A pilot study on the effect of indoor particle sources on indoor particle concentration in residential houses

Congrong He[a,]*, Lidia Morawska[a], Jane Hitchins[a], Dale Gilbert[b]

[a]*International Laboratory of Air Quality and Health, Centre for Medical, Health and Environmental Physics, Queensland University of Technology, Brisbane, QLD 4001, Australia;* [b]*Built Environment Research Unit, Queensland Department of Public Works and Housing, Brisbane, QLD 4001, Australia*

ABSTRACT
Characterization of indoor particle sources from 14 residential houses in Brisbane, Australia, was performed. The approximation of $PM_{2.5}$ and the submicrometre particle number concentrations were measured simultaneously for more than 48 h in the kitchen of all the houses by using a photometer (DustTrak) and a condensation particle counter (CPC), respectively. From the real time indoor particle concentration data and a diary of indoor activities, the indoor particle sources were identified. The study found that among the indoor activities recorded in this study, frying, grilling, stove use, toasting, cooking pizza, smoking, candle vaporizing eucalyptus oil and fan heater use, could elevate the indoor particle number concentration levels by more than five times. The indoor approximation of $PM_{2.5}$ concentrations could be close to 90 times, 30 times and three times higher than the background levels during grilling, frying and smoking, respectively.

INDEX TERMS
Air pollution; Indoor air quality; Submicrometre particle; $PM_{2.5}$

INTRODUCTION
Since indoor particle sources significantly affect indoor particle concentrations, it is essential that the exposures to indoor particles from these sources be quantified as a step towards assessing its role in human health risk.

A large number of indoor particle sources have been identified by many previous studies, with the most significant being environmental tobacco smoke and emissions from cooking, kerosene heating and wood burning stoves (for example, Long *et al*., 2000; Tucker, 2000). Other human activities such as dusting and vacuuming may also significantly contribute to elevated particle concentration levels indoors (Spengler *et al*., 1981; Monn *et al*., 1995; Ross *et al*., 1999). Previous studies have also showed that emission of pollutants from indoor sources may be short term, seasonal or continuous, depending on the type of source.

Combustion processes are the main indoor source of submicrometre particles, which contain a host of organic and inorganic material (Maroni *et al*., 1995). Other indoor sources, such as gas-to-particle conversion, sprays and biological contaminants, may also contribute to the submicrometre indoor particles. Re-suspension by human activities indoors is the main contributor to the coarse mode of indoor particles.

Smaller particles have been the subject of increasing concern as they can be high in number but contribute very little to particle mass (Jaenicke, 1993), have a higher probability of penetration into the deeper parts of the respiratory tract (James *et al*., 1991; Berico *et al*., 1997), and also contain higher levels of trace elements and toxins, such as the polycyclic aromatic hydrocarbons and mutagens (Ando *et al*., 1996; Kiss *et al*., 1998). Recent health

* Corresponding author.

effects studies have also suggested that number concentration may be a more appropriate predictor of health effects than mass concentration (Oberdörster *et al.*, 1995). Thus, it is clear that understanding the emission characteristics of indoor particles on a number basis is of importance in accurate exposure assessment and for developing appropriate control strategies. The existing database on source emission characteristics is, however, limited to mass emission characteristics, with significantly less information available on particle number emissions.

As part of a larger study investigating indoor air, the focus of the work presented in this paper was an investigation of the emission characteristics of indoor particle sources, in relation to $PM_{2.5}$ and particle number, in residential houses in Australia. This included the following aims: (1) to quantify contributions from common indoor particle sources to indoor number and mass particle concentration levels; and (2) to evaluate the effect of indoor activities on indoor particle concentration levels in different types of residential houses.

EXPERIMENTAL METHOD

Sampling Site and Houses

The sampling site and house information in relation to this study are described in detail by Morawska *et al*. (2001). Briefly, a residential suburb of Brisbane was chosen as the measurement site. The site has reasonably flat topography and a good mix of house types, both in terms of age and of style, i.e. newer and older houses, brick and timber, high set and low set. Fourteen houses in the suburb were chosen for the study. An additional house was chosen from another suburb as a comparison site.

Instrumentation

The total number concentration of submicrometre particles (0.007–0.808 µm) was determined using the TSI Model 3022A Condensation Particle Counter (CPC) (TSI Incorporated, St. Paul, MN, USA). Approximation of fine particle mass concentration ($PM_{2.5}$) was measured by the TSI Model 8520 DustTrak aerosol monitor (TSI Incorporated, St. Paul, MN, USA). These instruments were chosen as the most suitable for an indoor study because of their low flow rates (and thus negligible impact on particle concentrations indoors), quiet operation and their short sampling times of 10 and 30 s for CPC and DustTrak, respectively, which means provision of almost real time data.

Sampling Protocol

All measurements (except House1) were conducted between May and July 1999, which is wintertime in Brisbane. $PM_{2.5}$ and particle number concentrations were measured simultaneously for more than 48 h in the kitchens of all the houses. The CPC and DustTrak were placed side-by-side and positioned on average 2 m away from the stove in the kitchen. The occupants of the houses were required to fill in a diary, noting the time and duration of any activity occurring in the house during the time of the measurements.

Data Processing and Analysis

Data on indoor particle concentration and the information of indoor activities were used to quantify the contribution of indoor sources and activities to particle concentration levels. It was found that sometimes an indoor activity was recorded in the diary where there was no obvious concentration change in the time serial concentrations data. Conversely, sometimes there were obvious concentration changes, but no indoor activity was recorded in the diary for this time. Therefore, further data analysis was only conducted when obvious concentration changes in the time series concentration data were matched to a recorded indoor activity. When the distribution of the data was not normal, the robust analysis (trim off the maximum and minimum) was employed.

RESULTS

Source Identification

Based on the 48-h time series concentration data, human activities resulting in generation of particles were identified. About 148 such indoor activities were recorded in this study and they were catalogued into 20 different types. Additionally, three other types of activities: opening of the outside door, neighbour burning off rubbish and smoking outside were also recorded to identify their impact on indoor particle concentrations. A summary of indoor particle concentrations resulting from operation of the sources, in terms of particle mass ($PM_{2.5}$) and number is presented in Table 1. Median values of the measured peak $PM_{2.5}$ and submicrometre particle number concentrations, and the ratio of the respective peak values to the background indoor values are listed by indoor activities. Cooking in this table means different cooking activities carried out concurrently (e.g. boiling pasta and cooking sauce).

Source contribution to particle mass concentrations

It can be seen from Table 1 that the activities resulting in the highest median peak values included frying (745 $\mu g\,m^{-3}$), grilling (718 $\mu g\,m^{-3}$), candle vaporizing eucalyptus oil (132 $\mu g\,m^{-3}$) and smoking (79 $\mu g\,m^{-3}$). These activities clearly elevated the indoor $PM_{2.5}$ concentrations, which can be seen from the ratios of the peak to the background indoor values of $PM_{2.5}$ concentrations. For example, indoor $PM_{2.5}$ concentrations could be about 89 times, 32 times and three times higher than the indoor background levels during grilling, frying and smoking, respectively. The data in Table 1 indicate also that nearby outdoor fine particle sources could affect indoor fine particle concentration levels. Indoor $PM_{2.5}$ concentration levels could be elevated by about 20, 590 and 60% due to opening the outside door, a neighbour burning off rubbish and smoking outside, respectively.

Source contribution to particle number concentrations

By comparison with the average submicrometre particle number concentration in Brisbane city (7.4×10^3 particles cm^{-3}) (Morawska *et al.*, 1999), the median peak values of indoor particle concentrations were found to be about 15 times higher than the average outside concentration during cooking, frying, grilling and stove use (see Table 1). The ratios of peak to indoor background values for submicrometre particle number concentrations indicate that some types of indoor activities, such as cooking, frying and fan heater use, could elevate the indoor submicrometre particle number concentration levels close to or over 10 times, and grilling, stove use, toasting, cooking pizza and candle vaporizing eucalyptus oil could elevate the indoor submicrometre particle number concentration levels to more than five times.

From Table 1, it can be seen that outdoor submicrometre particle sources and thus outdoor concentrations affect indoor submicrometre particle concentration levels: opening the outside door and a neighbour burning off rubbish resulted in 180 and 210% increase of concentrations, respectively (but not smoking outside).

Table 1 Summary the of the peak values and the ratios of peak to indoor background values for $PM_{2.5}$ and submicrometre particle number concentrations resulting from operation of individual indoor sources

Activity	*N*	Peak values ($\mu g\ m^{-3}$) (mass)		Ratio (mass)		Peak values (particle. $cm^{-3} \times 10^3$)		Ratio (number)	
		Median	SD	Median	SD	Median	SD	Median	SD
Cooking	24	37	194	2.9	12.6	126	177	10.3	19.3
Frying	4	745	352	33.6	28.3	154	21.3	10.0	6.1
Grilling	6	718	3427	90.1	312	161	69.9	8.7	5.3
Kettle	25	13	20	1.1	0.7	15.6	14.0	1.1	0.6
Microwave	18	16	18	1.1	0.4	16.3	28.6	1.1	1.6
Open door	9	21	9	1.2	0.4	22.0	14.6	2.9	1.2
Oven	6	24	6	1.8	0.5	61.5	31.9	3.0	0.8
Smoking	10	79	29	4.0	1.8	26.6	13.6	1.5	1.0
Stove	4	57	264	2.4	19.7	179	287	12.5	10.5
Sweep floor	3	35	4	2.0	1.3	34.9	5.86	1.1	0.0
Toasting	18	35	32	2.1	8.3	114	160	6.3	7.4
Vacuuming	5	16	8	1.5	0.3	41.3	17.6	1.5	1.2
Washing	17	18	12	1.3	0.6	30.9	18.5	1.3	0.8
Candle eucalyptus oil	1	132		13.2		74.6		8.3	
Cooking pizza	1	735		73.5		137.3		9.8	
Dusting	1	22		1.7		14.1		1.0	
Fan	1	20		1.7		11.0		1.0	
Fan heater	1	15		1.5		87.1		27.2	
Hair dryer	1	45		1.4		9.5		1.1	
Neighbour burning	1	90		6.9		45.2		3.2	
Shower	1	20		1.1		10.7		1.4	
Smoking outside	1	33		1.7		12.5		1.0	
Washing machine	1	43		2.1		11.1		1.2	

Note: *N*: sample number.

DISCUSSION

The effect of indoor sources or activities on indoor particle concentration levels has been reported by a number of studies. For example, Lefcoe and Inculet (1975) found that household activities such as cleaning or children playing had a pronounced effect on indoor concentrations of particles with diameters larger than 1 μm and a smaller effect on particles with diameters less than 1 μm. The results for dusting in this study show that the $PM_{2.5}$ ratio of peak value to background value is 1.69, but the submicrometre number ratio is 1.00, which supports their findings.

Re-suspension of particles during indoor activities is an important factor influencing the indoor particle concentration in occupied residential houses. Kamens *et al*. (1991) found that indoor activity, particularly vacuuming, could cause a significant increase in the concentration of particles with diameters larger than 2.5 μm. In this study, for vacuuming, contrary results were found for particle $PM_{2.5}$ and submicrometre number concentration. For example, for one of the houses $PM_{2.5}$ concentration increased from 15 to 31 $\mu g\ m^{-3}$, while the concentration of submicrometre particles did not increase significantly (from 2.06×10^4 to 2.38×10^4 particles cm^{-3}). However, for another house the $PM_{2.5}$ concentration did not increase significantly (from 13 to 14 $\mu g\ m^{-3}$), while the concentration of submicrometre particles increased significantly (from 5.3×10^3 to 5.88×10^4 particles cm^{-3}). One possible reason is that different types of vacuum cleaners were used in the two houses and it has been shown that some vacuum cleaner motors generate submicrometre particles. An additional factor could be that different houses had different level of cleanliness (e.g. one house may be vacuumed regularly, the other irregularly), and therefore different levels of particles contributing to $PM_{2.5}$ are thus re-suspended. A different impact on indoor concentration was also shown in relation to oil heaters: in one house the operation of an oil heater did not have any effect on indoor concentrations, but in another house it had quite a significant effect (as can be seen from Table 1).

The impact of outdoor air on concentration levels indoors was quantified for a number of cases in this study. For example, during the 'neighbour burning off rubbish', both the $PM_{2.5}$ concentration and the number concentration of submicrometre particles increased significantly from 13 to 90 $\mu g\, m^{-3}$ and from 14.3×10^3 to 45.2×10^3 particles cm^{-3}, respectively. In another house, opening of the doors and windows upon returning home not only resulted in a decrease in $PM_{2.5}$ concentration from 32 to 25 $\mu g\, m^{-3}$ in 9 min, but also in a sharp increase of submicrometre particle concentration from 6.4×10^3 to 2.62×10^4 particles cm^{-3} in 5 min.

CONCLUSIONS

This study quantified the effect of some indoor sources and activities on indoor particle concentration levels. Among the indoor activities recorded in this study, frying, grilling, stove use, toasting, cooking pizza, candle vaporizing eucalyptus oil and fan heater use, could elevate indoor submicrometre particle number concentration levels to more than five times the background values. Indoor $PM_{2.5}$ concentrations could be about 89 times, 32 times and three times higher then the background levels during grilling, frying and smoking, respectively. The findings from this study are intended for application in modelling of indoor air quality and of total human exposure.

ACKNOWLEDGEMENTS

This project was funded by the Built Environment Research Unit, Queensland Department of Public Works, and Australian Research Council, through SPIRT Grant No. C69804416. The assistance of Ray Duplock, Keith Eigeland and Chris Greenaway is gratefully acknowledged. Members of the QUT ILAQH, in particular, Sandhya Parappukkaran, Milan Jamriska and Steve Thomas, are appreciated for their discussions and assistance with this study. The authors would like to express their special gratitude to the owners and occupants of the houses for their help and in assisting with this project. Without their help and assistance, this project could not have been conducted successfully.

REFERENCES

Ando, M., Katagiri, K., Tamura, K., Yamamoto, S., Matsumoto, F.M., Li, Y.R., Cao, S.D., Ji, R.K. and Liang, C. (1996). Indoor and outdoor air pollution in Tokyo and Beijing supercities. *Atmospheric Environment* **30** (5), 695–702.

Berico., M., Luciani, A. and Formignani, M. (1997). Atmospheric aerosol in an urban area—measurements of TSP and PM10 standards and pulmonary deposition assessments. *Atmospheric Environment* **31**, 3659–3665.

Jaenicke, R. (1993). Tropospheric Aerosols. In: Hobbs, P.V. (ed.), *Aerosol–Cloud–Climate Interactions*. London: Academic Press.

James, A.C. Stahlhofen, W., Rudolf, G., Egan, M.J., Nixon, W., Gehr, P. and Briant, J.K. (1991). The respiratory tract deposition model proposed by the ICRP task group. *Radiation Protection Dosimetry* **38**, 159–165.

Kamens, R., Lee, C.T., Weiner, R. and Leith, D. (1991). A study to characterize indoor particles in three non-smoking homes. *Atmospheric Research* **25A** (5/6), 939–948.

Kiss, G., Vargapuchony, Z., Rohrbacher, G. and Hlavay, J. (1998). Distribution of polycyclic aromatic hydrocarbons on atmospheric aerosol particles of different sizes. *Atmospheric Research* **46** (3–4), 253–261 (Special Issue).

Lefcoe, N.M. and Inculet, I.I. (1975). Particulates in domestic premises II. Ambient levels and indoor-outdoor relationship. *Archives of Environmental Health* **30**, 565–570.

Long, C.M. Suh, H.H. and Koutrakis, P. (2000). Characterization of indoor particle sources using continuous mass and size monitors. *Journal of the Air & Waste Management Association* **50** (7), 1236–1250.

Maroni, M., Seifert, B. and Lindvall, T. (eds). (1995). *Indoor Air Quality: A Comprehensive Reference Book*. New York: Elsevier Science.

Monn, Ch.; Fuchs, A.; Kogelschatz, D. and Wanner, H.-U. (1995). Comparison of indoor and outdoor concentrations of PM-10 and PM-2.5. *Journal of Aerosol Science* **26**, S515–S516.

Morawska, L., Thomas, S., Gilbert, D., Greenaway, C. and Rijinders, E. (1999). A study of the horizontal and vertical profile of submicrometer particles in relation to a busy road. *Atmospheric Environment* **33**, 1261–1274.

Morawska, L., He, C., Hitchins, J., Gilbert, D. and Parappukkaran, S. (2001). The relationship between indoor and outdoor airborne particles in the residential environment. *Atmospheric Environment* **35**, 3463–3473.

Oberdörster, G., Gelein, R.M., Ferin, J. and Weiss, B. (1995). Association of particulate air pollution and acute mortality: involvement of ultrafine particles*? Inhalation Toxicology* **7**, 111–124.

Ross, D.I. Upton, S.L., Hall, D.J. and Bennett, I.P. (1999). Preliminary measurement of ultrafine aerosol emission from gas cooking. *The Proceedings of the 8th International Conference on Indoor Air Quality and Climate*, Vol. 4, pp. 1043–1048.

Spengler, J.D., Dockery, D.W., Turner, W.A., Wolfson, J.M. and Ferris, B.G. (1981). Long-term measurements of respirable sulfates and particles inside and outside homes. *Atmospheric Environment* **15**, 23–30.

Tucker W.G. (2000). An overview of PM2.5 sources and control strategies*. Fuel Processing Technology* **65**, 379–392.