Ambient air filter efficiency in airtight, highly energy efficient dwellings – A simulation study to evaluate benefits and associated energy costs

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ABSTRACT

Highly energy efficient buildings such as ones built to the Passive House standard, require a very airtight building envelope and the installation of a mechanical ventilation with heat recovery (MVHR). MVHR systems incorporate ambient air filters, which reduce the introduction of particulate matter (PM) from outdoor sources into the dwelling. However, indoor PM sources, e.g. cooking, can also contribute substantially to occupants' exposure and need to be accounted for when designing ventilation or deriving recommendations for filter classes.

This simulation study investigates which ambient air filter class is a reasonable choice in terms of indoor air quality and energy use for highly airtight residential housing. It considers outdoor and indoor generated size-resolved PM, while comparing different cooktop ventilation concepts. Results confirm that a F7 filter according to EN 779 (or equivalent) is a reasonable choice for low or short-term moderate ambient air PM concentrations, as total PM exposure will be dominated by indoor sources and higher filter classes will therefore not provide a substantial exposure reduction. For locations with high outdoor PM concentrations, the use of a high-class filter like F9 is advisable, as it will further reduce the exposure. In locations with low ambient air pollution, cooking emissions could likely contribute a substantial or even dominant fraction of the total PM exposure, if no measures, like an effective cooker hood system, is used. Here, the use of an extracting hood shows clear advantages over a recirculating system. However, for cases with elevated ambient concentrations, the use of extracting kitchen hoods (with unfiltered make-up air) will increase the total PM exposure for cases with low or moderate cooking intensities.

KEYWORDS

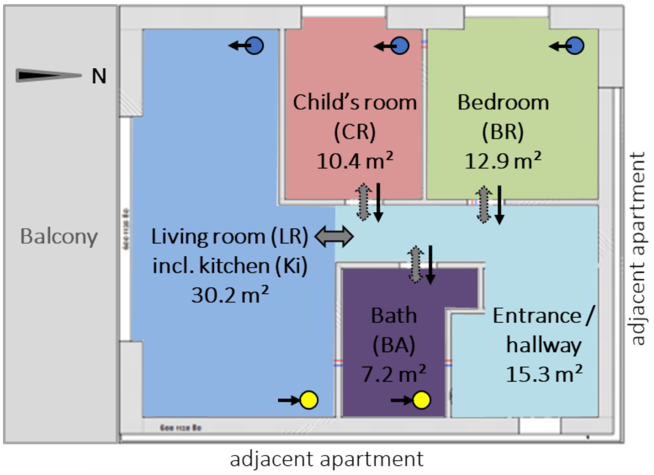
Particulate matter, $PM_{2.5}$, UFP, MVHR, filter, cooking, cooker hood, energy efficient, Passive House, Annex 68

1 INTRODUCTION

This work evaluates the exposure to fine and ultrafine particulate matter (PM) within a residential dwelling in Passive House standard with multi-zone airflow simulations. The study is performed within the framework of the project "IEA EBC Annex 68 - Indoor Air Quality Design and Control in Low Energy Residential Buildings".

2 METHOD

Based on a residential low-energy building project in Austria (Ploss and Hatt 2016), a two-bedroom apartment was modelled in CONTAM, a multi-zone air flow and contaminant transport simulation tool (Dols and Polidoro 2015). The floor plan is shown in Figure 1. It has a floor area of 76 m² and represents a typical Austrian apartment. In the reference model, the occupancy and window use is based on a literature review undertaken for previous simulation studies, e.g. (Rojas, Pfluger, and Feist 2016) with three occupancy schedules representing a full-time employed person, a person staying at home and a school child. Envelope leakages are modelled with two "cracks" in each exterior wall at two different heights (1 m and 2.2 m representing regular windows and 0 m and 2.2 m representing tall windows) to allow for stack-effect driven infiltration. The cracks are evenly distributed and dimensioned to result in an air exchange of 0.6 h^{-1} at 50 Pa, the threshold for Passive House certification. The wind pressure is calculated using a wind speed modifier, representing a height of 10 m in suburban terrain and wind pressure profile representing a low-rise building (ASHRAE 2005). Wind speed and ambient temperatures are defined by a standardised weather file for the city of Vienna generated with the software Meteonorm. The model-apartment has a balanced mechanical ventilation with heat recovery (MVHR), with filtered ambient air being supplied into bedrooms and living room and “used” air being extracted from kitchen area and bathroom. The supply and extract airflows are documented in Figure 1. The bedroom and child’s room door, modelled as two-way airflow paths, are closed during the night and open during the day (variations are performed in section 3.2). The bathroom door opens five times for 10 minutes each over the course of the day. The opening between hallway and living room is also modelled as a permanently open two-way airflow path, with 2.5 m height and 1.2 m width.



Ventilation air flows in m³/h (l/s)

	BR	CR	LR/Ki	BA	Total
Supply	40 (11.1)	20 (5.6)	30 (8.3)		90 (25)
Extract			60 (16.7)	30 (8.3)	90 (25)

Figure 1: Sketch of the simulated floor plan representing a typical new Austrian residential dwelling and the ventilation air flows as modelled in the reference model.

The particle exposure was modelled for sizes ranging from 1 nm to 10 µm with 21 bins evenly distributed on a log scale. The specific aspects for modelling the particle exposure are described in the following subsections.

2.1 Ambient concentration

The outdoor PM distribution was modelled based on values for archetypical urban air as reported in (Ruprecht 1993). The multimodal distribution (see Figure 2a) can be described as the sum of three lognormal distributions; their parameters are reported in the original work and e.g. in (Riley et al. 2002). The respective simulation input files were generated using the “CONTAM particle distribution calculator” (NIST n.d.). Figure 2b shows a characteristic aerosol distribution for rural areas used as alternative simulation input (see section 3.1).
Due to lack of time-resolved data, ambient air concentration was modelled constant. Note that the concentration levels for the reference case, i.e. a $PM_{2.5}$ of 42 µg/m³, will not necessarily represent a typical long-term average of a European city. E.g. the yearly $PM_{2.5}$ average in Austrian cities has been declining and was roughly around 15 µg/m³ in 2017. However, the used distribution may very well present a short-term average in an urban area in Europe or e.g. a long-term average in a moderately polluted Asian city.

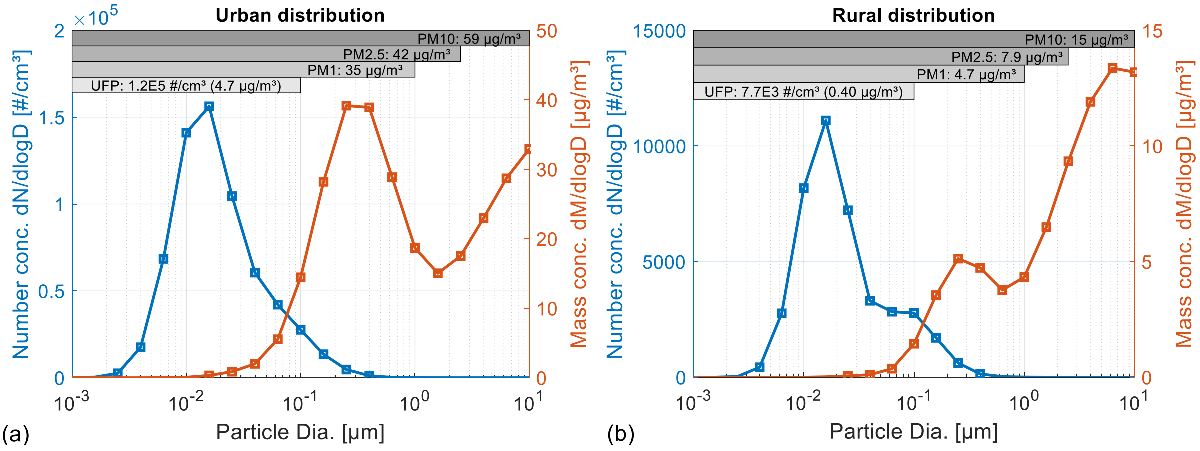


Figure 2: Characteristic ambient particle distributions for urban (a) and rural (b) areas taken from (Ruprecht 1993). The plots show the log-normalized distributions for particle number and mass concentration assuming a particle density of 1 g/cm³. The integrated values for UFP (≤0.1 µm), PM_1 (≤1 µm), $PM_{2.5}$ (≤2.5 µm), PM_{10} (≤10 µm) are also shown on the plots. Note the different scaling between urban and rural plots.

2.2 Filter quality and envelope penetration

The efficiency of ventilation filters is usually classified according to ASHRAE 52.2, EN 779 or to the new ISO 16890 standard. These standards define test methods to determine the fractional filtration efficiency for particles >0.3 µm, which is the lower threshold for most optical particle spectrometers. Therefore it is difficult to obtain efficiency curves for particle sizes <0.3 µm from filter manufacturers. Nevertheless, few studies have reported filtration efficiency curves for the entire (relevant) size spectrum (González et al. 2016; Hanley et al. 1994; Shi 2012; Shi, Ekberg, and Langer 2013). However, no data for filters classified according to the new standard ISO 16890, e.g. ISO ePM1 70%, could be sourced. Therefore, this study simulated filter classes M5, M6, F7, F8 and F9 (according to EN 779). Their fractional efficiency curves were taken from (Shi, 2012, see Figure 7.2), and are plotted in Figure 3a. These filter classes can be roughly translated to MERV 9/10, MERV 11/12, MERV 13, MERV 14 and MERV 15 (according ASHRAE 52.2), respectively (camfil n.d.). Note that other particle losses within the ventilation system, besides the removal by the filter, were not modelled in this study although several loss mechanism might change the ambient particle distribution as the air travels through the ventilation system. However, these losses can be considered very small compared to particle removal by the filter, see e.g. (Siegel and Nazaroff 2003; Sippola and Nazaroff 2003).

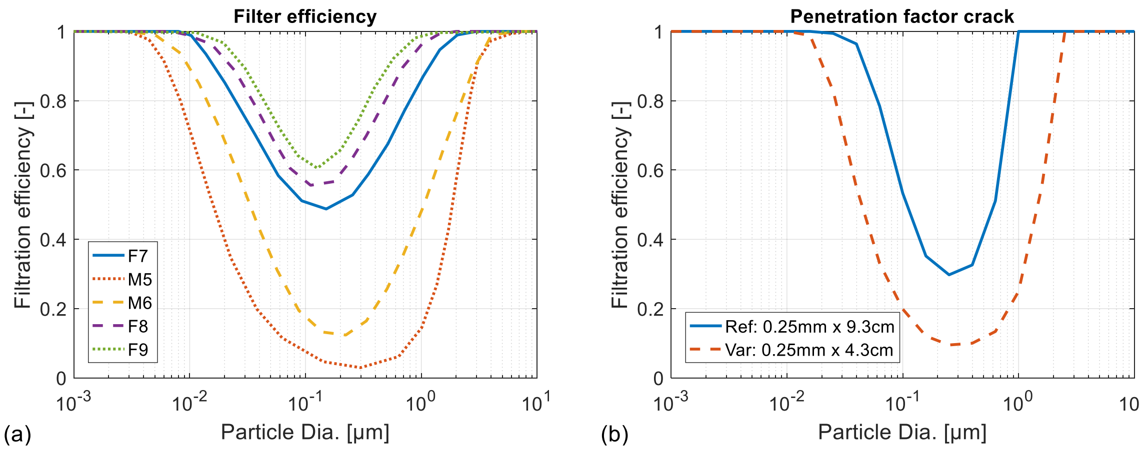


Figure 3: Fractional filtration efficiency of ventilation filter (a) and envelope cracks (b) as modelled for this study. The curves were derived / extracted from (Shi 2012) and (Liu and Nazaroff 2003).

Particle penetration through the building envelope has been investigated and characterized in numerous studies (Chao, Wan, and Cheng 2003; Lee et al. n.d.; Liu and Nazaroff 2003; Long et al. 2001; Stephens and Siegel 2012; Thatcher and Layton 1995; Tian et al. 2009). However, only a few allow the extraction of the particle size resolved penetration factor p for simulating highly airtight buildings as investigated herein. For this study the penetration factor curve as shown in (Liu & Nazaroff, 2003, see Figure 6) for an aluminium crack with a width of 0.25 mm and a flow length of 9.4 cm was implemented in the CONTAM model. To test the sensitivity of this parameter, the data for a crack with a width of 0.25 mm and a flow length of 4.3 cm was used alternatively. The resulting filtration efficiency (1-p) for these crack dimensions are shown in Figure 3b.

2.3 Indoor sources and deposition

Various indoor activities can substantially contribute to indoor PM exposure. These have been characterised in a number of studies, e.g. (Géhin, Ramalho, and Kirchner 2008; Hussein et al. 2006; Wallace 2006). Cooking is considered one of the major indoor PM source and numerous studies have investigated the resulting PM concentrations and/or characterised emission rates from various cooking activities, e.g. (Abdullahi, Delgado-Saborit, and Harrison 2013; Buonanno, Morawska, and Stabile 2009; Poon, Wallace, and Lai 2016; See and Balasubramanian 2008; Sjaastad, Svendsen, and Jorgensen 2008; Torkmahalleh et al. 2012; Wallace, Emmerich, and Howard-Reed 2004). To keep the numerical model and its interpretation as simple as possible, this study only implemented PM sources representing cooking activities, i.e. toasting, frying burger and heating oil. These three source events, modelled as a burst source (instantons release during one simulation time step of 5 min), were scheduled in the morning (7:30), at noon (12:00) and in the evening (18:30), respectively. The source strength was determined from experimental data gathered during laboratory measurements by the author. Preliminary results were reported in (Rojas, Delp, and Singer 2018), a detail report of that study, characterising filter efficiency of cooker hoods, is still to be published. The resulting $PM_{2.5}$ source strength compares well with values reported in literature, e.g. (He et al. 2004).

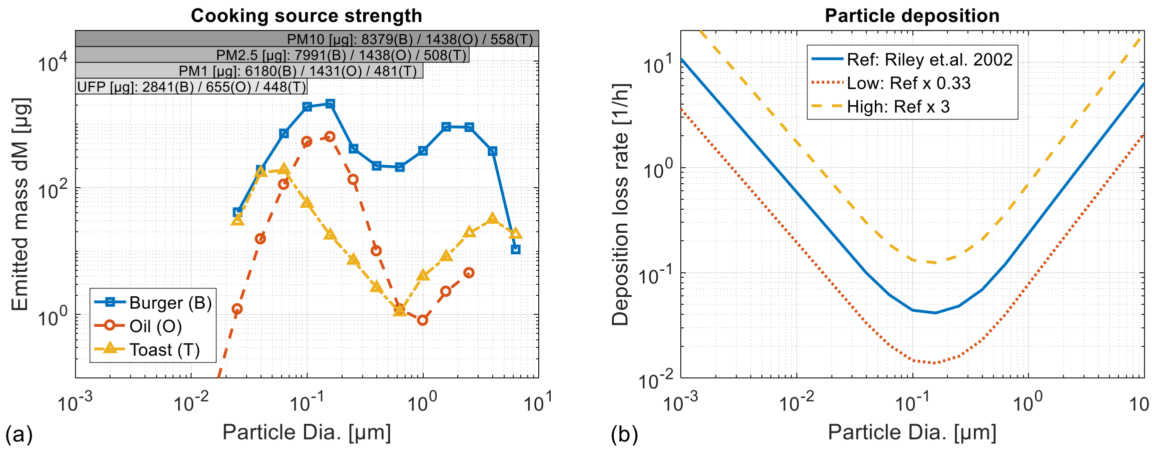


Figure 4: Cooking source strength (a) and particle deposition loss rate (b) as modelled in this study. The source strength in (a) was extracted from experimental data from measurements in a test chamber (Rojas et al. 2018). The reference curve for particle deposition in (b) is taken from (Riley et al. 2002).

Deposition is an important particle loss mechanism which strongly depends on particle size. Deposition rates in residential settings has been investigated numerously. Measurement results and/or a literature review can be found in e.g. (He, Morawska, and Gilbert 2005; Howard-Reed, Wallace, and Emmerich 2003; Riley et al. 2002). For this study, the deposition loss coefficient function as specified in (Riley et al., 2002, see Figure 3) was used for the reference model. It is based on experimental data for particle diameters >0.06 µm and on the smooth indoor surface particle deposition theory of (Lai and Nazaroff 2000) for diameters below that value. For the sensitivity analysis (see section 3.2), these values were divided / multiplied by a factor of three. The resulting deposition loss rates are shown in Figure 4b.

2.4 Exposure assessment

The ambient PM concentration was modelled constant and the occupant related schedules repeat every day. Therefore averaged exposure results, rather than temporal variations or peak values, were used for assessment. The simulation was performed for the full month of January (to average varying infiltration) with a time step of 5 minutes. The simulation results were analysed by assessing the average exposure of the "always-present-occupant" during the full month, i.e. the average concentration in the rooms where this person scheduled to be present. Note that this way the PM concentration in the child's room is not taken into account. According to the WHO guidelines for indoor air the $PM_{2.5}$ exposure should not exceed 25 µg/m³ if averaged in a 24h period or 10 µg/m³ if averaged in a period of one year (WHO 2005). The author is not aware of any standard or guidelines recommending exposure limit values for UFP.

3 RESULTS

Figure 5 shows the simulated PM concentration for the reference model during the course of one winter day. Since a constant ambient concentration was modelled, variations are dominated by internal sources (modelled cooking events) and door and window openings. There is little difference between PM_1, $PM_{2.5}$ and PM_{10} values, i.e. most of the time indoor exposure is mainly dominated by sub-micrometre sized particles. Figure 6 shows the size distribution for four distinct hours of the day: (a) night times: only outdoor-originated particles are present; (b) after breakfast (i.e. toasting): the number concentration is strongly increased by indoor-originated particles, however the mass concentration is still dominated by outdoor-originated particles (increased by morning airing event); (c) after lunch: the cooking event (frying burger) substantially increases the number and mass concentration; (d) after dinner: the number and mass concentration is notably increased by another cooking activity (heating oil).

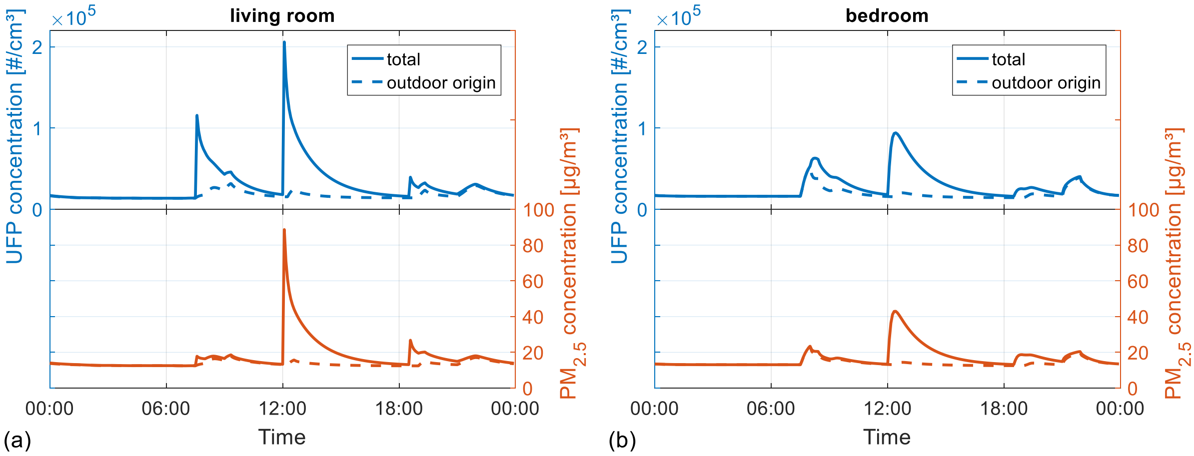


Figure 5: Simulated UFP and $PM_{2.5}$ concentration in living room/kitchen zone (a) and bedroom (b) over the course of one day for the reference case with F7 filter. The indoor concentration originating from outdoor PM is also plotted.

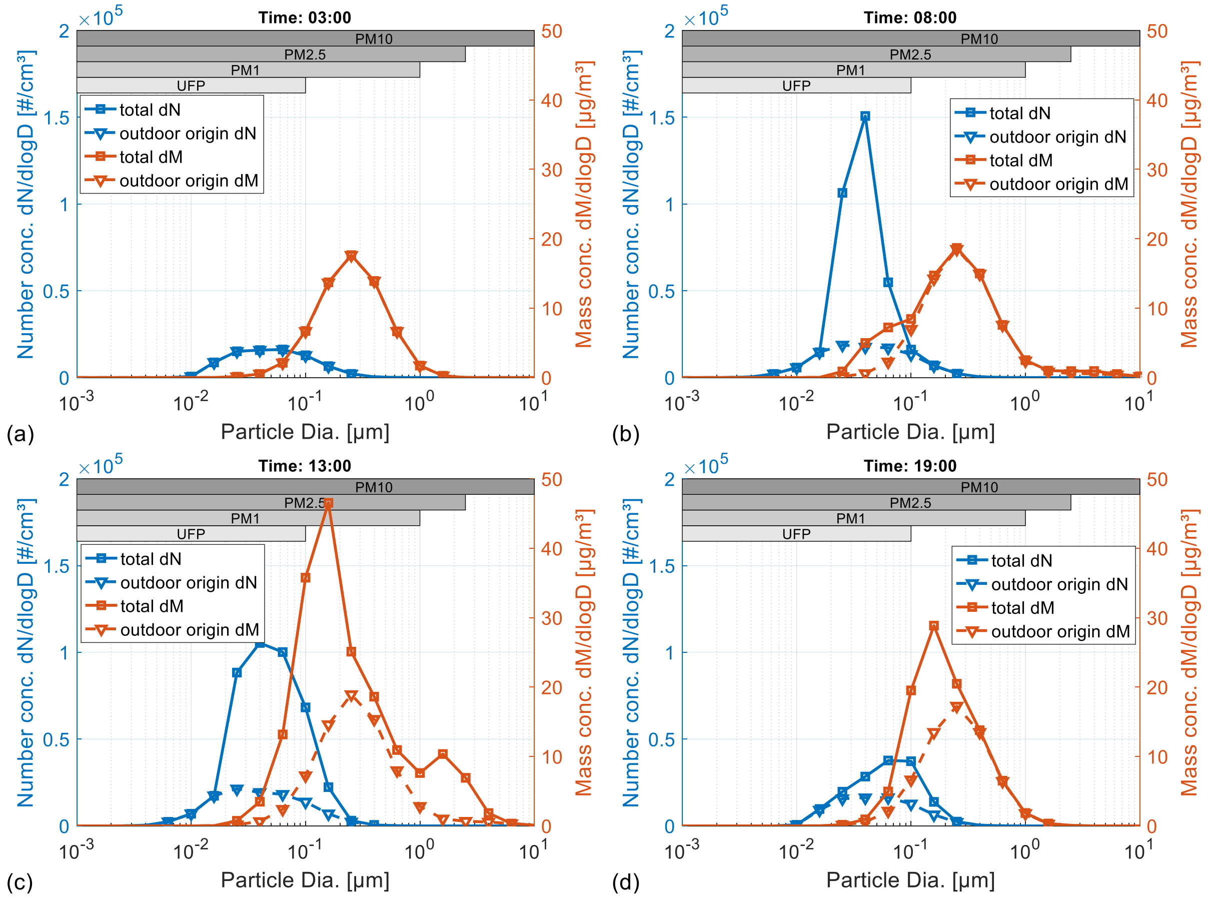


Figure 6: Log-normalized PM size distribution in the living room at four different hours of the day: during the night (a), after breakfast (b), after lunch (c), after dinner (d). The distribution of the outdoor-originated number and mass concentration is also plotted to differentiate between contributions from indoor and outdoor sources.

3.1 Effect of filter quality

To evaluate which filter quality is most favourable for the assumed boundary conditions, i.e. a very airtight housing with MVHR, the resulting mean $PM_{2.5}$ and UFP exposure was plotted against the estimated surplus electricity consumption due to the filter-induced pressure drop (see Figure 7). The pressure drop (average over lifetime) for each filter class was defined as reported in (Shi 2012, see Figure 8.5a). As one can see, $PM_{2.5}$ and UFP exposure is substantially reduced with the use of higher filter classes. However, the additional improvements are small for filter classes F8 and F9. For lower ambient PM concentration like assumed in the cases “Urban Low” and “Rural” (see Figure 2) a substantial fraction of the exposure stems from cooking originated particles. Therefore, the relative reduction of overall exposure does depend on the ambient air conditions (see Figure 8a). However, the relative reduction of outdoor-originated particles is practically independent of the ambient air concentration. A F7 filter would reduce the outdoor-originated particle exposure (from urban background) by around 55% vs. 72% with a F9 filter.

Figure 8b compares the exposure for three cases with MVHR, i.e. reference case, reduced and increased supply/extract flow, against the exposure obtained with an extract air ventilation (EAV) system. The EAV model assumed the same mechanical airflow as the MVHR reference case (90 m^3/h), with unfiltered trickle vents in bedroom, children’s room and living room. It was assumed that those openings had a pressure drop of 10 Pa at their nominal settings (corresponding to the supply air flow in the MVHR case). Note that for the EAV case, a substantial part (around 30%)% is drawn in through cracks, etc. despite the high airtightness of n_{50}=0.6 h^{-1}. As a result, the exposure between the EAV system and a MVHR system with a M5 is of comparable magnitude, with a F7 filter the exposure is roughly reduced by 50%. One can also see that the influence of the airflow rate setting of the MVHR system is minor.

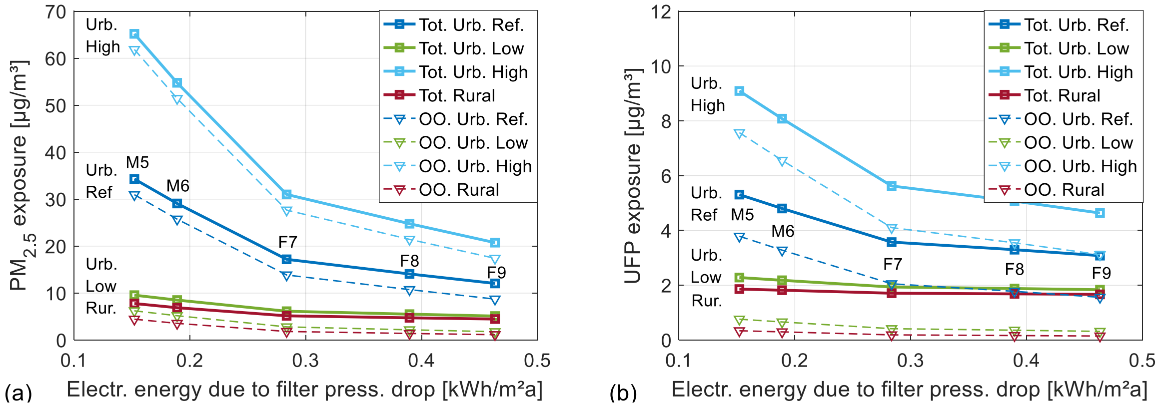


Figure 7: Average $PM_{2.5}$ (a) and UFP (b) exposure as a function of the electric energy consumption of the fan related to the pressure drop of the filter for different outdoor PM concentrations. The units refer to kWh per m² of floor area and year, assuming permanent fan operation. The contribution of the outdoor-originated (OO) PM is also plotted (dashed lines).

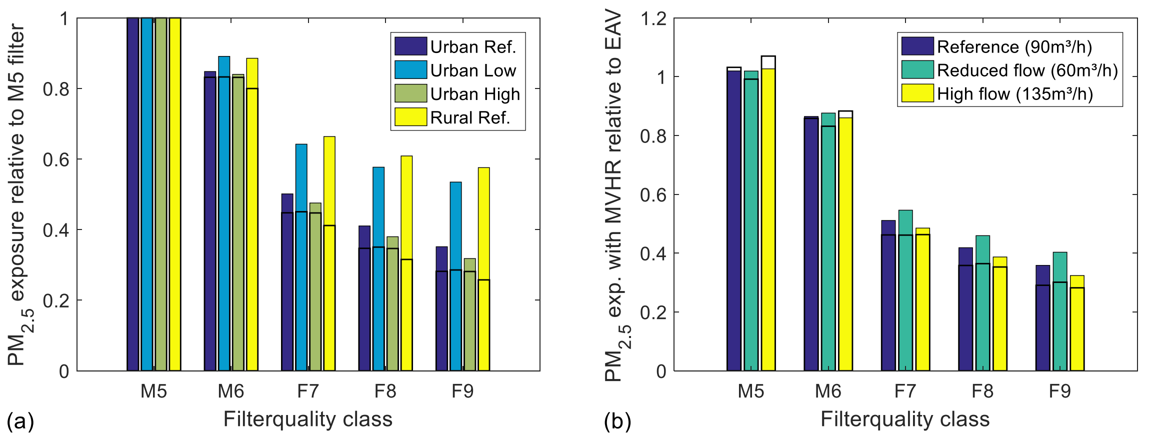


Figure 8: Average $PM_{2.5}$ exposure relative to exposure with a M5 filter (a) and average exposure for three cases with MVHR (reference, reduced and high flow) relative to average exposure for a case with extract air ventilation. In (a) the results for different outdoor air concentrations are shown. In (b) the results for different MVHR flow settings are shown. Exposure to outdoor originated PM is plotted with unfilled bars/horizontal line.

3.2 Effect of various PM related model parameters

To check the sensitivity of PM exposure to the chosen model parameters the reference model was varied as defined in Table 1. The opening schedule for bedroom and child's room door was modified from almost always closed (except for a few short opening events) to always open. The reference model included window opening behaviour based on observations in German Passive House apartments (Kah et al. 2010; Kah, Pfluger, and Feist 2005). Note that this might not be representative for locations with notably bad air quality, i.e. high outdoor particle concentrations. The window opening was modelled representing a tilted window resulting in roughly 50 m³/h (14 l/s) of air exchange during opening times. The sensitivity tests included a simulation run with no window opening and one with increased window opening duration, defined by the 95th percentile of the opening times observed in (Kah et al. 2010, 2005).

The n_{50} value, representing the airtightness of the building envelope, was varied between 0.3 h^{-1}, a value not uncommonly achieved in multi-family Passive Houses, and 1.5 h^{-1}. This

value is well above the Passive House criteria. However, it is often regarded as a threshold for an energetically reasonable operation of a MVHR system (DIN 4108-7 2011). The particle-size dependent deposition rate function was divided / multiplied by a factor of three (equally for all size bins) from the reference values. This results in a variation of nearly one order of magnitude and corresponds roughly to the variation reported in literature, see e.g. (Howard-Reed et al. 2003; Lai and Nazaroff 2000).
It can be assumed, that the air leakage cracks in the envelope of highly airtight buildings, like investigated in this study, have rather narrow gaps. There is limited data available on penetration factors for these kind of air leakage gaps. Therefore, only one additional simulation run was performed with the size-dependent penetration factor for a 0.25 mm wide and 4. m deep gap according to the data reported in (Liu and Nazaroff 2003) (see Figure 3b).

Table 1: Model variations for sensitivity analysis

	Reference	**Low**	**High**
Bed- / child's room door opening	8am – 10pm	4 x 10 min	0-24 hrs
Window opening (tilted): all	3.6 h/day	0 h/day	6.3 h/day
Kitchen area	3 x 20 min	-	3 x 35 min
Living room area	3 x 10 min	-	3 x 18 min
Bedroom	2 x 56 min	-	2 x 98 min
Childs room	2 x 6 min	-	2 x 11 min
Airtightness / n50	0.6 1/h	0.3 1/h	1.5 1/h
Deposition rate multiplier	1	0.33	3.0
Penetration factor for crack with dimensions	W 0.25 mm x L 9.4 cm	-	W 0.25 mm x L 4.3 cm

Figure 9 compares the average exposure to $PM_{2.5}$ and UFP of the "home-staying" adult. It shows that the results do not change substantially when these model assumptions are varied within reasonable bounds. Exceptions are the variation of the deposition rate and of the window airing duration. The deposition rate notably increases/decreases the exposure, however the effect is strongly reduced for filter classes F7 and higher. In contrast, the sensitivity towards the window airing duration increases for higher filter classes. Nevertheless, the conclusions from this simulation study will not be affected.

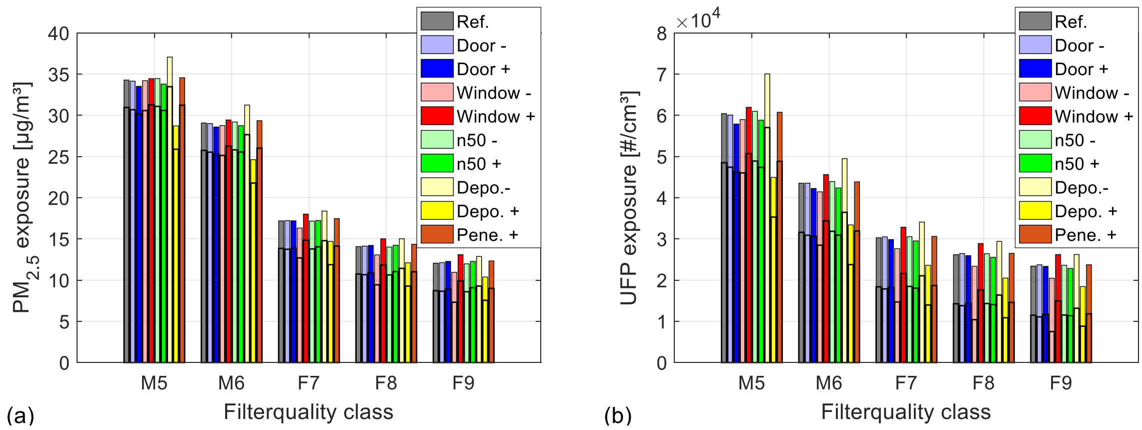


Figure 9: Average $PM_{2.5}$ (a) and UFP (b) exposure for a variation of the following model parameters: bedroom and child's room door opening, window airing duration in bedroom, child's room and living room / kitchen zone, building envelope airtightness, particle deposition rate and particle penetration through the building envelope. Refer to Table 1 for details. Exposure to outdoor originated PM is plotted with unfilled bars.

3.3 Variation cooking source strength and use of cooker hoods

Certainly, the amount and frequency of indoor generated particles can vary a lot, see e.g. (Abdullahi et al. 2013). Variations were performed to estimate how different generation rates might affect the results of the reference model. Therefore, the source strength was reduced to a third of the reference case and increased by a factor of three. That way, the cooking generated particle source strength is varied by roughly one order of magnitude between "low" and "high" case. Note that particular cooking activities and/or boundary conditions might result in even higher indoor concentrations. Additionally, the use of a recirculating and extracting cooker hood was simulated. The use of a recirculating hood was modelled by applying size-dependent reduction factors to the particle source strength of the lunch-time emissions (frying burger) and evening emissions (heating oil). The reduction factors were determined from a set of experiments performed at Lawrence Berkeley National Lab (Rojas et al. 2018) by comparing PM concentration in a test chamber with and without the use of a carbon filter installed in a recirculating cooker hood. Full capture of the plume was assured during these tests to determine the particle filtration efficiency (FE) of typical (carbon) filters of commercially available cooker hoods. To account for the fact that residential cooker hoods do not capture the entire cooking plume, a capture efficiency (CE) 0.7 was assumed for this simulation study for the recirculating and the extracting hood. It represents a rather optimistic scenario with the assumption that the cooking is performed at the rear burners were CE is generally higher, see e.g. (Rojas, Walker, and Singer 2017). The resulting source strength S_{ext} and S_{rec} for the extracting and recirculating cooker hood was calculated according to the following equations,

$$S_{ext} = S_0(1 - CE) \tag{1}$$

$$S_{rec} = S_0(1 - CE) + S_0 CE(1 - FE) \tag{2}$$

with S_0 representing the source strength of the cooking activity with no cooker hood in use. It was assumed that the cooker hoods are operated for 30 min during lunch and dinner preparation, starting with the modelled emission bursts. For the case with the extracting cooker hood, a make-up air opening (with no filter) producing a pressure drop of 10 Pa at a flow rate of 300 m³/h was activated in the kitchen zone during hood use.

Table 2: Particle source strength [µg] per cooking event modelled as burst source.

	Ref S_0	**Low** $S_{0\,min}$	**High** $S_{0\,max}$	**Recirc. hood** S_{rec}	**Extr. hood** S_{ext}
Breakfast	508	168	1525	508	508
Lunch	7991	2637	23974	6790	2397
Dinner	1438	475	4314	626	431

Figure 10 compares the average $PM_{2.5}$ and UFP exposure without with different cooktop ventilation strategies for different cooking source strength settings and different ambient concentration. One can see that for the "high" cook source scenario, the relative contribution from cooking becomes substantial or even dominant. For the case with reference cooking activity and low ambient concentration, the $PM_{2.5}$ exposure due to cooking is roughly equivalent to the exposure to outdoor originated PM. Not so for all the other cases, i.e. reference or high ambient concentration and low or reference cooking source strength. In those cases, the use of an extracting range hood, will not notably reduce PM exposure, in some cases it will even increase PM exposure. This is due to the fact that, large quantities of unfiltered make-up air are introduced during cooker hood operation.

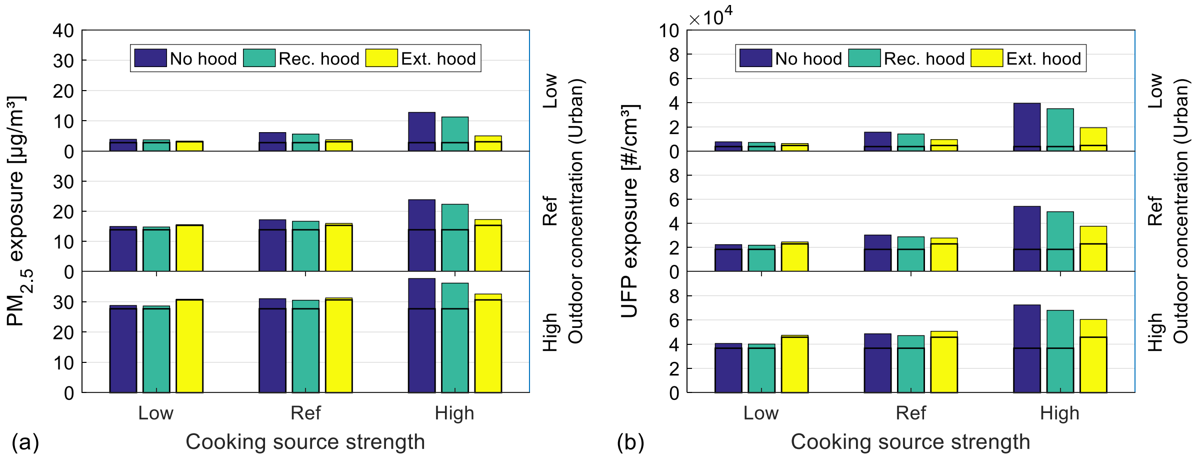


Figure 10: Average $PM_{2.5}$ (a) and UFP (b) exposure for different cooking source strength (see Table 2), different outdoor concentrations and different cooktop ventilation strategies for the reference case with a F7 filter. Exposure to outdoor originated PM is plotted with unfilled bars/horizontal lines.

4 CONCLUSIONS

This simulation study evaluates the benefits and the associated energy costs of using different filter qualities within the MVHR system focusing on boundary conditions encountered in highly energy efficient housing. Inherently, this study has a number of limitations. The most prominent being the limited ambient air quality data (constant values taken from older literature), fix occupancy and PM generation schedules and the neglect of phenomena like particle resuspension. Nevertheless, the results can be considered indicative for short-term exposure (e.g. 24 hours) with the assumed outdoor conditions. They provide useful insights into a reasonable choice of filter quality in energy efficient housing.

The results suggest that the use of F7 filters (or equivalent) provide good relation between reduction of exposure to outdoor-originated PM and electric energy consumption caused by their pressure drop. For locations with low ambient concentrations, the use of higher filter classes, e.g. F9 (or equivalent) do not seem to provide a substantial reduction of PM exposure. For these cases, indoor sources might dominated the total PM exposure, depending on occupant behaviour. For locations with high outdoor PM concentrations, the use of a high class filter like F9 is advisable, as it will further reduce the exposure to outdoor-originated PM compared to a F7 filter. This work will be extended to derive filter recommendations based on the new filter standard ISO 16890.

Comparing exposure terms from outdoor and indoor originated particles the results show that for locations with low outdoor PM pollution, cooking emissions could likely contribute a substantial or even dominant fraction of the total PM exposure, if no measures, like an effective cooker hood system, is used. Here the use of an extracting hood shows clear advantages over a recirculating system. However for cases with elevated ambient concentrations, like the “Ref.” and “High” case in this study, the use of extracting kitchen hoods (with unfiltered make-up air) will increase the total PM exposure if only few high-emission cooking activities are performed. Note that the health effect of outdoor and indoor originated particles might differ completely and this comparison should be interpreted with care.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

Abdullahi, Karimatu L., Juana Maria Delgado-Saborit, and Roy M. Harrison. 2013. “Emissions and Indoor Concentrations of Particulate Matter and Its Specific Chemical Components from Cooking: A Review.” *Atmospheric Environment* 71:260–94.

ASHRAE. 2005. “Airflow around Buildings.” *ASHRAE Fundamentals* 16.1 ff.

Buonanno, G., L. Morawska, and L. Stabile. 2009. “Particle Emission Factors during Cooking Activities.” *Atmospheric Environment* 43(20):3235–42.

camfil. n.d. “Comparison Chart, ASHRAE 52.2, 52.1, EN779, EN1822.” *2014*. Retrieved April 29, 2019 (https://www.camfil.at/FileArchive/Industries/Gas turbines and other power systems/Filter brochures/Filter_class_chart_ASHRAE_EN2012.pdf).

Chao, Christopher Y. H., M. P. Wan, and Eddie C. K. Cheng. 2003. “Penetration Coefficient and Deposition Rate as a Function of Particle Size in Non-Smoking Naturally Ventilated Residences.” *Atmospheric Environment* 37(30):4233–41.

DIN 4108-7. 2011. “Thermal Insulation and Energy Economy in Buildings – Part 7: Air Tightness of Buildings – Requirements, Recommendations and Examples for Planning and Performance.” 1–20.

Dols, W. Stuart and Brian J. Polidoro. 2015. *CONTAM User Guide and Program Documentation Version 3.2 - NIST Technical Note 1887*.

Géhin, Evelyne, Olivier Ramalho, and Séverine Kirchner. 2008. “Size Distribution and Emission Rate Measurement of Fine and Ultrafine Particle from Indoor Human Activities.” *Atmospheric Environment* 42(35):8341–52.

González, Luisa F., Aurélie Joubert, Yves Andrès, Myriam Liard, Christophe Renner, and Laurence Le Coq. 2016. “Filtration Performances of HVAC Filters for PM10 and Microbial Aerosols—Influence of Management in a Lab-Scale Air Handling Unit.” *Aerosol Science and Technology* 50(6):555–67.

Hanley, James T., David S. Ensor, Daryl D. Smith, and L. E. Sparks. 1994. “Fractional Aerosol Filtration Efficiency of In-Duct Ventilation Air Cleaners.” *Indoor Air* 4(3):167–78.

He, Congrong, Lidia Morawska, and Dale Gilbert. 2005. “Particle Deposition Rates in Residential Houses.” *Atmospheric Environment* 39(21):3891–99.

He, Congrong, Lidia Morawska, Jane Hitchins, and Dale Gilbert. 2004. “Contribution from Indoor Sources to Particle Number and Mass Concentrations in Residential Houses.” *Atmospheric Environment* 38(21):3405–15.

Howard-Reed, C., L. Wallace, and S. J. Emmerich. 2003. “Deposition Rates of Fine and Coarse Particles in Residential Buildings: Literature Review and Measurements in an Occupied Townhouse. NISTIR 7068.”

Hussein, Tareq, Thodoros Glytsos, Jakub Ondráček, Pavla Dohányosová, Vladimír Ždímal, Kaarle Hämeri, Mihalis Lazaridis, Jiří Smolík, and Markku Kulmala. 2006. “Particle Size Characterization and Emission Rates during Indoor Activities in a House.” *Atmospheric Environment* 40(23):4285–4307.

Kah, O., S. Peper, W. Ebel, B. Kaufmann, W. Feist, and B. Zeno. 2010. *Untersuchung Zum Außenluftwechsel Und Zur Luftqualität in Sanierten Wohnungen Mit Konventioneller Fensterlüftung Und Mit Kontrollierter Lüftung*. Darmstadt: Passivhaus Institut.

Kah, Oliver, Rainer Pfluger, and Wolfgang Feist. 2005. *Luftwechselraten in Bewohnten , Sehr Luftdichten Gebäuden Mit Kontrollierter Wohnungslüftung / Monitoring in Einem Passivhaus-Geschosswohnbau Luftwechselraten in Bewohnten , Sehr Luftdichten Gebäuden Mit Kontrollierter Wohnungslüftung / Monitoring in Ein*.

Lai, Alvin C. K. and William W. Nazaroff. 2000. “Modeling Indoor Particle Deposition from Turbulent Flow onto Smooth Surfaces.” *Journal of Aerosol Science* 31(4):463–76.

Lee, Byung Hee, Su Whan Yee, Dong-hwa Kang, Myoung Souk Yeo, and Kwang Woo. n.d. “Relationship between Indoor and Outdoor Particle Concentrations by Penetration Coefficient and Deposition Rate in Office Building.” (1).

Liu, De Ling and William W. Nazaroff. 2003. “Particle Penetration through Building Cracks.” *Aerosol Science and Technology* 37(7):565–73.

Long, Christopher M., Helen H. Suh, Paul J. Catalano, and Petros Koutrakis. 2001. “Using Time- and Size-Resolved Particulate Data to Quantify Indoor Penetration and Deposition Behavior.” *Environmental Science and Technology* 35(10):2089–99.

NIST. n.d. “CONTAM Particle Distribution Calculator.” Retrieved April 25, 2019 (https://www.nist.gov/node/1326541/software-tools/contam-particle-distribution-calculator).
Ploss, Martin and Tobias Hatt. 2016. “Modellvorhaben KliNaWo - Klimagerechter Nachhaltiger Wohnbau.” Pp. 8–59 in *economicum*.
Poon, Carmen, Lance Wallace, and Alvin C. K. Lai. 2016. “Experimental Study of Exposure to Cooking Emitted Particles under Single Zone and Two-Zone Environments.” *Building and Environment*.
Riley, William J., Thomas E. McKone, Alvin C. K. Lai, and William W. Nazaroff. 2002. “Indoor Particulate Matter of Outdoor Origin: Importance of Size-Dependent Removal Mechanisms.” *Environmental Science and Technology* 36(2):200–207.
Rojas, Gabriel, Woody Delp, and Brett C. Singer. 2018. “Testing Recirculating Cooker Hoods – Can Their Filter Reduce (Ultra) Fine Particle Loads during Cooking ?” Pp. 623–26 in *International Passivhaus Conference*, edited by W. Feist. Passive House Institute.
Rojas, Gabriel, Rainer Pfluger, and Wolfgang Feist. 2016. “Ventilation Concepts for Energy Efficient Housing in Central European Climate – A Simulation Study Comparing Indoor Air Quality , Mould Risk and Ventilation Losses.” in *Indoor Air 2016*. ISIAQ.
Rojas, Gabriel, Iain Walker, and Brett Singer. 2017. “Comparing Extracting and Recirculating Residential Kitchen Range Hoods for the Use in High Energy Efficient Housing.” Pp. 117–28 in *AIVC Proceedings*. AIVC.
Ruprecht, Jaenicke. 1993. “Tropospheric Aerosols.” Pp. 1–31 in *Aerosol-Cloud-Climate Interactions*, edited by P. Hobbs. Academci Press.
See, Siao Wei and Rajasekhar Balasubramanian. 2008. “Chemical Characteristics of Fine Particles Emitted from Different Gas Cooking Methods.” *Atmospheric Environment* 42(39):8852–62.
Shi, Bingbing. 2012. “Removal of Ultrafine Particles by Intermediate Air Filters in Ventilation Systems - Evaluation of Performance and Analysis of Applications Ventilation Systems.” Chalmers University of Technology, Göteborg, Sweden.
Shi, Bingbing, Lars E. Ekberg, and Sarka Langer. 2013. “Intermediate Air Filters for General Ventilation Applications: An Experimental Evaluation of Various Filtration Efficiency Expressions.” *Aerosol Science and Technology* 47(5):488–98.
Siegel, Jeffrey A. and William W. Nazaroff. 2003. “Predicting Particle Deposition on HVAC Heat Exchangers.” *Atmospheric Environment* 37(39–40):5587–96.
Sippola, Mark R. and William W. Nazaroff. 2003. “Modeling Particle Loss in Ventilation Ducts.” *Atmospheric Environment* 37(39–40):5597–5609.
Sjaastad, Ann Kristin, Kristin Svendsen, and Rikke Bramming Jorgensen. 2008. “Sub-Micrometer Particles: Their Level and How They Spread after Pan Frying of Beefsteak.” *Indoor and Built Environment* 17(3):230–36.
Stephens, B. and J. A. Siegel. 2012. “Penetration of Ambient Submicron Particles into Single-Family Residences and Associations with Building Characteristics.” *Indoor Air* 22(6):501–13.
Thatcher, Tracy L. and David W. Layton. 1995. “Deposition, Resuspension, and Penetration of Particles within a Residence.” *Atmospheric Environment* 29(13):1487–97.
Tian, Liwei, Guoqiang Zhang, Yaolin Lin, Jinghua Yu, Jin Zhou, and Quan Zhang. 2009. “Mathematical Model of Particle Penetration through Smooth/Rough Building Envelop Leakages.” *Building and Environment* 44(6):1144–49.
Torkmahalleh, M. A., I. Goldasteh, Y. Zhao, N. M. Udochu, A. Rossner, P. K. Hopke, and A. R. Ferro. 2012. “PM 2.5 and Ultrafine Particles Emitted during Heating of Commercial Cooking Oils.” *Indoor Air* 22(6):483–91.
Wallace, Lance. 2006. “Indoor Sources of Ultrafine and Accumulation Mode Particles: Size Distributions, Size-Resolved Concentrations, and Source Strengths.” *Aerosol Science and Technology* 40(5):348–60.
Wallace, Lance A., Steven J. Emmerich, and Cynthia Howard-Reed. 2004. “Source Strengths of Ultrafine and Fine Particles Due to Cooking with a Gas Stove.” *Environmental Science and Technology* 38(8):2304–11.
WHO. 2005. *WHO Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide*.