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Microenvironmental air quality impact of a commercial-scale biomass heating system☆

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A B S T R A C T

Initiatives to displace petroleum and climate change mitigation have driven a recent increase in space heating with biomass combustion. However, there is ample evidence that biomass combustion emits significant quantities of health damaging pollutants. We investigated the near-source micro-environmental air quality impact of a biomass-fueled combined heat and power system equipped with an electrostatic precipitator (ESP) in Syracuse, NY. Two rooftop sampling stations with $PM_{2.5}$ and CO_2 analyzers were established in such that one could capture the plume while the other one served as the background for comparison depending on the wind direction. Four sonic anemometers were deployed around the stack to quantify spatially and temporally resolved local wind patterns. Fuel-based emission factors were derived based on near-source measurement. The Comprehensive Turbulent Aerosol Dynamics and Gas Chemistry (CTAG) model was then applied to simulate the spatial variations of primary $PM_{2.5}$ without ESP. Our analysis shows that the absence of ESP could lead to an almost 7 times increase in near-source primary $PM_{2.5}$ concentrations with a maximum concentration above 100 μg m^{-3} at the building rooftop. The above-ground "hotspots" would pose potential health risks to building occupants since particles could penetrate indoors via infiltration, natural ventilation, and fresh air intakes on the rooftop of multiple buildings. Our results demonstrated the importance of emission control for biomass combustion systems in urban area, and the need to take above-ground pollutant "hotspots" into account when permitting distributed generation. The effects of ambient wind speed and stack temperature, the suitability of airport meteorological data on micro-environmental air quality were explored, and the implications on mitigating near-source air pollution were discussed.

1. Introduction

Recently, initiatives to displace petroleum and climate change mitigation have driven an increase in space heating with biomass combustion in the world (Demirbas, 2005). However, biomass (dominated by wood) combustion is a source of primary $PM_{2.5}$ emission, and can be a significant contributor to ambient wintertime $PM_{2.5}$ concentrations (Boman et al., 2003; Larson and Koenig, 1994; Maykut et al., 2003; Naeher et al., 2007; Schauer et al., 1996; Wang et al., 2011a; Zheng et al., 2002). Glasius et al. (2006) measured the contribution from residential wood combustion to local particulate matter (PM) concentrations and found it to be comparable to a busy roadway in Denmark. A similar finding was reported by Ries et al. (2009), which estimated the winter season intake fraction based on spatial temporal statistical models in Vancouver, Canada. Boman et al. (2003) and Naeher et al. (2007) reviewed studies on the health effect of ambient air pollution in relation to residential wood combustion, indicating that biomass burning is not less toxic than other emission sources of PM.

A critical aspect of assessing health risks from wood smoke exposure is the spatial variation of PM. The location of the emission sources, the surrounding urban landscape, and micro-meteorology all influence the spatial pattern of PM and unfavorable conditions could create "hotspots" of elevated concentrations. To date, only a few studies have focused on the spatial variation of wood-burning PM, and those studies mostly focused residential-scale wood combustion. For example, Larson et al. (2007) and Su et al. (2008, 2015) developed land use regression (LUR) models to predict the

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spatial variation of woodsmoke levels for urban areas. Allen et al. (2011) combined mobile and fixed-location monitoring to develop a LUR model for predicting the spatial variation of $PM_{2.5}$ in an rural area of upstate New York with valley topography.

Commercial-scale biomass-based heating systems are often located in populous urban areas with relatively short stack height, and few studies have investigated their impacts. Petrov et al. (2015) evaluated the health risk associated with a biomass combined heat and power (CHP) facility at a university campus using a dispersion model (CALPUFF) and the intake fraction method. For sites surrounded by major urban structures such as street canyons, neither LUR models nor dispersion models are able to fully take into account the complex turbulent flow field that significantly alters the plume trajectory (Pullen et al., 2005). By contrast, Computational Fluid Dynamics (CFD) is more capable of capturing the near-source flow patterns and plume dispersion but at greater computing cost (Gousseau et al., 2011; Tominaga and Stathopoulos, 2011; Tong et al., 2012; Wang et al., 2011b; Steffens et al., 2013).

The primary objective of this study is to evaluate the near-source micro-environmental impact of a commercial-scale biomass boiler with and without emission control using both on-site measurement and dispersion simulations using the CFD-based CTAG model. The selected biomass stack in this study was uniquely located adjacent to two large buildings with rooftop access, which allowed the measurement of the biomass plumes under varying wind directions. A fuel-based emission rate was derived from near-source measurement with emission control. The performance of CTAG simulations was evaluated with on-site wind and $PM_{2.5}$ measurements, and then we applied CTAG to simulate scenarios without emission control. In the second part of the study, we explored various design parameters including stack temperature and ambient weather conditions to provide recommendations for siting biomass-fueled heating equipment in order to mitigate near-source air pollution.

2. Experimental method

2.1. Site description

The Combined Heat and Power (CHP) facility with a wood pellet-fired boiler and an electrostatic precipitator (ESP) is located in the Gateway Building on the campus of SUNY College of Environmental Science and Forestry (ESF) in Syracuse, NY. The biomass CHP system was designed to supply both thermal and electrical energy for five campus buildings. ESP is generally accepted as a reliable and efficient particulate control device with low operating and maintenance costs (Lind et al., 2003). However, currently it is still rare for distributed biomass energy systems to be equipped with ESPs. During the field measurements, the system did not generate electricity, serving as a boiler for heating purpose only.

Even though the Gateway Building is located in an academic setting, the nearby structures including the Carrier Dome (CD) and Illick Hall (IH) make the surrounding area a good representation of a complex urban built environment (Fig. 1). The exhaust stack is on the roof of the Gateway Building about 16 m above the ground level, surrounded by CD (~42 m) and IH (~26 m). The presence of these two tall buildings with accessible rooftop areas allowed us to set up measurement stations and capture the near-source stack plumes. Other buildings are located further from the stack with lower heights as shown in Fig. 1.

2.2. Instrumentation

Two personal DataRam (pDR-1200, Thermo Scientific, Boston, MA, USA) with $PM_{2.5}$ size-selective cyclones were deployed to continuously collect data every 6 s. One CO_2 sensor (MI70, VAISALA) and one CO sensor (IAQ-CALC, TSI Model 7545) were employed in combination with $PM_{2.5}$ measurements to detect concurrent concentration spikes at the IH station. Three 3-D Gill sonic anemometers were strategically deployed to measure the instantaneous wind speed and direction at 1 Hz. Before the field trip, the two pDRs were cross-calibrated by co-locating them next to a traffic source to rectify any systematic differences between them. Three anemometers were cross-calibrated in an environmental wind tunnel to ensure consistency among them. Calibration details are available in the Supporting Information as shown in Figs. S1 and S2.

2.3. Sampling locations

Two rooftop sampling stations (CD and IH station) were established such that one can capture the plume while the other one serves as the background in comparison depending on the wind direction (Fig. 1). At the CD station, the pDR was placed on south edge facing the stack. At the IH station, the pDR and CO/CO_2 sensors were placed near the west edge of the roof facing the stack (Fig. 1). All instruments were raised vertically away from the floor in order to avoid boundary layer effect. The arrangement of the three anemometers was made according to the prevailing wind direction (West). One station was installed upwind of the Gateway Building 4.3 m from the ground level. The second anemometer station was installed at the green roof level of the Gateway Building 2.5 m from the floor. The third station was placed outside the south exit of the Gateway Building 2.6 m from the floor. The field measurements took place from March 16 to 20, 2015, respectively. A preliminary field campaign was conducted a month earlier (from February 16 to 19, 2015). There was a heavy snowstorm during the field campaign in which the rooftop access was not available due to safety reasons. The data presented in Section 4 corresponds to non-snow periods that did not exceed recommended operating temperature and humidity by the manufacturer ($-10°$–50 °C and 10–95% RH) during the campaign.

3. Model description

To evaluate the near-source air quality impacts of a biomass system in an urban neighborhood, it is essential to accurately model plume dispersion where exhaust momentum/buoyancy, surrounding structures and micrometeorology play significant roles. Based on CFD, the Comprehensive Turbulent Aerosol Dynamics and Gas Chemistry (CTAG) model was designed to resolve turbulent reacting flows, aerosol dynamics, and gas chemistry in complex urban environments. A full description of the model's theoretical background and implementation was presented in our previous work (Wang and Zhang, 2012; Wang et al., 2013a; Wang et al., 2013b; Steffens et al., 2014; Tong et al., 2016). In particular, a similar methodology was applied to simulate plume dispersion of diesel backup generators in New York City (Tong and Zhang, 2015). Large Eddy Simulation (LES) was employed to resolve the unsteady turbulent flow field. A dynamic subgrid model for LES was chosen, which allows the Smagorinsky constant to vary in space and time (Germano et al., 1991). A logarithmic wall function was applied to the near-wall region since it was computationally impractical to resolve every viscous sublayer in a large domain (Launder and Spalding, 1974). LES is a suitable turbulence model for simulating unsteady flow over bluff bodies like urban canopies, because it explicitly resolves large scale eddies created by urban structures, and only require models the small-scale, unresolvable turbulent motion which is less influenced by the physical boundaries (Rodi, 1997; Xie and Castro, 2006).