Development of a Unique Thermal and Indoor Air Quality Probabilistic Modelling Tool for Assessing the Impact of Lowering Building Ventilation Rates

James McGrath[1], Miriam Byrne[*1]

1 School of Physics and Centre for Climate and Air Pollution Studies,
Ryan Institute,
National University of Ireland, Galway,
University Road,
Galway
Ireland

ABSTRACT

Adequate ventilation is necessary to maintain thermal comfort and remove indoor air pollutant concentrations (Crump et al., 2005). Indoor pollutant concentrations vary considerably depending on occupants' behaviour patterns, building characteristics and meteorological parameters and seasonal effects. Experimental measurements are time consuming and expensive to carry out, while computational models are regarded as a valid complement. The team at NUI, Galway have recently developed the IAPPEM model (described in (McGrath et al., 2014a)representing the state-of-the-art in probabilistic modelling of indoor air quality; the model is currently capable of highlighting locations of different pollutant concentrations within the same building by considering the infiltration of outdoor air pollutants, meteorological parameters and seasonal effects, indoor activities of occupants, emissions from indoor air pollutants, removal by deposition, the dilution of indoor air pollutants through external and internal air exchange and internal house layout.

To date no computational model exists that examines both inter-zonal and external temperatures in combination with assessing indoor air pollutants, and the enhancement of the IAPPEM source code framework to incorporate these features constitutes the main tasks of the current work. This will allow an assessment of individuals' thermal comfort and exposure to airborne pollutants, and will also allow an assessment of the heat loss to surroundings as a result of changing ventilation rates, a feature that is highly relevant in the context of energy efficient homes. While previous studies have examined the effect of heat loss due to ventilation, no model to date has combined the temperature and airborne pollutant components in a single computational structure.

In this paper, a plan to incorporate a temperature parameter into the existing model is described; this would allow the unique capability to assess, for the first time, the effects of ventilation and occupant behaviour on both an individual's thermal comfort and airborne pollutant exposure. The basis of the IAPPEM code adaptation strategy will be the addition of a source term and a loss term to account for localised heating sources, such as radiators in each room, solid fuel fires, and cooking events. A loss term will account for the removal of heat through the building walls and windows. Ventilation rates will define the transfer of heat between rooms but also between indoor and outdoor, allowing the assessment of heat loss as well as thermal comfort. This would provide a vital tool in defining optimum building air exchange rates that do not have a negative impact on human health.

.

KEYWORDS

Indoor Air Quality, Thermal Comfort, Probabilistic modelling, emission sources,

1 INTRODUCTION

Particulate Matter (PM) has become a major environmental concern because of its known impacts on human health (COMEAP, 2009, COMEAP, 2010). A WHO project REVIHAAP (WHO, 2013) reported a large body of evidence linking the effects of long term PM exposure on both cardiovascular mortality and all causes of mortality. PM related morbidity outcomes include aggravated asthma, chronic respiratory disease, increased emergency room visits and hospital admissions, acute respiratory symptoms, decrease in lung function and even premature mortality. (Brook et al., 2010) reported that short-term PM2.5 exposure over a few hours to weeks can trigger cardiovascular morbidity and mortality events. WHO (2013) reported that significant evidence, based on toxicological and clinical studies, linking peak exposures to combustion-derived particles of short duration (ranging from less than an hour to a few hours) leads to immediate physiological changes.

Most of the general population in North America or Europe spent 89% of their time indoors, with 69% spent in the residential indoor environment (Klepeis et al., 2001, Schweizer et al., 2006), and homemakers or the elderly spending up to 90% of their time in the residential indoor environment (Torfs et al., 2008). Therefore, the residential environment deserves particular attention.

The need to achieve carbon and greenhouse gas emissions has promoted energy efficiency improvements because of the potential saving in energy costs. Reduction in energy usage in buildings is a significant component of the national CO_2 reduction strategies. For example, the Technical Guidance Document L of Part L of the Irish Building Regulations (SI 259 of 2011) sets out new performance levels for air permeability to be 7 $m^3/hr/m^2$ at 50Pa. Under the European directive (2010/31/EU, 2010), all new building must adhere to minimum energy performance requirements. Irish legislation (S.I. No. 259/2008, 2008) refers to reducing heat loss in building through increasing the air tightness.

However, as buildings air-tightness increases, a reduction occurs in the air exchange rates (AERs) reducing heat loss, while increasing the indoor pollutant concentrations if significant indoor sources are present (Gens et al., 2014). Wilkinson et al. (2009) reported that changes in energy efficiencies in domestic homes may impact on indoor air quality, due to increasing air-tightness without alternative methods of reducing indoor generated pollutants. Bone et al. (2010) highlights that the driver for more energy efficiency homes will harm occupant health.

The World Health Organization's (WHO, 2010) guidance on thermal comfort ensures satisfaction with the ambient temperature, but also links to human health. The guidance for the home environment aims at protecting human health particularly those most susceptible, such as the very young and the elderly (Ormandy and Ezratty, 2012). Additionally, thermal comfort has been reported to influence individuals’ behavioural patterns; Andersen et al. (2009) reported that window opening behaviour in Danish dwellings is strongly linked to the outdoor temperature. (Rijal et al., 2007, 2008) found relationships between the thermal environment and the occupants’ behaviour in relation to windows/doors opening patterns and the usage of HVAC system. McGrath et al. (2014b) investigated variations in PM concentrations due to interzonal airflow in a six-room apartment layout. The study found that peak concentrations in adjoining rooms were directly linked to the time of the door opening/closing events.

Andersen et al. (2009) reported that the use of internal heating was correlated with the outdoor temperature and the presence of a wood-burning stove within the dwelling. In Ireland, the use of solid fuel burning in fireplaces is often used as means of secondary heating source (McGrath et al., 2011, Semple et al., 2012).

Indoor PM concentrations are affected by infiltration of outdoor particles, meteorological parameters and seasonal effects, indoor activities of occupants, emissions from indoor PM sources, removal of particulates by deposition, the dilution of indoor PM through external and internal airflow and internal house layout (Ferro et al., 2009, Singer et al., 2002, Ott, 1999). Numerous studies have highlighted the indoor activities that contribute to PM concentrations, such as smoking, frying, solid fuel fire and use of incense and candles (He et al., 2004, See and Balasubramanian, 2011, Semple and Latif, 2014) and also resuspension activities such as walking, dusting or sitting on furniture (Ferro et al., 2004, Jing et al., 2008).

It is often impractical or expensive to obtain large-scale indoor or personal exposure measurements to account for the range of indoor factors (indoor emission sources, indoor deposition and resuspension, and the occupant's behaviour). Computational modelling is an effective tool at separating out the contribution of indoor emission source from outdoor generated air pollution; this approach allows for effective exposure reduction strategies to be devised. For the proper management of air quality to be fully evaluated, indoor exposures need to be further separated into the contributions of indoor sources and the penetration of outdoor pollution. Modelling approaches are essential if this is be effectively achieved (Dimitroulopoulou et al., 2000).

Steinle et al. (2013) highlights that exposure models are an appropriate tool to increase sample sizes and reduce the cost of experimental exposure studies. Exposure models need to integrate a wide range of factors (e.g. economic, social and demographic), to assess relations and associations between human exposure to environmental air pollutants and potential health effects. In recent years, a number of models have predicted indoor pollutant concentrations in indoor environments (Dimitroulopoulou et al., 2006, Fabian et al., 2012, Sohn et al., 2007, Parker and Bowman, 2011). Fabian et al., (2012) reported challenges imposed on simulations due to the large variation in emission strengths. Limitations in these physical pollutant models have led to poorer estimations of indoor air pollutant exposure assessment.

Probabilistic modelling is one approach that overcomes these issue. McGrath et al. (2014a) developed IAPPEM, a state-of-the-art probabilistic model for indoor PM concentration estimation, capable of simulating up to 15 interconnecting rooms with the incorporation of up to 12 simultaneously-operating emission sources. IAPPEM proved to be capable of simulating the large variation in emission rates, predicting both peak and mean PM_{10} and $PM_{2.5}$ concentrations. IAPPEM provided a detailed analysis of overall PM contribution from multiple different emission sources, in a variety of different internal locations in a dwelling, and the effect that both emission source location and internal household configuration has on PM transfer throughout a dwelling has been quantified.

The current work plans to incorporate temperature parameters into the existing model; this would allow the unique capability to assess, for the first time, the effects of ventilation and occupant behaviour on both an individual's thermal comfort and airborne pollutant exposure. This would provide a vital computational tool that has wide relevance in epidemiology studies, building design, ventilation studies, traffic management studies, and many other fields.

2 METHODOLOGY

2.1 Air pollutant model

The current model, titled Indoor Air Pollutant Passive Exposure Model (IAPPEM), is an advanced probabilistic modelling tool that evaluates the contribution of both indoor and outdoor sources to the air pollution concentration in the indoor environment. IAPPEM calculates the change in indoor pollutant concentrations by solving the differential equation 1; considering the infiltration of outdoor air pollution, the generation of air pollution indoors and its transport between rooms, and the indoor deposition of air pollution. At each time interval, probability density functions are used to simulate a range of possible values for each parameter, assessing the range of likely outcomes when specific details are unavailable. This can encompass uncertainties in experimental obtained data, but can also encompass uncertainties in the selection of appropriate modelling parameters between studies. Further details on the parameterisation of the pollutant model are available in McGrath et al. (2014a).

$$\frac{dC_k}{dt} = \frac{(\lambda_{0k})}{V_k}(f_k * (C_0 - C_k)) - v_g(\frac{A_k}{V_k})C_k + \frac{Q_k}{V_k} + \sum_{i=1}^{n} \frac{\lambda_{ik}}{V_k}(C_i - C_o) \quad (1)$$

Equation 1 is solved for each k, where k represents each individual room. Subscripts of 0, 1 and 2 are used to represent outside, room 1 and room 2 for different parameters. C_k represents the concentrations of the pollutant in that room μg m^{-3}, where C_0 represents the outdoor concentration (μg m^{-3}). f_k represents the building filtration factors between the outdoor and that room. v_g is the deposition velocity of the pollutant (m hr^{-1}) λ_{ik} is the interzonal airflow between internal rooms, e.g. λ_{12} represents the transport of pollutants from room 1 into room 2, and λ_{0k} the external airflow between the outside and room k (m^3 hr^{-1}). A_k is the surface area of room k (m^2). V_k is the volume of room k (m^3). Q_k is the indoor emission rate of the pollutant in room k (μg hr^{-1}).

2.2 Addition of a Temperature Parameter

The current work comprises of altering the model's source code to include the temperature parameters, allocating a source file to account for time-varying outdoor temperature concentrations, as well as incorporating a temperature parameter to each room. A 'source' term will allow for internal heating sources (solid-fuel burning, central heating, electric fan heater or HVAC). A 'decay' term will allowing for heat losses through the building fabric through external and internal walls, as well as floors and ceilings. Airflow rates in Equation 1 will be used to assess the heat loss to the outdoors but also the internal transfer of heat between zones. Additionally, a heat 'recovery' term will be added to account for any heat recovery systems.

The model's parameterisation will account for variation in building fabrics; window types and wall and roof insulation. Altering the model's parameterisation will allow assessments of performance pre and post retrofitting a building.

3 RESULTS

The application of the air pollutant model is demonstrated by a number of simulations below. The simulation are based on the 11-room dwelling described in McGrath et al. (2014a). The emission scenarios comprised of two frying events in the kitchen and five smoking events in the living room while internal doors remained closed. Each frying event lasts for 15-minutes, while each smoking event lasts for nine minutes. Figure 1 and 2 shows a section of the 24hour time-series profile for $PM_{2.5}$ concentrations in both the kitchen and the living room.

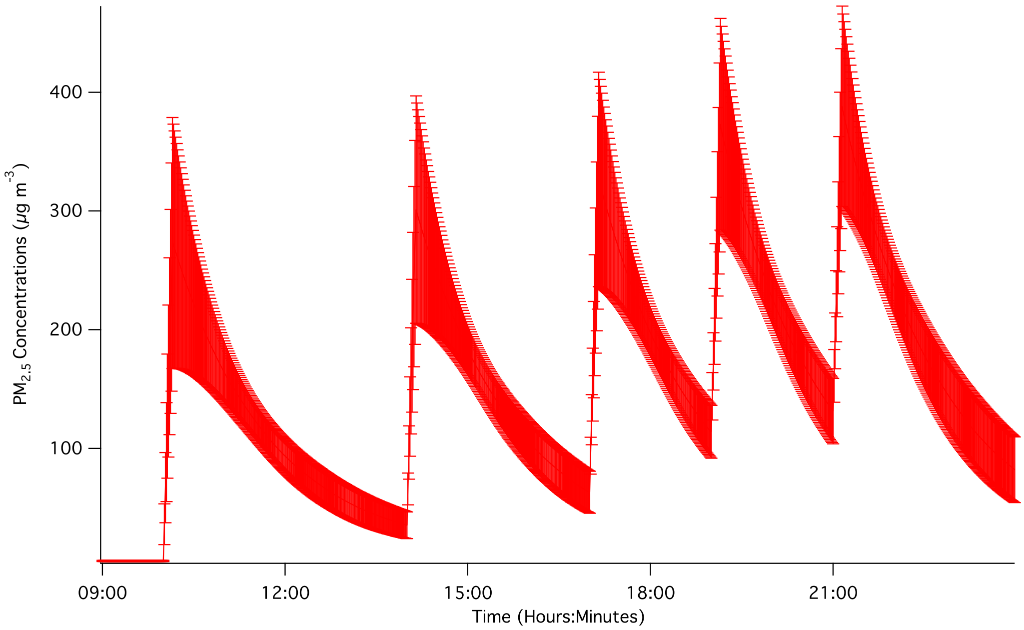

Figure 1. $PM_{2.5}$ concentrations in the living room. The time axes have been scaled to focus on the emission periods. The 'y' bars represent one standard deviation at each time step, highlighting the probabilistic nature of the model. Each of the peak concentrations refers to the end of the smoking events.

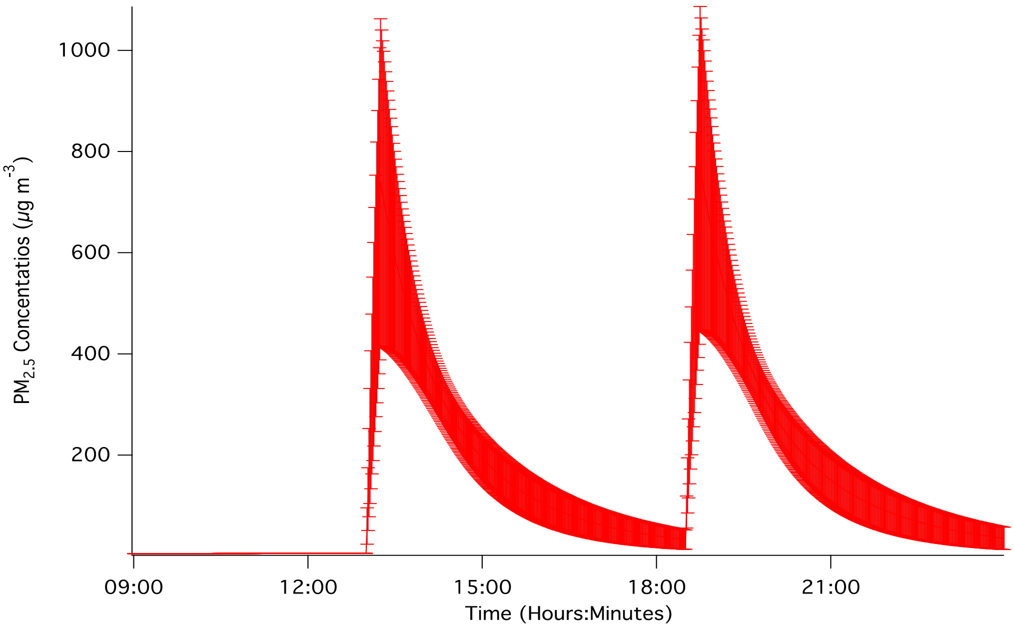

Figure 2. $PM_{2.5}$ concentrations in the kitchen. The time axes have been scaled to focus on the emission periods. The 'y' bars represent one standard deviation at each time step, highlighting the probabilistic nature of the model. Each of the peak concentrations refers to the end of the frying event.

Table 1 shows the effect that reducing AERs have on indoor $PM_{2.5}$ concentrations. The values of 0.30, 0.44, 0.70 ACH^{-1} reflect similar AERs reported in literature for European dwelling (Crump et al., 2005, Dimitroulopoulou, 2012). It can be seen that PM concentrations increase with decreasing AERs; this is a major concern considering that the World Heath Organisation (WHO, 2006, 2013) recommends a 24-hour mean $PM_{2.5}$ concentration guideline of 25 μg m^{-3}.

Table 1 shows the 24-mean PM2.5 concentrations in both the kitchen and sitting room under three different air exchange rates in units of Air Changes per Hour (ACH^{-1}).

Location	0.7 ACH^{-1}	0.44 ACH^{-1}	0.3 ACH^{-1}
Kitchen	70 ± 6 μg m^{-3}	95 ± 9 μg m^{-3}	112 ± 12 μg m^{-3}
Sitting Room	74 ± 4 μg m^{-3}	100 ± 7 μg m^{-3}	122 ± 10 μg m^{-3}

The proposed enhancement to the model will simultaneously allow time-series analysis of internal room temperatures in combination with indoor air quality. Any proposed changes in AERs can then be assessed in terms of potential energy saving strategies to analyse the effect on the reduction in heat loss but also the effect on indoor air quality.

4 CONCLUSIONS

The modified model will make simulations to assess both thermal comfort and indoor air pollutants, resulting in a time-series analysis of both parameters. This will allow simulations of variations in household characteristics, occupants behavioral patterns, mechanical and natural ventilation.

The results of this project will inform policy makers and the public on energy usage reduction in the built environment sector, and any mis-understanding regarding potentially adverse effects of reduced ventilation on indoor air quality could be extremely detrimental in this regard. The model can assess the potential benefits of retrofitting a residential dwelling while ensuring there is no reduction in indoor air quality.

This unique computational tool can be used to define the optimum ventilation rates for energy efficient homes ensuring thermal comfort and also an appropriate level of indoor air quality. One potential strategy could examine increasing the external airflow in rooms that experience higher air pollutant concentrations while reducing the external airflow in rooms that experience lower air pollutant concentrations.

5 ACKNOWLEDGEMENTS

This work was funded by Sustainable Energy Authority of Ireland (SEAI) under the SEAI Renewable RD&D Programme 2014.

6 REFERENCES

ANDERSEN, R. V., TOFTUM, J., ANDERSEN, K. K. & OLESEN, B. W. 2009. Survey of occupant behaviour and control of indoor environment in Danish dwellings. *Energy and Buildings,* 41**,** 11-16.

BONE, A., MURRAY, V., MYERS, I., DENGEL, A. & CRUMP, D. 2010. Will drivers for home energy efficiency harm occupant health? *Perspectives in public health,* 130**,** 233-238.

BROOK, R. D., RAJAGOPALAN, S., POPE, C. A., BROOK, J. R., BHATNAGAR, A., DIEZ-ROUX, A. V., HOLGUIN, F., HONG, Y., LUEPKER, R. V. & MITTLEMAN, M. A. 2010. Particulate matter air pollution and cardiovascular disease an update to the scientific statement from the American Heart Association. *Circulation*, 121**,** 2331-2378.

COMEAP 2009. Long term exposure to air pollution: Effect on mortality.: Committee on the Medical Effects of Air Pollutants.

COMEAP 2010. Review of Evidence on Health Aspects of Air Pollution REVIHAAP Project: Final technical report.

CRUMP, D., DIMITROULOPOULOU, S., SQUIRE, R., ROSS, D., PIERCE, B., WHITE, M., BROWN, V. & COWARD, S. 2005. Ventilation and indoor air quality in new homes. *Pollution atmosphérique,* 1**,** 71.

DIMITROULOPOULOU, C. 2012. Ventilation in European dwellings: A review. *Building and Environment,* 47**,** 109-125.

DIMITROULOPOULOU, C., ASHMORE, M. R., BYRNE, M. A., HILL, M. T. R., KINNERSLEY, R. P., MARK, D. & NI RIAIN, C. 2000. Modelling of indoor aerosol concentrations in UK buildings. *Journal of Aerosol Science,* 31.

DIMITROULOPOULOU, C., ASHMORE, M. R., HILL, M. T. R., BYRNE, M. A. & KINNERSLEY, R. 2006. INDAIR: A probabilistic model of indoor air pollution in UK homes. *Atmospheric Environment,* 40**,** 6362-6379.

FABIAN, P., ADAMKIEWICZ, G. & LEVY, J. I. 2012. Simulating indoor concentrations of NO 2 and PM 2.5 in multifamily housing for use in health-based intervention modeling. *Indoor Air,* 22**,** 12-23.

FERRO, A. R., KLEPEIS, N. E., OTT, W. R., NAZAROFF, W. W., HILDEMANN, L. M. & SWITZER, P. 2009. Effect of interior door position on room-to-room differences in residential pollutant concentrations after short-term releases. *Atmospheric Environment,* 43**,** 706-714.

FERRO, A. R., KOPPERUD, R. J. & HILDEMANN, L. M. 2004. Source strengths for indoor human activities that resuspend particulate matter. *Environmental science & technology,* 38**,** 1759-1764.

GENS, A., HURLEY, J. F., TUOMISTO, J. T. & FRIEDRICH, R. 2014. Health impacts due to personal exposure to fine particles caused by insulation of residential buildings in Europe. *Atmospheric Environment,* 84**,** 213-221.

HE, C., MORAWSKA, L., HITCHINS, J. & GILBERT, D. 2004. Contribution from indoor sources to particle number and mass concentrations in residential houses. *Atmospheric Environment,* 38**,** 3405-3415.

JING, Q., FERRO, A. R. & FOWLER, K. R. 2008. Estimating the Resuspension Rate and Residence Time of Indoor Particles. *Journal of the Air & Waste Management Association (Air & Waste Management Association),* 58**,** 502-516.

KLEPEIS, N. E., NELSON, W. C., OTT, W. R., ROBINSON, J. P., TSANG, A. M., SWITZER, P., BEHAR, J. V., HERN, S. C. & ENGELMANN, W. H. 2001. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal of Exposure Analysis and Environmental Epidemiology,* 11**,** 231-252.

MCGRATH, J., BYRNE, M., ASHMORE, M., TERRY, A. & DIMITROULOPOULOU, C. 2014a. Development of a probabilistic multi-zone multi-source computational model and demonstration of its applications in predicting PM concentrations indoors. *Science of The Total Environment,* 490**,** 798-806.

MCGRATH, J. A., BYRNE, M. A., ASHMORE, M. R., TERRY, A. C. & DIMITROULOPOULOU, C. Simulation of Solid Fuel Burning Events in Irish Fireplaces under Varying Air Exchange Rates. The 12th International Conference on Indoor Air Quality and Climate. Indoor Air 2011., 2011 Austin, Texas.

MCGRATH, J. A., BYRNE, M. A., ASHMORE, M. R., TERRY, A. C. & DIMITROULOPOULOU, C. 2014b. A simulation study of the changes in PM2.5 concentrations due to interzonal airflow variations caused by internal door opening patterns. *Atmospheric Environment,* 87**,** 183-188.

ORMANDY, D. & EZRATTY, V. 2012. Health and thermal comfort: From WHO guidance to housing strategies. *Energy Policy,* 49**,** 116-121.

OTT, W. R. 1999. Mathematical models for predicting indoor air quality from smoking activity. *Environmental Health Perspectives,* 107**,** 375-381.

PARKER, S. & BOWMAN, V. 2011. State-space methods for calculating concentration dynamics in multizone buildings. *Building and Environment,* 46**,** 1567-1577.

RIJAL, H. B., TUOHY, P., HUMPHREYS, M. A., NICOL, J. F., SAMUEL, A. & CLARKE, J. 2007. Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings. *Energy and Buildings,* 39**,** 823-836.

RIJAL, H. B., TUOHY, P., NICOL, J., HUMPHREYS, M. A., SAMUEL, A. & CLARKE, J. 2008. Development of adaptive algorithms for the operation of windows, fans and doors to predict thermal comfort and energy use in Pakistani buildings. *ASHRAE transactions,* 114**,** 555-573.

SCHWEIZER, C., EDWARDS, R. D., BAYER-OGLESBY, L., GAUDERMAN, W. J., ILACQUA, V., JANTUNEN, M. J., LAI, H. K., NIEUWENHUIJSEN, M. & KÜNZLI, N. 2006. Indoor time–microenvironment–activity patterns in seven regions of Europe. *Journal of Exposure Science and Environmental Epidemiology,* 17**,** 170-181.

SEE, S. W. & BALASUBRAMANIAN, R. 2011. Characterization of fine particle emissions from incense burning. *Building and Environment,* 46**,** 1074-1080.

SEMPLE, S., GARDEN, C., COGGINS, M., GALEA, K. S., WHELAN, P., COWIE, H., SANCHEZ-JIMENEZ, A., THORNE, P. S., HURLEY, J. F. & AYRES, J. G. 2012. Contribution of solid fuel, gas combustion, or tobacco smoke to indoor air pollutant concentrations in Irish and Scottish homes. *Indoor Air,* 22**,** 212-223.

SEMPLE, S. & LATIF, N. 2014. How Long Does Secondhand Smoke Remain in Household Air: Analysis of PM2. 5 Data From Smokers' Homes. *Nicotine & Tobacco Research***,** ntu089.

SINGER, B. C., HODGSON, A. T., GUEVARRA, K. S., HAWLEY, E. L. & NAZAROFF, W. W. 2002. Gas-phase organics in environmental tobacco smoke. 1. Effects of smoking rate, ventilation, and furnishing level on emission factors. *Environmental Science & Technology,* 36**,** 846-853.

SOHN, M. D., APTE, M. G., SEXTRO, R. G. & LAI, A. C. 2007. Predicting size-resolved particle behavior in multizone buildings. *Atmospheric Environment,* 41**,** 1473-1482.

STEINLE, S., REIS, S. & SABEL, C. E. 2013. Quantifying human exposure to air pollution—moving from static monitoring to spatio-temporally resolved personal exposure assessment. *Science of the Total Environment,* 443**,** 184-193.

TORFS, R., BROUWERE, K. D., SPRUYT, M., GOELEN, E., NICKMILDER, M. & BERNARD, A. 2008. Exposure and risk assessment of air fresheners. VITO.

WHO 2006. WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide. *World Health Organisation*.

WHO 2010. Housing, Energy and Thermal Comfort. A review of 10 countries within the WHO European Region. *World Health Organisation*.

WHO 2013. Review of Evidence on Health Aspects of Air Pollution REVIHAAP Project: Final technical report. World Health Organization.

WILKINSON, P., SMITH, K. R., DAVIES, M., ADAIR, H., ARMSTRONG, B. G., BARRETT, M., BRUCE, N., HAINES, A., HAMILTON, I. & ORESZCZYN, T. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. *The Lancet*, 374**,** 1917-1929.