A Biomass Combustion Chamber: Design, Evaluation, and a Case Study of Wheat Straw Combustion Emission Tests

Jie Tian[1,2,3], Judith C. Chow[1,4], Junji Cao[1,5*] Yongming Han[1,2*], Haiyan Ni[1,3], L.-W. Antony Chen[1,4], Xiaoliang Wang[1,4], Rujin Huang[1], Hans Moosmüller[4], John G. Watson[1,4]

[1] *Key Laboratory of Aerosol Chemistry & Physics (KLACP), Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710061, China*
[2] *State Key Laboratory of Loess and Quaternary Geology (SKLLQG), Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710061, China*
[3] *University of Chinese Academy of Sciences, Beijing 100049, China*
[4] *Division of Atmospheric Sciences, Desert Research Institute, 2215 Raggio Parkway, Reno, Nevada 89512, USA*
[5] *Institute of Global Environmental Change, Xi'an Jiaotong University, Xi'an 710049, China*

ABSTRACT

Open biomass burning is a significant source of trace gases and particulate pollutants on a global scale and plays an important role in both atmospheric chemistry and climate change. To study the emission characteristics of biomass burning, with a focus on crop residue combustion in Northwest China, a combustion chamber was established. This paper describes the design, structure, and operating principles of the chamber. A series of evaluation tests were conducted, demonstrating its applicability in emission studies. The combustion chamber was equipped with a thermoanemometer and a dilution sampler as well as multiple sampling ports for interfacing with different monitors. A case study of wheat straw combustion was performed to demonstrate reproducibility and comparability of the derived emission factors with prior studies. The combustion chamber may be applied to develop emission factors to update emission inventories and source profiles for improving source apportionment.

Keywords: Combustion chamber; Dilution sampling; Open burning; Biomass; Emission factor.

INTRODUCTION

Biomass burning includes the open burning of crop residues, forest fires, and grassland fires. It is a large source of many trace gases and fine particulate matter (PM, usually measured as $PM_{2.5}$, particles with aerodynamic diameters < 2.5 μm) that cause adverse health hazards, visibility impairment, and other environmental impacts on regional and global scale (Crutzen and Andreae, 1990; Andreae, 1991; Penner *et al.*, 1992; Duan *et al.*, 2004; Li *et al.*, 2010; Huang *et al.*, 2012b; Malamakal *et al.*, 2013). In China, ~180 terragram [Tg, 10^{12} grams] of biomass was openly burned in the mid-1990s, emitting ~280 Tg of carbon dioxide (CO_2), ~16 Tg of carbon monoxide (CO), ~0.82 Tg of reactive nitrogen oxides (NO_x), ~0.08 Tg of sulfur dioxide (SO_2), ~0.23 Tg of ammonia (NH_3), ~0.54 Tg of methane

(CH_4), ~2.7 Tg of non-methane volatile organic compounds (NMVOCs), ~0.73 Tg of organic carbon (OC), and ~0.11 Tg of black carbon (BC) (Streets *et al.*, 2003). Crop-residue burning on agricultural lands is commonly used to eliminate waste after harvesting, it accounted for ~60% of CO_2, ~63% of CO, ~51% of NO_x, ~50% of SO_2, ~61% of NH_3, ~56% of CH_4, ~63% of NMVOCs, ~49% of OC, and ~73% of BC of open burning in China (Streets *et al.*, 2003).

Only a few emission characterization studies have been conducted in China (Li *et al.*, 2007; Zhang *et al.*, 2008; Zhang *et al.*, 2013), with inventory estimates (Streets *et al.*, 2003; Yan *et al.*, 2006; Huang *et al.*, 2012a) based on emission factors (EFs) extrapolated from measurements taken elsewhere (e.g., Andreae and Merlet, 2001; Akagi *et al.*, 2011). Detailed multi-pollutant source profiles for $PM_{2.5}$ and VOCs emissions are lacking, but these are needed for speciated emission inventories and source apportionment (Li *et al.*, 2007; Zhang *et al.*, 2007; Wang *et al.*, 2014). U.S. EPA's SPECIATE database (Simon *et al.*, 2010) does not include measurements from China, and unrepresentative profiles can lead to biases in source contribution estimates (Watson *et al.*, 2002).

Real-world emission characterization is preferred to

---

* Corresponding author.
  Tel.: +86-29-62336205; Fax: +86-29-62336234
  E-mail address: cao@loess.llqg.ac.cn;
  yongming@ieecas.cn

acquire EFs and source profiles (e.g., Yokelson *et al.*, 2008; Watson *et al.*, 2012), but it limits the ability to evaluate a large number of fuels and burning conditions (Lobert *et al.*, 1991; Lobert and Warnatz, 1993). Laboratory tests complement field measurements that allow for: 1) use of more complex instrumentation to measure a larger range of pollutants; 2) better control of dilution and cooling to account for condensation and near-source chemistry; 3) separation of emissions from specific burning phases, especially flaming and smoldering; 4) comparison of different fuels and fuel conditions, such as moisture content and soil content, that can guide more efficient burning (McMeeking *et al.*, 2009; Chen *et al.*, 2010); and 5) evaluation of emission uncertainties through replicate tests (Yokelson *et al.*, 2008; Burling *et al.*, 2010).

An open burning simulation chamber was established to acquire multi-pollutant emission rates and source profiles of crop residue combustion at the Institute of Earth Environment, Chinese Academy of Sciences (IEECAS). Combustion of wheat straw, a major form of crop residues in North/Northwest China, and its reproducibility is demonstrated.

THE BIOMASS COMBUSTION CHAMBER

Previous simulation facilities and their applications are evaluated to optimize the design, as summarized in Table S-1 (Supporting Information). Laboratory tests use small quantities (approximately 10 g to 13.6 kg) of fuel burned under controlled combustion conditions with portions of the exhaust directed to various continuous and integrated (e.g., filters, canisters, and adsorbents) sampling systems.

The following combustion chamber features were identified and incorporated: 1) a tilting stage to evaluate heading and backing fires [i.e., flames moving with and against the wind, respectively]; 2) provision for diluting and aging of samples prior to collection to allow for vapor condensation and fast chemical reactions (Hildemann *et al.*, 1989; Lipsky and Robinson, 2005; Watson *et al.*, 2012; ISO, 2013); 3) control of combustion air and outlet flows to simulate flaming and smoldering phase of combustion; and 4) availability of numerous sampling ports and sufficient throughput to accommodate multi-pollutant measurements.

The schematic of the combustion chamber is illustrated in Fig. 1. The 3 mm thick aluminum is used to withstand high combustion temperatures with dimensions of 1.8 m (L) × 1.8 m (W) × 2.2 m (H) and a volume of ~8 m³. No rubber, plastics, greases, or oils are used to minimize organic contamination. Valves on the top and bottom of the chamber allow for chamber sealing and control of combustion air and updraft speeds. The combustion air inlet is preceded by High Efficiency Particulate Air (HEPA) filters (3M Company, St Paul, MN, USA) with nominal filtration efficiencies of 95% for > 0.3 μm PM, and an air blower. Fuels of 50–300 g (depending on study objectives) are placed on the fuel tray during tests, and ignited by a butane pilot light. A ~0.15 m² fuel tray is affixed to 0.6 m (L) × 0.6 m (W) × 0.55 m (H) stage at the center of the chamber that can be adjusted to different angles to simulate different wind directions (i.e.,

heading and backing fires). An electric fan mixes the smoke within the chamber. This is accompanied by a lamp inside the chamber (with switch outside) allowing the fire to be observed and recorded through a window. The initial fuel and final residual masses are weighted using a balance with a resolution of ± 0.1 g.

Exhaust is drawn from the chamber through a 0.15 m diameter exhaust duct by a venting fan with adjustable speed. The thermoanemometer (960 probe, TSI Inc., Shoreview, MN, USA) measures gas velocity, temperature, and pressure in the duct. Sampling ports in the duct allow for extraction of the exhaust into various devices, including the dilution sampler (Model 18, Baldwin Environmental Inc., Reno, NV, USA). Three non-dispersive infrared CO_2 sensors (PP Systems, Amesbury, MA, USA) are used to measure CO_2 concentrations in the undiluted effluent, dilution (ambient) air, and diluted plume at 1-sec resolution, respectively. Dilution ratios range from 0 to 40. The smoke residence time in the dilution tunnel is 4–11 s to allow for condensation, coagulation, and rapid reactions before sampling. Tests were made to evaluate: 1) the enclosure seal; 2) uniformity of exhaust flow and pollutant concentrations across the exhaust duct; 3) stability of the air flow; and 4) PM levels in the combustion and dilution air.

To perform a leak test, the top and bottom valves were closed and the electric fans inside the chamber were switched on. Approximately 30 g of biomass, loosely packed on the stage, was burned to produce CO_2. CO_2 concentration was continuously monitored by a Q Trak (TSI Inc., Shoreview, MN, USA) located inside the chamber. Fig. 2 shows a rapid increase of CO_2, ~1200 s after ignition, from the background level of ~510 ppm to a maximum of ~3200 ppm (1500 s; fired died before 1500 s). After the burn was completed, the CO_2 concentration declined by only ~2% after more than 30 min. The valves, venting fan, and blower were opened at ~3300 s, the CO_2 concentration reduced to below ~50% of the peak concentration within 1 minutes achieved back ground levels after another 9 min.

Sampling probes may draw the effluent from different parts of the exhaust duct, which is valid if there is a homogeneous distribution across the duct's cross-section. An inertial droplet separator (IDS) nozzle, sampling the smoke isokinetically (Baldwin *et al.*, 2012), was inserted into one of the sampling ports at various distances from the duct's centerline (Fig. 3(a)), with CO_2 concentrations varied by < 5% from the average concentration of 1240 ppm (Fig. 3(b)). Flow velocities, measured with a thermoanemometer at five different positions, also reported < 5% variation from the average velocity of 3.6 m s⁻¹ (Fig. 4).

Fig. 5 shows the stability of CO_2 concentrations with the venting fan and blower turned on. Background CO_2 was about 550 ppm, while a 100,000 ppm CO_2 stream was introduced into the combustion chamber. The CO_2 concentration increased gradually to a steady-state level of ~919 ppm with a standard deviation (SD) of 24 ppm, ~240 s after injection.

Since average ambient PM₂.₅ concentrations in Xi'an achieve 375 μg m⁻³ in winter and 131 μg m⁻³ in summer owing to contributions from biomass burning, coal combustion, and vehicle exhaust (Cao *et al.*, 2005, 2007),
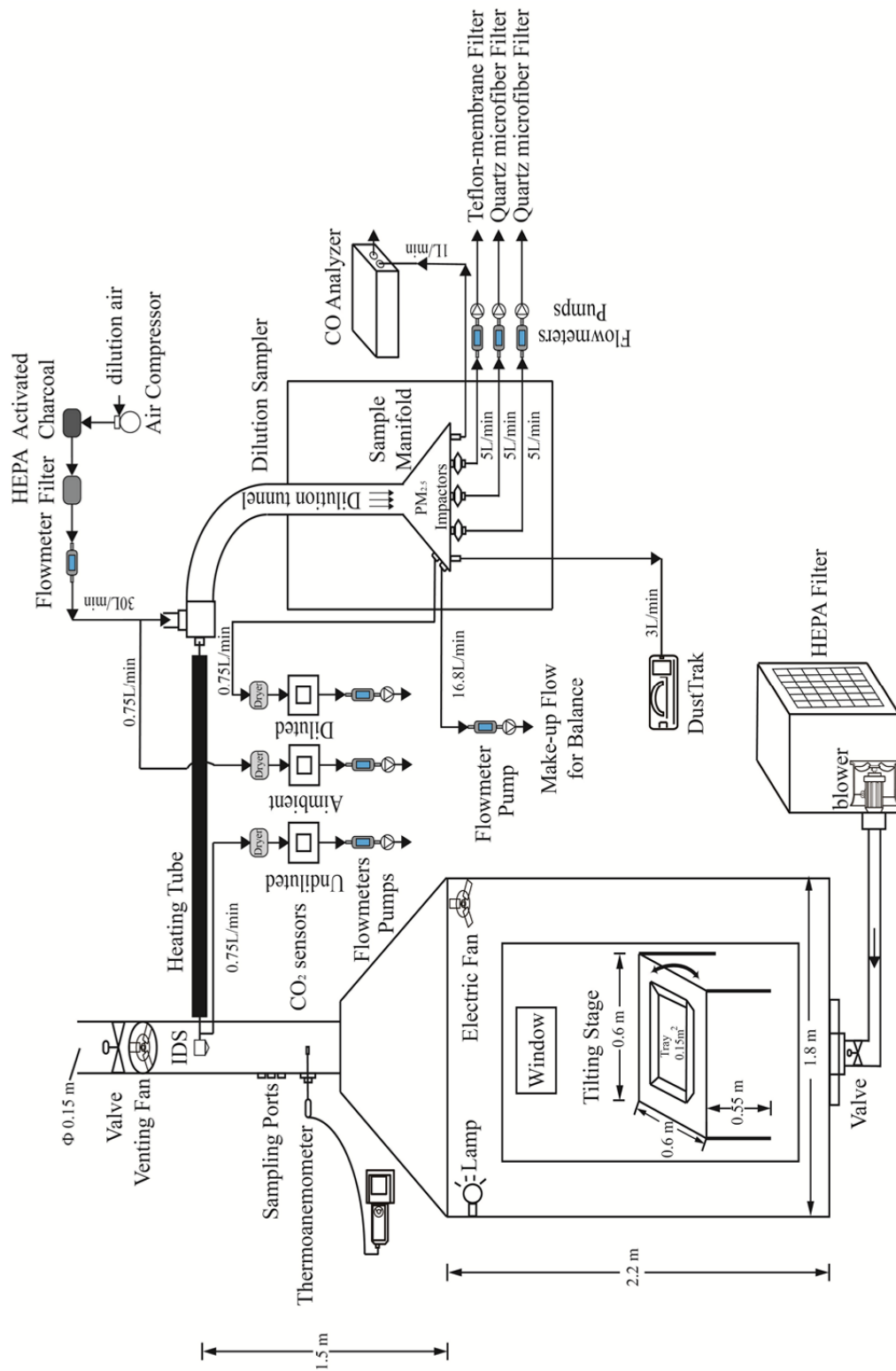
Fig. 1. Schematic of the combustion chamber. The smoke are first diluted by a dilution sampler (Model 18, Baldwin Environmental Inc., Reno, NV, USA), then collected and sampled by three parallel filter packs, three CO_2 sensors (PP Systems, Amesbury, MA, USA), a CO analyzer (Thermo 48i; Thermo Scientific Inc., Franklin, MA, USA), and a DustTrak (Model 8543, TSI Inc., Shoreview, MW, USA). The listed flow rates are for operation with a flow-based dilution ratio of 5 (see Eq. (3) in the text) which can be adjusted by changing the dilution air and make-up flows. The undiluted, diluted, and ambient CO_2 concentrations measured by corresponding CO_2 sensors can be used in Eq. (4) to calculate CO_2-based dilution ratio. The chamber is based on an original design from a DRI team led by Dr. Hans Moosmüller.
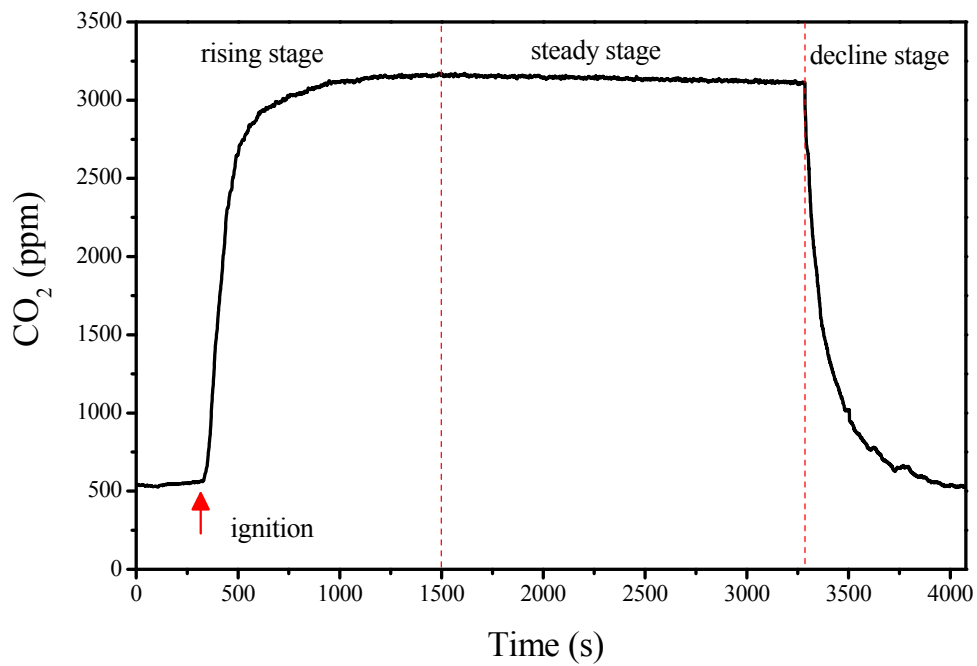
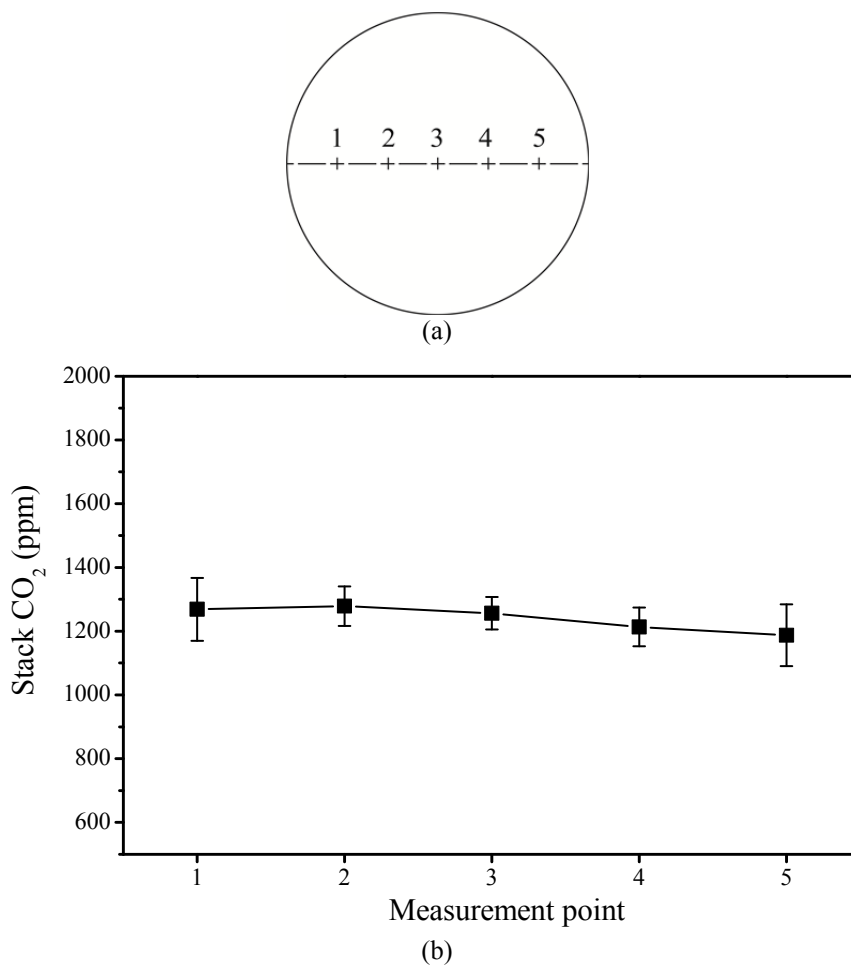**Fig. 2.** Changes in the CO_2 concentrations during the leak test.

Fig. 3. (a) Gas and effluent velocity measurement locations across the sampling duct; and (b) CO_2 concentrations corresponding to locations in (a), demonstrating concentration homogeneity and that sampling at a single location provides a reasonable estimate of emission rates and composition.
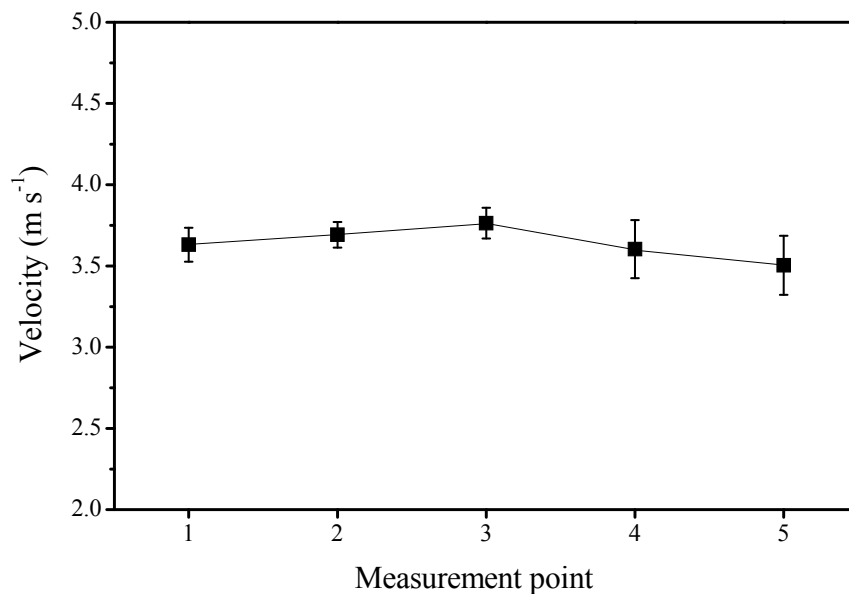
Fig. 4. Velocities across the sampling duct, showing a maximum of 3.7% reduction from the average velocity of 3.64 m s^{-1} near the duct wall and a maximum of 3.4% increase from the average at the duct center. See Fig. 3(a) for corresponding measurement points.
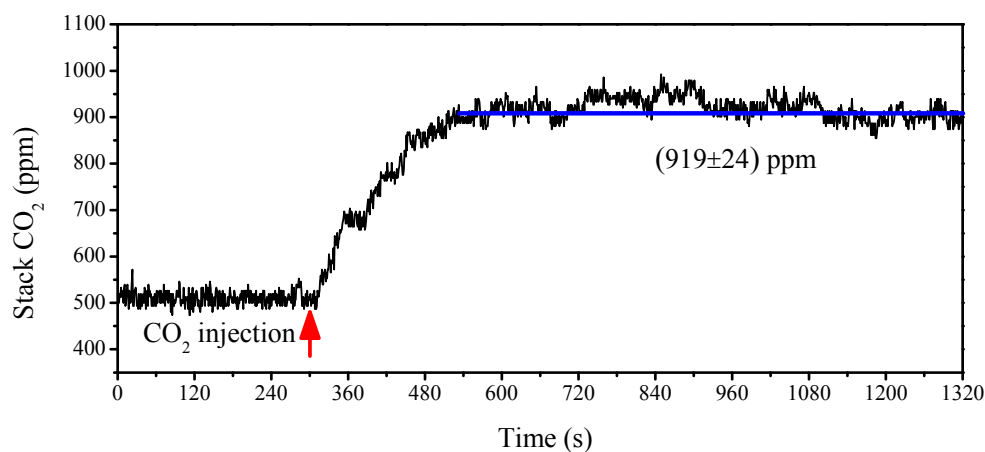

Fig. 5. Example of a CO_2 injection to the combustion chamber, approximately 240 seconds are needed to obtain equilibrium concentrations within the dilution chamber.

both combustion and dilution air needs to be filtered. The combustion air introduced into the chamber is preceded by High Efficiency Particulate Air (HEPA) filters and an air blower. Fig. 6 shows the variation of $PM_{2.5}$ concentration measured with a DustTrak (Wang *et al.*, 2009) before and after HEPA filtration with a dilution ratio of ~5. The dilution air is generated by a compressor, and filtered by actived carbon and a HEPA filter (Wang *et al.*, 2012a). Filtration reduced $PM_{2.5}$ levels from 55 µg m^{-3} to 2 µg m^{-3}, corresponding to a removal efficiency of > 95%. For other pollutants, such as CO, NO$_x$, and SO_2, the background concentration can be measured to correct for emission calculation.

EMISSION FACTORS FOR WHEAT STRAW COMBUSTION

Wheat straw was collected from Hebei Province, China, and stored at ambient temperature (~20°C) and humidity (35 to 45%) for at least one month before the experiment. Its characteristics are summarized in Table 1. The wheat straw (~100 g) and ashes were weighed before and after each burn. For each of the five replicate burns, wheat straw was stacked horizontally on the fuel tray (Fig. 1), and ignited with a butane pilot lighter. Each burn lasted ~30 min from ignition until concentrations of measured pollutants (i.e., CO_2, CO, and $PM_{2.5}$) returned to the background levels. Dilution ratio was ~5 for each test. $PM_{2.5}$ samples were collected on three parallel 47-mm filters (1 Teflon-membrane filter (2 µm pore size, R2PJ047, Pall Life Sciences, Ann Arbor, MI, USA), and 2 quartz microfiber filters (QM/A, Whatman, Midstone, Kent, England) of the dilution sampler at a flow rate of 5 L min^{-1} per channel.
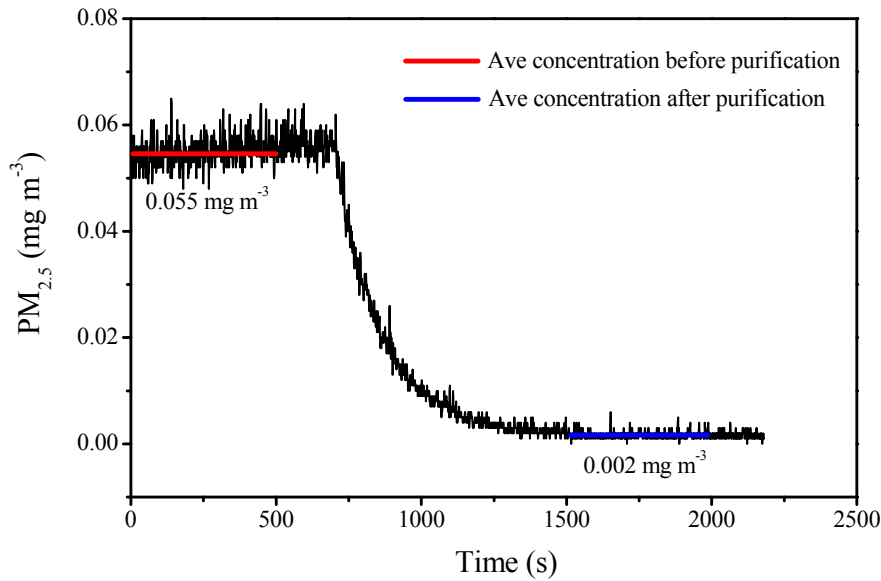
Fig. 6. PM$_{2.5}$ mass concentrations before and after purification by High Efficiency Particulate Air (HEPA) filters.

Table 1. Tested wheat straw composition*.

Proximate analysis (as received, mass %)		Ultimate analysis (dry basis, mass %)	
Moisture	8.30	C	47.34
Volatile matter	71.78		
Ash	6.28	N	0.30
Fixed carbon	13.64		

* Proximate and Ultimate analysis were conducted to determine the carbon (C) and nitrogen (N) content in dry mass. In addition, moisture, volatile matter, ash, and fixed carbon content were measured. See details in Liao *et al.* (2004).

Gravimetric analysis was conducted on the Teflon membrane filters after 24-hr equilibrium at ~25°C and 35% relative humidity using a microbalance with a ± 1 μg sensitivity (Sartorius, Göttingen, Germany). Total carbon (TC), organic carbon (OC) elemental carbon (EC), and their thermal carbon fraction were determined on quartz fiber filters with a Desert Research Institute (DRI) Model 2001 Thermal/Optical Carbon Analyzer (Atmoslytic Inc., Calabasas, CA, USA) following the IMPROVE_A thermal/ optical protocol (Chow *et al.*, 2007). Real-time measurements of CO_2, CO and PM$_{2.5}$ were made at 1-s resolution.

Emission factors were calculated by dividing the mass of pollutant released by the mass of the consumed fuel, and expressed as grams of emission per kilogram of dry fuel consumed (g kg^{-1}) (Andreae and Merlet, 2001). For CO_2 and CO, the time-integrated EF$_i$ is:

$$EF_i = \frac{\sum_{t=1}^{t=t_{sample}} C_{Dil,i} \times DR \times V_{Stk} \times D}{m_{fuel}} \tag{1}$$

and for particulate pollutants (i.e., PM$_{2.5}$, OC and EC), the EF$_p$ is:

$$EF_p = \frac{m_{filter} \times DR \times t_{sample} \times V_{Stk} \times D}{Q_{filter} \times m_{fuel}} \tag{2}$$

where $C_{Dil,i}$ is the diluted concentration of pollutant i in mg m^{-3} under standard conditions (temperature [T_{Std}] = 293 K and pressure [P_{Std}] = 1 atm); t_{sample} is the sampling duration in seconds; V_{Stk} is the average stack flow velocity in m s^{-1} at standard conditions; D is the stack cross section in m^2; m_{fuel} is the fuel consumption in g determined from the difference of initial and final fuel weights; m_{filter} is the mass of pollutants collected on the filter in mg; Q_{filter} is the sampling volume through the filter in m^3 at standard temperature and pressure (Wang *et al.*, 2012a). DR is the dilution ratio, controlled by the flow balance (i.e., the ratio of sample flow (from stack) and total inflow (sample flow + dilution flow)) of the dilution sampler, where:

$$\text{Flow-Based DR} = \frac{\text{Total Inflow or Outflow}}{\text{Sample Flow}} \tag{3}$$

Total inflow equals total outflow, which is the sum of flows through all the filter packs, online monitors, and make-up flow. DR can also be verified by CO_2 concentrations (CO_2-Based DR) measured at the exhaust duct (undiluted $CO_{2,Stk}$), sampler (diluted $CO_{2,Dil}$), and background (ambient $CO_{2,Bkg}$). Thus:

$$CO_2\text{-Based DR} = \frac{CO_{2,Stk} - CO_{2,Bkg}}{CO_{2,Dil} - CO_{2,Bkg}} \tag{4}$$

The agreement of the two DR estimates (Flow-Based and CO_2-Based DR) indicates that either method is sufficient to obtain an accurate EF.

Emissions vary between different burning phases (e.g., flaming versus smoldering), which can be differentiated by combustion efficiency (CE) - the ratio of carbon (C) emitted as CO_2 to the total amount of C emitted (Ward and Hardy, 1991).When only CO_2 and CO are monitored, CE can be simplified as the modified combustion efficiency (MCE), defined as:

$$MCE = \frac{\Delta CO_2}{\Delta CO_2 + \Delta CO} \quad (5)$$

When ΔCO_2 and ΔCO exceed the molar mixing ratio, MCE indicates the relative importance of flaming and smoldering combustion (Koppmann *et al.*, 2005; Chen *et al.*, 2007). MCE is typically close to 1 during the flaming phase, and ranges between 0.7 and 0.9 for the smoldering phase (Hao and Ward, 1993; Yokelson *et al.*, 1997; Reid *et al.*, 2005).

Table 2 shows the $PM_{2.5}$ mass collected on the three parallel filters from each of the five replicate wheat straw combustion tests. The consistent results between both types of filters and among replicates, as indicated by the low relative standard deviations (RSD) of $PM_{2.5}$ mass (< 10%), demonstrate the capability of the system and reproducibility of the results. The mass on Teflon filter was always more than that on quartz fiber filters. $PM_{2.5}$ samples were collected on three parallel 47-mm filters (1 Teflon-membrane filter and 2 quartz microfiber filters) of the dilution sampler at a flow rate of 5 L min^{-1} per channel. So theoretically, the mass on these three filters from each test should be the same. However, it becomes complex when considering the positive and negative sampling artifacts. Adsorption of organic vapors onto the quartz filters leads to overestimation of the $PM_{2.5}$ mass load (positive artifact), while volatilization of the collected PM from the filter results in the underestimate of the $PM_{2.5}$ mass load (negative artifact) (Turpin *et al.*, 2000). Positive and negative artifacts occur simultaneously and hence are difficult to isolate and quantify. Previous studies report that the positive artifact appears to dominate on samples taken with bare quartz filters (Turpin *et al.*, 1994; Kirchstetter *et al.*, 2001), so it is reasonable to expect more mass on quartz filters than on Teflon. However, quartz filters are known to be fragile and may be prone to fiber loss during weighing, handling, and sampling, which may cause weight loss on quartz filter. The mass difference between quartz and Teflon filters ranged from 8.6% to 14.5%, which falls into a reasonable range considering the sampling and handling uncertainty.

The homogeneity of $PM_{2.5}$ filter deposits was also tested by dividing the quartz filter from one channel into four quadrants for separate carbon analyses. Average carbon concentration are presented in Table 3, good reproducibility was found with RSD ranging from 3–9% for TC, 3–9% for OC, and 1–10% for EC.

Response to combustion emissions by the real-time instruments is usually delayed due to the time it takes to travel from the sample probe to the sensor and the residence time in each instrument's sensing volume. The delays vary with instrument and need to be accounted for in order to align instrumental responses for post-sampling data processing (Wang *et al.*, 2012b). Instruments were first sampled with ambient air for a few minutes to obtain background readings. Then a match was lit near the inlet of the sampling probe to measure time delays. Table 4 shows the delays determined for each instrument to detect a 10% change from background concentration. Delay times of 11–16 s were determined relative to the DustTrak, since the DustTrak responds first (i.e., the delay time of DustTrak was assumed to be 0).

The data were processed to calculate the EFs and MCE following Eqs. (1) to (5) (parameters used to estimate EF were listed in Table S-2, and the calculated EFs are presented in Table 5). MCE were > 0.9 for all five tests, in this study, indicating flaming-dominated combustion. Average EFs were 1460 ± 99 g kg^{-1} for CO_2, and 56.6 ± 7.9 g kg^{-1} for CO. These levels are in reasonable agreement with published those values (Li *et al.*, 2007; Sahai *et al.*, 2007; Cao *et al.*, 2008; Zhang *et al.*, 2008), which were mostly in the range of 1377 to 1787 g kg^{-1} for CO_2, and 28 to 141 g kg^{-1} for CO. Differences in the EFs could be attributed to the fuel properties, such as bulk densities, size, and moisture, which could affect burning conditions, and further affect the EFs (ASI *et al.*, 2003; McMeeking *et al.*, 2009; Chen *et al.*, 2010). For example, the relative higher CO_2 EF, and lower CO EF reported by Sahai *et al.* (2007) was associated with its higher combustion efficiency. The average $PM_{2.5}$ EF for wheat straw was 5.41 ± 0.41 g kg^{-1}, lower than the 7.6 g kg^{-1} reported by Li *et al.* (2007), but higher than the 4.71 ± 0.04 g kg^{-1} reported by Hays *et al.* (2005). The OC and EC EFs

Table 2. $PM_{2.5}$ mass on each filter (mg) for the five replicate wheat straw combustion tests.

$PM_{2.5}$ Mass	Test 1	Test 2	Test 3	Test 4	Test 5	Average[**]	SD[**]	RSD (%)[**]
Filter 1 (Q)[*]	0.375	0.372	0.358	0.388	0.389	0.376	0.012	3.3
Filter 2 (Q)[*]	0.347	0.354	0.352	0.371	0.347	0.354	0.010	2.9
Filter 3 (T)[*]	0.380	0.414	0.393	0.425	0.393	0.401	0.018	4.5
Average[***]	0.367	0.380	0.368	0.395	0.376			
SD[***]	0.018	0.031	0.022	0.027	0.025			
RSD (%)[***]	4.9	8.1	6.0	6.9	6.6			

* Q means quartz microfiber filter, and T means Teflon-membrane filter;
** Average, standard deviation (SD), and relative standard deviations (RSD) for each test;
*** Average, SD, and RSD for the five replicate tests. With the stable system, experiments have a good reproducibility.

Table 3. Average concentrations of total carbon, organic carbon, element carbon, and their thermal fractions measured from each quadrant of sample filter ($\mu g\ cm^{-2}$) for the five replicate wheat straw combustion tests.

	Quadrant	TC	OC	EC	OC1	OC2	OC3	OC4	EC1	EC2	EC3	OP
	1	9.82	8.25	1.57	0.54	1.61	2.46	2.50	2.71	0	0	1.14
	2	10.44	8.70	1.74	0.58	1.63	2.81	2.98	2.44	0	0	0.70
	3	9.81	8.35	1.46	0.63	1.66	2.45	2.48	2.59	0	0	1.13
Test 1	4	9.60	8.05	1.55	0.55	1.64	2.45	2.84	2.12	0	0	0.57
	Average	9.92	8.34	1.58								
	SD	0.36	0.27	0.12								
	RSD (%)	3.7	3.3	7.4								
	1	10.79	7.87	2.92	0.56	1.61	2.28	2.34	4.00	0	0	1.08
	2	11.81	8.33	3.48	0.63	1.85	2.54	2.78	4.01	0	0	0.53
	3	11.93	8.51	3.42	0.63	1.83	2.62	2.92	3.91	0.02	0	0.51
Test 2	4	12.31	8.83	3.48	0.68	1.80	2.91	2.81	4.02	0.09	0	0.63
	Average	11.71	8.39	3.33								
	SD	0.65	0.40	0.27								
	RSD (%)	5.5	4.8	8.2								
	1	9.68	6.05	3.63	0.49	1.39	1.84	1.89	4.07	0	0	0.44
	2	11.29	7.07	4.22	0.71	1.65	2.37	2.31	4.23	0.02	0	0.03
	3	10.38	6.96	3.42	0.51	1.56	2.26	2.46	3.18	0.11	0.30	0.17
Test 3	4	10.44	6.77	3.67	0.68	1.52	2.16	1.99	4.09	0	0	0.42
	Average	10.45	6.71	3.74								
	SD	0.66	0.46	0.34								
	RSD (%)	6.3	6.8	9.1								
	1	12.56	9.85	2.71	0.53	1.97	3.75	3.51	2.54	0.09	0.17	0.09
	2	12.46	9.68	2.78	0.54	2.02	3.56	3.30	2.67	0.13	0.24	0.26
	3	11.39	8.58	2.81	0.43	1.81	3.03	3.25	2.47	0.10	0.30	0.06
Test 4	4	11.47	8.65	2.82	0.46	1.85	2.99	3.33	2.36	0.15	0.33	0.02
	Average	11.97	9.19	2.78								
	SD	0.63	0.67	0.05								
	RSD (%)	5.2	7.3	1.8								
	1	10.57	7.91	2.66	0.68	1.68	2.36	2.66	3.19	0	0	0.53
	2	11.61	8.89	2.72	0.76	1.81	2.60	2.31	4.11	0.02	0	1.41
	3	11.46	8.63	2.83	0.66	1.92	2.56	2.85	3.45	0.02	0	0.64
Test 5	4	9.69	7.26	2.43	0.46	1.39	2.33	2.24	3.27	0	0	0.84
	Average	10.83	8.17	2.66								
	SD	0.89	0.74	0.17								
	RSD (%)	8.2	9.0	6.3								

Carbon analysis follows IMPROVE_A protocol (Chow *et al.*, 2007). OC1 (140°C), OC2 (280°C), OC3 (480°C), and OC4 (580°C) are OC evolved in 100% helium atmosphere, EC1 (580°C), EC2 (740°C), and EC3 (840°C) are EC evolved in 98% helium/2% oxygen atmosphere. Pyrolyzed carbon (OP) is optically monitored by the IMPROVE thermal/optical reflectance (TOR) carbon analysis protocol (Chow *et al.*, 1993, 2001), when OC = OC1 + OC2 + OC3 + OC4 + OP; EC = EC1 + EC2 + EC3 – OP; TC = OC + EC.

Table 4. Delay time for each instrument.

Measurement	Elapsed time to first 10% change from background (sec)	Delayed time relative to DustTrak (sec)
DustTrak, $PM_{2.5}$ mass	72	0
Thermo 48i, CO	83	11
CO_2 analyzer, stack CO_2	86	14
CO_2 analyzer, diluted CO_2	88	16

were 1.39 ± 0.20, and $0.50 \pm 0.15\ g\ kg^{-1}$, respectively. These values fall within the range (1.23–$2.7\ g\ kg^{-1}$ for OC, and 0.35–$0.79\ g\ kg^{-1}$ for EC) reported in the literature (Turn *et al.*, 1997; Hays *et al.*, 2005; Li *et al.*, 2007; Dhammapala *et al.*, 2007), in which the highest EC EF correspond with lower combustion efficiencies.

CONCLUSION

A combustion chamber was designed and tested, and a

Table 5. Comparison of emission factors in wheat straw burning among studies.

location	measurement approach	weight of straw burned each time	moisture content (%)	combustion efficiency	EF (g kg⁻¹)					References
					CO_2	CO	$PM_{2.5}$	OC	EC	
China	chamber	~100 g	8.3*	0.93 ± 0.02[a]	1460 ± 99	56.6 ± 7.9	5.41 ± 0.41	1.39 ± 0.20	0.50 ± 0.15	this study
China	burning tower	0.5–1.9 kg			1378 ± 431	57.8 ± 24.8				Cao et al. (2008)
China	field measurement	40–60 kg	9.59*	0.92 ± 0.03[b]	1470 ± 46	60 ± 23	7.6 ± 4.1	2.7 ± 1.0	0.49 ± 0.12	Li et al. (2007)
China	chamber			0.92 ± 0.01[a]	1558 ± 86	141 ± 15				Zhang et al. (2008)
India	field measurement		14**	0.97 ± 0.02[b]	1787 ± 35	28 ± 20				Sahai et al. (2007)
USA	chamber	~750 g	9.6*	0.94–0.96[b]			3 ± 0.6	1.9 ± 1.1	0.35 ± 0.16	Dhammapala et al. (2007)
USA	chamber		8.8*				4.71 ± 0.04	1.23 ± 0.03	0.52	Hays et al. (2005)
USA	wind tunnel		7*	0.86[b]				2.1	0.79	Turn et al. (1997)

a. MCE; b. CE;
* as received, mass%,; **dry weight basis, mass%.

series of tests were conducted to verify its performance in terms of the enclosure seal against gas/particle loss, flow stability and uniformity in the stack, and purification of the dilution air. In this study, the combustion chamber was equipped with a dilution sampler and real-time instruments for measuring multi-pollutant emissions (e.g., CO_2, CO, $PM_{2.5}$, OC, and EC). Data obtained from wheat straw burning, with a focus on its emission factors and combustion efficiencies, were reported to demonstrate the reproducibility of the results and comparability with prior studies. Biomass of interest in Northwest China can be burned in the combustion chamber to develop emission factors for refining emission inventories and source profiles for more accurate source apportionment.

ACKNOWLEDGMENTS

SUPPLEMENTARY MATERIALS

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

REFERENCES

Akagi, S., Yokelson, R.J., Wiedinmyer, C., Alvarado, M., Reid, J., Karl, T., Crounse, J. and Wennberg, P. (2011). Emission Factors for Open and Domestic Biomass Burning for Use in Atmospheric Models. *Atmos. Chem. Phys.* 11: 4039–4072.

Andreae, M. (1991). Biomass Burning-Its History, Use, and Distribution and Its Impact on Environmental Quality and Global Climate. In *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*. Levine, J.S. (Ed.), MIT Press, Cambridge, MA. pp. 3–21.

Andreae, M.O. and Merlet, P. (2001). Emission of Trace Gases and Aerosols from Biomass Burning. *Global Biogeochem. Cycles* 15: 955–966.

ASI (Air Sciences Inc.) (2003). Final Reprot: Cereal-Grain Residue Open-Field Burning Emissions Study. Project 152-02.

Baldwin, T.A., Watson, J.G. and Neulicht, R. (2012). New Test Method for Measuring Fine Particulate Matter ($PM_{2.5}$) in Wet Stacks. Proceedings, Air Quality Measurement Methods and Technology. Air & Waste Management Association. Pittsburgh, PA, pp. 88-1–88-6.

Burling, I., Yokelson, R.J., Griffith, D.W., Johnson, T.J., Veres, P., Roberts, J., Warneke, C., Urbanski, S., Reardon, J. and Weise, D. (2010). Laboratory Measurements of Trace Gas Emissions from Biomass Burning of Fuel

Types from the Southeastern and Southwestern United States. *Atmos. Chem. Phys.* 10: 11115–11130.

Cao, G., Zhang, X., Gong, S. and Zheng, F. (2008). Investigation on Emission Factors of Particulate Matter and Gaseous Pollutants from Crop Residue Burning. *J. Environ. Sci.* 20: 50–55.

Cao, J., Wu, F., Chow, J., Lee, S., Li, Y., Chen, S., An, Z., Fung, K., Watson, J. and Zhu, C. (2005). Characterization and Source Apportionment of Atmospheric Organic and Elemental Carbon during Fall and Winter of 2003 in Xi'an, China. *Atmos. Chem. Phys.* 5: 3127–3137.

Cao, J., Lee, S., Chow, J.C., Watson, J.G., Ho, K., Zhang, R., Jin, Z., Shen, Z., Chen, G. and Kang, Y. (2007). Spatial and Seasonal Distributions of Carbonaceous Aerosols over China. *J. Geophys. Res.* 112: D22S11, doi: 10.1029/2006JD008205.

Chen, L.W.A., Moosmüller, H., Arnott, W.P., Chow, J.C., Watson, J.G., Susott, R.A., Babbitt, R.E., Wold, C.E., Lincoln, E.N. and Hao, W.M. (2007). Emissions from Laboratory Combustion of Wildland Fuels: Emission Factors and Source Profiles. *Environ. Sci. Technol.* 41: 4317–4325.

Chen, L.W.A., Verburg, P., Shackelford, A., Zhu, D., Susfalk, R., Chow, J. and Watson, J. (2010). Moisture Effects on Carbon and Nitrogen Emission from Burning of Wildland Biomass. *Atmos. Chem. Phys.* 10: 6617–6625.

Chow, J.C., Watson, J.G., Pritchett, L.C., Pierson, W.R., Frazier, C.A. and Purcell, R.G. (1993). The DRI Thermal/Optical Reflectance Carbon Analysis System: Description, Evaluation and Applications in US Air Quality Studies. *Atmos. Environ.* 27: 1185–1201.

Chow, J.C., Watson, J.G., Crow, D., Lowenthal, D.H. and Merrifield, T. (2001). Comparison of IMPROVE and NIOSH Carbon Measurements. *Aerosol Sci. Technol.* 34: 23–34.

Chow, J.C., Watson, J.G., Chen, L.W.A., Chang, M.O., Robinson, N.F., Trimble, D. and Kohl, S. (2007). The IMPROVE_A Temperature Protocol for Thermal/Optical Carbon Analysis: Maintaining Consistency with a Long-Term Database. *J. Air Waste Manage. Assoc.* 57: 1014–1023.

Crutzen, P.J. and Andreae, M.O. (1990). Biomass Burning in the Tropics: Impact on Atmospheric Chemistry and Biogeochemical Cycles. *Science* 250: 1669–1678.

Dhammapala, R., Claiborn, C., Jimenez, J., Corkill, J., Gullett, B., Simpson, C. and Paulsen, M. (2007). Emission Factors of PAHs, Methoxyphenols, Levoglucosan, Elemental Carbon and Organic Carbon from Simulated Wheat and Kentucky Bluegrass Stubble Burns. *Atmos. Environ.* 41: 2660–2669.

Duan, F., Liu, X., Yu, T. and Cachier, H. (2004). Identification and Estimate of Biomass Burning Contribution to the Urban Aerosol Organic Carbon Concentrations in Beijing. *Atmos. Environ.* 38: 1275–1282.

Hao, W.M. and Ward, D.E. (1993). Methane Production from Global Biomass Burning. *J. Geophys. Res.* 98: 20657–20661.

Hays, M.D., Fine, P.M., Geron, C.D., Kleeman, M.J. and

Gullett, B.K. (2005). Open Burning of Agricultural Biomass: Physical and Chemical Properties of Particle-Phase Emissions. *Atmos. Environ.* 39: 6747–6764.

Hildemann, L., Cass, G. and Markowski, G. (1989). A Dilution Stack Sampler for Collection of Organic Aerosol Emissions: Design, Characterization and Field Tests. *Aerosol Sci. Technol.* 10: 193–204.

Huang, X., Li, M., Li, J. and Song, Y. (2012a). A High-Resolution Emission Inventory of Crop Burning in Fields in China Based on MODIS Thermal Anomalies/Fire Products. *Atmos. Environ.* 50: 9–15.

Huang, X., Song, Y., Li, M., Li, J. and Zhu, T. (2012b). Harvest Season, High Polluted Season in East China. *Environ. Res. Lett.* 7: 044033.

ISO (2013). ISO 25597:2013: Stationary Source Emissions--Test Method for Determining $PM_{2.5}$ and PM_{10} Mass in Stack Gases Using Cyclone Samplers and Sample Dilution. Prepared by International Organization for Standardization, Geneva, Switzerland.

Kirchstetter, T.W., Corrigan, C.E. and Novakov, T. (2001). Laboratory and Field Investigation of the Adsorption of Gaseous Organic Compounds onto Quartz Filters. *Atmos. Environ.* 35: 1663–1671.

Koppmann, R., Czapiewski, K.V. and Reid, J. (2005). A Review of Biomass Burning Emissions, Part I: Gaseous Emissions of Carbon Monoxide, Methane, Volatile Organic Compounds, and Nitrogen Containing Compounds. *Atmos. Chem. Phys. Discuss.* 5: 10455–10516.

Li, W., Shao, L. and Buseck, P. (2010). Haze Types in Beijing and the Influence of Agricultural Biomass Burning. *Atmos. Chem. Phys.* 10: 8119–8130.

Li, X., Wang, S., Duan, L., Hao, J., Li, C., Chen, Y. and Yang, L. (2007). Particulate and Trace Gas Emissions from Open Burning of Wheat Straw and Corn Stover in China. *Environ. Sci. Technol.* 41: 6052–6058.

Liao, C., Wu, C. and Huang, H. (2004). Chemical Elemental Characteristics of Biomass Fuels in China. *Biomass Bioenergy* 27: 119–130.

Lipsky, E.M. and Robinson, A.L. (2005). Design and Evaluation of a Portable Dilution Sampling System for Measuring Fine Particle Emissions. *Aerosol Sci. Technol.* 39: 542–553.

Lobert, J., Scharffe, D. and Hao, W.M. (1991). Experimental Evaluation of Biomass Burning Emissions-Nitrogen and Carbon Containing Compounds. In *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*. Levine, J.S. (Ed.), MIT Press, Cambridge, MA, pp. 289–304.

Lobert, J.M. and Warnatz, J. (1993). Emissions from the Combustion Process in Vegetation. In *Fire in the Environment: The Ecological, Atmospheric and Climatic Importance of Vegetation Fires*. Crutzen, P.J. and Goldammer, J.G. (Eds.), pp. 15–39.

Malamakal, T., Chen, L.W.A., Wang, X., Green, M.C., Gronstal, S., Chow, J.C. and Watson, J.G. (2013). Prescribed Burn Smoke Impact in the Lake Tahoe Basin: Model Simulation and Field Verification. *Int. J. Environ. Pollut.* 52: 225–243.

McMeeking, G.R., Kreidenweis, S.M., Baker, S., Carrico,

C.M., Chow, J.C., Collett, J.L., Hao, W.M., Holden, A.S., Kirchstetter, T.W. and Malm, W.C. (2009). Emissions of Trace Gases and Aerosols during the Open Combustion of Biomass in the Laboratory. *J. Geophys. Res.* 114: 19210, doi: 10.1029/2009JD011836.

Penner, J.E., Dickinson, R.E. and O'Neill, C.A. (1992). Effects of Aerosol from Biomass Burning on the Global Radiation Budget. *Science* 256: 1432–1434.

Reid, J., Koppmann, R., Eck, T. and Eleuterio, D. (2005). A Review of Biomass Burning Emissions Part II: Intensive Physical Properties of Biomass Burning Particles. *Atmos. Chem. Phys.* 5: 799–825.

Sahai, S., Sharma, C., Singh, D., Dixit, C., Singh, N., Sharma, P., Singh, K., Bhatt, S., Ghude, S. and Gupta, V. (2007). A Study for Development of Emission Factors for Trace Gases and Carbonaceous Particulate Species from in Situ Burning of Wheat Straw in Agricultural Fields in India. *Atmos. Environ.* 41: 9173–9186.

Simon, H., Beck, L., Bhave, P.V., Divita, F., Hsu, Y., Luecken, D., Mobley, J.D., Pouliot, G.A., Reff, A. and Sarwar, G. (2010). The Development and Uses of EPA's SPECIATE Database. *Atmos. Pollut. Res.* 1: 196–206.

Streets, D., Yarber, K., Woo, J.H. and Carmichael, G. (2003). Biomass Burning in Asia: Annual and Seasonal Estimates and Atmospheric Emissions. *Global Biogeochem. Cycles* 17: 1099.

Turn, S.Q., Jenkins, B.M., Chow, J.C., Pritchett, L.C., Campbell, D., Cahill, T. and Whalen, S.A. (1997). Elemental Characterization of Particulate Matter Emitted from Biomass Burning: Wind Tunnel Derived Source Profiles for Herbaceous and Wood Fuels. *J. Geophys. Res.* 102: 3683.

Turpin, B.J., Huntzicker, J.J. and Hering, S.V. (1994). Investigation of Organic Aerosol Sampling Artifacts in the Los Angeles Basin. *Atmos. Environ.* 28: 3061–3071.

Turpin, B.J., Saxena, P. and Andrews, E. (2000). Measuring and Simulating Particulate Organics in the Atmosphere: Problems and Prospects. *Atmos. Environ.* 34: 2983–3013.

Wang, H., Lou, S., Huang, C., Qiao, L., Tang, X., Chen, C., Zeng, L., Wang, Q., Zhou, M. and Lu, S. (2014). Source Profiles of Volatile Organic Compounds from Biomass Burning in Yangtze River Delta, China. *Aerosol Air Qual. Res.* 14: 818–828.

Wang, X., Chancellor, G., Evenstad, J., Farnsworth, J.E., Hase, A., Olson, G.M., Sreenath, A. and Agarwal, J.K. (2009). A Novel Optical Instrument for Estimating Size Segregated Aerosol Mass Concentration in Real Time. *Aerosol Sci. Technol.* 43: 939–950.

Wang, X., Watson, J., Chow, J., Kohl, S., Chen, L., Sodeman, D., Legge, A. and Percy, K. (2012a). Measurement of Real-World Stack Emissions with a Dilution Sampling System. In *Alberta Oil Sands: Energy, Industry and the Environment*. Percy, K.E. (Ed.), Elsevier Press, Oxford, UK. pp. 171–192.

Wang, X., Watson, J.G., Chow, J.C., Gronstal, S. and Kohl, S.D. (2012b). An Efficient Multipollutant System for Measuring Real-World Emissions from Stationary and Mobile Sources. *Aerosol Air Qual. Res.* 12: 145–160.

Ward, D.E. and Hardy, C.C. (1991) Smoke Emissions from Wildland Fires. *Environ. Int.* 17: 117–134.

Watson, J.G., Zhu, T., Chow, J.C., Engelbrecht, J., Fujita, E.M. and Wilson, W.E. (2002). Receptor Modeling Application Framework for Particle Source Apportionment. *Chemosphere* 49: 1093–1136.

Watson, J., Chow, J., Wang, X., Kohl, S., Chen, L. and Etyemezian, V. (2012). Overview of Real-World Emission Characterization Methods. In *Alberta Oil Sands: Energy, Industry, and the Environment*. Percy, K.E. (Ed.), Elsevier Press, Amsterdam, The Netherlands, pp. 145–170.

Yan, X., Ohara, T. and Akimoto, H. (2006). Bottom-Up Estimate of Biomass Burning in Mainland China. *Atmos. Environ.* 40: 5262–5273.

Yokelson, R.J., Susott, R., Ward, D.E., Reardon, J. and Griffith, D.W. (1997). Emissions from Smoldering Combustion of Biomass Measured by Open-Path Fourier Transform Infrared Spectroscopy. *J. Geophys. Res.* 102: 18865–18877.

Yokelson, R.J., Christian, T.J., Karl, T. and Guenther, A. (2008). The Tropical Forest and Fire Emissions Experiment: Laboratory Fire Measurements and Synthesis of Campaign Data. *Atmos. Chem. Phys.* 8: 3509–3527.

Zhang, H., Ye, X., Cheng, T., Chen, J., Yang, X., Wang, L. and Zhang, R. (2008). A Laboratory Study of Agricultural Crop Residue Combustion in China: Emission Factors and Emission Inventory. *Atmos. Environ.* 42: 8432–8441.

Zhang, Y., Shao, M., Lin, Y., Luan, S., Mao, N., Chen, W. and Wang, M. (2013). Emission Inventory of Carbonaceous Pollutants from Biomass Burning in the Pearl River Delta Region, China. *Atmos. Environ.* 76: 189–199.

Zhang, Y.X., Shao, M., Zhang, Y.H., Zeng, L.M., He, L.Y., Zhu, B., Wei, Y.J. and Zhu, X.L. (2007). Source Profiles of Particulate Organic Matters Emitted from Cereal Straw Burnings. *J. Environ. Sci.* 19: 167–175.