Indoor Air 2010; 20: 399–411
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Published 2010

INDOOR AIR
doi:10.1111/j.1600-0668.2010.00664.x

Characterization of particulate matter size distributions and indoor concentrations from kerosene and diesel lamps

Abstract Over one-quarter of the world's population relies on fuel-based lighting. Kerosene lamps are often located in close proximity to users, potentially increasing the risk for respiratory illnesses and lung cancer. Particulate matter concentrations resulting from cook stoves have been extensively studied in the literature. However, characterization of particulate concentrations from fuel-based lighting has received minimal attention. This research demonstrates that vendors who use a single simple wick lamp in high-air-exchange market kiosks will likely be exposed to $PM_{2.5}$ concentrations that are an order of magnitude greater than ambient health guidelines. Using a hurricane lamp will reduce exposure to $PM_{2.5}$ and PM_{10} concentrations by an order of magnitude compared to using a simple wick lamp. Vendors using a single hurricane or pressure lamp may not exceed health standards or guidelines for $PM_{2.5}$ and PM_{10}, but will be exposed to elevated 0.02–0.3 μm particle concentrations. Vendors who change from fuel-based lighting to electric lighting technology for enhanced illumination will likely gain the ancillary health benefit of reduced particulate matter exposure. Vendors exposed only to ambient and fuel-based lighting particulate matter would see over an 80% reduction in inhaled $PM_{2.5}$ mass if they switched from a simple wick lamp to an electric lighting technology.

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Key words: Kerosene; Lamps; $PM_{2.5}$; PM_{10}; Indoor air; light emitting diode lighting.

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Received for review 21 September 2009. Accepted for publication 6 May 2010.

Practical Implications

Changing lighting technologies to achieve increased efficiency and energy service levels can provide ancillary health benefits. The cheapest, crudest kerosene lamps emit the largest amounts of $PM_{2.5}$. Improving affordability and access to better lighting options (hurricane or pressure lamps and lighting using grid or off-grid electricity) can deliver health benefits for a large fraction of the world's population, while reducing the economic and environmental burden of the current fuel-based lighting technologies.

Introduction

Poor indoor air quality in developing countries is a large societal burden (Zhang and Smith, 2007). Inhalation of particulate matter resulting from indoor combustion processes can cause a range of adverse health effects to the lungs (Bai et al., 2007; Dockery et al., 1993; Dominici et al., 2003). In developing countries, indoor particulate matter typically comes from two sources: cook stoves and fuel-based lighting. International studies show that wood and biomass cook stoves can produce indoor $PM_{2.5}$ concentrations that range from 101 to 8200 $\mu g/m^3$ (Armendariz Arnez et al., 2008; Brauer et al., 1996; Dionisio et al., 2008; Naeher et al., 2001; Pandey et al., 1990; Siddiqui et al., 2009).

In comparison with cook stoves, almost no research has quantified the particulate matter concentrations that roughly 1.6 billion people worldwide are exposed to when using fuel-based lighting to conduct business, study, and perform tasks after dark (Mills, 2005). In total, these people spend nearly $40 billion annually to purchase 77 billion liters of lighting fuel (Mills, 2005). In Kenya, for example, 88% of the population (over 25 million people) used kerosene as a lighting source in 2000 (Kamfor, Ltd. 2002). While kerosene is the dominant fuel in practice, diesel is used when it is the cheaper fuel or where government programs limit the availability of kerosene (Jones et al., 2005). Despite efforts at rural electrification, the number of people without access to grid electricity is growing in sub-Saharan Africa (International Energy Agency 2002).

The population that is operating without the use of electric lighting is being exposed to a range of health risks from fuel-based lighting including: burns, complications of fires or explosions arising from fuel adulteration, child poisoning because of inadvertent consumption, exposure to unburned fuel, compromised 'visual health' because of sub-standard luminance levels, and complications of indoor air pollution (Schwebel et al., 2009, Shepherd and Perez, 2008; WHO 2002). Exposures to these health risks vary by type of lighting technology, fuel choice, hours of use, and location of the lamp. Many of these factors, in turn, are determined by user demographics and lamp type.

Many of the lamps used for fuel-based lighting combust kerosene inefficiently (Figure 1). Simple wick lamps are typically the cheapest option for lighting. These lamps are made from locally available cans or jars using cotton for wicks. Users buy fuel in amounts they can afford, often five-to-ten milliliters at a time. Hurricane lamps are a more expensive capital investment, give off more light, and typically use fuel at a higher rate. Pressure lamps are the most expensive type of fuel-based lighting technology, give off the most light, and utilize a mantle. The mantle is a net-like filament that emits light when heated. Pressure lamp use is relatively costly, uncommon, and limited primarily to market shops without electricity and other non-household settings.

The exposure to particulate matter resulting from fuel-based lighting is an understudied health risk in developing countries. In 1995, Schare and Smith measured total suspended particulate matter (TSP) concentrations in a simulated village house with a volume of 16.9 m^3. Indoor steady state TSP concentrations were measured as 1200 ± 450 $\mu g/m^3$ for a single hurricane lamp and 3400 ± 900 $\mu g/m^3$ for a single simple wick lamp (Schare and Smith, 1995). The authors did not determine the fraction of emitted particles that were in the size range that could impact human health. In 2001, Fan and Zhang examined the performance of a kerosene hurricane lamp in a 0.15 m^3 chamber (Fan and Zhang, 2001). The peak number concentrations for a hurricane lamp were $1.4 \times 10^{11}/m^3$ for particles with 0.3–0.4 μm diameters. Fan and Zhang also estimated peak PM_{10} concentrations of 640 $\mu g/m^3$ for a 40 m^3 room with an air exchange rate of 2/h. In addition to hurricane lamp, this study examined space heaters, portable gas ranges, and candles. It did not examine particulate matter concentrations resulting from the use of simple wick lamps or pressure lamps.

The research presented here is part of a larger effort to analyze the economic feasibility and use patterns of early adaptors of the light emitting diode (LED) technology in Kenyan markets (Radecsky et al., 2008). Market vendors were targeted in this effort as early adaptors as they were the most likely to be able to afford LED lamps. The work included a combination of laboratory and field-based research conducted in Kenya in June and July of 2007 and 2008. The objective of the research presented here was to quantify the reduction in exposure to particulate matter concentrations (and by inference the potential associated health benefits) that market vendors would gain by switching from various fuel-based light sources to electric light sources. Specifically, this research sought to determine the following: (i) the particle sizes emitted from various lamp types; (ii) the dependence of particle mass concentrations on the lamp burn rate in a vendor's kiosk; and (iii) whether the location of the vendor in an enclosed kiosk impacts the exposure to particulate matter (Figure 2).

Methods

To achieve the objectives, a variety of lamps were operated with diesel and kerosene fuel to determine particle size distributions and particle mass concentrations under a range of possible exposure scenarios. The primary concern in this research was characterizing potential particulate matter concentrations in kiosks where vendors use fuel-based lighting to sell products

Fig. 1 An illustrative subset of the tested lamps. Left to Right: Three simple wick lamps, two hurricane lamps, one pressure lamp

Fig. 2 Illustration of proximity to kerosene simple wick lamps in a Kenyan market (Photos by Evan Mills)

at night (Figure 3). Vendors work in drafty kiosks that often have large open windows, resulting in erratic and inconsistent air exchange. This erratic air exchange minimizes the effectiveness of determining kiosk particulate matter concentrations from emission rates. Hence, concentrations were directly measuring in a representative 6.34 m^3 experimental kiosk that was constructed out of plywood based on observations in the field. The experimental kiosk was located outside on the roof of a building exposed to varying wind conditions.

Lamps and fuel

Eight different lamps were operated under a variety of scenarios (Figure 1, five simple wick lamps (three shown), two hurricane lamps, and one pressure lamp). Simple wick lamps were tested using both diesel and kerosene fuel. The hurricane and pressure lamps were tested using kerosene.

Because of difficulties related to the international transport of flammable fuels, the kerosene and diesel used were purchased in the United States. Kerosene meeting ASTM 1-K grade specifications was used for all kerosene combustion experiments. Ultra-low sulfur highway diesel fuel containing a maximum of 15 ppm sulfur (EPA 2006) was used for the diesel combustion experiments.

Particle size measurements

A TSI AeroTrak Optical Particle Counter was used to measure the number concentration of particles in the 0.3–10 μm diameter range. The AeroTrak device was programmed to differentiate between six particle size ranges: 0.3–0.5 μm, 0.5–1.0 μm, 1.0–2.5 μm, 2.5–5 μm, 5–10 μm, and >10 μm. The device continuously recorded 25-s average number concentrations for each particle size range. According to the manufacturer, the AeroTrak measures the 0.3–0.5 size range at a 50% counting efficiency, and all other size ranges at a 100% counting efficiency. A TSI P-Trak Ultrafine Particle Counter was used to measure particles of diameter 0.02–1.0 μm, and the device recorded a sample once per second. To determine the fraction of particles in the 0.02–0.3 μm size range, Equation 1 was used.

$$C_{0.02-0.3} = C_{0.02-1.0} - 2C_{0.3-0.5} - C_{0.5-1.0}. \quad (1)$$

The AeroTrak and P-Trak were both factory calibrated prior to the start of this research. Before each experiment the instruments were attached to zero-count filters to ensure that each responded correctly to zero concentrations.

Fig. 3 Example vendor kiosk in Kenya (Photo by Evan Mills) and experimental kiosk used in experiments

Particle mass estimates

Particle number concentrations reported by the P-Trak and AeroTrak were converted into mass concentration units following the method used by Sarwar et al. (2003). Each particle size range was represented as the geometric mean diameter of the size range limits. The mass of each particle was estimated by assuming spherical particles (Sarwar et al., 2003) and a particle density of 1900 kg/m^3. This is similar to the density of kerosene soot described by Wen et al. of 2000 kg/m^3. Mass concentrations were estimated by multiplying the particle number concentration from the P-Trak and AeroTrak by the mass per particle. Mass concentrations within each particle size range were summed appropriately to calculate total $PM_{2.5}$ and PM_{10} concentrations.

Air exchange measurements

The air exchange rate of the kiosk was measured to determine the amount of time necessary to run the experiments for documentation of representative concentrations. Air exchange rates were measured by monitoring the decay of carbon dioxide concentrations in the kiosk. The initial ambient carbon dioxide concentration was recorded for 5 min using a carbon dioxide monitor (Telaire 7001), while measurements were logged with a data logger (HOBO U12-013). The monitor was placed in the center of the kiosk at an elevation of 0.9 m. Carbon dioxide was released into the kiosk from a paintball gun canister via the front window. Carbon dioxide was injected into the kiosk until the concentration reached 2000 ppm. The experiments were concluded when the concentration decayed to approximately 700 ppm.

The average of 17 preliminary air exchange rate (λ) measurements of the kiosk for sample location dependency experiments, i.e. with the window open and no fan, was 25/h (standard deviation 11/h, minimum 12/h, maximum 60/h). The variation was primarily because of changes in the ambient wind speed (average 0.6 m/s with standard deviation of 0.4 m/s). A box model predicts that the concentration of a contaminant in a room should reach 95% of a steady state value after an emission source is lit in a time of $3/\lambda$ assuming no reactions or settling of that contaminant. At the average air exchange rate, the concentrations in the kiosk should have stabilized after roughly 7 min (minimum of 3 min, maximum of 15 min). These data were used in designing the length of the experiments.

Experiments

To measure particulate concentrations to which a vendor might be exposed the experimental chamber was operated to mimic Kenyan market kiosks. The window was opened, imitating the sales window in the Kenyan kiosk as in Figure 3. These types of kiosks are common in Kenya and other parts of the world, although vendors do operate in other types of structures or outdoors. There were no fans in the chamber as all mixing was carried out by natural ventilation.

Two sets of experiments were conducted. The first series of experiments sought to determine whether different lamp types emitted different particle sizes and whether the particle mass emitted was dependent upon the lamp burn rate. In the second set of experiments, one lamp was used to investigate whether the kiosk particle concentrations a vendor would inhale were dependent upon the vendor's location within the kiosk under normal operations, i.e. with the window open.

Lamp experiments. Experiments were performed to determine the influence of the types of lamps and burn rates on particle concentrations to which a kiosk proprietor would be exposed. Five simple wick lamps (wick diameters varied from 0.60 to 1.15 cm), two different size hurricane lamps (large and small, Figure 1), and one pressure lamp were tested. Each lamp was placed on the center of the open window in the kiosk on a 50 cm wide shelf (representing the surface on which goods for sale would typically be displayed). For each experiment, the AeroTrak and P-Trak were placed at an elevation of 1.5 m, a horizontal location of 0.6 m behind the lamp (into the kiosk) and at the center of the kiosk lengthwise. This location approximates the breathing zone of the kiosk occupant. Measurements for each lamp were conducted for 30 min, and data were averaged for the last 10 min of each experiment. Based on the minimum value for the air exchange rate, if the kiosk behaved as an ideal reactor steady state concentrations should have been achieved after no more than 15 min.

The mass of the lamp and fuel were measured at the beginning and end of each experiment. Lamp burn rates were determined from the reduction in the mass (fuel consumption) during the experiment divided by the time of the burn. To vary the burn rates, the wick heights of the simple wick and hurricane lamps were varied for each experiment. The burn rate of the pressure lamp was adjusted by adjusting the throttle valve. Target burn rates bracketed field measurements of those in Kenyan kiosks made in June and July of 2007 and 2008 (Table 1).

Sample location dependency experiments. Particle number concentration measurements were taken at multiple positions to determine whether the kiosk was well mixed. The tested lamp was located in the center of the 50 cm wide shelf located in the window (Figure 3) at the front of the kiosk. The two particle counters were moved throughout the kiosk at 0.3-m intervals in a three-dimensional grid.

A simple wick lamp was tested three times with particle monitors at the primary breathing zone elevation (1.5 m) of the kiosk proprietor, once at an elevation of 1.2 m, and once at an elevation of 1.8 m. A hurricane lamp was tested three times at an elevation of 1.5 m. For each experiment, particle concentrations were measured over a horizontal grid at distances from the lamp into the shed of 0.3, 0.6, and 0.9 m and lateral distances from the lamp from negative 0.9 m to positive 0.9 m. For each measurement, both instruments were positioned to sample at the same monitoring location. A sample hose attachment was used on the P-Trak; no attachment was used on the AeroTrak.

After measuring particle concentrations at each position in the grid, the instruments were moved to the next sampling position. The lamp, burn rate, and lamp location did not change. A box model of the kiosk predicts that particulate concentrations should have stabilized 7 min after moving the instruments. Each grid location was sampled for at least 10 min. Moving the instruments at 10-min intervals typically did not alter the particle concentrations to values that were outside the standard deviation of the concentration for the final 5 min of sampling at each grid location. Data from the initial 5 min at each sampling location were not used to allow particle concentrations to stabilize; data from the remaining 5 min were averaged to determine the particle concentration at a given location in the grid.

Table 1 Summary of burn rates from kerosene lamps used in Kenyan kiosks measured in the June and July of 2007 and 2008

	Simple wick (g/h)	Small hurricane (g/h)	Large hurricane (g/h)	Pressure (g/h)
Average consumption rate	14.9	14.4	20.5	74.1
Maximum consumption rate	25.0	18.3	54.1	115.5
Minimum consumption rate	4.5	11.4	9.3	18.8
Standard deviation	6.6	2.6	6.0	15.6
Number of tests	10	10	81	44
Number of lamps tested	10	2	14	7

Results

The objective of the research was to quantify the reduction in exposure to particulate matter (and the potential ancillary health benefits) that market vendors would gain by switching from various fuel-based light sources to electric light sources. This was carried out by determining the following: (i) the particle sizes emitted from various lamp types; (ii) the dependence of the particle mass concentrations on lamp burn rates; and (iii) the relationship between the location of the vendor in an enclosed kiosk and exposure to particulate matter.

Particle size concentrations

To determine the particle size concentrations resulting from various lamp types, a subset of the lamp experiment data was examined. Figure 4 illustrates the particle size distribution functions for typical burn rates of lamps in the experimental vendor kiosk. As with Figures 5–8, the first six data points on the right side are from the AeroTrak data and the leftmost data point is from combined data using Equation 1. Particle size concentrations are graphed vs. the geometric average diameter of the bin sizes.

For particle sizes greater than 1 μm, the simple wick lamp particle number concentrations for each size range were approximately two orders of magnitude greater than those of the other three lamps. Below 1 μm, the small hurricane lamp had particle number concentrations that approached those of the simple wick lamp. All lamps produced elevated number particle concentrations within the smallest size range (0.02–0.3 μm). For a hurricane lamp, the number particle concentrations are lower than those measure by Fan and Zhang (2001). Fan and Zhang determined differential number particle concentrations of $1.4 \times 10^{11}/m^3$ for particles with 0.3–0.4 μm diameters, while experiments in this study resulted in number particle concentrations of $3 \times 10^7/m^3$ to $6 \times 10^9/m^3$ (depending on the burn rate) for particles with 0.3–0.5 μm diameters. The airflow around the flame for the two experiments were likely different, as the average overall removal rate for Fan and Zhang's experiments was three times the air exchange in the present experiments.

The particle size distributions did not change appreciably for a range of burn rates for the simple wick lamps and pressure lamp. Illustrative high and low burn rates for each lamp are shown in Figures 5 and 6. These burn rates bracket average burn rates measured in Kenyan kiosks (Table 1). In contrast, increasing the burn rate for the large and small hurricane lamps increased emissions of all of the particle sizes by nearly two orders of magnitude (Figures 7 and 8). The high burn rates for these lamps are not typical of what is seen in Kenyan kiosks, but are approached in some cases (Table 1).

Figure 9 illustrates that all lamps increase the 0.02–0.3 μm particle number concentration by at least an order of magnitude from background levels over a wide range of burn rates. In locations where lamps are used, the background 0.02–0.3 μm particle number concentration may be higher. Regardless of background concentration levels, all fuel-based lamps will increase the 0.02–0.3 μm particle number concentrations in indoor environments. Despite different flame environments, simple wick lamps and pressure lamps

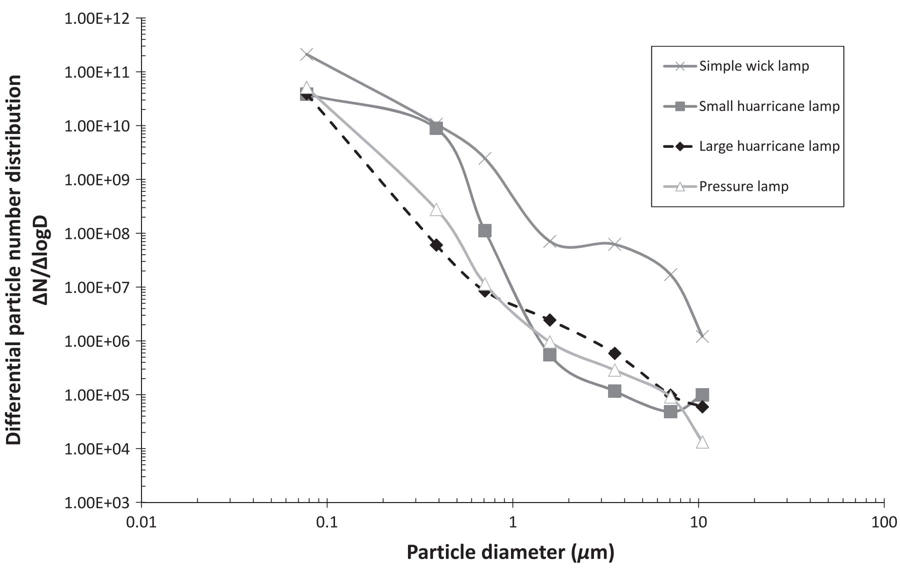

Fig. 4 Differential particle number distributions (#/m^3) for various kerosene lamps at average burn rates. Data points on the figure represent the differential particle number for each bin size measured; data points are connected for trend visualization purposes

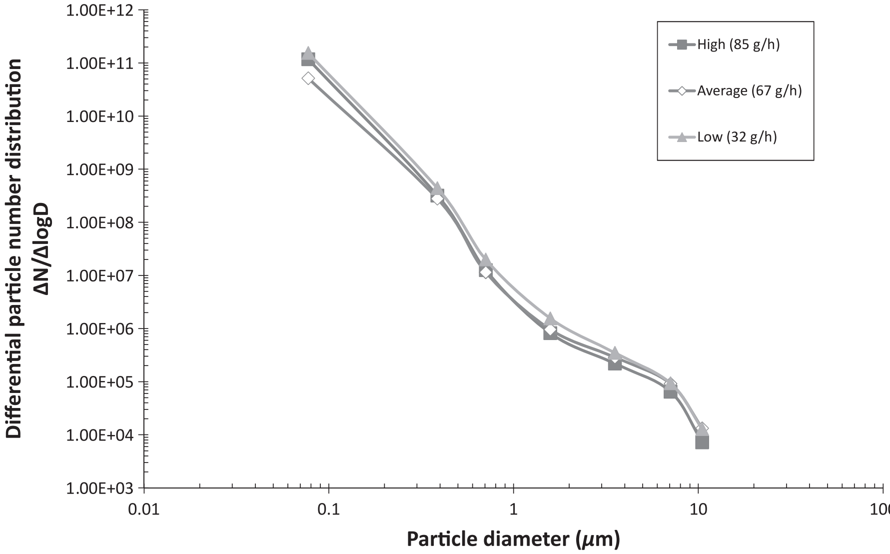

Fig. 5 Differential particle number distribution (#/m^3) for a pressure kerosene lamp at three burn rates. Data points on the figure represent the differential particle number for each bin size measured; data points are connected for trend visualization purposes

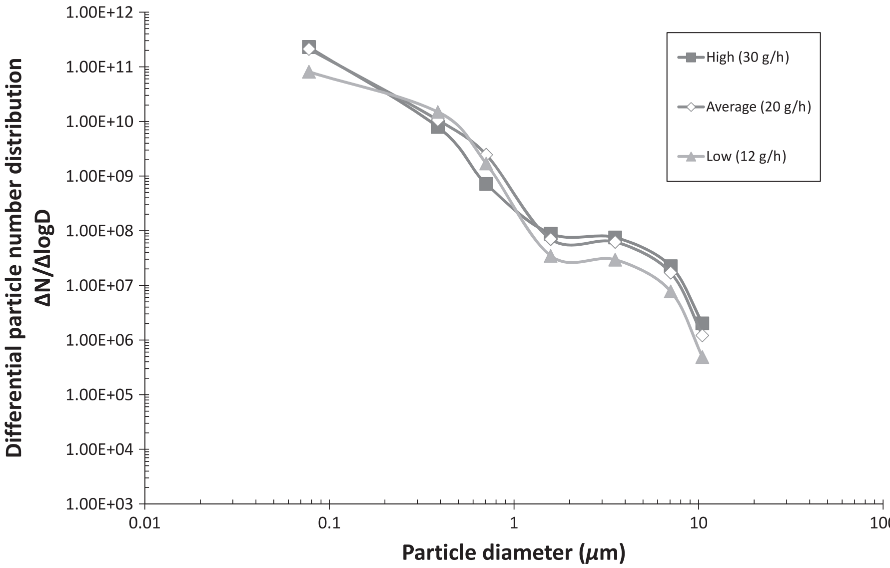

Fig. 6 Differential particle number distribution (#/m^3) for a simple wick kerosene lamp at three burn rates. Data points on the figure represent the differential particle number for each bin size measured; data points are connected for trend visualization purposes

produce similar 0.02–0.3 μm particle number concentrations in the experimental conditions. An increase in the 0.02–0.3 μm particle concentration occurred for both sizes of hurricane lamps when the burn rate was increased. At burn rates typically used by vendors (<20 g/h for small hurricane and <30 g/h for large hurricane, Table 1), the 0.02–0.3 μm particle number concentrations from hurricane lamps are an order of magnitude lower than those of either the simple wick lamp or the pressure lamp.

Particle mass concentrations

To determine the dependence of the particle mass concentrations in the experimental kiosk on lamp burn rates, 55 separate experiments were conducted (31 simple wick lamp experiments, nine small hurricane experiments, 10 large hurricane, and five pressure lamp experiments). The mass of particles in a size bin was determined from particle number concentration data by assuming an average soot density and spherical particles.

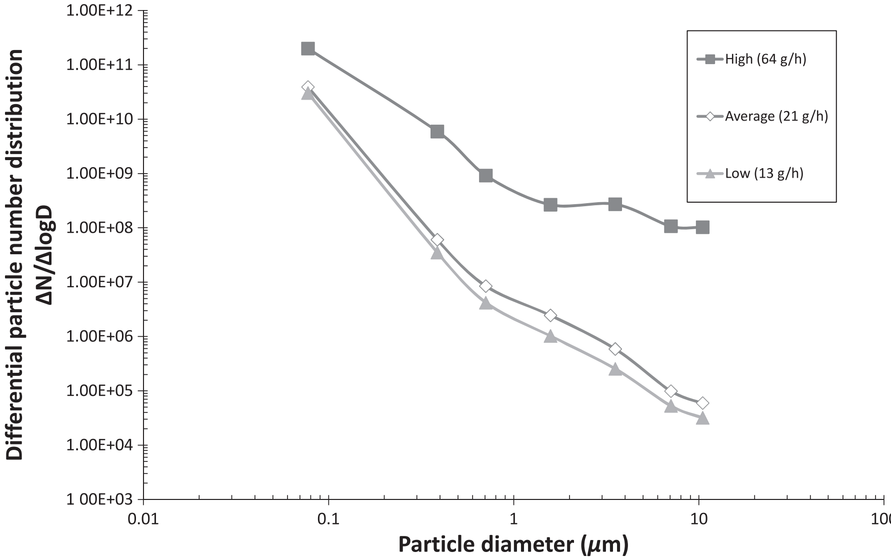

Fig. 7 Differential particle number distribution (#/m^3) for a large hurricane kerosene lamp at three burn rates. Data points on the figure represent the differential particle number for each bin size measured; data points are connected for trend visualization purposes

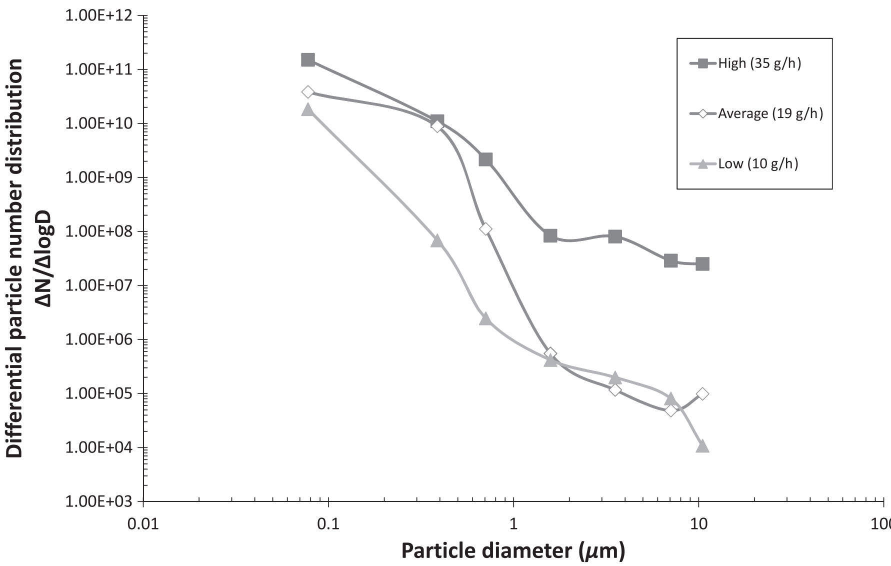

Fig. 8 Differential particle number distribution (#/m^3) for a small hurricane kerosene lamp at three burn rates. Data points on the figure represent the differential particle number for each bin size measured; data points are connected for trend visualization purposes

Figure 10 illustrates that for the simple wick lamp and pressure lamp, the $PM_{2.5}$ mass is relatively independent of the burn rate. For a simple wick lamp burning in a kiosk, the $PM_{2.5}$ concentrations are relatively constant across a range of burn rates from 7 to 60 g/h for both diesel and kerosene. The constant results were observed in a wide range of ambient conditions (maximum wind speeds from 0.3 to 1.2 m/s resulting in air exchanges from 12 to 60/h).

In contrast to the simple wick and pressure lamps, the $PM_{2.5}$ concentrations for both hurricane lamps increased as the burn rate increased. At burn rates that are typically used by vendors (<20 g/h for small hurricane and <30 g/h for large hurricane), the $PM_{2.5}$ concentrations in the experimental kiosk are below the 24-h World Health Organization guideline. Figure 11 shows the same trends for PM_{10} concentrations as $PM_{2.5}$ concentrations for both hurricane lamps and the pressure lamp.

Location dependence

The last question this research sought to answer was whether the location of the vendor within the kiosk

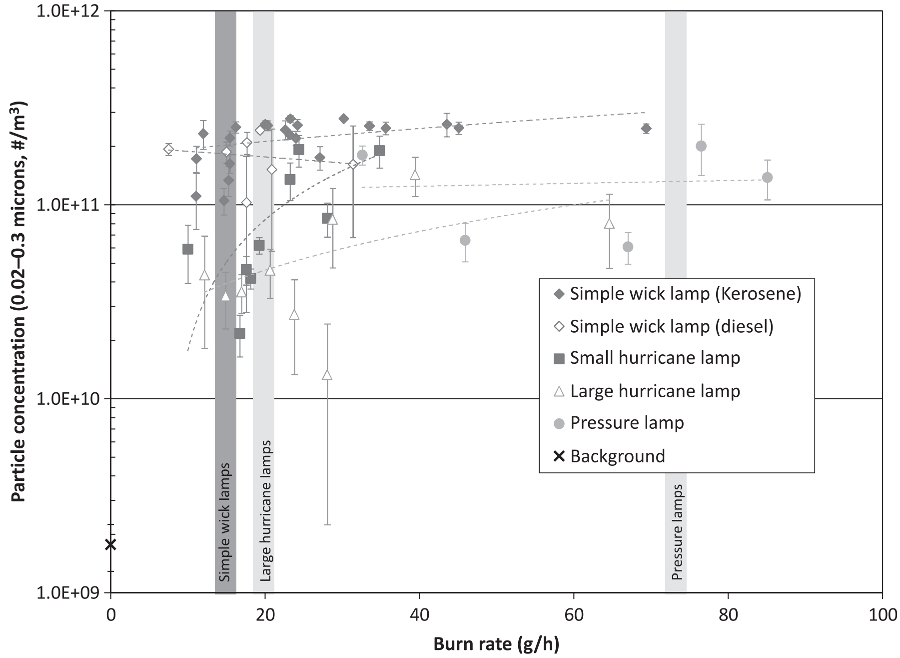

Fig. 9 Particle number concentrations (0.02–0.3 μm) in a 6.34 m^3 test kiosk at a range of ambient air exchange rates and multiple burn rates for various lamps. Fuel is kerosene unless noted. Dotted lines show trends for each lamp type. No US EPA standards exist for particles in this size range. Vertical bars represent average burn rates for each type of lamp

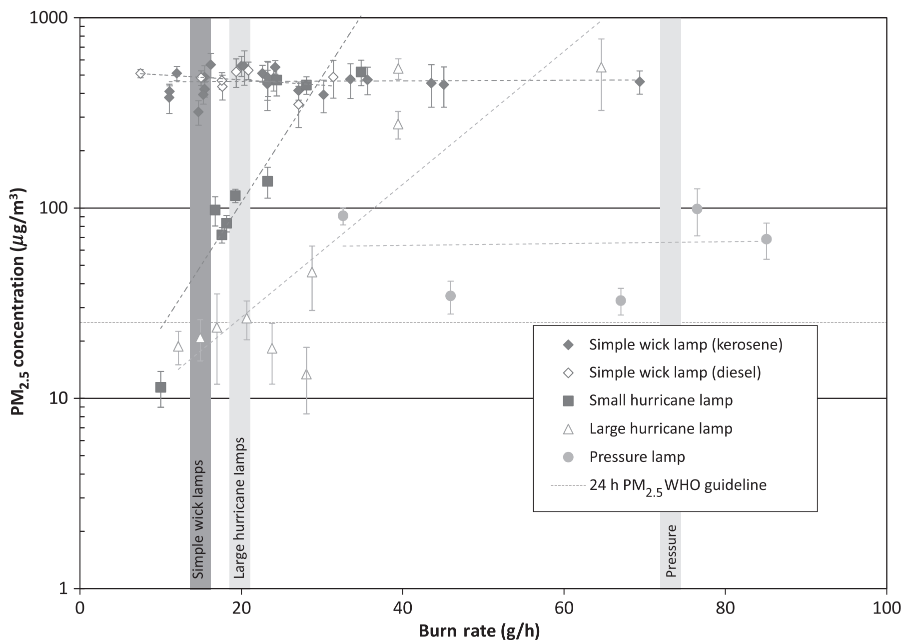

Fig. 10 $PM_{2.5}$ concentrations in a 6.34 m^3 test kiosk at a range of ambient air exchange rates and multiple burn rates for various lamps. Fuel is kerosene unless noted. Dotted lines show trends for each lamp type. Vertical bars represent average burn rates for each type of lamp

impacted the particle concentration to which the vendor was exposed. To determine whether the kiosk was well mixed, the sampling instruments were moved to 21 different sample grid locations in the kiosk to measure $PM_{2.5}$ and PM_{10} concentrations. Figure 12 illustrates that for the simple wick lamp the $PM_{2.5}$ and, to a greater extent, the PM_{10} concentrations appear to increase with breathing zone elevation. Data (not shown) were also collected at an elevation of 1.5 m for both the simple wick lamp and large hurricane lamp. For the hurricane lamp, the average $PM_{2.5}$ concentration decreased as the vendor moved farther away from the lamps. For the simple wick lamp, the opposite was true.

Discussion

Simple wick lamps are the least expensive option for vendors to illuminate their goods at night. Vendors with a shop that provides sufficient revenue may opt for other lighting alternatives which have higher capital and operational costs. The switch to other lighting options may bring ancillary health benefits from the reduction in exposure to particulate matter.

Particle size concentrations

The migration from a simple wick lamp to either a pressure lamp or hurricane lamp will likely have health benefits related to the size of particles that are inhaled by the vendor. Smaller particles can penetrate deeper into the lungs, irritating the respiratory system. Particles smaller than 0.1 μm can be transported from the lungs directly into the bloodstream, potentially causing circulatory problems (Bai et al., 2007). Switching from a simple wick lamp to another lamp type will result in the reduction of exposure to respirable particles (i.e. those in the 0.3–2.5 μm range, Figure 4) that may have health impacts. The switch from hurricane lamps to pressure lamps will increase the illumination of the vendor's goods. However, this switch increases exposure to the smallest particle concentration size measured (0.02–0.3 μm) and provides no concentration reduction in the 0.3–2.5 μm range (Figures 4 and 9). Hence, the potential economic benefit from enhanced illumination of a vendor's goods because of switching from hurricane lamps to pressure lamps may be offset by the increased exposure to respirable particles. A switch to electric lighting, including off-grid lamps using LED or fluorescent technology, would minimize exposure to all particle sizes and increase illumination.

Under the air quality regulatory frameworks of most industrialized countries, a vendor's exposure to particulate matter from fuel-based lighting in a market kiosk would be classified as an occupational exposure. However, there are no known appropriate standards in any countries regulating the occupational exposure to particulate number concentrations produced from an open kerosene flame. There are also no guidelines specifically designed to protect the general public from particulate number concentrations resulting from kerosene lamps. However, the absence of standards does not mean there is an absence of risk.

Particle mass concentrations

$PM_{2.5}$ and PM_{10} concentrations (Figure 10 and 11) were calculated by multiplying the number concentrations by a density and volume for each size range (Sarwar et al., 2003). Number concentrations for the simple wick lamp experiments likely exceeded the maximum concentration that the AeroTrak can accu-

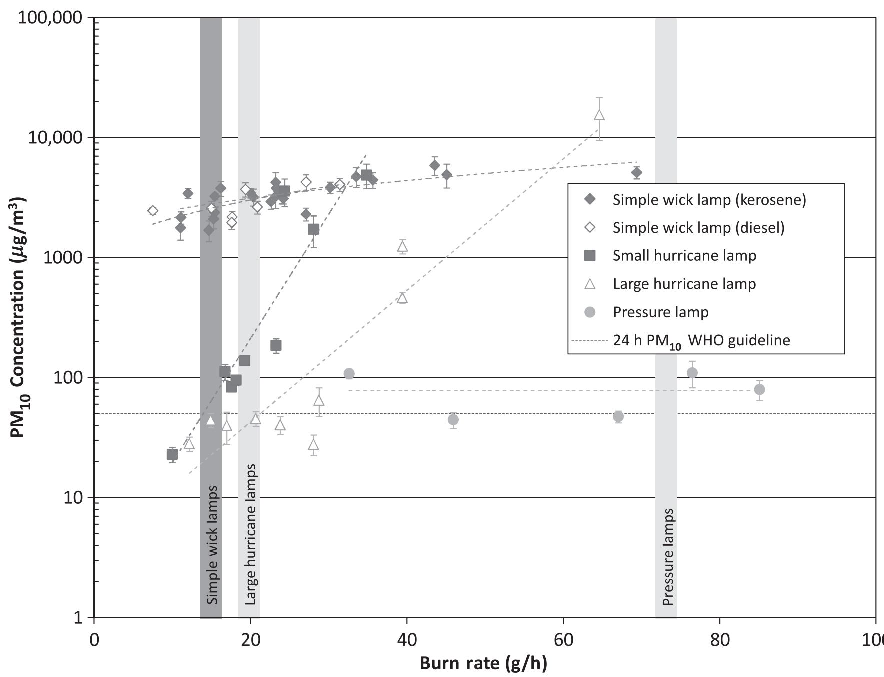

Fig. 11 PM_{10} concentrations in a 6.34 m^3 test kiosk at a range of ambient air exchange rates and multiple burn rates for various lamps. Fuel is kerosene unless noted. Dotted lines show trends for each lamp type. Vertical bars represent average burn rates for each type of lamp

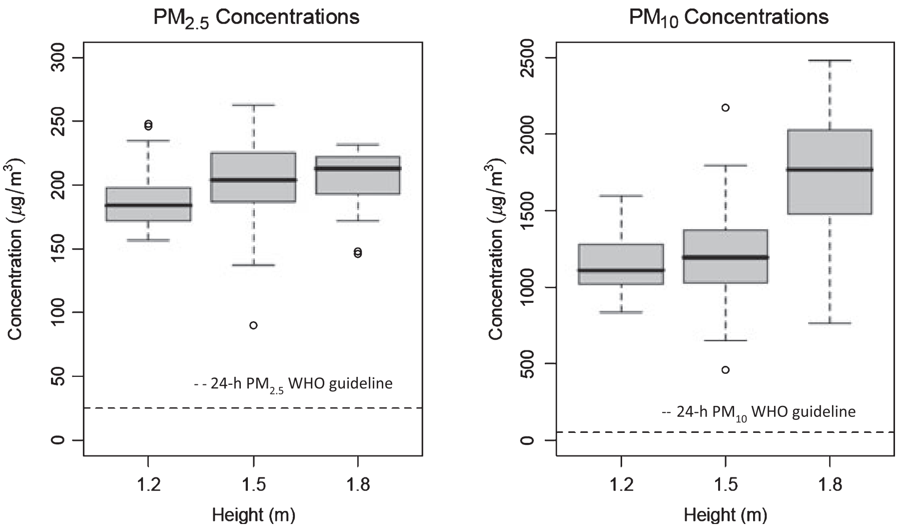

Fig. 12 $PM_{2.5}$ and PM_{10} concentrations in test kiosk at multiple heights for the simple wick lamps. Dark lines show the average, box shows the middle two quartiles, error bars show the next two quartiles, and dots show outliers. The experiments were run at an average burn rate of 15.3 g/h

rately record (77 million total counts per cubic meter). This means that the calculated mass concentrations (both $PM_{2.5}$ and PM_{10}) for the simple wick lamp may be low. Regardless, a vendor switching from a simple wick lamp to either a hurricane lamp or LED light would experience a reduction in exposure to both $PM_{2.5}$ and PM_{10} concentrations.

Again, there are no directly applicable occupational standards or general health guidelines for $PM_{2.5}$ and PM_{10} concentrations resulting from the use of fuel-based lighting. Most occupational standards are based on the mass concentration of a specific chemical. Although not directly applicable, ambient $PM_{2.5}$ and PM_{10} air quality guidelines can provide a context for the measured particulate mass concentrations from this study. The 2005 World Health Organization air quality guidelines establish target concentrations of air pollutants for use by developing countries. The guidelines for average $PM_{2.5}$ concentrations are 10 $\mu g/m^3$ (annual) and 25 $\mu g/m^3$ (24 h). PM_{10} guideline average concentrations are 20 $\mu g/m^3$ (annual) and 50 $\mu g/m^3$ (24 h) (WHO 2006). Particulate matter concentrations in developing countries are often higher than the World Health Organization guidelines. Because of the frequent exceedance of these guidelines, the World Health Organization proposed interim target levels that encourage incremental reductions in particulate matter concentrations in developing countries (WHO 2006). The World Health Organization Working Group has stated that the guidelines are potentially applicable to all indoor and outdoor microenvironments (WHO 2006).

The World Health Organization $PM_{2.5}$ and PM_{10} guidelines provide a context to compare the particulate matter concentration reductions in kiosks. The 24-h World Health Organization $PM_{2.5}$ concentration guideline was exceeded by at least an order of magnitude for all simple wick lamp burn rates with only one simple wick lamp burning in the kiosk (Figure 10). While many kiosk vendors use a single lamp, some may use more than one lamp at a time. The result would be an increase in $PM_{2.5}$ concentrations in the kiosk.

Switching from a single simple wick lamp to a large hurricane lamp operating at typical burn rates would reduce $PM_{2.5}$ concentrations by over 95% (the absolute $PM_{2.5}$ concentration would be reduced from 20 times the 24-h World Health Organization $PM_{2.5}$ concentration guideline to the guideline value). Switching from a pressure lamp to a large hurricane lamp operating at typical burn rates would reduce $PM_{2.5}$ concentrations by over 60% (the absolute $PM_{2.5}$ concentration would be reduced from 2.5 times the 24-h World Health Organization $PM_{2.5}$ concentration guideline to the guideline value). Switching from a large hurricane lamp to a LED light would result in a $PM_{2.5}$ concentration reduction roughly equal to the 24-h World Health Organization $PM_{2.5}$ concentration guideline.

At high burn rates (Figures 7 and 8), the hurricane lamp's increased particle emissions coat the inside of the glass chimney to the point that minimal light is emitted from the lamp (see small hurricane lamp in Figure 1). Laboratory measurements at Humboldt State University and field measurements in Kenya confirm that the Kenyan vendors have optimized the burn rate of their hurricane lamps (roughly 20 g/h) so that the lamps emit as much light as possible while minimizing the amount of particulate matter deposited on the interior of the glass chimney. Once these burn rates were exceeded, both hurricane lamps produced a one to two order of magnitude increase in $PM_{2.5}$ concentrations. This increase may be because of the fact that the lamp's glass chimney design limits the amount of oxygen to the flame. At high burn rates, this lack of oxygen might result in incomplete combustion and the associated increase in particulate matter.

Location dependence

The next question this research sought to answer was whether the location of the vendor within the kiosk impacted the particle concentration to which the vendor was exposed. Several recent indoor studies using computational fluid dynamics have shown that indoor environments are not always well represented by assuming the air is well mixed (Gadgil et al., 2003; Rim et al., 2009). If the air in the kiosk is not well mixed, then the location of the vendor in the kiosk may influence the vendor's exposure to particulate matter.

Figure 12 illustrates that for the simple wick lamp both the $PM_{2.5}$ and, to a greater extent, PM_{10} concentrations increase with breathing zone elevation. This indicates that the kiosk may not be well mixed. The thermal plume from the flame may be the cause of this concentration increase. When practical, vendors using fuel-based lighting should try to remain in a sitting position as much as possible to minimize thermal plume impacts.

The $PM_{2.5}$ concentrations for all locations in the kiosk where a single simple wick lamp was burning exceeded the 24-h World Health Organization $PM_{2.5}$ guideline by nearly an order of magnitude. However, $PM_{2.5}$ concentrations increased at greater distances from the lamp (data not shown). Despite the kiosk not being a well-mixed environment, most locations in a kiosk where a simple wick lamp is in use may be dangerous to the vendor's health.

Particulate matter intake

Another way to put $PM_{2.5}$ concentration from fuel-based lighting in context is to compare the intake of $PM_{2.5}$ mass from using a fuel-based lamp in a kiosk, to the intake from ambient $PM_{2.5}$ mass. Equation 2 illustrates the total nominal $PM_{2.5}$ mass a vendor would inhale in 1 day if they use fuel-based lamp for light:

$$\text{Intake}_{\text{Total}} = B_{\text{ambient}} C_{\text{ambient}} t_{\text{ambient}} + B_{\text{lamp}} C_{\text{lamp}} t_{\text{lamp}}, \quad (2)$$

where B_{ambient} is the breathing rate when exposed to ambient background concentrations, C_{ambient} is the ambient $PM_{2.5}$ concentration, t_{ambient} is the time of ambient concentration inhalation, B_{lamp} is the breathing rate when exposed to the lamp, C_{lamp} is the $PM_{2.5}$ concentration resulting from one lamp, and t_{lamp} is the time the lamp is burned. For this analysis, it was assumed that the breathing rate was the same for all exposures [1.25 m^3/h (EPA 1991)]. If vendors use simple wick lamps to illuminate their wares in enclosed kiosks, they may be exposed to $PM_{2.5}$ concentrations of approximately 500 $\mu g/m^3$ (C_{lamp}, Figure 10). If it is assumed that vendors typically light their kiosks for 2.5 h/day (t_{lamp}, an average value from the authors' field survey in Kenya in 2008), then a vendor would intake a daily nominal $PM_{2.5}$ mass ($\text{Intake}_{\text{Lamp}}$) solely from the simple wick lamp of roughly 1560 μg/day. The daily ambient nominal $PM_{2.5}$ mass intake ($\text{Intake}_{\text{ambient}}$) based on the World Health Organization guidelines ($C_{\text{ambient}} = 10\ \mu g/m^3$; in many locations where kerosene lamps are used this may be a low estimate, $t_{\text{ambient}} = 24$ h) would be 300 μg/day. The total $PM_{2.5}$ intake for the vendor would be 1860 μg/day.

Hence, a vendor in a kiosk using a single simple wick lamp for 2.5 h a day would receive over 80% of their $PM_{2.5}$ intake as a result of using a fuel-based lamp (assuming no other sources of $PM_{2.5}$ such as cook stoves). This assessment only holds for kiosk vendors using a single simple wick lamp. If vendors use more than one lamp in the kiosk, the total intake contribution from the fuel-based lamp will increase. The assessment also does not account for exposure in other indoor spaces, such as children studying in homes, where lamps may be used in locations with lower air exchange rates resulting in higher particulate concentrations. Future analyses will examine fuel-based lamp emission rates to investigate these scenarios.

Switching to LED lighting would reduce the vendor's daily intake of $PM_{2.5}$ by 80% (assuming the only other exposure to $PM_{2.5}$ is ambient outdoor air). Recently, the Lighting Africa program of the World Bank Group (http://www.lightingafrica.org), the Lumina Project (http://light.lbl.gov), and other efforts have worked to enable the formation of markets in developing countries to replace fuel-based lighting with off-grid lighting systems based on LED or fluorescent illumination technologies. Given the current costs of LED and fluorescent lighting systems, the reduction in $PM_{2.5}$ intake is important to end-users who consider both economic and non-economic factors when making their lighting technology selections.

Approximately 90% of rural Kenyans live within 10 km of the electrical grid, but under 10% have grid power in their homes (Jacobson, 2004) Hence, the delivery of a small amount of electricity via grid-independent charging or rechargeable batteries (recharged using small solar photovoltaic modules or at grid connected charging stations that currently charge cell phones) to run battery powered off-grid lighting systems is a relatively simple change, and indeed is already occurring in some places (Radecsky et al., 2008). The growth of the off-grid lighting market for LED and fluorescent lamps in developing markets has significant potential to improve the health of the users of fuel-based lighting.

Conclusion

Switching from simple wick lamps to higher efficiency and more cost-effective lighting technologies can provide health benefits. The cheapest, crudest kerosene lamps (relied upon disproportionately by the poorest users) emit the largest amounts of both $PM_{2.5}$ and PM_{10}. The use of higher cost kerosene lighting options reduces exposure to 0.3–2.5 μm particulate matter and to a lesser extent the 0.02–0.3 μm particles. As such, improving affordability and access to better lighting options (e.g. hurricane and pressure kerosene lamps; electric lighting including off-grid lamps that use LED or fluorescent technology) will have health benefits for a large portion of the world's population.

The implications of fuel-based lighting for indoor air quality have received little attention in the literature. Many further questions remain after this study, including (i) analysis of other fuels, such as resins (Bhusal et al., 2007), candles, and fuel wood used to produce light in developing country contexts; (ii) measurement of the particulate concentrations from fuel-based light operating with the lower quality fuels frequently found in developing counties (e.g. kerosene with high sulfur concentrations may have different particulate emission profiles than the kerosene used in this study); (iii) analysis of the similarity and differences between the situation in Kenyan kiosks and those elsewhere; and (iv) examination of particulate matter concentrations in other contexts, e.g. households, clinics, and schools.

Acknowledgements

The authors would like to acknowledge Kristen Radecsky, Peter Johnstone, and Jenny Tracy for collecting data in Kenya in 2008 and 2009. We thank Art Rosenfeld and the Blum Center for Developing Economies at the University of California at Berkeley for providing generous financial support for this research, through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

References

Armendariz Arnez, C., Edwards, R.D., Johnson, M., Zuk, M., Rojas, L., Jimenez, R.D., Riojas-Rodriguez, H. and Masera, O. (2008) Reduction in personal exposures to particulate matter and carbon monoxide as a result of the installation of a Patsari improved cook stove in Michoacan Mexico, *Indoor Air*, **18**, 93–105.

Bai, N., Khazaei, M., Eden, S. and Laher, I. (2007) The pharmacology of particulate matter air pollution-induced cardiovascular dysfunction, *Pharmacol. Ther.*, **113**, 16–29.

Bhusal, P., Zahnd, A., Eloholma, M. and Halonen, L. (2007) Replacing fuel based lighting with light emitting diodes in developing countries: energy and lighting in rural Nepali homes, *J. Illum. Soc. North Am.*, **3**, 277–291.

Brauer, M., Bartlett, K., Pineda, R.J. and Perez-Padilla, R. (1996) Assessment of particulate concentrations from domestic biomass combustion in rural Mexico, *Environ. Sci. Technol.*, **30**, 104–109.

Dionisio, K.L., Howie, S., Fornace, K.M., Chimah, O., Adegbola, R.A. and Ezzati, M. (2008) Measuring the exposure of infants and children to indoor air pollution from biomass fuels in The Gambia, *Indoor Air*, **18**, 317–327.

Dockery, D., Pope, C., Xu, X., Spengler, J., Ware, J., Fay, M., Ferris, B. and Speizer, F. (1993) An association between air pollution and mortality in six U.S. cities, *N. Engl. J. Med.*, **329**, 1753–1759.

Dominici, F., McDermott, A., Zeger, S. and Samet, J. (2003) Airborne particulate matter and mortality: timescale effects in four US cities, *Am. J. Epidemiol.*, **157**, 1055–1065.

EPA. (1991) *Risk Assessment Guidance for Superfund; Volume I: Human Health Evaluation Manual; Supplement Guidance "Standard Default Exposure Factors"*. Office of Emergency and Remedial Response Toxics Integration Branch, U.S. Environmental Protection Agency.

EPA (2006) Technical amendments to the highway and nonroad diesel regulations; final rule and proposed rule, 40 CFR 80. *Fed. Regist.*, **71**, 25706.

Fan, C. and Zhang, J. (2001) Characterization of emissions from portable household combustion devices: particle size distributions, emission rates and factors, and potential exposures, *Atmos. Environ.*, **35**, 1281–1290.

Gadgil, A.J., Lobscheid, C., Abadie, M.O. and Finlayson, E.U. (2003) Indoor pollutant mixing time in an isothermal closed room: an investigation using CFD, *Atmos. Environ.*, **37**, 5577–5586.

International Energy Agency (2002) *World Energy Outlook 2002*. Paris. (available at: http://www.iea.org/textbase/nppdf/free/2000/weo2002.pdf) last accessed 8 January 2010.

Jacobson, A. (2004) *Connective Power: Solar Electrification and Social Change in Kenya*. Ph.D. Dissertation. Energy and Resources Group, University of California, Berkley.

Jones, R., Du, J., Gentry, Z., Gur, I. and Mills, E. (2005) Alternatives to fuel-based lighting in rural China, In: *Right Light 6*. Shanghai.

Kamfor, Ltd. (2002) *Study on Kenya*'s Energy Demand, Supply and Policy Strategy for Households, Small-Scale Industries and Service Establishments, Nairobi, Kenya, Ministry of Energy.

Mills, E. (2005) The specter of fuel-based lighting, *Science*, **308**, 1263–1264.

Naeher, L.P., Smith, K.R., Leaderer, B.P., Neufeld, L. and Mage, D.T. (2001) Carbon monoxide as a tracer for assessing exposures to particulate matter in wood and gas cookstove households of highland Guatemala, *Environ. Sci. Technol.*, **35**, 575–581.

Pandey, M.R., Neupane, R.P., Gautam, A. and Shrestha, B. (1990) The effectiveness of smokeless stoves in reducing indoor air pollution in a rural hill region of Nepal, *Mt. Res. Dev.*, **10**, 313–320.

Radecsky, K., Johnstone, P., Jacobson, A. and Mills, E. (2008) *Solid-State Lighting on a Shoestring Budget: The Economics of Off-Grid Lighting for Small Businesses in Kenya*, Lumina Project Technical Report #3. (available at: http://light.

lbl.gov/pubs.html) last accessed 10 January 2010.

Rim, D., Novoselec, A. and Morrison, G. (2009) The influence of chemical interactions at the human surface on breathing zone levels of reactants and products, *Indoor Air*, **19**, 324–334.

Sarwar, G., Corsi, R., Allen, D. and Weschler, C. (2003) The significance of secondary organic aerosol formation and growth in buildings: experimental and computational evidence, *Atmos. Environ.*, **37**, 1365–1381.

Schare, S. and Smith, K.R. (1995) Particulate emission rates of simple kerosene lamps, *Energy Sustain. Dev.*, **2**, 32–35.

Schwebel, D., Swart, D., Simpson, J., Hui, S.A. and Hobe, P. (2009) An intervention to reduce kerosene-related burns and poisonings in low-income South African communities, *Health Psychol.*, **28**, 493–500.

Shepherd, J.E. and Perez, F. (2008) Kerosene lamps and cookstoves – the hazards of gasoline contamination, *Fire Safety J.*, **43**, 171–179.

Siddiqui, A.R., Lee, K., Bennett, D., Yang, X., Brown, K.H., Bhutta, Z.A. and Gold, E.B. (2009) Indoor carbon monoxide and PM2.5 concentrations by cooking fuels in Pakistan, *Indoor Air*, **19**, 75–82.

WHO (2002) *Emergency and Humanitarian Action Annual Report 2001*. Geneva, Department of Emergency and Humanitarian Action (available at: http://www.who.int/hac/about/annual_report_2001.pdf) last accessed 8 January 2010.

WHO (2006) *Air Quality Guidelines – Global Update 2005*, WHO/SDE/PHE/OEH/06.02. World Health Organization (available at: http://whqlibdoc.who.int/hq/2006/WHO_SDE_PHE_OEH_06.02_eng.pdf) last accessed 8 January 2010.

Zhang, J. and Smith, K.R. (2007) Household air pollution from coal and biomass fuels in China: measurements, health impacts, and interventions, *Environ. Health Perspect.*, **115**, 848–855.