CHAPTER 2
BACKGROUND

2.1 Carbonaceous Aerosol

2.1.1 Definition of carbonaceous aerosol

Carbon is the largest elemental fraction of atmospheric aerosol particles that can be presented in various chemical and physical forms. Total carbon (TC) consists of organic carbon (OC) and inorganic carbon (IC: elemental carbon (EC) or Black carbon (BC)). Definition of minor fractions are defined by measurement method

"Organic carbon" (OC) fraction is defined as carbon fraction of aerosol that is oxidized and released up to a certain threshold temperature in thermal analysis. Some components of OC can be weakly light-absorbing in the visible spectrum, but mainly light-scattering.

"Elemental carbon" (EC) is a near-elemental soot-carbon-like composition, and usually refers to the fraction of carbon that is oxidized above a certain temperature threshold, and is only presented in oxygen containing atmosphere.

"Black carbon" (BC) is the component of aerosol that absorbs visible light and mostly determined by optical methods (Watson et al., 2005).

Previously, Black carbon (BC) was defined as "black particulate carbon having a graphitic microstructure" (Novakov, 1984). However, nowadays most definitions of BC concern the light-absorbing property of carbonaceous aerosol or component of soot and smoke that absorb optically (Penner et al., 1993).

Elemental carbon (EC) and black carbon (BC) are different in thermal, optical and chemical behavior. The EC is determined by thermal method, and BC is defined when optical method is applied. In this study, the EC is considered by thermal analysis. The OC can be produced from both primary and secondary sources. The incomplete combustion generates EC and/or BC, where BC is a main issue in global warming because of light absorption (Gelencsér, 2004, Andreae and Gelencsér, 2006; and Venkatachari et al., 2006).

2.1.2 Sources of carbonaceous aerosol

Sources of carbonaceous aerosol are burning of carbon contained fuel (Garivait et al., 2006). Global sources of carbonaceous emission load are from two major sectors, which area biomass burning and fossil fuel combustion. Soot formation is mainly from lignin and organic species if formed by burning of holocellulose (cellulose and hemicelluloses). Major phase of combustion that generates soot is flaming, with deficient oxygen supply. Little soot is also produced in smoldering phase. Most carbonaceous fraction released during smoldering phase is in form of tar (Gelencsér, 2004). Emission load of EC from biomass burning was an estimated 19 Tg/y that contributes to >86% of global source (<22 Tg/y). Annual agricultural waste was burned 2,020 Tg and release 910 TgC/y (Andreae, 1991). Global emission loads specific to TC, BC and OC from agricultural residues burning were 7.0, 2.2 and 1.8 Tg/y, respectively, estimated by result of EF (Andreae and Merlet, 2001) and amount of agricultural residues burning 540 Tg/y (Logan and Yevich in Andreae and Merlet, 2001). Amount of agricultural residues burning is consistent with 475 Tg/y (Bond et al., 2004). Information of carbonaceous emission inventory of each source is presented in Table 2.1.

Table 2.1 Global sectoral carbonaceous emission inventory

Emission load (Gg/year)	BC	OC	OC:BC Ratio
Open burn:			
Forest	1,238	11,239	9.1
Savanna	1,715	12,147	7.1
Crop residue	328	1,567	4.8
Contained combustion			
Coal power	7	5	0.71
Diesel-on-road	792	292	0.37
Wood-residential	880	3506	4
Ag waste-residential	393	1492	3.8
Animal waste – resident	208	750	3.6
Coal – industry	642	450	0.7
Diesel-residential	85	28	0.33
Coal-residential	480	422	0.88
Diesel-off-road	579	288	0.5
Gasoline-transport	125	904	7.2
Other	478	776	1.6
Total	7,950	33,866	4.3

(Bond et al., 2004)

From Table 2.1, source of BC and OC consists of open burn of forest, savanna, and crop residue; and combustion of fuel in power plant, residential, industry, and transport. Open burning release higher OC/BC than fuel combustion. The emission load of BC from agricultural residue burning estimated in Table 2.1 is lower than Andreae and Merlet (2001) for 7 times. Results in Table 2.1 are more up-to-date and obtained from field experiment, model, and national/international statistics; so it is more reliable data.

Contributions of open burning were the first rank 42% for BC and 74% for OC from global sources (fossil fuel, biofuel, and open burning). The major source of carbonaceous aerosol is open burning in savanna that releases 22% BC and 35% OC of global sources. Share of forest and savanna sources cover more than 50% of total OC emission sources in the world. Emission load from crop residue open burning share is 4% for BC and 5% for OC.

Summary of annual global black carbon and organic carbon emission load (Tg/y) from fossil and biomass burning are presented in Appendix A.

2.1.3 Analytical method of carbonaceous aerosol

a) Sampling method of carbonaceous aerosol

Carbonaceous aerosol is determined by chemical analytical method so that a sufficient amount of sample can be characterized. The transition of chemical component by environmental condition (especially organic aerosol determined by thermal analysis), and purity of medium for collecting are important in sampling method to reduce error and uncertainties. Two widely used methods consist of filter-based and impactor sampling, the details of which are described:

1) Filter sampling: High-purity quartz filter is preferred for organic aerosol sampling to be determined by thermal analysis. Properties of quartz filter are approximately 6.5 mg/cm^2 density, neutral surface, above 30 nm particle collection efficiency, and relatively good adsorbency. Good adsorbency property can absorb volatile or semi-volatile organic species from the gas-phase. Therefore, pre-baked at high temperature (typically 500-700 °C) to reduce organic compound in filter is required. Sampling should be done at high temperature and precaution must be taken during storage and transport to avoid adsorption. Blank filter can reduce these uncertainties.

2) Impactor sampling: Impactor sampling of organic aerosol usually use non adsorption substrates i.e. aluminum foils. This sampling method can classify size of organic aerosol. Major problems of this method are particle bounce and re-entrainment at high particle loading, which can be reduced by applying grease or oil on impactor substrates to improve collection efficiency; and another problem is large pressure drop in lower stages of the impactor.

b) Method of carbonaceous aerosol determination

Analytical method of carbonaceous aerosol components can be classified into 3 main methods: optical method, thermal method, and thermo-optical method.

1) Optical methods of BC analysis: Optical method is usually used to quantify BC. The optical method is divided into two categories: in situ and filter-based absorption. In-situ uses photoacoustic instrument to measure BC by quantifying minute changes in speed of sound in response to heating and cooling of PM by a modulated laser beam. Filter-based absorption is determined by Aethalometer to measure optical aerosol absorption by quantifying the attenuation of light transmitted through a filter tape on which aerosol particles are collected. Optical methods can be classified into Smoke shade method, Aethalometer, Particle soot absorption photometer (PSAP), Integrating plate method, Integrating sphere method, Photoacoustic spectrometry, and Raman spectroscopy.

2) Thermal methods of EC analysis: Thermal method is a widely used method; however, the pyrolysis of organic carbon (OC) causes an overestimate of elemental carbon (EC). The carbon in biomass is converted to CO_2, and detected directly or converted to CH_4 for more sensitive detection. Thermal analysis methods consist of VDI methods, Thermal manganese oxidation (TMO) method, and On-line monitoring thermal techniques for EC determination.

3) Thermo-optical methods of OC/EC analysis: The transmittance or reflectance of the filter sample is monitored during the thermographic analysis. The thermal-optical method is capable of pyrolysis correction by monitoring the reflected and/or transmitted lights of a sample filter during analysis (Shuichi et al., 2005). The thermo-optical methods consist of Thermo-optical reflectance (TOR) method and Thermal/optical transmission method (TOT) (Gelencsér, 2004, Andreae and Gelencser, 2006; and Venkatachari et al., 2006).

This study used quartz filter sampling method to collect aerosol sample and analyze TC by thermal method and applied continuous optical measurement method (Micro Aethalometer) to determine BC. Several of the thermal methods for estimating TC, OC, and EC are presented in Appendix A.

2.1.4 Emission factor of carbonaceous aerosol from agricultural sector

Emission load is widely estimated by emission factor, which specific to BC, EC and OC released from specific types of biomass open burning is still scarce. Summary of carbonaceous is presented in Table 2.2.

Table 2.2 Emission factor of carbonaceous aerosol from agricultural residues burning

Biomass	BC (g/kg)	EC (g/kg)	OC (g/kg)	References
Rice straw	-	0.17±0.04	8.94±0.42	Hays et al., 2005[1]
Wheat straw	-	0.52±0.00	1.23±0.03	Hays et al., 2005
Wheat straw	1.59		2.38	Sahai, 2007 (previous work)
Wheat straw	0.16±0.07		0.29±0.12	Sahai, 2007 (present work)
Agricultural residues	1.0	-	3.3	Bond et al., 2004[2]
Agricultural residues	0.69 ± 0.13	-	3.3	Andreae and Merlet, 2001[3]
Agricultural residues	0.75	-	-	Turn et al., 1997
Wheat straw	-	0.49 ± 0.12	2.7 ± 1.0	Li et al., 2007[4]
Maize stover	-	0.35 ± 0.10	3.9 ± 1.7	Li et al., 2007

Note:

[1] Burning experiment in enclosure wind tunnel chamber to analyze chemical component of $PM_{2.5}$

[2] EF of open burning obtained from comprehensive search available data including scientific papers, individual country communications to the UNFCCC Secretariat, Global Fire Monitoring Center publications, and FAO statistics

[3] Value is best guess from comprehensive review

[4] Field experiment of agricultural open burning by preparing residues in windrow

The most well-known and world-wide emission factor is Andreae and Merlet (2001). The emission factor represents global source so plenty of research uses these EF values to estimate emission inventory (Streets et al., 2003). Moreover, the EF greenhouse gases (CO_2, CO, CH_4, N_2O, and NO_x) of Andreae and Merlet (2001) are default value in IPCC (2006).

The suitable emission factor should be specific to each agricultural type and place because of difference in activity data i.e. method of seeding, fertilizing, harvesting, burning, climate, topography and so on can result in different emission factor.

2.2 Estimation of Emission Load from Biomass Open Burning

2.2.1 Methodology to Estimate Emission Load from Biomass Open Burning

Emission load information is presented in two forms: emission ratios and emission factors. The emission ratio relates the emission load of a particular species of interest to that of a reference species such as CO_2 or CO. The emission factor relates the emission load to the amount of fuel burned. The factor defined as the amount of a compound released (M_x) per amount of dry fuel consumed ($M_{biomass}$), expressed in units of g/kg. An emission load estimation based on emission factor, can be calculated as follows:

$$E_i = M \times EF_i \qquad \text{Equation 2.1}$$

where, E is the air pollutant i emission load (kg or ton), EF is emission factor ($g_{species}/kg_{\text{ biomass dry basis}}$) of i and M represents amount of biomass burned (g). This equation is the same as methodology to estimate non-CO_2 emission load estimation derived from variety of sources in IPCC (2006).

$$Emission = A \times EF \qquad \text{Equation 2.2}$$

where, *Emission* is non-CO_2 emissions load, ton of the non-CO_2 gas, A is activity data relating to the emission source (can be area, animal numbers or mass unit, depending on the source type) EF is emission factor for a specific gas and source category, ton/unit of A.

Estimation of greenhouse gas emission loads from fire (IPCC, 2006) also calculated by similar methodology as in following equation:

$$L_{fire} = A \times M_B \times C_f \times G_{ef} \times 10^{-3} \qquad \text{Equation 2.3}$$

where, L_{fire} = amount of greenhouse gas emission loads from fire, ton of each GHG e.g., CH_4, N_2O, etc.; A = area burned, ha; M_B = mass of fuel available for combustion, ton/ha; C_f = combustion factor, dimensionless; and G_{ef} = emission factor, g/kg dry matter burned. From Eq. 2.1, *EF* and *M* are obtained by

$$EF_x = \frac{m_x}{m_{biomass}} = \frac{m_x}{m_C}[C]_{biomass} \qquad \text{Equation 2.4}$$

$$M_{biomass} = \frac{M_C}{[C]_{biomass}} \qquad \text{Equation 2.5}$$

$$EF \cong \frac{M_x \times [x]}{M_{CO2} \times [CO_2] + M_{CO} + M_{CH4}} \qquad \text{Equation 2.6}$$

The estimation of the amount of biomass burned can be calculated as follows.

$$M = A \times D \times F \qquad \text{Equation 2.7}$$

where A = area burned (m^2), D = biomass loading ($kg_{\text{dm biomass}}/m^2$), F = burning efficiency or fraction burned in field.

$$R = P \times N \times D \times B \times F \qquad \text{Equation 2.8}$$

where, R = total mass of crop residue burned in the field; P = crop production; N = crop-specific production-to- residue ratio; D = dry-matter-to-crop ratio; B = the percentage of dry matter residues that are burned in the field, and F = the crop-specific burn efficiency ratio (Streets et al, 2003).

RPR corresponds to the residue to product ratio, which are dependent on types of residues and their weight to the weight of the core product, e.g. in the case of rice, given that the residues are rice straw, the RPR would be

$$\frac{m_{straw}}{m_{grain}} \qquad \text{Equation 2.9}$$

where, m_{straw} and m_{grain} are mass of residues and product of rice, respectively.

Sources of these factors to estimate emission load from agricultural burning are described based on Eq. 2.1 that emission load is evaluated from emission factor and amount of biomass burned.

2.2.2 Methodology of Emission Factor Estimation

For agricultural residue open burning in the field, the emission factors are influenced by several factors including the factors that affect the combustion efficiency (CE): amount of available oxygen, combustion temperature, stubble moisture content, residence time of ventilation air, prevalent meteorological conditions, rate of flame spread, fire management techniques and turbulence. EFs are also affected by the residue characteristics including fuel type and chemical make-up, residue orientation, extent of compaction in the field, residue mass per unit area (biomass load), actual amount of carbon in the pre-burned dry matter, size, shape, and moisture content of the sample. Moreover, burning stage (flaming versus smoldering pattern) of the burning process also have affect on EF (Ward et al., 1996; and Dhammapala, et al., 2006). Emission factor can be calculated by direct and indirect methods as followings.

a) Calculation of Emission Factor

1) Direct method: In the case that a steady-state flow-through chamber is well mixed, uniform conditions and concentrations are expected throughout the chamber, including in the exit stream. The emission factors are determined by direct method as follows:

$$EF(x) = M(X)/M(biomass) \qquad \text{Equation 2.10}$$

M(X) is the mass of species (*X*) emitted and *M* (biomass) is the mass of fuel actually burned or

$$EF_x(g/kg) = \left[\frac{\Delta C_x \times Q_{chamber} \times t_{run}}{1000mg/kg \times m_{burned}}\right] \qquad \text{Equation 2.11}$$

where EF_x is the emission factor (g of pollutant *x*/ kg dry matter burned), ΔC_x the exit concentration of pollutant *x* in excess of the background (mg/m^3), $Q_{chamber}$ the flow rate of dilution air into the burn chamber (m^3/min), t_{run} the sampling time (min), and m_{burned} the mass of dry straw consumed during the burn (kg).

2) Carbon balance method: This method is used for evaluating emission factors during field experiments. However, this method can be applied in combustion chamber experiment. Emission factor based on carbon balance method requires knowing the carbon content of the fuel to calculate EFs. In this method, all the burned carbon is assumed to be emitted into the atmosphere as carbonaceous particles and carbonaceous gases such as CO_2, CO, CH_4, and NMHCs, which is described in the following equation,

$$C_f - C_a = C_{CO2} + C_{CO} + C_{CH4} + C_{NMHCs} + C_{PM} \qquad \text{Equation 2.12}$$

where C_f and C_a are the carbon mass in the fuel and ash, respectively. C_{CO2}, C_{CO}, C_{CH4}, C_{NMHCs}, and C_{PM} are the carbon mass in CO_2, CO, CH_4, NMHCs, and particles, respectively. Organic carbon (OC) and elemental carbon (EC) in $PM_{2.5}$ are considered in the calculation as carbon mass in the particles (Li et al., 2007). The EFs is determined by

$$EF(X) = \Delta X / (\Delta\Sigma[CO_2],[CO],[CH_4],[C_{VOC}],[C_{aerosol}],\ldots) \times [C]_{biomass} \qquad \text{Equation 2.13}$$

where Δ is the difference between concentrations in the background and in smoke conditions, and $(\Delta\Sigma[CO_2],[CO],[CH_4],[C_{VOC}],[C_{aerosol}],\ldots)$ is the species concentration expressed as the amount of carbon. EF(X) is commonly referred to $(\Delta\Sigma[CO_2],[CO])$ as these two species represent generally 95-99% of the carbon-containing emissions. When EF(X) corresponds to the ratio of the production of species X to the production of CO (or CO_2), it is called emission ratio (ER) (Andreae and Merlet, 2001). Otherwise, EF can be expressed as

$$EF_x(g/kg) = \frac{\Delta C_x \times (1000g/kg) \times C_{fraction}}{(\Delta CO_2 - C + \Delta CO - C + \Delta THC - C + \Delta PM_{2.5} - C)},$$ Equation 2.14

where, $C_{fraction}$ is the mass fraction of C in dry matter (%). The $C_{fraction}$ can be calculated by

$$C_{fraction}(\%) = \frac{(\Delta CO_2 - C + \Delta CO - C + \Delta THC - C + \Delta PM_{2.5} - C)}{m_{burned} \times C_{fraction} \times 0.01} \times Q_{chamber} \times t_{run}$$

Equation 2.15

The carbon content of the biomass fuel is inversely proportional to the moisture content and the non-carbon ash content (Dhammapala et al., 2006). The similar method carbon mass balance of Ward et al. (1996) calculated particle emission factors by all of the carbon combusted in a fire is emitted into the measurable portions of a smoke plume in five forms of carbon: CO_2, CO, CH_4, non-methane hydrocarbons, and particulate carbon.

$$EF_n = \frac{[C]_n}{[C]_{CO2} + [C]_{CO} + [C]_{CH4} + [C]_{NMHC} + [C]_{pc}}$$ Equation 2.16

The emission factor of a species, n, is calculated from the ratio of the mass concentration [C] of that species to the total carbon concentration emitted in the plume. Source of the emission factor to quantify emission load from agricultural open burning can be obtained from literature review (Andreae and Merlet, 2001; Bond et al., 2004; IPCC, 2006), field experiment (Li et al., 2007; Sahai et al., 2007; and Nguyen et al., 1994), laboratory experiment (Hays et al., 2005; Zárate et al., 2000; and Jenkins et al., 1993). The laboratory and chamber experiments are reviewed.

b) Measurement of Emission Factor

The emission factor can be determined by field experiment and/or chamber experiment. Examples of sampling and measurement of emission concentrations to estimate emission factors have been reviewed as the following:

1) Field experiment

1.1) Nomad Sampler (US EPA): Emission concentrations of Organic Air Toxics from Open Burning are difficult to measure because of unstable plume direction so it is not easy to measure at the flame front. Therefore, the U.S. EPA has developed a hand-held boom sampler (a Nomad Sampler) that can measure the emission concentration by inserting the suction end into the smoke plume without getting close to the smoke or fire. The Nomad sampler is portable, which is used for mobile and infield sampling. However, it is used as stationary in the study of Gulett and Touati (2003). The Nomad that is applied in the study consists of a TO-9 head and PUF/XAD/PUF cartridge coupled to a high-volume sampler. Sampling is operated by inserting probe into the burned area. Measurement of emission concentration by Nomad Sampler is presented in Figure 2.1.

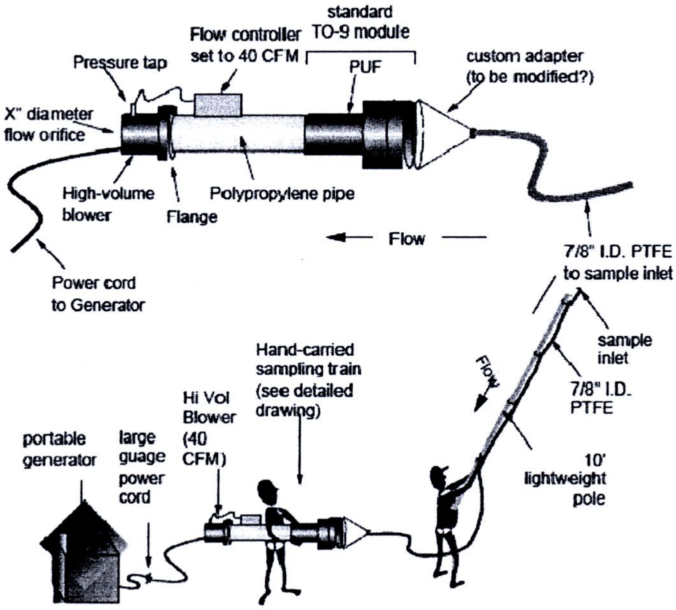


Figure 2.1 Nomad Sampler.
USEPA, 2002

1.2) Prescribed burn: Prescribed burns of wheat straw and corn stover were conducted in the field by Li et al. (2007). The prescribed fire was conducted to control distribution of combustion by windrow pattern arrangement. The biomass was arranged in two windrows for wheat straw and one windrow for maize stover for the experiment. To characterize PM and trace gases emission, composition and emission load were assessed by calculating emission factor (EF) from carbon mass balance (Li et al., 2007).

1.3) On-site burning: The on-site burning experiment was conducted in wheat field in India to develop emission factors to trace gases and carbonaceous particulate species. A monitoring station was set up downwind away from the field for 3-4 m at 3 m height. The experiment was carried out for four days to cover the fire event, including preburning for three days and post-burning for one day. The study provided EF of CO and NO_x by online analyzers measurement: CO_2, CH_4, and N_2O by grab sampling in nitrogen flushed and evacuated stainless steel canisters and glass samplers then analyzed by gas chromatograph (GC, model 8610C, SRI, USA) with flame ionization detector (FID) for CO_2 and CH_4 and with electron capture detector (ECD) for N_2O. The concentration of $PM_{2.5}$ was monitored by dust monitor (model: EPAm-5000, Environmental Devices Corporation, USA) with frequency in min. Carbonaceous aerosol was collected through pre-heated, pre-weighed and equilibrated (desiccated for 48 h) filter paper (Whatman Q-A quartz microfiber, and Whatman-41 cellulose filters) and analyzed by two step thermal treatment (350 and 550 °C) of filter samples in oxidizing atmosphere. Ionic analysis of Na^+, K^+, Ca^{2+}, Mg^{2-}, NH_4^+, NO^{3-}, Cl^-, and SO_4^{2-} was also conducted (Sahai et al, 2007).

2) Combustion Chamber Experiment

An effective way to develop emission factors for open burning sources is through laboratory simulations using a flux chamber approach. In a laboratory simulation, small amounts of biomass are burned in as representative a manner as possible while making detailed measurements of the mass of burning material, combustion air and dilution air flow rates, relevant temperatures, and the concentrations of the pollutants of interest.

2.1) Open Burning Test Facility (OBTF): The USEPA developed an Open Burning Test Facility (OBTF) to evaluate emission concentrations from a wide variety of open burning sources. Sources that have been tested in the OBTF are tire fires, fiberglass burning, open burning of land clearing debris, automobile shredder fluff fires, household waste, agricultural plastics, agricultural residues, and forest fires. The OBTF has been used to estimate emission loads of PCDD/F from uncontrolled domestic waste burning by feeding 6.8 kg into the test container or the barrel place on an electronic scale platform to monitor mass consumed by time for burning rate. To reduce recirculation potential of combustion gases through the barrel, an aluminum skirt was placed around the outer circumference. A continuous influx of dilution air was applied to simulate ambient dilution. Air was mixed by fans. Ambient sampling equipment is positioned inside the interior of the facility, or extractive samples can be taken through the sample duct. Figure of OBTF is presented in Figure 2.2.

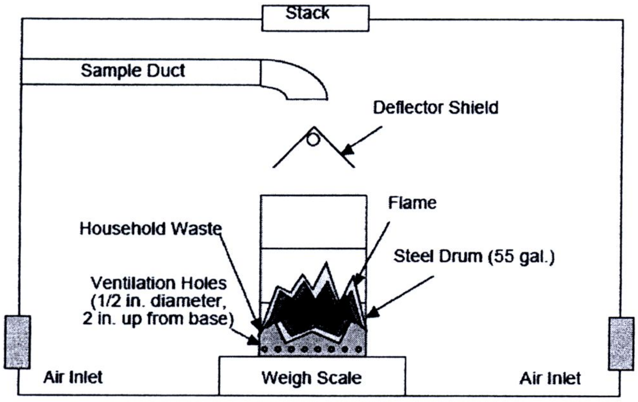


Figure 2.2 Open Burning Test Facility (OBTF), USEPA.

2.2) Cloud condensation nuclei determining chamber: The chamber is designed to determine cloud condensation nuclei by developing a dark test chamber adapted from an aerosol dilution chamber, previously built and used for work on ice nuclei. The chamber allows combustion experiments, aerosol as well as gas sampling, and monitoring from the outside. The other gas and aerosol analyzers are around the outside walls. The figure of experimental set up is presented in Figure 2.3.

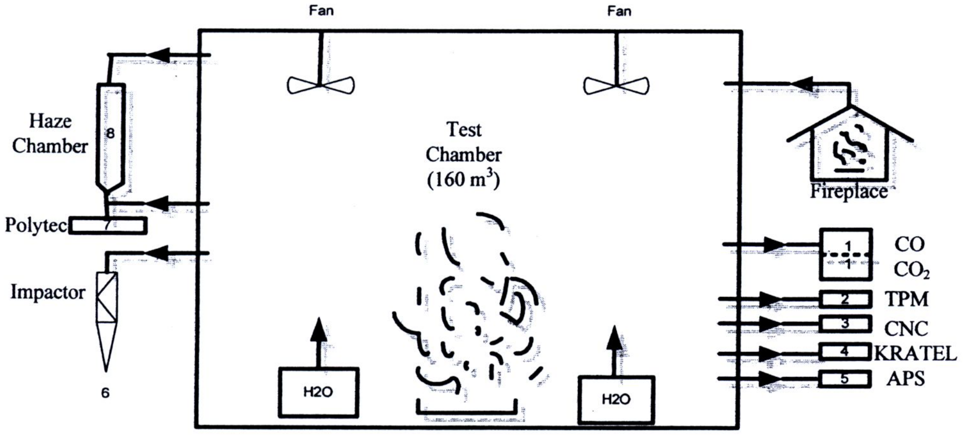


Figure 2.3 Experimental chamber for investigating combustion aerosol particles.

Note: (1) test chamber, with main devices involved in analyzing CO/CO_2; (2) total particulate matter; (3) number of condensation nuclei; (4) geometric size distribution of particles; (5) aerodynamic size distribution of particles; (6) aerodynamic size mass distribution of particles; (7,8) CCN supersaturation spectrum (Dinh et al., 1996).

2.3) Open fires chamber for various fuels: A combustion chamber was developed for conducting open fires to study nitrogen and carbon emission concentrations from various fuels i.e. wood, pine needles, savanna grass, hay, and straw. The chamber consists of a hood in inverted funnel, a burning table of 60×60 cm^2, and a high-resolution balance, which is presented in Figure 2.4. The burning table allows simulating different wind directions, i.e. heading and backing fires, by moving to an angle of 45°. All major parts are made of stainless steel. Flow rate of the stack gases was measured by a differential pressure sensor (not a fan wheel-anemometer) because of high dirt. An electrical fan was built at the top of the chimney to provide a minimum draft during low-temperature combustion and to prevent the reaction gases leaving the funnel from the bottom. Parameters that measured included temperature of stack gas and fuel, CO, CO_2, and NO_x concentration. Continuous measurements were also conducted and recorded with a data logger (WES) at a frequency of 1 to 0.2 sec^{-1}. Burning period was 15-20 minutes from ignition until the fuel bed cooled (Lobert et al., 1990). This chamber was also used for measuring stable isotope composition of CO from burning plants (Kato et al., 1999).

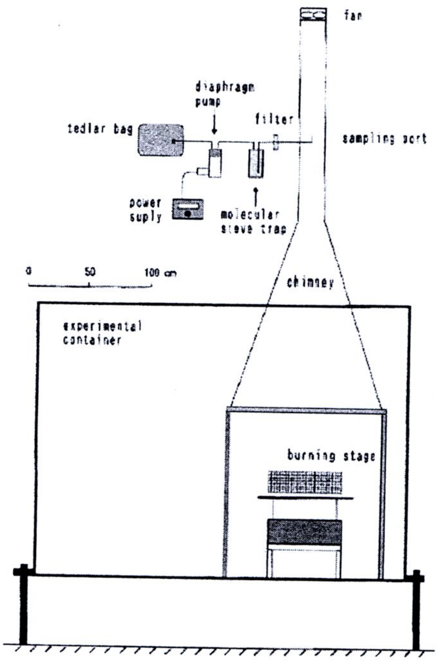
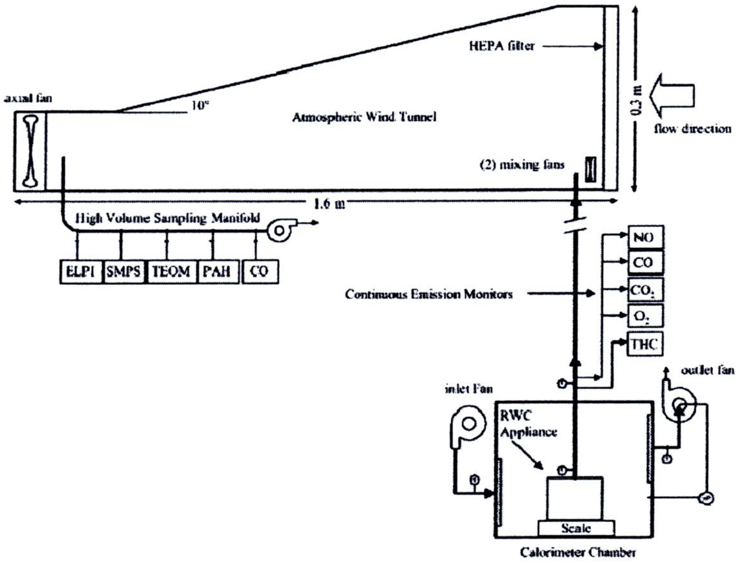


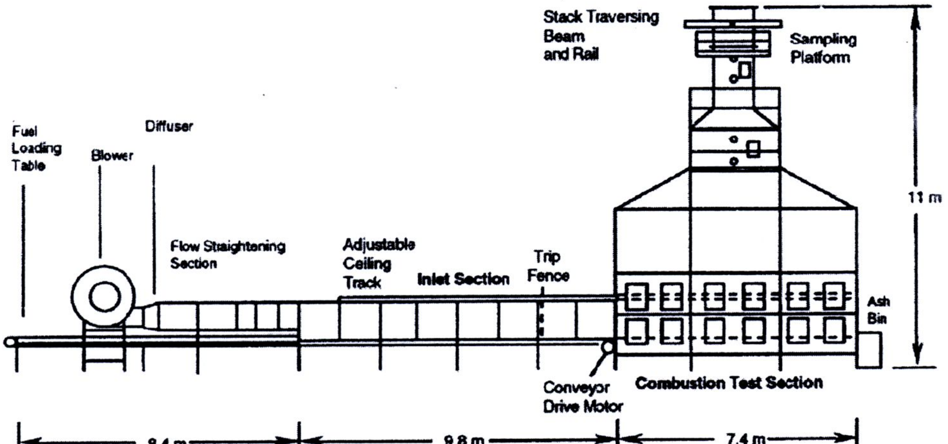
Figure 2.4 Combustion chamber (Lobert et al., 1991).

2.4) Combustion Chamber and Wind Tunnel: Hays et al. (2003) determined the polycyclic aromatic hydrocarbon (PAH) composition in size-segregated aerosols from residential wood combustion. The wind tunnel is designed to adequately sample and mimic atmospheric dilution and cooling of the aerosol plume, which is made of stainless steel.

CO_2, NO, THC, and O_2 emission concentrations and temperature were measured at stack height 2.4 m above combustion chamber. Temperature measurements were taken at 0.15 m height above combustion zone (Hays et al., 2003). Example of combustion chamber and wind tunnel are presented in Figure 2.5.



a) Hays et al., 2003



b) Jenkins et al., 1993

Figure 2.5 Combustion chamber and wind tunnel.

2.5) Drum and Kiln Type Chamber: Francisco et al. (2005) determined polycyclic aromatic hydrocarbons (PAHs) in 76 smoke samples produced by burning pine wood, pine needles, prickly pear and almond skin from two types of combustion devices that were usually used by Canarian farmers to remove plant debris and smoke cheese. First combustion device is a drum type (Figure 2.6), which consists of a metallic cylinder 90 cm high and 63 cm in diameter, without a lid on the upper part, where the smoke is sampling. Through a hole made in the lower part, the biomass to be burned is introduced.

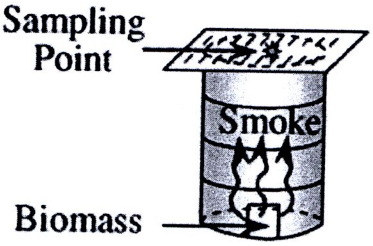


Figure 2.6 Drum type chamber (Francisco et al., 2005).

Another is a kiln type (Figure 2.7), which contains two metallic chambers, one for combustion and the other for smoking, connected by a duct, through which the smoke circulates without control mechanisms.

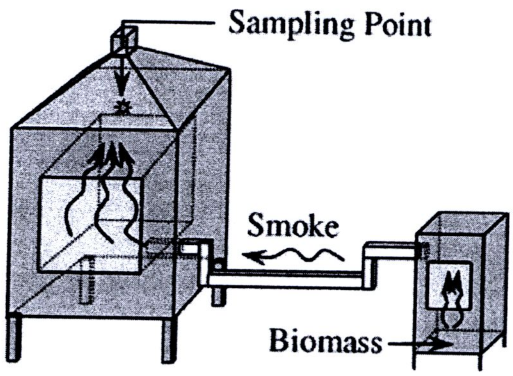


Figure 2.7 Kiln type chamber (Francisco et al., 2005).

2.3 Amount of biomass burned

Amount of biomass burned can be quantified by cooperation between remote sensing and ground based data. Application of these two methods as follows:

2.3.1 Remote Sensing Data

Application of remote sensing data in this study is used for estimating burned area to quantify amount of biomass burned and emission load from agricultural residues open burning in Thailand. The area of interest is Thailand, which is a very large and remote area so a low resolution satellite data is required to cover the studied area. After open burning for 2-3 days to a week, farmers drain water into the field to prepare for a new crop so burned clue is resisted in a short period; so satellite that passes over Thailand frequently is preferred.

In order to select satellite data to estimate biomass load, basic criteria of considerations as follows:

1) Spatial resolution is considered by size of scope area. For national/provincial level, TERRA/AQUA-MODIS, NOAA, LANDSAT, IRS, RADARSAT can be applied. At the higher resolution scale i.e. specific area for one crop plot around 10 rai (16,000 m^2), SPOT-5, MODIS 250 m resolution, and THEOS can be applied.

2) Spectral resolution: Band range of remote sensing data that can identify biomass consisting of TIR/IR/R.

3) Temporal resolution: Time scale of data analysis is monthly data for at least 3 years (2007-2009) to see variation of landuse, agricultural fire, and agricultural practice.

4) Timelines: Duration of agricultural practice that we are interest in is after harvesting because agricultural residues are usually burned during that time.

Satellite data that provide the information are summarized in Table 2.3.

Table 2.3 Summary of satellite provision of information for biomass load

	Spatial resolution (m)	Imaging swath (km)	Orbit Cycle (days)	Images/ month
MODIS	250 (band 1-2), 500 (3-7), 1,000 (8-36)	2,330	4 times/day	120
NOAA	1,100	2,399	-	-
LANDSAT	30 (XS)	185	16	2
IRS	5.8	70-180	24 days (LISS-III) 5 days (WiFS and PAN)	1
RADARSAT	3-100	20-500	24	1
SPOT-5	10 (MS) 5 (PAN)	60	26	1
THEOS	15 (MS) 2 (PAN)	90	26	1

MODIS can also estimate biomass load by vegetation indices (VI) and normalized difference vegetation index (NDVI). The vegetation indices are dimensionless, radiometric measures of green biomass and percentage of green cover. The VI is usually used to reduce effects of atmospheric conditions of different soil backgrounds on spectral reflectance values. The NDVI is calculated by NDVI = (NIR-R)/(NIR+R). The red solar energy is reflected by vegetation cover depending on chlorophyll content. The reflected NIR energy by vegetation can be used to estimate amount and condition of green biomass, leaf tissue structure, and water content. In China, the MODIS-based NDVI data was used to estimate biomass and carbon stock of forest ecosystems using the NDVI value corresponding to different land cover classes in growing season by city 49, cropland 70.6, grassland 79.2, forest 96.3, water body 32, wet land 29, and barren land 6.4 (Xia et al., 2005).

Most studies quantify amount of biomass by ground based information i.e. RPR, biomass load, because it is simple and reliable. Quantification of burned biomass by ground based data is described as follows:

2.3.2 Ground Based Data

Biomass load can be quantified by field experiment and statistic data.

a) Field experiment There is no standard method for experiment to quantify agricultural residues in the agricultural field, but there is a handbook guideline for estimate biomass for fuel (Calle, et al., 2007). Example of field experiment to quantify biomass load is the field experiment to quantify wheat residues in India by measuring weight of wheat residues in $1\text{m} \times 1\text{m}$ randomly then moisture content was analyzed to obtain dry weight basis (Sahai et al., 2007). Most studies quantify biomass load by statistic data.

b) Statistic data Existing main global source of data on the supply of biomass is Food and Agriculture Organization (FAO). The FAO data has its origin from country reports, whose Thai agricultural statistic data is based on Office of Agricultural Economics (OAE). FAO focus on commercial applications, not the residues yield. Therefore, the residues are estimated using residue to production coefficient (RPR).

Definition of RPR is amount of residues per product ratio. Calculation of biomass load by RPR value is defined by

$$\text{Biomass load} = \text{RPR} \times \text{Product} \qquad \text{Equation 2.17}$$

Information of RPR rice, corn, and sugarcane is reviewed and summarized in Appendix A.

2.4 Agricultural Open Burnings in Asia

2.4.1 Situation of Agricultural Open Burnings in Asia

Agricultural residues burning in Asia accounts for half of global crop residues burning amount. Significant agricultural residues' burning was presented in China and India. Thailand is moderate level with 7.7 Tg/y. Some Asian countries do not present burning of crop residue i.e. Bhutan, Brunei, Mongolia, and Singapore, located in mountain or island areas in which cultivation is not presented. Annual amount of agricultural waste burning was determined as presented in Table 2.4.

Table 2.4 Annual amount of agricultural waste burning

Region/Country	Agricultural burned amount (Tg/y)
Global[1]	540
Asia[2]	250
Bangladesh[2]	11
Cambodia[2]	0.9
China[2]	110
India[2]	84
Indonesia[2]	5.8
Japan[2]	1.9
Korea, DPR[2]	0.9
Korea, Rep. of[2]	1.7
Laos[2]	0.5
Mongolia[2]	0.8
Myanmar[2]	4
Nepal[2]	2
Pakistan[2]	10
Philippines	7.1
Sri Lanka[2]	0.2
Taiwan, China[2]	0.4
Thailand[2]	7.7
Vietnam[2]	6.1

Note: [1]Andreae and Merlet, 2001, [2]Streets et al., 2003

Streets et al. (2003) quantify agricultural biomass by FAO agricultural statistics and RPR based on work by Koopmans and Koppejan (1997), Lu (1993), and Strehler and Stutzle (1987), dry matter fractions from Koopmans and Koppejan (1997), and percentage of dry matter burned in the field from Hao and Liu (1994) - except South Asia, from personal communication with C. Venkataraman, an expert from Indian Institute of Technology. The results contain a great deal of uncertainty because the data is not from any specific country.

Information of biomass burned amount in Andreae and Merlet (2001) is obtained from Yevich R. and Logan J. (2002) by personal communication in 2001 (Appendix A). Source of the biomass burning in the fields is obtained from RPR and FAO (1986).

2.4.2 Situation of Agricultural Cultivation in Thailand

Agricultural biomass in this study includes rice, corn, and sugarcane. Definition of rice, corn, and sugarcane are as follows:

Major Rice means rice that cultivates from May 1 to October 31 (except Nakhonsithammarat, Pattalung, Songkhla, Pattani, Yala, Narathivat province that major rice cultivates during June 16 to Feburary 28 in the next year). Second rice means rice that cultivates in dry season or off rainy season during November 1 to April 30 in the next year (except Nakhonsithammarat, Pattalung, Songkhla, Pattani, Yala, Narathivat province in which second rice cultivates from March 1 to June 15)

Industrial corn means corn for animal feeding, which is important to Thai economics because of high demand of food in animal industry. Major source of industrial corn can be found in various region of Thailand: North (Petchaboon, Nakhonsawan, and Pitsanulok), NE (Nakhonratchasima, Sisaket, and Chaiyabhume), Central (Saraburi and Lopburi), West (Supanburi and Kanchanaburi), East (Sakaew and Chantaburi), but no cultivation in South. Planting period of industrial corn is May 1 to April 30 (OAE, 2008).

Industrial sugarcane is sugarcane that is harvested for selling to sugar factory from October 1 to May 31 in the next year (OAE, 2008). Agricultural statistics of rice, corn, and sugarcane product is presented in Appendix A.

2.5 Conclusions

1) Carbonaceous aerosol is a significant pollutant released mainly from biomass burning that contribute to >86% of global sources.

2) Although, emission factors of carbonaceous aerosol are in the same range among sources, global emission inventory is not the same among various sources i.e. BC from crop residue open burn 328 Gg (Bond et al., 2004), 2.2 Tg (Andreae and Merlet, 2001).

3) Design of combustion chambers for biomass burning is closed system and controlled air supply, which cannot represent open burning in the field - calm wind is usually presented in Thailand.

4) Most studies quantify biomass by statistic data from residue to production coefficient (RPR) and production from FAO. The FAO data is obtained from country report, which is specific to each country. However, RPR value is global value, not country specific. Therefore, biomass load is different from real practice in each country and consequently the result is over/under estimating emission inventory.