: In the first step, the temperature is kept high to avoid any uncontrolled condensation. The air heater therefore heats the dilution air going to the porous tube diluter. The heater is installed between the mass flow controller and porous tube dilution inlet. A photo of the air heater together with the temperature controller is shown in Figure 4. The temperature is set to 150 °C. The heating rate of the dilution air is restricted to 10 °C/min in the PID *(*proportional integral derivative) settings to avoid overshooting of the temperature and consequently damaging of the air heater elements.

Figure 4: A photo of the air heater with the temperature controller

Ejector diluter (ED): The ejector diluter is a secondary diluter installed downstream of the porous tube diluter. The advantage of the ejector diluter is that it stabilizes the flow of the diluted sample. Secondly, the ejector has a relatively stable dilution ratio and due to the high speed at the ejector nozzle. It also provides a good mixing which is essential before sampling for particle analysis. Stabilization of the ED gives the possibility to add or remove instruments after ED without affecting the dilution ratio. The ED is 360 mm long and the sample inlet diameter of the ED is 12 mm. The ED material is AISI 316L stainless steel. The combination of the PRD and ED also allows for a wider range in dilution ratio.

The operation principle of the ejector diluter is based on the high speed of a pressurized dilution gas flow around ejector nozzle. The ejector diluter is shown in Figure 5. This causes a pressure drop which draws the aerosol sample through the nozzle and subsequent mixing with the dilution gas flow. The primary flow is passed through a nozzle, where the pressure energy is converted into kinetic energy. The high velocity dilution air entrains the secondary flow. The two flows mix in the mixing chamber. The ejector diluter has no moving parts, which the convenience of the dilutor.



(a) (b)

Figure 5: (a) Schematic diagram and (b) a photo of the ejector diluter used in the experiments

2.3 Instruments used

A HORIBA PG-250 portable gas analyzer was used to continuously measure the CO_2 concentration of the raw sample at the suction point in front of the PRD. The CO_2 measurement principle of the Horiba gas analyzer is non-dispersive infrared (NDIR). The gas analyzer was calibrated with appropriate gas bottles at zero and span points, before and after the measurements. The Horiba analyzer has a sample flow rate of 0.4 liter per minute (lpm). It takes about 1 hour to warm-up and to stabilize the analyzer after the power switch is turned on. A RS-232C interface port is connected between the analyzer and the computer for data transmission. A portable gas conditioning system, shown in Figure 1, was placed upstream of the Horiba PG250 analyzer to dry the CO_2 sample gas.

Another Vaisala Carbocap GMP 343 analyzer was used to continuously measure the concentration of the diluted sample at the downstream of the ED. The CO_2 measuring principle of the GMP 343 analyzer is also non-dispersive infrared (NDIR). The gas analyzer was calibrated with appropriate gas bottles at zero and span points, before and after the measurements. A portable gas conditioning system was placed upstream of the Carbocap GMP 343 analyzer to dry the CO_2 sample gas.

2.4 Suction line and composition of the CO_2 bottle

A gas mixture with 13 vol % CO_2 from a bottle (Westfalen, a Belgian company) was drawn to the suction line to the porous tube diluter (PRD). An empty plastic bottle (Figure 2) was connected between the gas bottle and the suction line of the probe. There was an additional outlet in the plastic bottle for the excess CO_2 to escape. About 2.5-6 lpm of CO_2 gas was supplied into the plastic bottle and the suction in the probe was about 0.95-2.1lpm. The gas flow in the suction line of the probe depends on the applied flow of pressurized dilution air into the PRD and ED tunnels. The gas bottle contains the mixture of CO_2, O_2 and Ar (Argon). Since Ar, N_2 and O_2 behave as perfect gases at these temperatures and pressures, there is no problem in using an available Ar bottle instead of N_2 and O_2. The exact concentration of CO_2 is measured from the raw and diluted samples by two gas analyzers.

2.5 Air filtering system

The dilution air was filtered in four stages by means of Festo filters; with a condensate separator to remove water from the pressurized dilution air, a pre-filter to remove coarse particles (<40 µm), a micro filter (<1 µm) to remove hydrocarbons and oils and a post fine filter to remove fine particles (< 0.01 µm). Figure 6 shows a photo of the air filtering system used in the measurements. A pressure regulator placed on the top of the condensate separator was used to control the pressure according to the requirements. The compressed air pressure in the supply line was about 8 bar but it was required to reduce this pressure to 2-3 bar for the application.

Figure 6: A photo of the air filtering system

2.6 Dilution air flow control

The pressurized dilution air flows into the porous tube diluter and the ejector diluter were controlled separately via two mass flow controllers (brand Aalborg, Germany) of 20 lpm and 200 lpm respectively. The pressurized dilution air flow applied into the diluters was recorded for all the measurements. A photo of the mass controllers is shown in Figure 7.

Figure 7: A photo of the mass controllers used in all the measurements

III. OPTIMAL DILUTION RATIO

It is unclear from literature what should be the ‘optimal’ dilution ratio, and even less what would be the optimal combination of a PRD and ED dilution ratio. On the one hand, temperatures must go below the ELPI+ maximum allowable value, which is almost 45 °C. This will lead to a minimum permissible DR. Taking into account the air heater in the PRD, there is a minimum of some 3.5 for the ED dilution ratio, derived as follows.

$$T_{\mathrm{a}} \cong 295\ \mathrm{K}$$

$$T_{\mathrm{PRD}} \cong 420\mathrm{K}$$

$$T_{\mathrm{sample}} \cong 318\mathrm{K}$$

$$ED_{\mathrm{ratio}} = \frac{\dot{m}_{\mathrm{sample}}}{\dot{m}_{\mathrm{PRD}}} = ? \qquad \text{(Eq. 1)}$$

Where, T_{a}, T_{PRD} and T_{sample} are the temperature in Kelvin of the ambient air, the PRD exit and the exit sample respectively.

The mass and energy balances over the dilution system yields:

$$\dot{m}_{\mathrm{in}} + \dot{m}_{\mathrm{PRD}} + \dot{m}_{\mathrm{ED}} = \dot{m}_{\mathrm{sample}} \qquad \text{(Eq. 2)}$$

$$\dot{m}_{\mathrm{in}} \cdot C_{\mathrm{pst}} \cdot T_{\mathrm{st}} + \dot{m}_{\mathrm{PRD}} \cdot C_{\mathrm{pa}} \cdot T_{\mathrm{PRD}} + \dot{m}_{\mathrm{ED}} \cdot C_{\mathrm{pa}} \cdot T_{\mathrm{a}} = \dot{m}_{\mathrm{sample}} \cdot C_{\mathrm{pa}} \cdot T_{\mathrm{sample}} \qquad \text{(Eq. 3)}$$

Where, $\dot{m}_{\mathrm{in}}$, $\dot{m}_{\mathrm{PRD}}$, $\dot{m}_{\mathrm{ED}}$ and $\dot{m}_{\mathrm{sample}}$ are the mass flow rates in the probe, PRD, ED and the exit sample respectively. C_{pst} and C_{pa} are the specific heats at constant pressure. T_{st} is the stack temperature in Kelvin.

Assuming, $\dot{m}_{in} << \dot{m}_{PRD}$ yields

$$\frac{\dot{m}_{\mathrm{sample}}}{\dot{m}_{\mathrm{PRD}}} \cong \frac{T_{\mathrm{PRD}} - T_{\mathrm{a}}}{T_{\mathrm{sample}} - T_{\mathrm{a}}} \cong 3.5 \qquad \text{(Eq. 4)}$$

On the other hand, the PRD dilution is a compromise between on the one hand a minimum to sufficiently reduce the particle interactions and on the other hand to limit the amount of hot air supply.

A value of 10 can be considered as a minimum to reduce particle interactions by one order of magnitudes. The DR’s have been chosen as follows.

$$\text{ED dilution} \cong 3.5(\text{minimum})$$

$$\text{PRD dilution} \cong 10\ (\text{minimum})$$

$$\text{Total} \cong 35$$

IV. DILUTION RATIO CALCULATION

The dilution ratio(DR) is evaluated based on the ratio of the CO_2 (dry) concentration in the raw sample to the diluted sample using the following equation [14].

$$DR = \frac{CO_{2,RG} - CO_{2,BG}}{CO_{2,S} - CO_{2,BG}} \qquad \text{(Eq. 5)}$$

Where, $CO_{2,RG}$ is the concentration in the raw gas, $CO_{2,BG}$ is the background dilution air and $CO_{2,S}$ is the diluted sample. This method normally gives a more precise value of the DR comparing to one where values of DR are calculated from the flow rates of the raw sample and dilution air [15].

The concentrations of $CO_{2,RG}$ and $CO_{2,S}$ were recorded continuously in order to determine the prevailing dilution ratio using a Horiba PG-250 and a Vaisala Carbocap GMP-343 respectively. The DR of the tunnel is controlled by adjusting the dilution air flows and by monitoring and measuring CO_2 concentrations in the raw gas sample and the diluted gas sample. The concentration of the $CO_{2,BG}$ was measured by a Vaisala Carbocap GMP-343 before and after the measurements.

V. DESCRIPTION OFTHE MEASUREMENTS

Fifteen measurements with four flow settings of the dilution air into the PDR and the ED were performed. First, a certain flow rate (15 to 20 lpm) of dilution air from the compressed air line was applied into the PRD. Then the raw sample CO_2 gas (from a bottle) was drawn into the probe of the PRD. The raw gas was diluted in two steps. In the first dilution step, dry, filtered and pressurized air was injected into the PRD via a mass flow controller and air heater. The temperature of the air heater was kept at 150 ^{o}C. In the PRD, the CO_2 sample is passed through a porous tube, while the preheated pressurized dilution air is introduced through the pores of the porous tube wall to prevent thermophoresis particle losses and vapor condensation on walls[13, 16, 17].Second, another dilution air flow (higher than the PRD flow) into the ED was applied. Third, the flow in the suction probe was set zero. This was accomplished by slowly controlling and adjusting the flow into the ED through the mass flow controller. Soap foam was used to check whether there was zero flow in the suction line of the probe. Zero suction in the probe was easily visualized by observing the inlet of the probe by entering and leaving of the soap foam at the same time.

Next, the suction flow rate into the probe of the PRD was established by increasing the flow of the ED or by decreasing the flow of the PRD. After that, the CO_2 gas was supplied into the suction line of the probe. Each flow setting was continued until CO_2 concentrations at the outlet of the ED became stable for several minutes. After stabilizing the CO_2 concentration, the next setting of dilution air flow into the PRD and the ED diluter was applied. All these tests were performed for several hours at the Renewable Energy Laboratory of the VUB. Finally, the diluted sample gas was drawn to the CO_2 analyzer through a gas conditioning chiller to remove the water content from the diluted sample gas. There were in total fifteen tests conducted with the following flow settings, chosen to keep the suction flow at the PRD between 0.95 to 2.1 lpm, whilst offering a wide range of dilution ratios.

- Setting A: PRD flow: 19.0lpm and ED flow: 50 lpm
- Setting B: PRD flow: 20.0lpm and ED flow: 53 lpm
- Setting C: PRD flow: 20.0lpm and ED flow: 55 lpm
- Setting D: PRD flow: 17.5 lpm and ED flow 49 lpm

The corresponding suction flows into the probe for the flow settings A, B, C and D were 1.10 lpm, 0.95 lpm, 1.85 lpm and 2.10 lpm respectively. Different flows of CO_2 from the bottle were supplied at the suction of the probe to observe how it affects the dilution ratio. The CO_2 flows from the gas bottle were supplied as follows.

- CO_2 flow 2.5 lpm: for measurement nos. 1, 3, 4 and 8
- CO_2 flow 5 lpm: for measurement nos. 2, 4, 5, 11, 12 and 13
- CO_2 flow 6 lpm: for measurement nos. 3, 7, 10, 14 and 15

VI. EXPERIMENTAL RESULTS AND DISCUSSIONS

Table 1 shows a summary of the results obtained from all the dilution tunnel tests. The results include average CO_2 concentrations of the raw sample and diluted sample, the PRD flow, ED flow, suction flow at the probe and the dilution ratio (DR). Each test was continued for about 5-6 minutes. The DR of the tunnel is controlled by adjusting the dilution air flows and monitored by measuring CO_2 concentration in the raw gas sample and the diluted sample. The pressure of the dilution air was kept at about 2-3 bar by the pressure regulator placed at the top of the condensate separator of the air filtering system. It is observed that the measured value of the CO_2 raw sample varied among the tests. This is probably due to the atmospheric pressure fluctuations and not controlling perfectly the pressure inside the plastic bottle. The average DR varied from 67 to 86 for flow setting A, 75 to 110 for setting B, 41 to 52 for settings C and 34 to 43 for setting D. Therefore, the dilution ratio from these measurements is limited between 34 and 110. The DR results obtained in our experiments with the partial flow diluters are quite similar to the results presented in the literature [15, 18, 19].

Table 1: Summary of the results obtained from all the tests

Flow Setting	Test No.	Sampling time (min)	CO_2 in raw sample (vol %)	CO_2in diluted sample (ppm)	DR
Setting A: PRD: 19 lpm	1	5	12.6±0.05	1795±54	85.9± 3.3
ED: 50 lpm	2	6	12.1±0.05	2100±51	68.4±1.9
Suction: 1.1 lpm	3	6	12.4±0.01	1793±43	84.7±2.5
Setting B: PRD: 20 lpm	4	5	12.4±0.01	1549±62	101.8±11.1
ED: 53 lpm	5	5	12.4±0.03	1985±151	75.4±7.1
Suction:	6	6	12.0±0.06	1441±105	108.3±6.1
0.95 lpm	7	5	12.3±0.01	1456±68	109.7±6.4
Setting C:	8	6	11.9±0.04	2696±31	50.6±0.8
PRD: 20 lpm	9	6	12.2±0.04	3298±50	41.1±0.62
ED: 55 lpm	10	5	12.3±0.01	2690±53	52.4±1.2
Suction: 1.85 lpm	11	6	12.4±0.01	2714±41	52.0±0.9
Setting D:	12	6	11.9±0.01	3081±55	43.1±0.7
PRD: 17.5lpm	13	6	12.3±0.03	3621±45	38.1±1.1
ED: 49lpm	14	5	11.9±0.02	3324±37	39.8±1.1
Suction: 2.1 lpm	15	6	12.1±0.01	3910±63	33.8±0.85

6.1 Time series of CO_2 concentrations

Figures 8 to 10 illustrate how the DR varies with the variation of CO_2 concentrations of the raw sample and diluted sample by applying different dilution air flows into the PRD and ED from the measurements. The figures show that in some tests (1, 5 and 7) slow increase or decrease of concentrations are observed. This is probably due to the effect of thermal inertia of the dilution tunnel. It is observed that the CO_2 concentration of the diluted sample varies by changing the flow of dilution air into the PRD and the ED. As a result, a wide range of dilution ratios is observed. It is also observed that the CO_2 flow from the gas bottle did not have an effect on the DR.

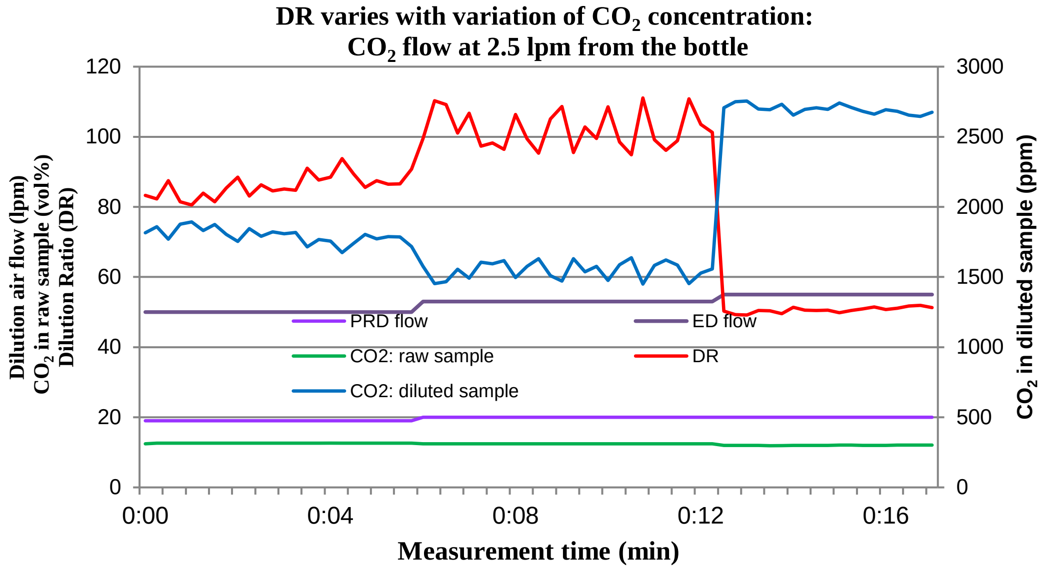


Figure 8: DR varies with variation of CO₂ concentration in diluted sample by applying different flows of dilution air, obtained from measurement nos.1, 4 and 8

The figures show that the DR increases when the flow into the PRD increases (decreasing CO₂ concentration in the diluted sample). This means that keeping the ED flow constant while increasing the dilution air flow into the PRD resulted in a lower flow into the suction of the PRD probe. But, the DR decreases when the flow into the ED increases (increasing CO₂ concentrations in the diluted sample) due to a higher suction flow into the probe of the PRD.

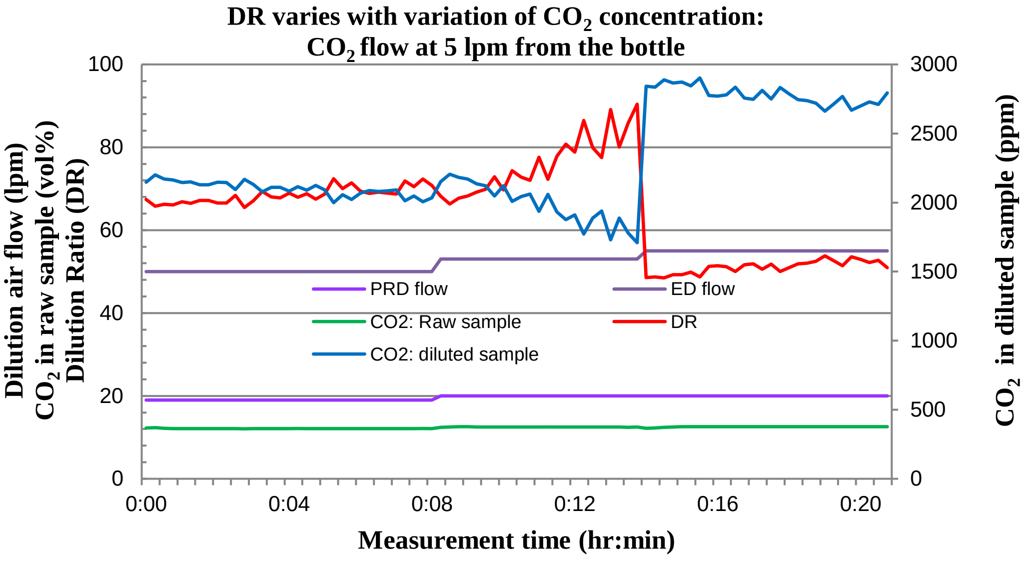


Figure 9: DR varies with variation of CO₂ concentration in diluted sample by applying different flows of dilution air, obtained from measurement nos. 2, 5 and 11

The fluctuations of the diluted CO_2 sample is due to irregularities in the flow regulation of the mass flow controllers and CO_2 supply through the (open) suction point. In real measurements, the accuracy of the PM measurements depends only on the accuracy of the instantaneous CO_2 measurements and eventual DR fluctuations are corrected via the recalculation to 13 % O_2 concentrations (see Section 3.6.1).

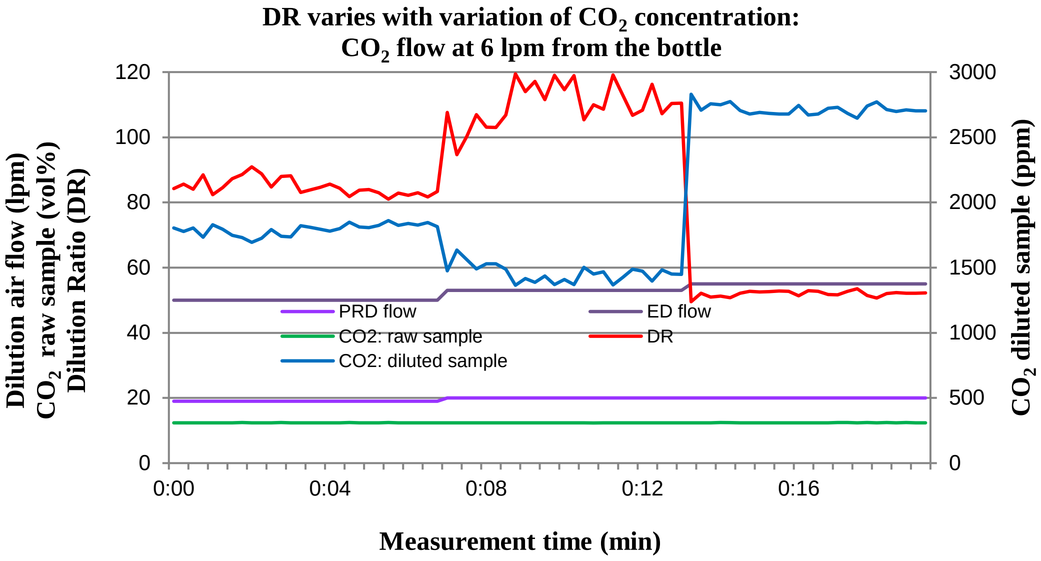


Figure 10: DR varies with variation of CO_2 concentration in diluted sample by applying different flows of dilution air, obtained from measurement nos. 3, 7 and 10

6.2 Dilution ratio as function of dilution air flow

Figure 11 shows the dilution ratio obtained from all the measurements with the four flow settings. The average values of the DR are reported in Figure 8. From the figure, it can be seen that limited variations of the PRD and ED flows lead to a wide range of the total DR value, with a minimum of 38, which is just above the chosen minimum. Besides, the adjustments of PRD and ED air flows, the vacuum pump also effects the DR, but since the ELPI+ was used, the DR is expected (and found) to remain in the range of approximately 40.

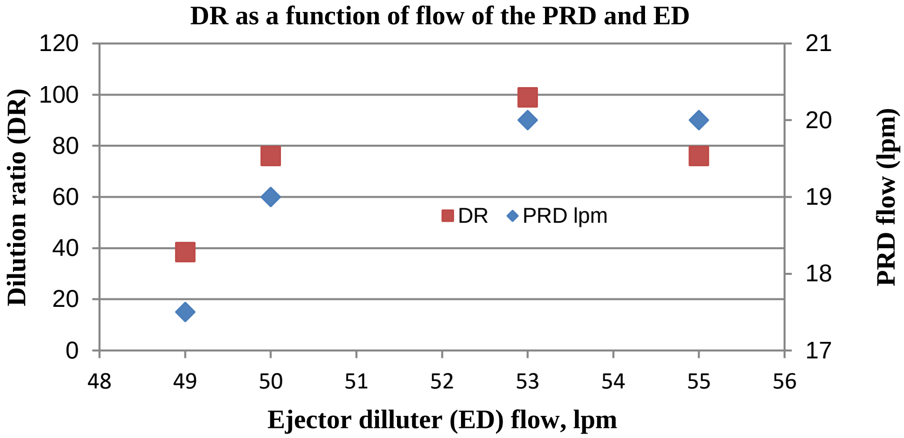


Figure 11: Dilution ratio as a function of flow of the PRD and ED

The DR results from all the tests of each flow setting were quite stable. Therefore, all the flow settings (A, B, C and D) into the PRD and ED can be used in the particle emission measurements from biomass combustion.

6.3 DR from the literature

The scope of the literature survey was to compile the reported dilution ratios applied in both laboratory and field measurement conditions from the commonly used small scale biomass combustion appliances. Table 2 presents the average dilution ratio from different biomass combustion appliances available in the literature. The dilution ratio varies from 14 to 65 for pellet boilers, 8 to 45 for pellet burners, 24 to 78 for the stoves and 24 to 60 for masonry heaters. In most of the studies, the DR was determined using CO_2 concentrations from the undiluted raw gas sample and diluted sample. The DR results obtained from our experiments are quite similar with the literature results as presented in Table 2.

Table 2: Average dilution ratio from different combustion appliances

Appliances	Fuels and Moisture (m) content	Dilution Tunnel	Instru-ment	DR	DR measured by	Ref
Pellet boiler 25 kW	Wood pellet	PRD +ED	DLPI	13.6-14.2	CO_2 conc.	[18]
Pellet boiler 25 kW	Wood pellet m: 8 %	PRD+ED	DLPI	14	CO_2 conc.	[20]
Pellet boiler 20 kW	Wood pellet	Two stages ED	ELPI	55-65	-	[21]
Pellet burner 20 kW	Wood pellet m: 5.3 %	PRD+ED	ELPI	42	CO_2 conc.	[19]
Pellet burner 20 kW	Rape seed bark pellet, m: 6.8 %	PRD+ED	ELPI	39	CO_2 conc.	[19]
Pellet burner 20 kW	Rape seed m: 5.5 %	PRD+ED	ELPI	45	CO_2 conc.	[19]
Pellet burner 10 kW	Bark Pellet m: 10 %	ED	LPI	7.64	-	[22]
Pellet burner 10 kW	Bark Pellet m: 11 %	ED	LPI	7.64	-	[22]
Pellet Stove 8 kW	Birch stem m: 7 %	Dilution Tunnel	ELPI	73	CO_2 conc.	[23]
Pellet Stove 8 kW	Spruce stem m: 6 %	Dilution Tunnel	ELPI	76	CO_2 conc.	[23]
Pellet Stove 8 kW	Pine stem m: 5.8 %	Dilution Tunnel	ELPI	78	CO_2 conc.	[23]
Sauna Stove	Birch wood logs, m: 7.4 %	PRD+ED	DLPI	23.8 35.9	CO_2 conc.	[18]
Sauna Stove	-	Two stages ED	ELPI	60	CO_2 conc.	[24]
Sauna Stove	Birch wood logs, m: 11.5 %	PRD+ED	DLPI	30	-	[20]
Wood stove	Briquettes m: 9 %	PRD+ED	Tecora	25	-	[25]
Masonry heater	Birch wood logs, m: 7.4 %	Two stages ED	ELPI	60	CO_2 conc.	[24]
Masonry heater	Birch wood m: 7 %	Dilution tunnel	DLPI, ELPI	180-330	CO_2 conc.	[26]
Modern Masonry Heater	Birch log m: 12 %	PRD+ED	DLPI	24	CO_2 conc.	[20]
Modern masonry heater	Birch wood logs, m: 7.4 %	Two stages ED	ELPI	60	CO_2 conc.	[24]
Conventional masonry stove	Birch logs m: 11.5 %	PRD+ED	DLPI	24	CO_2 conc.	[20]
Fireplace	Portuguese oak, m: 14 %	PRD+ED	Tecora	25	-	[25]

VII. CONCLUSIONS

Full flow dilution tunnel is depended on the exhaust gas volume. Therefore, the greater the volume of the exhaust gas from the combustion test unit, the larger the dilution system must be. A full flow system is quite large in size and expensive. This tunnel is suited for steady state measurements and is not suitable for field measurements. The partial flow dilution tunnel can eliminate this problem by sampling a part of the total exhaust flow. Therefore, a partial flow dilution system is chosen in our measurements for developing the particle sampling setup. This study presents how the dilution ratio measurements were performed with a partial flow dilution tunnel. The tests were performed at the Renewable Energy laboratory of the VUB There were a total of fifteen tests with four flow settings (Setting A: PRD 19 lpm and ED 50 lpm, Setting B: PRD 20 lpm and ED 53 lpm, Setting C: PRD 20 lpm and ED: 55 lpm, Setting D: PRD 17.5 lpm and ED 49 lpm) conducted. Results from a wide range of dilution ratios were presented in the study. The results show that the dilution tunnel works well. Following conclusion can be drawn from this study.

- The DR increases when the flow into the PRD increases (decreasing CO_2 concentration in the diluted sample). But, the DR decreases when the flow into the ED increases (increasing CO_2 concentration in the diluted sample). The average DR varied from between 67 and 86 for flow setting A, 75 to 110 for setting B, 41 to 52 for settings C and 34 to 43 for setting D. Therefore, with these measurements, the dilution ratio is limited from 34 to 110.
- The flow settings (A, B, C and D) applied into the PRD and ED can be used in the particle emission measurements from small scale biomass combustion appliances.
- The combination of a porous tube and an ejector diluter is considered as the best option to reproduce the exhaust PM emissions, maintaining the particles distributions as they are when leaving from the stack.

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Nomenclature:

AH	Air heater
°C	Degree Celsius
$CO_{2,RG}$	Concentration in the raw gas
$CO_{2,BG}$	Background dilution air and
$CO_{2,S}$	Diluted sample
Conc.	Concentration
C_{pa}	Specific heats at constant pressure
C_{pst}	Specific heats at constant pressure
DLPI	Dekati Low Pressure Impactor Plus

DR	Dilution Ratio
ED	Ejector Diluter
ELPI+	Electrical Low Pressure Impactor
K	Temperature in Kelvin
LPI	Low Pressure Impactor
lpm	Liter per minute
MFC	Mass flow controller
$\dot{m}_{\mathrm{in}}$	Mass flow rates in the probe
$\dot{m}_{\mathrm{PRD}}$	Mass flow rates in the PRD
$\dot{m}_{\mathrm{ED}}$	Mass flow rates in the ED
$\dot{m}_{\mathrm{sample}}$	Mass flow rates in the exit sample
NDIR	Non Dispersive Infra-Red
PID	Proportional integral derivative
PM	Particulate Matter
PRD	Porous Tube Diluter
VUB	Vrije Universiteit Brussel
TC	Temperature controller
T_a	Ambient temperature
T_{PRD}	Temperature at the PRD exit
T_{sample}	Exit sample Temperature
T_{st}	Stack temperature

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