Modelling of domestic fine particles indoor exposure, its main sources and potential mitigation measures: the case of Beijing

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Abstract

This paper presents a case study with an aim to examine the indoor impact of fine particles with a maximum aerodynamic diameter of 2.5 microns (PM2.5) and evaluate its main sources of generation within one typical residential dwelling of Beijing's housing stock in order to define optimal mitigation measures. Based upon available data, through the validated multi-zone indoor air quality (IAQ) model the relationship between impact of indoor/outdoor factors and indoor mass concentration of PM2.5 was examined. As a referent dwelling, one of Beijing's housing stock representatives was selected. Its key parameters were combined and modelled in order to create the universal framework consisted of five baseline typical housing stock cases. The main modelling drive parameters were physical and mechanical dwelling performances: five envelope's permeability (p) values (10, 20, 30, 40 and 50 m³/m²/h @50Pa) and different types of ventilating, throughout the year (heating and non-heating period). The simulation results suggest that under present day conditions, average indoor concentrations of PM2.5 are appreciably higher than the outdoor annual average value of $102\mu gm^{-3}$ because of indoor sources. In the case of naturally ventilated dwellings during heating period, cooking represents the largest contributor, generating particulate matter at concentrations four times greater than annual average outdoor mass concentration of PM2.5. Modelling demonstrated that removal of PM2.5 generated by cooking activity depends on the type of ventilation and most important on its use pattern. Furthermore, modelling provided fundamental data for evaluating indoor pollutant reduction measures. Based on previous analysis, following mitigation measures are analysed: increased EF capacity and its period of use, kitchen isolation (by closing the door) from the rest of dwellings and change of occupant behaviour regarding smoking activity. Compared to the naturally ventilated dwelling in winter period, analysed measures could decrease average indoor PM2.5 mass concentrations by almost 50%. This kind of method was found to be suitable for questioning different measures of improvement and the way for this framework to be easily broadened to the bigger scale, at the urban level.

1. Introduction

Concentrations of ambient air pollution in China have changed considerably during the last decade reaching an extremely critical state. The World Health Organization (WHO) is concerned about the situation in China, where cities such as Beijing regularly experience dangerously high levels of outdoor air pollution. In 2012, a total of 2.8 million deaths were estimated to be caused by air pollution in the Western Pacific Region (WHO China). The size of pollutant particles is directly linked to their potential for causing health problems. Fine particles less than 2.5 micrometres in diameter (PM2.5) pose the greatest problems, because they can lodge deep in the lungs, and some may even enter the bloodstream. They are capable of penetrating deeply into human lungs and represent serious offenders as indoor pollution (Listorti, et al., 2001).

Considering indoor air quality (IAQ), concentrations of PM2.5 in houses are affected by the infiltration of outdoor particles, emissions from indoor sources and the removal from the internal air by deposition, filtration and exfiltration, though some re-suspension also occurs largely related to domestic activities (Gehin et al., 2008).

The primary sources of ambient or outdoor air pollution include natural dust particles blown by the wind, large combustion plants, industrial and motor vehicle emissions and household heating. The main sources of household or indoor pollution are cooking emissions, as well as second-hand smoke from tobacco products (WHO China).

Respiratory infections are transmitted by airborne particles, droplets or physical contact, which are extremely difficult to control, mostly due to implementation problems of necessary behavioural change in highly populated areas especially cities (Listorti, et al., 2001). Outdoor climate and weather conditions combined with occupant behaviour affect IAQ. Weather conditions influence whether building occupants keep windows open or closed and whether they operate air conditioners (AC) or heaters, all of which can impact IAQ.

The study was based on the application of CONTAM (Emmerich, 2001), a validated multi-zone IAQ model, to predict concentrations of $PM_{2.5}$ from both indoor and outdoor sources, in specific zones/rooms of one typical dwelling in Beijing. The objective was to examine indoor $PM_{2.5}$ mass concentration values and evaluate impact of its sources throughout the year. In order to create and examine potential mitigation scenarios, this paper examines how occupant behaviour affects the reduction of indoor pollutants.

2. Modelling of $PM_{2.5}$ indoor exposure-baseline scenario

With respect to the whole housing stock of Beijing and available data, one typical dwelling on the 2nd floor of one typical multi-apartment building (MAB), of a total of 75m² in area, was selected in order to model indoor fine particle mass concentration and investigate potential changes trough given scenario (Fig. 1). Regarding the apartment's physical, mechanical properties and the outdoor pollution impact, five typical case models was suggested (Fig. 2). Later, each of these five models varied by five levels of permeability creating the baseline framework of 25 cases.

The modelling was performed using CONTAMW software (version 3.1.), a multi-zone indoor air

quality and ventilation analysis computer program, in order to determine airflows, contaminant concentrations and personal exposure.
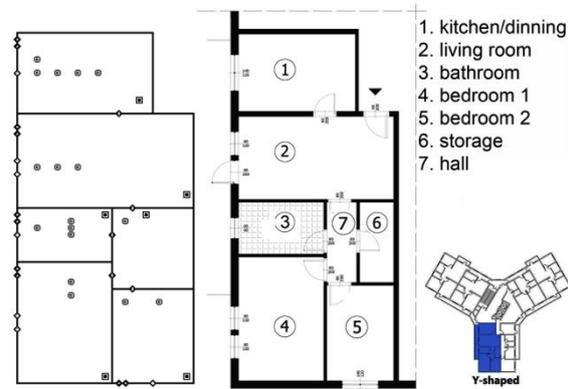

Fig. 1 – Typical multi-apartment building (MAB) dwelling unit

2.1 Modelling dwelling parameters

2.1.1. Physical parameters of dwelling

Air pollutants enter/exit buildings through open doors, open windows, cracks in structures and ventilation systems. Regarding that, cracks in structure (wall permeability) were the physical key input parameter, considered to potentially have a significant impact on the building performance and IAQ. Permeability represents the airflow through the fabric of a building, made at a steady high pressure difference, normally 50Pa, when the effects of wind and buoyancy forces are effectively eliminated (Etheridge, 2012). Since there is no reliable data detailing building permeability in Beijing, wall permeability was varied by increments of 10 from 10 to 50m³/(h.m²)@50Pa in order to capture a range of building air-tightness. Internal walls were considered impermeable.

2.1.2. Mechanical parameters of dwelling

Over the key inputs selection in terms of the mechanical parameters of the dwelling, the time of year played the most important role, regarding district heating use. Since the majority of residents in Beijing use a natural gas district heating system at present, modelling included only this type of heating. However, the dwelling was modelled with two scenarios during the heating period (district heating) and three scenarios during non-heating period. The heating period implied two cases: 1)

only natural ventilated dwellings (NV) and 2) natural ventilated dwellings with extract fans use (NV+EF). The non-heating period involved the same cases as the heating period and one more case which involves AC use (EF+AC) (Fig. 2). This approach was selected to determine the key building features that affect dwelling indoor environment.
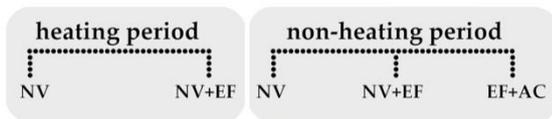

Fig. 2 – Modelling of indoor PM$_{2.5}$ exposure – baseline scenario scheme

2.2. Modelling input data

2.2.1. Ambient PM$_{2.5}$ mass concentration, weather and wind data

Since the ambient PM$_{2.5}$ value in Beijing is stochastic variable with high value oscillations during the day and whole year (Fig. 3), as a modelling input the average annual value was used (U.S. Department of State, the Mission China air quality monitoring program, Beijing).
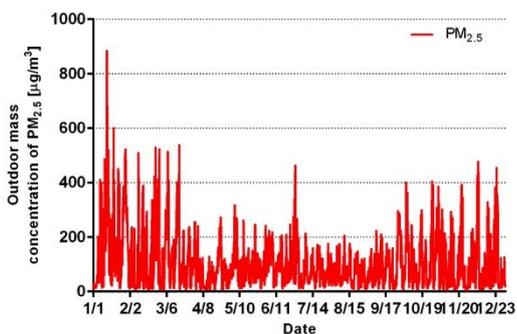

Fig. 3 – Ambient mass concentration data of PM$_{2.5}$ during the year of 2013. in Beijing.

Thus, as an input ambient mass concentration of PM$_{2.5}$, the annual average constant value of 102µgm^{-3} was used. This mean value is nearly three times higher than the value (35µgm^{-3}) of the interim target-1 standard for annual mean PM$_{2.5}$ recommended by the WHO (Zhang R. Et al., 2013). However, in the short periods the level of PM$_{2.5}$ in Beijing reaches the value even 8 times greater than the average (fig. 3).

Modelling was performed using transient weather and wind data for Beijing, taken from the EnergyPlus energy simulation software data (U.S. Department of Energy).

2.2.2. Cooking PM$_{2.5}$ emission rate

Previous studies in the United States have indicated that the cooking of food is one of the largest sources of fine organic aerosols in urban areas, especially in major cities where millions of people must be fed several times per day. It was established that the composition of particles emitted from the cooking of food is strongly dependent on cooking procedure, including the materials used, cooking temperature, and cooking time (Wang, et al., 2009). However, only a few studies have examined the impact of cooking on ambient air quality (Huang et al., 2006; Zhao et al., 2007). A recent study carried out by Berkeley National Laboratory, USA provided a database of pollutant emission rates associated with cooking. The study collected cooking emission rate data for 541 cooking events from 13 studies and, by analyzing and comparing them, found that the PM$_{2.5}$ cooking emission rates resulted in distinctly different distributions depending on several cooking parameters: food type, type of oil, type of cooking and type of appliance used (Hu, 2014). Considering that the goal of modelling was a general assessment of PM$_{2.5}$ emissions during cooking episodes, for the generation rate the average value of 2.2 mg min^{-1} was taken from the Berkeley National Laboratory study, as the average value of four high impact cooking conditions (Hu, 2014). Of all the above mentioned parameters which condition the amount of emitted particles, in order to model the mitigation scenario, only the duration of cooking activities was taken into consideration. As a reference, frequency of cooking and cooking time study (Hokoi, 2013) were used. Approximately 100 - 200 residential units in two cities in China were surveyed. According to this study, the cooking time for breakfast was established to be 0–10 min during weekdays and 10–20 min during weekends. The cooking time for lunch or dinner formed two peaks at 20–30 min or 50–60 min. Based on this study, the cooking schedule applied in modelling is shown in table 1.

Table 1 – Applied cooking schedule

day	breakfast	lunch	dinner
weekday	07:20-07:30	12:00-12:40	18:00-18:30
weekend	09:00-09:20	12:00-13:00	18:00-18:40

2.2.3. Smoking PM$_{2.5}$ emission rate and schedules

Internally dominant sources of PM$_{2.5}$ included environmental tobacco smoke (ETS). Tobacco smoke consists of solid particles and gases. More than 4,000 different chemicals have been identified in tobacco smoke. The number of these chemicals that are known to cause cancer in animals, humans, or both is reported to be in the range from 30 to 60 (Canadian Centre for Occupational Health and Safety). Based on the absence of suitable data, all models are assumed to be smoking dwellings. Modelling of smoking emissions assumed the presence of one smoker per unit. Smoking was practiced only in the kitchen and living room. The number of smoked cigarettes in each of the smoking permitted rooms ranged from 0 to 10. Modelling assumed 7 cigarettes on weekdays and 10 at weekends in the living room, 3 cigarettes on weekdays and smoke-free weekend in the kitchen, giving 0.99 mg min^{-1} emissions of PM$_{2.5}$ at 5 min per cigarette (Shrubsole, 2012).

2.2.4. PM$_{2.5}$ deposition rate and air exchange rate

In indoor environments, particle deposition rate and air exchange rate are the two main components of the overall particle removal rate from the air (He, et al., 2005). For the mean PM$_{2.5}$ deposition rate value of 0.39 1 h^{-1} was used, guided by the Particle Total Exposure Assessment Methodology (PTEAM) study carried out by United States Environmental Protection Agency (US EPA) and National Exposure Research Laboratory (NERL) (Clayton, 1992).

Since it is noted that windows are usually closed in the winter when central heating is used and in the summer when air conditioning is on, the air exchange rate maintained at 1.0 1 h-1 during both summer and winter, in accordance with JCJ134-2001: design standards for energy efficiency of residential buildings in hot summer and cold winter zones (Wang, et al., 2004).

2.2.5. Occupant behavior - airflow path and equipment schedules

CONTAM software entails an airflow path as a building component through which air can move between two adjacent zones. These components can be cracks in the building envelope (wall permeability), windows, open doorways, exhaust fans, etc. Weather conditions are a key factor influencing window opening behaviour and also subject to high uncertainty (Rune, A. et al. 2009). For the Beijing dwelling, we assumed a seasonal window opening schedule as presented in table 2.

Table 2 – Window opening schedule

room type	summer	winter
kitchen	100% open during cooking activities, otherwise 10%	only 10% open during cooking activities
living room	from 9 to 21h 10% open	3 times a day for 15 min 100% open
bathroom	50% open during shower/bath activities, otherwise 10%	50% open for 15 min after shower/bath activities
bedrooms	always open 10%	100% open for 15 min 2 times a day

In the absence of suitable data, the assumed schedule for the doorway airflow pats was: kitchen door was closed during cooking activities; in the living room the door was open during day activities, from 8 to 23h; the bathroom door was closed during shower/bath activities and bedroom doors were closed during sleeping activities only.

Regarding equipment that influences IAQ, in some modelling cases intermittent extract fans (EF) and constant air conditioners (AC) were applied. Application of EF implied installation of one with a capacity value of 300 m³h^{-1} in the kitchen and 80 m³h^{-1} in the bathroom in accordance with GB50096-1999: Residence design standard (Wang, et al.,

2004). Cases with EF use practiced ventilation only during cooking activities.

AC was modelled only in one case of the non-heating period where the optimal indoor temperature was maintained at 26-28°C in summer and 16-18°C in winter, according to JCJ134-2001: design standards for energy efficiency of residential buildings in hot summer and cold winter zones (Wang, et al., 2004).

3. Modelling results

The simulation results suggest that under present day conditions, average indoor concentrations of $PM_{2.5}$ are appreciably higher than the outdoor annual average value of $102\mu gm^{-3}$ because of indoor sources. Figure 4 presents calculated average indoor $PM_{2.5}$ mass concentration dependence on wall permeability for the analysed 5 baseline cases. The highest concentration (up to 400 μgm^{-3}) is obtained for case a (for naturally ventilated dwelling in winter heating period). For case b (same dwelling but with extra fan ventilation in winter heating period) a much lower indoor concentration (up to 250 μgm^{-3}) is obtained. In summer (non-heating) period (case c, d and e) average indoor $PM_{2.5}$ mass concentration is much lower compared with analogue cases in winter, due to much longer periods of natural ventilation of the dwelling by opened windows. In all five cases average indoor $PM_{2.5}$ mass concentration decreases when the façade permeability value is increased. However, a higher façade permeability value will result in lower energy efficiency of the building due to increased heat loss through the envelope.

The main contribution to the increased indoor $PM_{2.5}$ mass concentration is from cooking-related sources as indicated in Fig. 5 where daily kitchen indoor mass concentration of $PM_{2.5}$ for naturally a ventilated apartment during heating period is presented. There are high peaks in kitchen mass concentration of $PM_{2.5}$ after cooking activities.
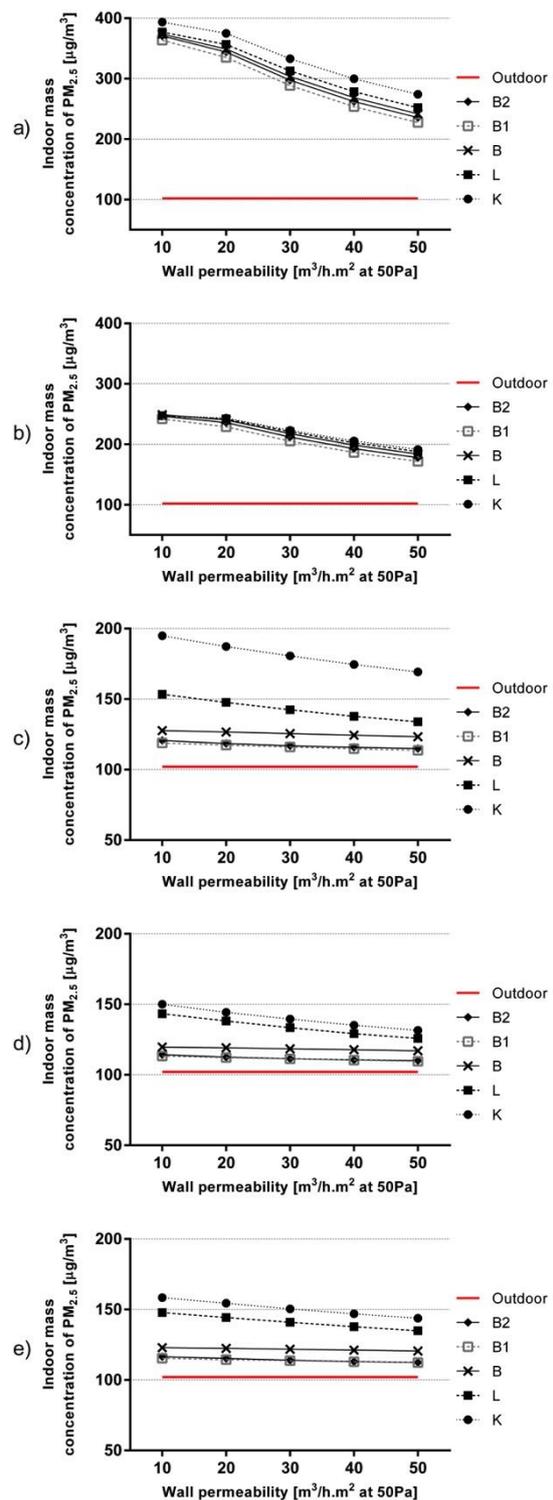

Fig. 4 – Typical dwelling unit average indoor mass concentration of PM2.5 for the range of wall permeability values for: a) naturally ventilated during heating period; b) naturally ventilated during heating period, with EF use; c) naturally ventilated during non-heating period; d) naturally ventilated during non-heating period, with EF use; e) during non-heating period with EF and AC use.
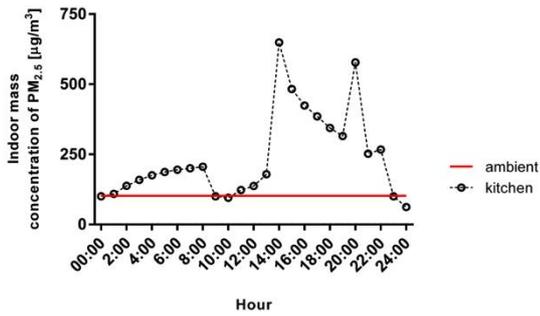
Fig. 5 - Daily kitchen indoor mass concentration of $PM_{2.5}$ for naturally ventilated apartment during heating period

Particles are able to spread quickly, thus the kitchen and living room are most endangered, with the average $PM_{2.5}$ mass concentration several times bigger that the ambient average value. During the heating period, the naturally ventilated dwelling in comparison with the same one with EF use during cooking activities has up to 44% higher indoor emissions (Fig. 4 a compared to 4 b).

The contribution from EF use can be noticed in the cases during the non-heating period as well, but more frequent and longer natural ventilation effects indoor emissions to be reduced up to 33% (Fig. 4 c compared to 4 d).

The non-heated dwelling with EF and AC use has 5.3% higher emissions due to the absence of natural ventilation (Fig. 4 e compare to 4 d).

4. Mitigation scenario

$PM_{2.5}$ exposures in homes can be mitigated through various approaches including kitchen exhaust ventilation, filtration, pollution source reduction and designing ventilation systems to reduce the entry of $PM_{2.5}$ from outdoors (Hu, 2014).

Based on previous analysis, the following mitigation measures are analysed: increased EF capacity and its period of use, kitchen isolation (by closing the door) from the rest of dwellings and change of occupant behaviour (smoking habit).

4.1 Discussion

In the previous discussion, the importance of EF use during cooking-related activities was emphasized. Results of the simulation of the extract fan with higher capacity value (500 m³h⁻¹)

installed in the kitchen, (in accordance with GB50096-1999: Residence design standard) instead of EF with a capacity value of 300 m³h⁻¹ are presented on Fig. 6. Figure presents kitchen average indoor mass concentration for the cases b, d and e from Fig. 4 (with the wall permeability value of 10 m³/(h.m²)@50Pa only) for two EF capacity values. The results suggest that this mitigation measure is most effective in winter while in summer it has lower benefits.
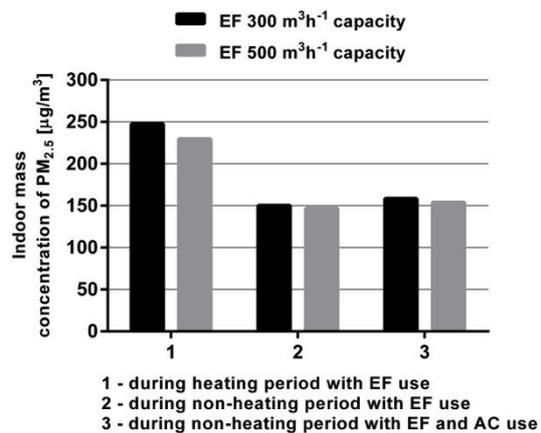

Fig. 6 – The kitchen average indoor mass concentration of $PM_{2.5}$ with the use of EF with different capacity for three typical cases.

Figure 7 presents simulation results for the proposed mitigation measures in the winter period when indoor $PM_{2.5}$ concentrations are expected to be the highest (Fig 7a = Fig 4b). Change of occupant behaviour regarding smoking activity (no smoking indoors) could decrease average indoor $PM_{2.5}$ concentrations by ~9% (Fig. 7b compared to 7a). Keeping the kitchen door closed as much as possible (Fig. 7c) compared to the case when it is closed only during cooking (Fig. 7a) will increase average $PM_{2.5}$ concentrations in the kitchen but decrease in all other rooms. Installation of EF in the kitchen with increased capacity, 500m³h⁻¹ (Fig. 7d) compared with lower EF capacity, 300m³h⁻¹ (Fig. 7c) would further decrease average $PM_{2.5}$ concentrations in the kitchen and in all other rooms. In case of implementation all analysed mitigation measures, average indoor $PM_{2.5}$ concentrations in the winter period (Fig. 7e) would be ~20% lower than in the baseline case (Fig. 7a). Compared to the naturally ventilated dwelling in winter period, without EF use (Fig. 4a), analysed
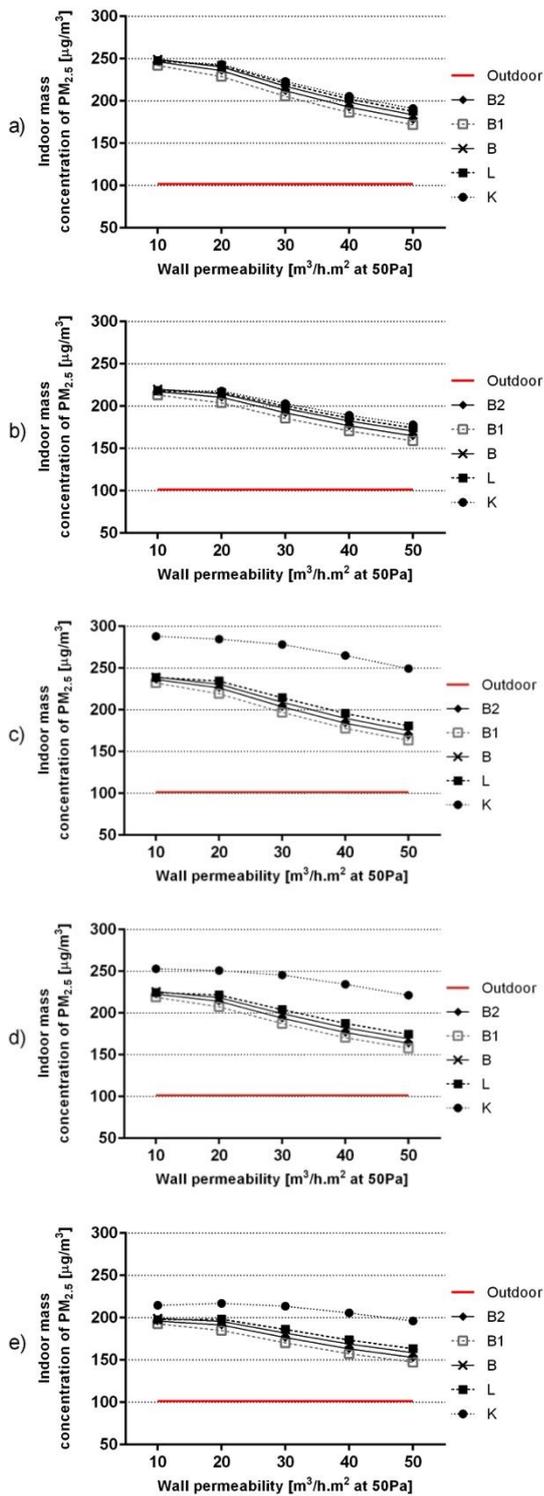
measures (Fig. 7e) could decrease average indoor PM$_{2.5}$ concentrations in almost 50%. Further decreases in indoor PM$_{2.5}$ concentrations could be obtained only by implementing more expensive measures like installation of special cooking filters.

4. Conclusion

Considering the mechanical and physical properties, the IAQ modelling of the referent dwelling units in Beijing was performed. High indoor exposure to PM$_{2.5}$ has been found, especially the one generated by cooking activity. Dwellings with the highest peak results are those with no mechanical ventilation, with the average indoor level of PM$_{2.5}$ up to four times greater than the already very high annual average outdoor concentrations. Mitigation scenario simulation demonstrated that generation of PM$_{2.5}$ greatly depends on EF use during cooking-related activities, its capacity, kitchen isolation (by closing the door) from the rest of dwellings and change of occupant behaviour (smoking habit). This resulted in a PM$_{2.5}$ reduction of up to 50%. Implementation of more expensive measures like improved capture of cooking emissions above the stove by fume extraction and filtration would contribute substantially to improvements in both indoor and outdoor air quality, and hence a reduction in human exposure.

5. Acknowledgement

Fig. 7 – Impact of mitigation measures on average indoor PM$_{2.5}$ mass concentration of naturally ventilated dwelling during heating period for the range of wall permeability values: a) with EF (300m^{3}h^{-1}) use; b) with EF (300m^{3}h^{-1}) use and without tobacco emission sources; c) with EF (300m^{3}h^{-1}) use and closed kitchen door; d) with EF (500m^{3}h^{-1}) use; e) with EF (500m^{3}h^{-1}) use, without tobacco emission sources and with closed kitchen door.

5. Nomenclature

Symbols

$PM_{2.5}$	fine particles less than 2.5 micrometres in diameter ($\mu g/m^3$)
p	wall permeability ($m^3/m^2/h$ @ 50Pa)

Subscripts/Superscripts

AC	air conditioners
EF	extract fan
ETS	environmental tobacco smoke
IAQ	Indoor air quality
MAB	multi apartment building
NV	natural ventilation

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