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Particles in the Indoor Environment

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1. Introduction

As a result of a change in living and work habits, we now stay in industrial countries every day more than 90% of the time inside buildings. Against this backdrop findings about the exposure of users are relevant. Given their heterogeneity, very complex exposure patterns exist in the indoor environment in respect of which not only input from the outdoor air but also important sources inside the rooms themselves have to be taken into account. At any rate, different indoor environments have to be identified (e.g. living, bed, handicraft, leisure and cellar rooms, working rooms and workplaces in buildings, public buildings, restaurants and inns, community facilities such as schools and kindergartens as well as spaces in motor vehicles and other public transportation systems). Furthermore, it has been shown that the amount of airborne particle content in indoor environments can be highly variable in terms of space but also in terms of time. Apart from the conditions prevailing in the outdoor air close to the indoor environment (e.g. location close to a heavily trafficked street or in a rural region) and the current climatic conditions, the structural conditions of the building and the ventilation conditions are important. Furthermore, activities in indoor environments, such as the deposition and resuspension of house dust, cooking and cleaning activities or smoking can make a considerable contribution to the respective pollution situation.

Particulates (particulate matter, PM) which are dispersedly distributed in the air form colloidal systems with the gases which are also referred to as aerosols. Overall, the composition of aerosols strongly depend on the specific sources. The particles of the fine fraction develop primarily through transformation processes from gases or within the framework of combustion processes. They are typically composed of nitrates, sulphates, ammonium, elementary carbon, a large number of organic compounds and trace elements. By contrast, the particles in the coarse fraction develop largely mechanically following the disintegration of larger solid particles and consist typically of whirled up dust from industrial processes and biological material such as pollen and bacteria and their fragments.

PM in indoor environments consist of very different particles which are considerably varying in terms of size, form and chemical composition. Whereas the larger particles determine primarily the mass of the environmental aerosol, the particle number concentration (PNC) and the particle surface are dominated almost exclusively by the ultra fine particles (<100 nm).

Concerning the measurement of PM in air, different sampling conventions have established themselves, often using the aerodynamic diameter of the particles. In order to better reflect the human respiratory characteristics, conventions such as PM_{10} (Particulate Matter) or $PM_{2.5}$ were introduced by the US Environmental Protection Agency and European authorities. $PM_{2.5}$ is, for instance, the particle fraction which passes through a size-selective air inlet which has a separation efficiency of 50% for an aerodynamic diameter of 2.5 µm. Depending on the specific context, other definitions may be applied, for example in indoor working environments.

2. Behaviour, transport, and fate of particles in the indoor environment

The transport and fate of particles in indoor environments are fundamentally influenced by a series of physical and chemical processes (Fig. 1). This can lead to considerable changes in terms of their chemical composition, their physical characteristics, their distribution patterns and finally the measurable contents (Thatcher et al., 2001; Morawska & Salthammer, 2003; Nazaroff, 2004).

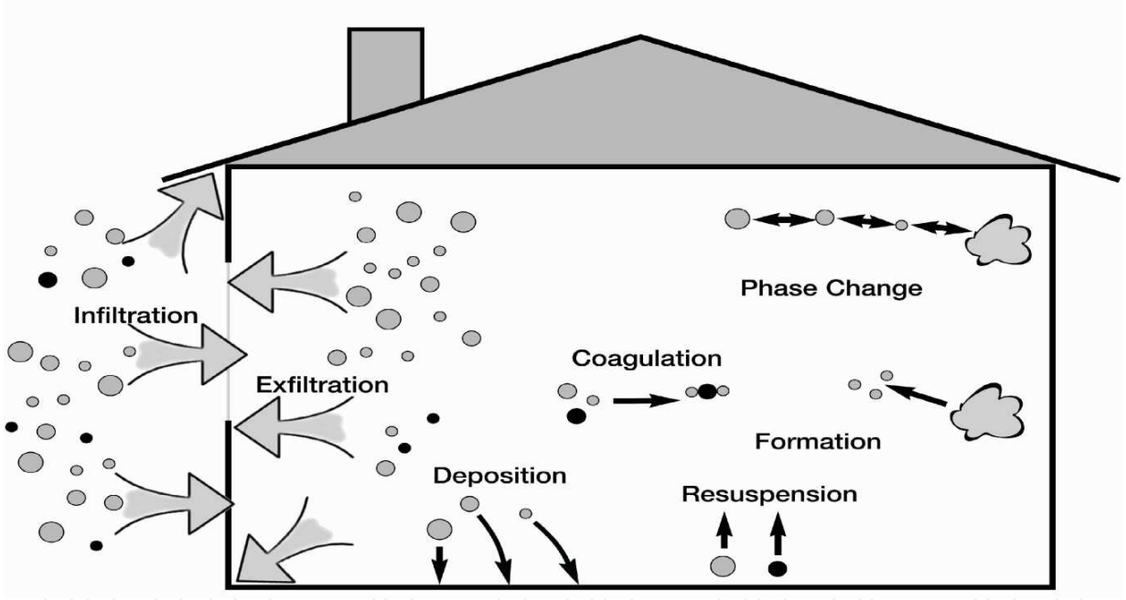

Fig. 1. Transport and transformation processes with impact on the indoor concentration of particulate matter (modified from Thatcher et al., 2001)

2.1 Infiltration/ penetration

The dimensionless penetration factor (P) is defined as the share of the particle fraction with a specific diameter which reaches the indoor environment through the inflow of outdoor air. In the scientific literature there are results of different studies which are based on the observation of the indoor to outdoor ratio of the particles, manipulations of the external building envelope, experimental simulations in the laboratory or mathematical modelling (e.g. Long et al., 2000; Vette et al., 2001; Riley et al., 2002; Riley et al., 2002; Liu & Nazaroff, 2003; Chen & Zhao, 2011). The results show that for different types of buildings and gap /

crack diameters and geometry, the largest penetration factor seems to exist for the particles with diameter between approximately >0.05 and < 1 µm (see Fig. 2).

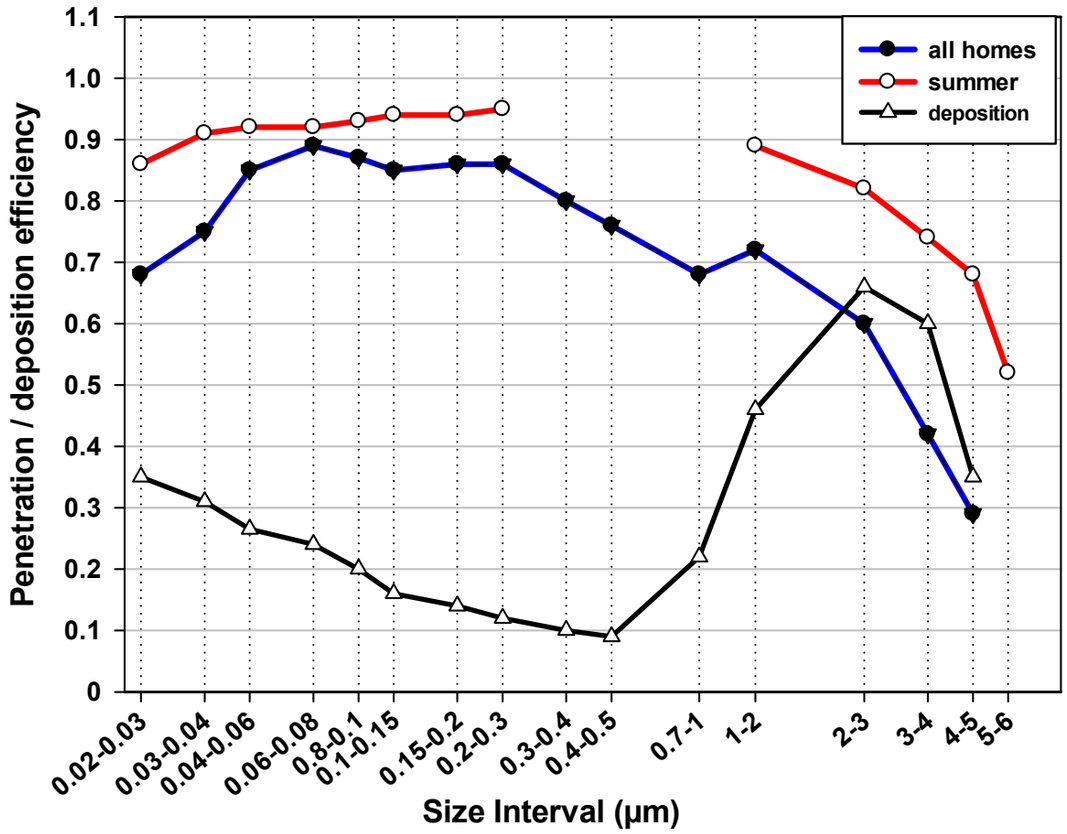

Fig. 2. Penetration efficiencies (P) and deposition rates (k) (all homes nightly averaged data from n=98-106 and in summer from n=8) (modified from Long et al., 2001)

2.2 Deposition

The deposition of particles on surfaces is based on different physical mechanisms such as gravitation and diffusion. Apart from the deposition speed, this process is described by the so-called deposition rate (k) (example, Fig. 2). This process is strongly dependent on the particle diameter and reaches a minimum for particles with an aerodynamic diameter of approximately 0.4 µm. However, there is a considerable variation range (Morawska & Salthammer, 2003; Miguel et al., 2005; Hussein et al., 2009). The particle deposition, in particular of coarse particles, increases with a rising draught in the room and an increasing room area and also varies depending on the degree of interior decoration.

2.3 Resuspension

Particles deposited on the surfaces of the room can become resuspended in the indoor air in particular through activities in the indoor environment (Thatcher & Layton, 1995; Hussein et al., 2006). Hu et al. (2005) state that essentially three parameters like mechanical vibration, aerodynamic as well as electrostatic forces can achieve a stronger effect than gravitation and

hence influence the resuspension of particles. In different field studies it was shown that activities in the indoor environment (e.g. running, playing kids) resulted in a significant increase in PM contents, whereby essentially coarse particles were whirled up (Thatcher & Layton, 1995; Long et al., 2000; Miguel et al., 2005) (Fig. 3). Moreover it could be shown that the resuspension in rooms with wall to wall carpet was significantly higher compared to rooms with a smooth flooring (Long et al., 2000).

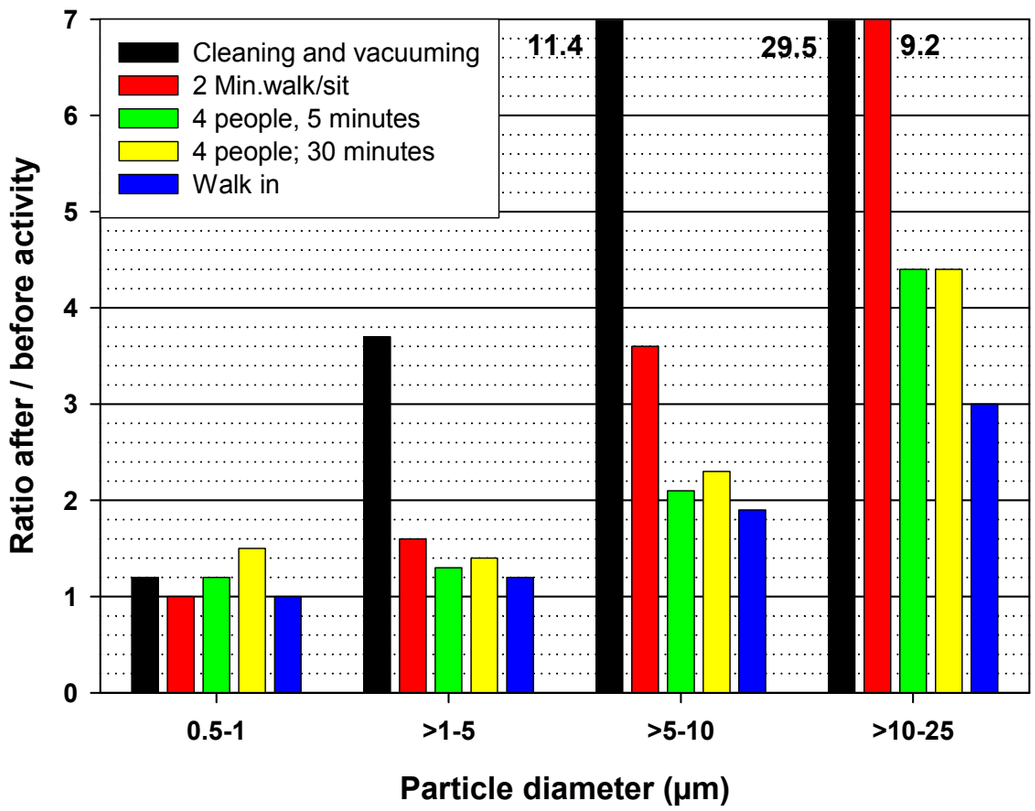

Fig. 3. The ratio of the suspended particle concentration after a resuspension activity to the indoor concentration before that activity, by particle size (modified from Thatcher & Layton, 1995)

2.4 Particle formation

Within the framework of chemical processes in the indoor environment particles can be newly formed or there can be a growth in particle size. The coagulation of particles in the indoor environment is based on the fact that e.g. depending on the particle number they come together with a certain probability and then tend to agglomerate. This process is, for instance, relevant for ultra fine particles in indoor environments, since the latter exist e.g. in high number concentrations when for example burning candles. They then agglomerate over time; this can be observed through a shift in the peak value of particle distribution (Dennekamp et al., 2001). The phenomenon of phase transition, too, describes an "ageing process" during which a growth of the particles is observed through the adsorption of organic substances or water.

3. Sources of particles indoors

3.1 Burning processes

Tobacco smoking constitutes an essential particle source in indoor environments which results in an increase in the particle mass as well as the ultrafine particles. In the Harvard Six City Study, for instance, the annual mean values in smoker households were higher by approximately factor 3 compared to non smoker households (Neas et al., 1994). Fig. 4 shows the increase in indoor pollution depending on the number of cigarettes smoked. In the same way the particle number increases considerably during cigarette smoking, partly to values up to 213,000 particles/cm³ (He et al., 2004; Afshari et al., 2005; Hussein et al., 2006).

When burning candles or oil lamps in indoor environments, an increase in ultrafine particles was likewise observed (Fine et al., 1999; Hussein et al., 2006; Wallace & Ott, 2011). This involved significantly higher concentrations when extinguishing candles compared to the burning itself (Hussein et al., 2006). During the burning of incense sticks it is also possible to detect high particle contents, in particular in the range from 0.06 to 2.5 µm, in indoor air (Chao et al., 1998; Jetter et al., 2002).

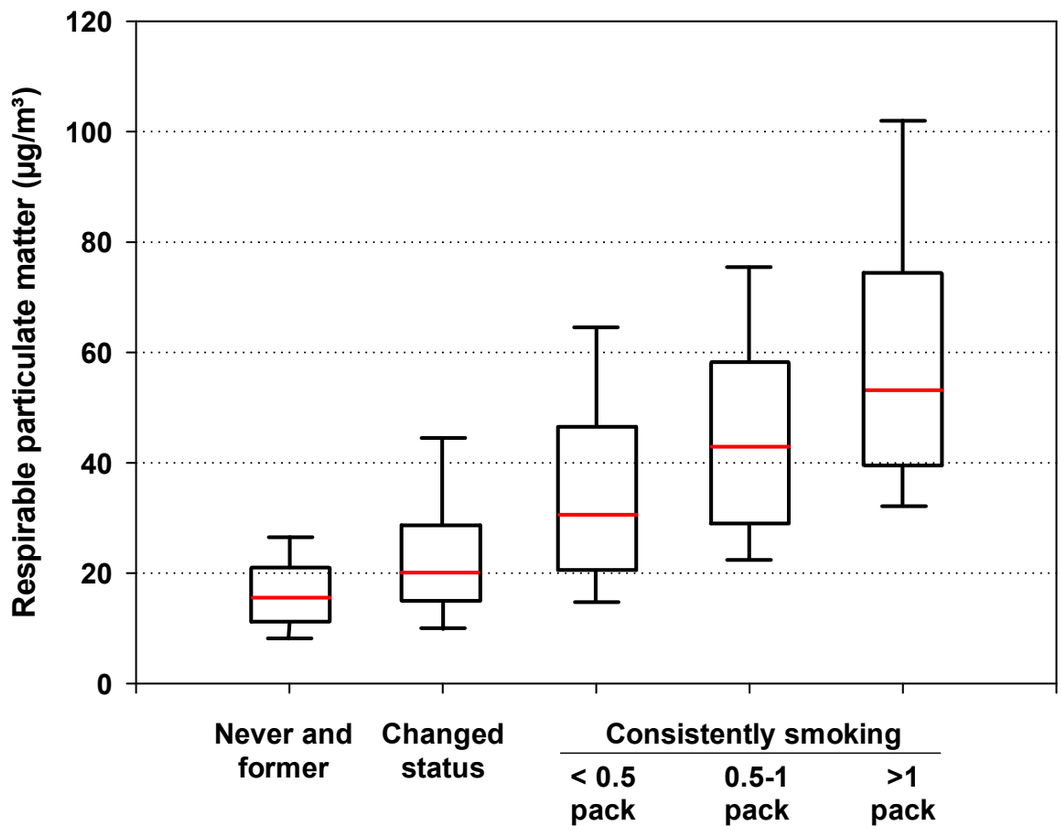

Fig. 4. Distribution percentiles for the annual average concentration of indoor particulate matter by household smoking status and the estimated number of cigarette packs smoked in the home (modified from Neas et al., 1994)

3.2 Cooking activities

During cooking, too, fine and ultrafine particles are released. Different working groups were able to detect very high peak pollutions during cooking with electric stoves and in particular gas stoves of 100,000 to 560,000 particles /cm³ (Morawska et al., 2003; Dennekamp et al., 2001; He et al., 2004; Afshari et al., 2005; Ogulei et al., 2006; Hussein et al., 2006). The large concentration range is attributable to the different cooking activities (eg baking, roasting, frying, toasting), the use of energy, the respective cooking goods, the ventilation conditions and the room geometry. Dennekamp et al. (2001) describe PNCs of up to 110,000 or 150,000 particles/cm³ when using four electric or gas rings. Peak values of up to 590,000 ultra fine particles/cm³ were reached at the frying of bacon on a gas stove. After a short period of time the particles grew up in the indoor air and a displacement towards larger diameters. (Abt et al., 2000; Dennekamp et al., 2001; Hussein et al., 2006). After the end of the cooking activity the concentration rapidly decreases (Fig. 5). Referred to the particle mass, these activities likewise constitute a certain source. In the American PTEAM Study it was determined by means of a regression model that cooking increased the basic load of PM_{10} in the indoor environment by approximately 12 - 26 µg/m³ ($PM_{2.5}$: approximately 13 µg/m³) (Wallace et al., 2003). Extremely high pollutions are to be expected when cooking on open fireplaces as, for instance, in third world countries (e.g. Naeher et al., 2000).

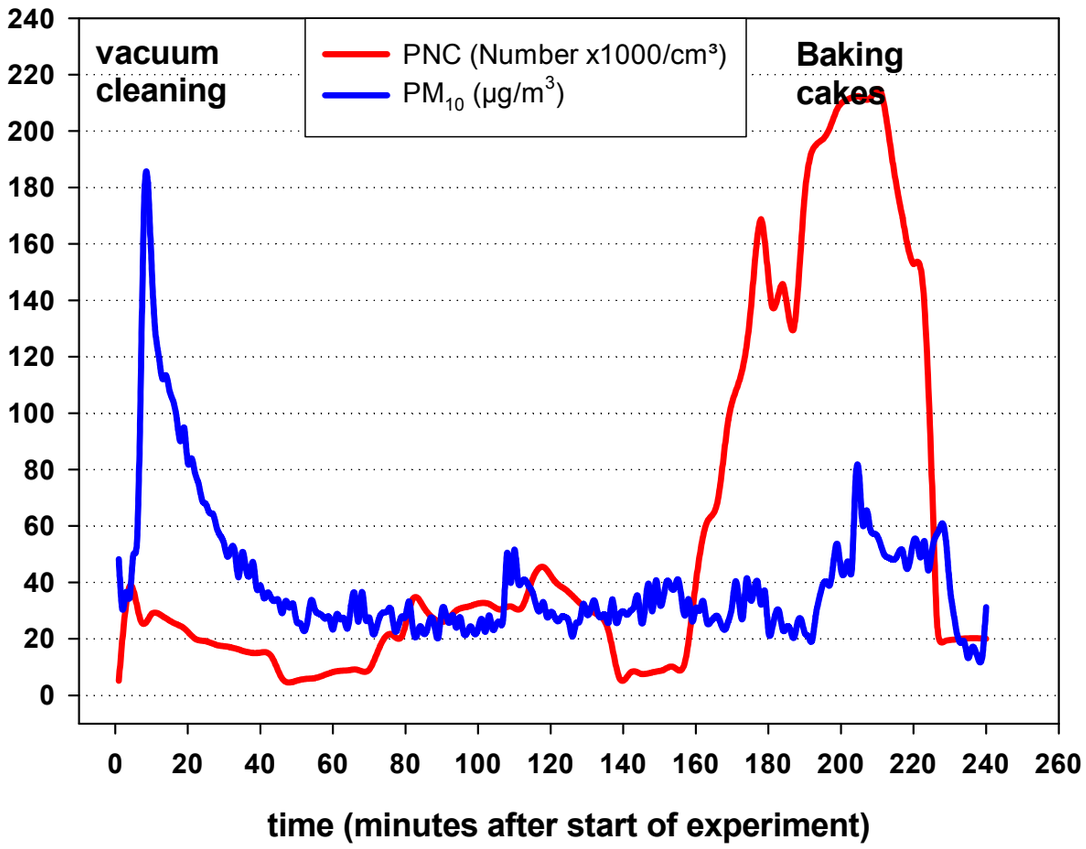

Fig. 5. Particle number concentration (PNC) and PM_{10} in the kitchen baking with an electric oven or vacuuming

3.3 Cleaning activities

During cleaning and in particular vacuum cleaning, an increase in coarse particles and hence in particular the particle mass is observed in indoor air (Abt et al., 2000). See also figure 5. In two US studies the contribution of cleaning activities to the $PM_{2.5}$ indoor pollution was estimated at 23-32 µg/m³ (Long et al., 2000; Ferro et al., 2004). Afshari et al. (2004) describe, by contrast, merely an insignificant minor increase for ultrafine particles.

Long et al. (2000) investigated the influence of the use of commercial cleaning agents on a pine oil basis on the exposure in a living room. During the activities the PNCs rose from initially 2,000 particles/cm³ to a maximum of 190,000 particles/cm³ and the $PM_{2.5}$ contents increased from 5 to 38 µg/m³. This phenomenon was explained by referring to the new particle formation and / or particle growth through oxidative processes in the indoor environment. Other working groups, too, were able to detect in test chambers in the presence of ozone and the simultaneous application of terpene-containing cleaning agents a significant increase in particle number concentrations and the particle mass (Sarwar et al., 2004; Singer et al., 2006; Destaillats et al., 2006).

3.4 Secondary organic aerosols (SOA)

Following chemical reactions of the gas and aerosol phase, so-called secondary organic aerosols (SOAs) are newly formed in indoor environments (Weschler et al. 2006). The formation of SOAs through the reaction of ozone with terpenes and other unsaturated organic compounds was demonstrated and confirmed in many test chamber experiments (e.g. Wainman et al., 2000; Fan et al., 2003; Sarwar et al., 2004; Liu et al., 2004b; Vartiainen et al., 2006; Destaillats et al., 2006; Aoki & Tanabe, 2007). In two office rooms, for instance, there was an increase in the particle mass and the PNC (Fig. 6) with realistic ozone and limonene contents (Weschler et al., 2003). Ozone was in these experiments the limiting factor in the formation of SOAs.

3.5 Outdoor air as a source

The contribution of outdoor air to the amount of PM concentration in indoor air depends, in addition to the particle fraction, in particular on the ventilation behaviour of the room user, the tightness of the building envelope, the dust deposition rates indoors, the resuspension effects in the room and the coagulation behaviour of the particles. The ventilation behaviour itself is naturally dependent to a large extent on the season and the meteorology (Nazaroff, 2004). Through the windows and doors but also through leakages of the building envelope there is an exchange of air between the indoor air and the outdoor air. This results in a highly variable share of outdoor air in the amount of particle concentration in the indoor air. Other factors such as the building geometry (e.g. floor height) and location (e.g. close to a heavily trafficked road) can have a significant influence on the exposure situation. Cyrys et al. (2004) report in respect of the examination of two model rooms without an indoor activity that 75% of the indoor air contents of $PM_{2.5}$ but only 43% of the PNCs can be explained by corresponding outdoor air contents. During the parallel measurements of particle distribution in rooms without indoor source and outdoor air there were in the event of closed windows and doors in the indoor environments significantly lower contents in the particle size classes than outdoors (Franck et al., 2003). Fig. 7 shows results which represent the ventilation-related influencing of PM from outside to residential indoor environments (Riley et al., 2002).

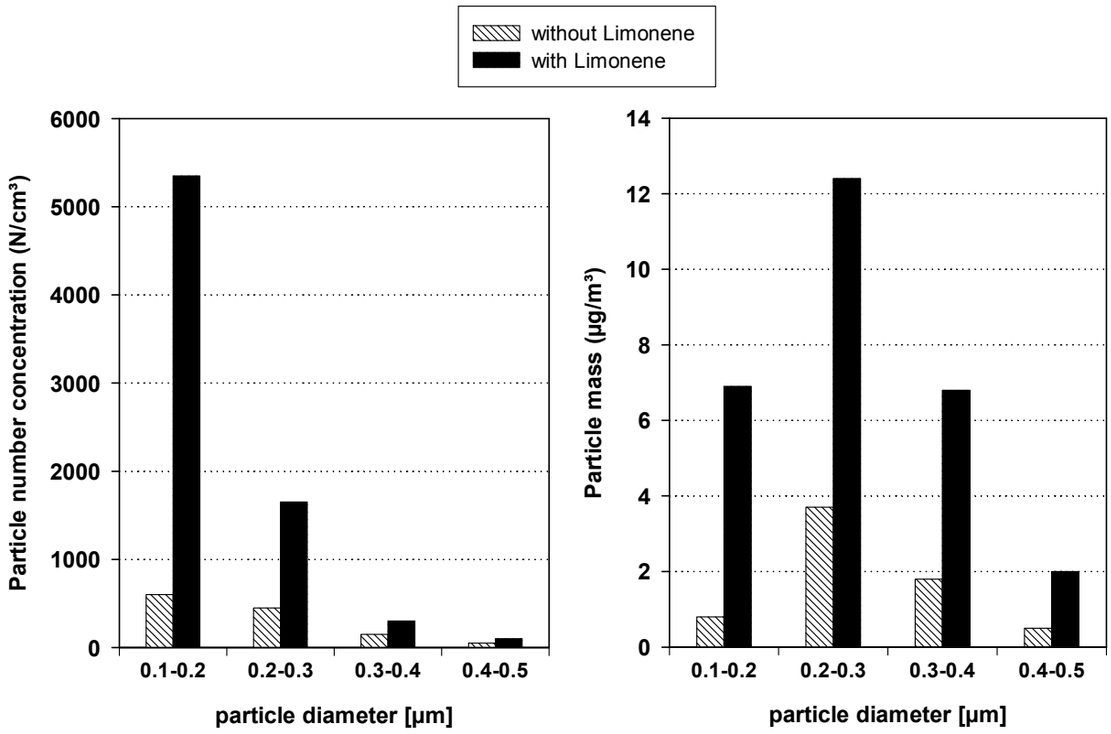

Fig. 6. Comparison between the concentrations of particles (left: number, PNC; right: mass) in an office with a limonene source and one without (modified from Weschler et al., 2003)

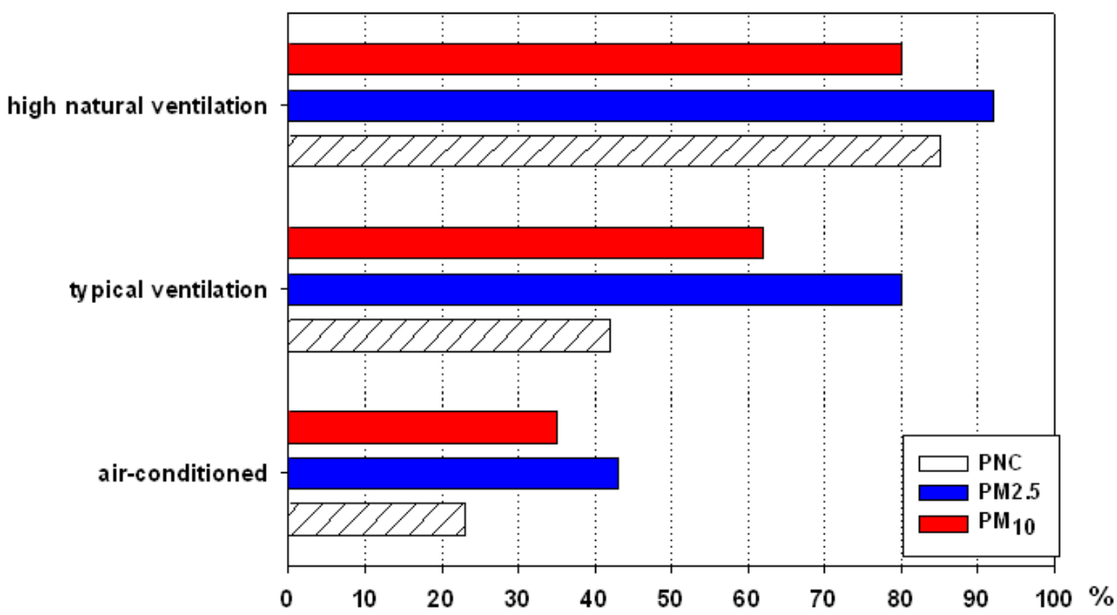

Fig. 7. Predicted proportion of outdoor particles in three urban residential scenarios (modified from Riley et al., 2002)

4. Occurrence of particles in indoor spaces

4.1 Particles in residences

In the scientific literature a large number of measurements of particle mass concentrations in indoor air are described. Table 1 shows the results for the mass-related measurements in residential indoor environments. It must be taken into account that due to different sampling and measurement methods the results can only be compared to a limited extent.

Reference	Concentration	Description
Europe		
Hänninen et al., 2004+	31 (A), 26 (B), 13 (H), 36 (P)	A: Athens, B: Basel, H: Helsinki, P: Prague; n: 186; 1996-2000
Lai et al., 2004	10	UK; n: 42; 1998-2000
Fromme et al., 2005*	30 (Wi), 27 (Su)	Berlin, Germany; n: 62; WI: 1997/98; SU: 2000
Raaschou-Nielsen et al., 2011	13	Denmark; n: 389; 1999-2002
Link et al., 2004	19	Germany; n: 126; 2001-2002
Franck et al., 2011	32	Germany; n: 129; 2001/2002
Stranger et al., 2007+	36	Belgium; n: 19; 2002-2003
Wichmann et al., 2010	10	Sweden; n: 29; 2003/2004
Osman et al., 2007	18	Scotland; n: 75; 2004/2005
Santen et al., 2009	3-15	Germany; n: 50; 2007
Cattaneo et al., 2011	23	Italy; n: 107; 2007/2008
America, Australia		
Wallace et al., 2003+	28	USA; n: 294; 7 cities
Meng et al., 2005	14	USA; n: 212; 1999-2001
Breysse et al., 2005+	26	USA; n: 90
Simons et al., 2007	35 (a), 10 (b)	USA; n: 100 city (a), 20 suburban (b)
Baxter et al., 2007	17	USA; n: 43; 2003-2005
Héroux et al., 2010	6	Canada; n: 96; 2007
Jung et al., 2010	14	USA; n: 286; 2005-2010
Asia		
Li & Lin, 2003+	39 (Wi), 37 (Su)	Taiwan; urban; n: 10; 1999-2000
Chao & Wong, 2002+	45	Hong Kong; n: 34; 1999-2000
Lim et al., 2011	48	Korea; n: 60; 2008

Wi: winter; Su: summer; S: smoker; NS: non smoker; *: PM_4; +: mean

Table 1. Median concentrations of $PM_{2.5}$ in the indoor air of residences in µg/m³

In different studies it could be shown that smoking is the most important influencing factor for the PM contents (e.g. Özkaynak et al., 1995; Wallace & Howard-Reed, 2002; Lai et al., 2004; Fromme et al., 2005; Breysse et al., 2005; Héroux et al., 2010; Franck et al., 2011). In Germany, the mean PM_4 concentrations in smoker households amounted in winter and summer, for instance, to 109 µg/m³ and 59 µg/m³ respectively, and in non smoker households they amounted during the two seasons only to 28 µg/m³ (Fromme et al., 2005). Other important influencing factors for the indoor air contents are the season, the outdoor air, the ventilation behaviour, the age and the location of the buildings and indoor activities such as cooking, the use of ovens and the burning of incense sticks (Mönkkönen et al., 2005; Martuzevicius et al., 2008; Santen et al., 2009; Rodes et al., 2010; Héroux et al., 2010; Byun et al., 2010; Raaschou-Nielsen et al., 2011).

Studies on the ultrafine particles (as particle number concentration, PNC) in residences resulted in Germany in cities on average in 20,400 particles/cm³ (Link et al., (2004) or to between 4,000 and 25,000 particles/cm³ in a monthly median (n: 50) (Santen et al., 2009) and in an epidemiological study in 59 residences in the median of 9,000 particles/cm³ (Franck et al., 2011). McLaughlin et al. (2005) report in seven Irish residences about mean PNCs between 4,900 and 105,200 particles/cm³ with a maximum value of up to 485,300 particles/cm³. In a Swedish study three residences were investigated with mean daily values between approximately 1,800 and 8,300 particles/cm³ (Matson, 2005). The proportion of indoor to outdoor ranged between 0.7 and 2.5.

In the USA in an apartment in Boston mean PNCs of 16,000 particles/cm³ (Levy et al., 2002) and in seven Californian homes values of 9,200 to 35,000 particles/cm³ were measured (Bhangar et al., 2011). With indoor sources a mean value of 18,700 particles /cm³ (maximum: 300,000 particles/cm³) was found in a house; without indoor sources it only amounted to 2,400 particles/cm³ (maximum: 58,000 particles/cm³) (Wallace & Howard-Reed, 2002). In 36 houses in Canada mean contents of 21,600 particles/cm³ were determined during the afternoon whereas during the night the average contents were only at 6,700 particles/cm³ (Weichenthal et al., 2007). In another Canadian study median PNCs of 2,700 particles/cm³ (summer) were determined in 94 flats, 3,700 particles/cm³ (winter) and 2,600 particles/cm³ (summer) (Kearney et al., 2011).

In Australia Morawska et al. (2003) measured mean PNCs of 18,200 particles/cm³ (during indoor activities) and 12,400 particles/cm³ (without corresponding activities) when examining kitchens in 15 flats in 1999.

4.2 Particles in schools

Figure 8 shows some examples of results from schools. In most of the studies the $PM_{2.5}$ contents ranged on average between 8 and 20 µg/m³. Merely in a study in 27 Belgian schools 61 µg/m³ were described, i.e. comparatively high concentrations (Stranger et al., 2007). By contrast, the PM_{10} contents at schools were highly variable with medians in the range of 50 - 100 µg/m³. Significantly higher contents were determined in a Greek study in which there was, however, also a high outdoor air pollution (Diapouli et al., 2007). In a European survey of 45 schools contents between 14 and 260 µg/m³ (PM_{10}) were measured (HESE, 2006).

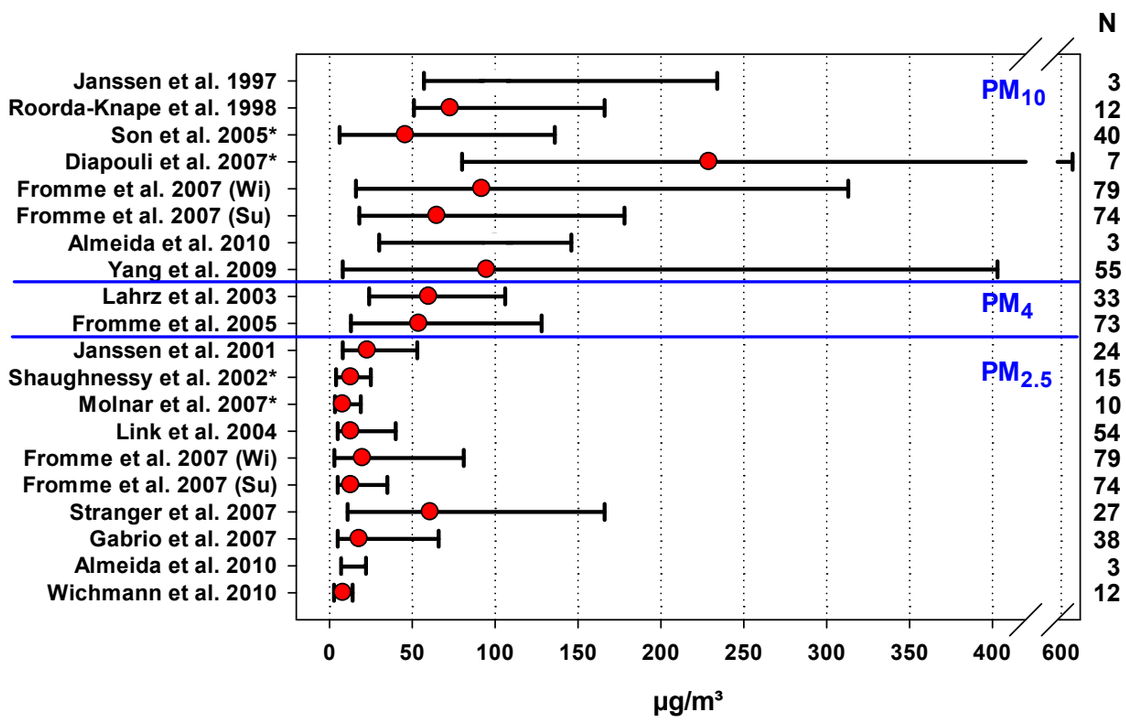

Fig. 8. Particulate matter in the indoor air of schools (minimum, median, maximum); *: mean; Su: summer; wi: winter

Different studies showed for $PM_{2.5}$ a ratio of indoor to outdoor air was in the range of 1 and a strong dependence on the outdoor air contents (Diapouli et al., 2007; Fromme et al., 2007; Wichmann et al., 2010; Guo et al., 2010). The situation is different if coarse particle fractions are considered. In a German study it was observed that 90% of the variability of the daily indoor medians of PM_1 were attributable to differences between the schools and / or the days but in this way only 45% of the PM_{10} variants could be explained (Fromme et al., 2007). Indoor sources themselves seem to be highly significant in this connection. In order to be able to assess the contribution of different sources and outdoor air, different studies also determined the elementary and/or ionic composition of PM (Diapouli et al., 2007; Molnar et al., 2007; Fromme et al., 2008). It turned out that in particular the coarse particles did not originate from the outdoor air but that the source was the classroom itself. Examinations of the filters by EDX (energy dispersive X-ray spectroscopy) suggested that the PM_{10} contents were mainly composed of floor particles and other mineral substances, attrition of building materials and chalk dust (Fromme et al., 2008). A further study revealed significantly more silicate particles (36% of all particles), organic particles (29%, probably from human skin) and Ca carbonate particles (12%, probably from paper) indoors, whereas in the corresponding outdoor filters in particular Ca sulphate containing particles (38%) were determined (Oeder et al., 2011).

The physical activity of the pupils and the associated whirling up of suspended particles from the floor seems to be the main reason for the high PM_{10} concentrations in classrooms (Fromme et al., 2007, 2008; Almeida et al., 2010; Guo et al., 2010; Oeder et al., 2011).

Measurements of the particle number concentration (PNC) have only been carried out so far in some cases at schools. In 36 German classrooms PNCs of 2,600 to 12,100 particles/cm³ were measured (Fromme et al., 2007). In another German study the contents ranged between 2,400 and 75,500 particles/cm³ (city) or 1,720 and 47,100 particles/cm³ (rural area) (Link et al., 2004). In a study in Greece mean PNCs of 24,000 particles/cm³ were determined during the class time at seven primary schools in Athens (Greece) which correlated well with the outdoor air contents (32,000 particles/cm³) (Diapouli et al., 2007). In an Australian study 3,100 particles/ cm³ were determined as mean value which increased within the framework of indoor activities such as cooking or cleaning of the floor surfaces to a maximum of 100,000 particles/cm³ (Guo et al., 2010). Since in school classrooms these classical sources for ultra fine particles are as a rule missing, the exposure of pupils during class time is essentially determined by the pollution of the outdoor air.

4.3 Particles in offices

Table 2 represents the mass related contents in indoor air of office buildings. The study results are difficult to compare with one another, since it was partly not mentioned whether smoking was allowed in the rooms. The median $PM_{2.5}$ and PM_{10} values in non-smoker

Reference	Median (Min-Max)	Description
PM_{10}		
Phillips et al., 1998	53 (NS) *; 63 (S) *	France; n: 222 personal monitoring; 1995
Gemenetzis et al., 2006	103 (25- 370)	Greece; 40 rooms in 2 buildings; natural ventilated
Heavner et al., 1996	30 (<DL- 98)(NS) * 67 (18- 217) (S) *	USA, New Jersey, Pennsylvania; n: 52 (NS) and 28 (S); 1992
Burton et al., 2000	11 (3- 35) +	USA; n: 100; with AC; 1994-1998
Reynolds et al., 2001	14 to 36#	USA; n: 6; with AC; 1996/1997
Liu et al., 2004a	63 (14- 166)	China, Peking; n: 11; 2002/2003
$PM_{2.5}$		
Mosqueron et al., 2005	26 (5- 265)	France; n: 55; 1999/2000
Lahrz et al., 2002	29 (5- 120) (NS)	Germany; n: 25; natural ventilation; 2001
Gemenetzis et al., 2006	77 (11- 250)	Greece; 40 rooms in 2 buildings; natural ventilated
Vardavas et al., 2007	51 (39- 63)* (NS) 107 (39- 63) (S)	Greece; n: 6; natural ventilation; 2006
Horemans et al., 2007	11 (5- 28)	Belgium; n:9; natural ventilation; 2007
Burton et al., 2000	7 (1- 25) +	USA ; n: 100; with AC; 1994-1998
Liu et al., 2004a	28 (3- 103)	China, Peking; n: 11; 2002/2003

*: Mean; +: geometric mean; #: geometric mean per building; DL: detection limit; S: smoker; NS: non smoker

Table 2. Concentrations of particulate matter in the indoor air in office buildings in µg/m³

offices ranged between 7 – 51 µg/m³ and 30 - 63 µg/m³, respectively. Noticeably low values resulted from the most extensive examination in 100 buildings with air conditioning systems in the USA (Burton et al., 2000). By contrast, particularly high concentrations were observed in Greek offices (Gemenetzis et al., 2006). These are attributed to the high outdoor air concentrations and the presence of smokers.

Concerning the ultra fine particles, higher PNCs were observed in offices exposed to tobacco smoke than in outdoor air whereby they ranged between approximately 1,000 and 13,000 particles/cm³ in offices with air conditioning (Matson, 2005). In an Australian study a mean concentration of 6,500 particles/cm³ was measured during and 1,200 particles/cm³ after working hours (He et al., 2007) in an open plan office with ventilation and air conditioning system and smoking ban. The highest measured concentration amounted to 38,000 particles/cm³ in this study.

4.4 Particles in hospitality venues

An overview of the exposure in pubs, restaurants and similar venues is provided by Table 3. The worldwide studies all reach the conclusion that in venues in which smoking is permitted very high concentrations have to be expected. A German study in discos (n = 10) resulted, for instance, for PM_{10} in a median of 1,014 µg/m³ and for $PM_{2.5}$ of 869 µg/m³ (Bolte et al., 2008). In pubs (n = 18) the same working group measured medians of 210 µg/m³ (PM_{10}) and 195 µg/m³ ($PM_{2.5}$). Figure 9 shows, for instance, the $PM_{2.5}$ concentration time course in three venues which were examined during the above mentioned study.

Results about the development of indoor air pollution in bars, restaurants and similar venues after the introduction of smoking bans are available so far to a larger extent from the USA, Italy, Ireland, Scotland and Norway (summary in Fromme et al., 2009). Overall, it turned out that a considerable reduction of the $PM_{2.5}$ contents between 70 and 97%, mostly above 90%, can be achieved through the implementation of a consistent smoking ban in these venues alone.

On the other hand, the published results proved that through spatially not completely separated smoking areas in pubs and with ventilation systems no or only a low decrease in particle pollution is achieved. This is confirmed in a position paper by the American Society of Heating, Refrigerating and Air Conditioning Engineers which does not see ventilation systems as a useful instrument to protect from passive smoking in these venues (ASHRAE, 2005).

So far there are hardly any study results on the number of ultrafine particles. Milz et al., (2007) investigated 2 restaurants in two American cities. Whereas in non-smoker restaurants the mean contents amounted to ca. 15,000 particles/cm³, 82,000 particles/cm³ and ca. 106,000 particles/cm³ were observed in smoker rooms. Concerning ultrafine particles, smoker rooms result in a pollution of areas nearby in which smoking is banned. In Germany very high median PNCs of 221,100 particles/cm³ were measured in 4 cafés/ restaurants, 119,100 particles/cm³ in 2 bars and 289,900 particles/cm³ in 7 discos (Bolte et al., 2008).

Reference	Median (Min-Max)	Description
Europe		
Bohanon et al., 2003	194 (56- 312)+	Restaurants; France
	75 (0- 277) +	Restaurants; Schwitzerland
	201 (62- 391) +	Restaurants; UK
Gee et al., 2006	94*+	59 pubs; England; 2001
Edwards et al., 2006a	167 (54- 1395)	33 pubs, with cooking; UK; 2004
	217 (15- 1227)	31 Pubs; no cooking; UK; 2004
Goodman et al., 2007	35,5 *	42 pubs; Ireland; 2004/2005
Valente et al., 2007	119	40 locations; Italy; 2005
Schneider et al., 2008	173 (22- 831)	38 restaurants; Germany; 2005
	131 (24- 1029)	20 cafes; Germany; 2005
	378 (144- 2022)	11 bars; Germany; 2005
Bolte et al., 2008	164 (55- 570)	11 restaurants, cafes; Germany; 2005/2006
	203 (103- 1250)	7 pubs and bars; Germany; 2005/2006
	869 (291- 4475)	10 discotheques; Germany; 2005/2006
Vardavas et al., 2007	268 (19- 612)*	31 bars, pubs, cafes, clubs; Greece; 2006
Semple et al., 2010	197 (8- 902)	42 bars; Scotland; 2006
	92 (5- 1005)	52 bars; England; 2007
	184 (16- 872)	12 bars; Wales; 2007
Rosen et al., 2007	465 (66- 862)+	6 bars, pubs; Israel; 2007
	52 (18- 557)+	8 cafes; Israel; 2007
Daly et al., 2011	83 (51- 108)*	70 bars, cafes, restaurants; Switzerland; 2008
America, Australia		
Maskarinec et al., 2000	66 (0- 233) +	Restaurants; USA; 1996/1997
	82 (0- 768) +	Bars; USA; 1996/1997
Brauer et al., 2000	(11- 163)	11 restaurants; Canada
	(47- 253)	4 bars; Canada
Repace et al., 2006	178 (43- 323)	6 pubs; USA; 2003
Connolly et al., 2005	206 (23- 727)	28 locations, USA; 2005
Brennan et al., 2010	61 (6- 338)	19 pubs; Australia; 2007
Jiang et al., 2011	63 (18- 183)	36 casinos, USA; 2008
Asia		
Baek et al., 1997	159 (33 - 475)+	6 restaurants; Korea; 1994/1995
Lee et al., 1999	400 - 1760	3 restaurants; China; 1996/1997
Bohanon et al., 2003	194 (0- 611) +	Restaurants; Japan
	107 (54- 172) +	Restaurants; Korea
Lee et al., 2010	92 (17- 565)*	55 restaurants; 7 countries; 2008/2009
	114 (14- 565)*	35 cafes; 7 countries; 2008/2009
	191 (33- 748)*	34 bars, clubs; 7 countries; 2008/2009
	169 (4- 881)*	44 entertainment venues; 7 countries; 2008/2009

*: mean; +: PM_4 or respirable particulate matter (RPM)

Table 3. Concentrations of particulate matter ($PM_{2.5}$) in indoor air of hospitality venues in $\mu g/m^3$

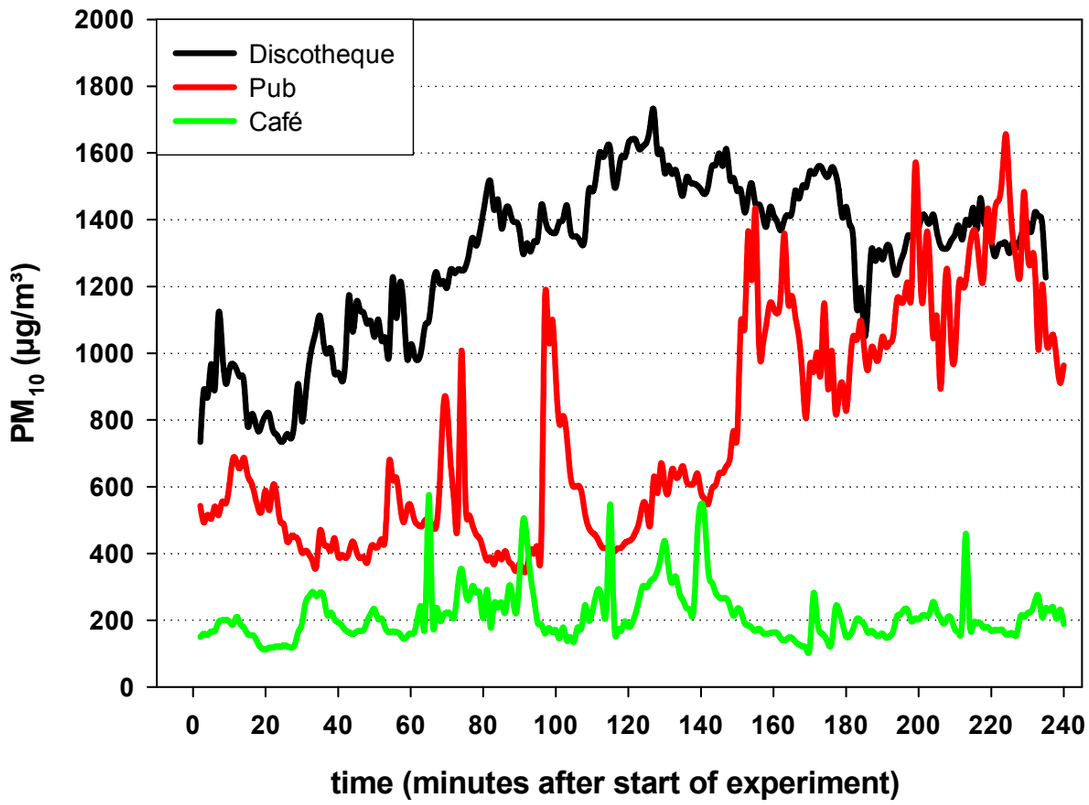

Fig. 9. Time course of $PM_{2.5}$ in three hospitality venues in Germany (modified from Bolte et al., 2008)

4.5 Particles in transportation systems

4.5.1 PM in aboveground transportation systems

The contents of $PM_{2.5}$ in above ground buses and cars are shown in Figure 10. The highest contents in cars and buses were observed in Asian cities; merely in one study in Mexico City, in Boston (Levy et al., 2002) and in Peru (Han et al., 2005) similar high concentrations were described. The other studies, in particular in Europe and Australia, refer, by contrast, to a mean exposure level for $PM_{2.5}$ of approximately 10 - 40 µg/m³; as a rule the concentrations are significantly higher indoors than in the ambient air. There was a dependency of the indoor air contents on the outdoor levels, the time of day and the day of week (e.g. Lee et al., 2010).

Table 4 shows the results of the measurements of ultrafine particles in cars and buses. The mean PNC ranges between 10,000 and 50,000 particles/cm³. By contrast, very high contents were described by Kaur et al. (2005) in the City of London which ranged on average between 90,000 and 100,000 particles/cm³. During a drive on the freeway with an open window high concentrations were likewise determined (Eiguren-Fernandez et al., 2005). Under special conditions, eg a diesel truck ahead, short term peak concentrations of up to 500,000 particles/cm³ were observed (Abraham et al., 2002; Eiguren-Fernandez et al., 2005).

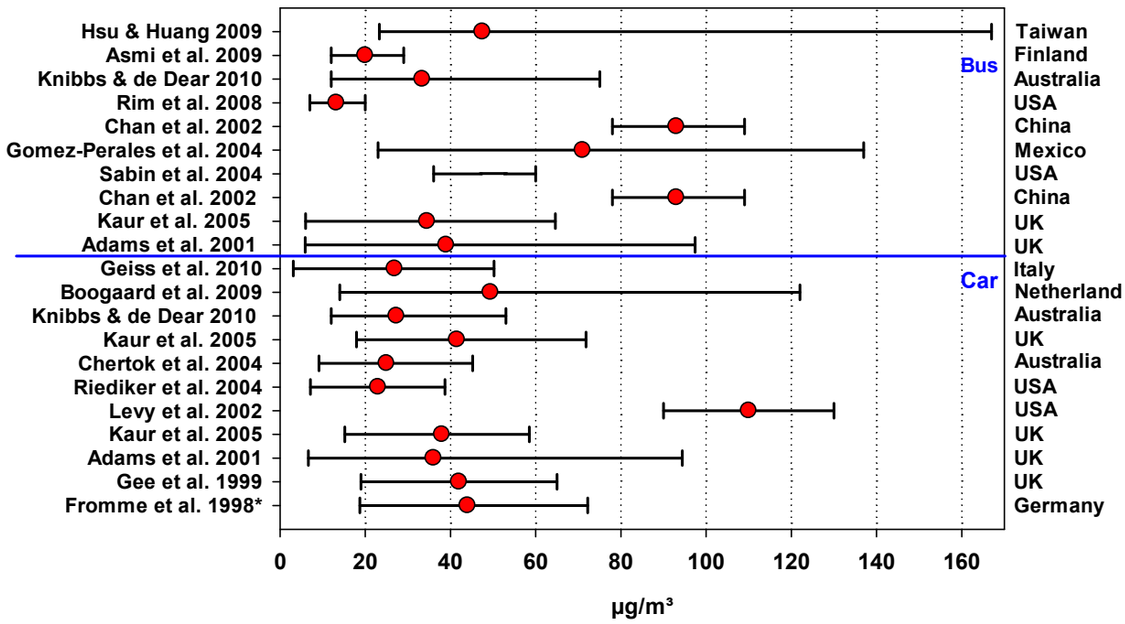

Fig. 10. Concentrations of $PM_{2.5}$ in cars and buses (*: PM_4) (minimum, median, maximum)

Overall, the exposure in the indoor environment of transportation systems is influenced by many different factors such as ventilation, quality of driving, traffic volume and traffic composition, built-up area and meteorology. Car passengers seem to be exposed to a slightly higher $PM_{2.5}$ and PNCs than cyclists (Adams et al., 2001; Kaur et al., 2005), whereas they are stated as the same or only slightly different in other studies (Gulliver & Briggs, 2004; Boogaard et al., 2009; Zuurbier et al., 2010; Int Panis et al., 2010). In this connection it must, however, be taken into account that due to the approximately 2 – 4.5 fold higher breathing volume cyclists have a significantly higher inhaled dose compared to car and bus users (Zuurbier et al., 2010; Int Panis et al., 2010).

In addition, air conditioning and filter systems, which can have a major influence on the contents in the indoor environment of transportation systems depending on the quality and the separation level, must be taken into account (Rim et al., 2008). Studies in an urban environment also showed a higher exposure for pedestrians than during car use or compared to the general outdoor air pollution (Kaur et al., 2005).

A special pollution situation results from passive smoking exposure. During a drive in Wellington with a fully opened side window mean $PM_{2.5}$ contents of 169 µg/m³ (maximum: 217 µg/m³) were measured while smoking a cigarette (Edwards et al., 2006b). With a closed window the mean values were 2,962 µg/m³ (maximum: 3,645 µg/m³) and in a Canadian study mean $PM_{2.5}$ contents between 790 and 4,626 µg/m³ (maximum: 7,635 µg/m³) were determined (Sendzik et al., 2006). Rees & Connolly (2006) determined in 45 measurements during smoking with closed windows mean $PM_{2.5}$ values of 271 µg/m³ (maximum: approximately 500 µg/m³) and with opened side windows approximately 50 µg/m³ (maximum: approximately 100 µg/m³). Liu & Zhu (2010) observed inside cars the tenfold PNC and 120-fold $PM_{2.5}$ contents compared to outdoor air.

Reference	Mean (Min-Max)		Description
Europe			
Dennekamp et al., 2002	53 (-) [a]	bus	Aberdeen, UK; n: 11
Mackay, 2004	44 (10-143) 58 (8-282)	bus car	Leeds, UK
Krausse & Mardaljevic, 2005	- (46-116)		Leicester, UK; n:133
Kaur et al., 2005	101 (65-159) 100 (37-152) 88 (52-114)	bus car taxi	London, UK; 2003
Diapouli et al., 2007	94 (25-217)	car	Athens, Greece; through city
Geiss et al., 2010	16 (8-30)	car	Italy; 18 cars; 2009
North America, Australia			
Abraham et al., 2002	30 [b] (4-190)		New York, USA; 3 city routes
Levy et al., 2002	~32 (12-80) ~39 (11-83)	bus car	Boston, USA; 2000
Eiguren-Fernandez et al., 2005	25 (X, AC) 55 (X, nAC) 69 (Y, AC) 246 (Y,nAC)	car	Los Angeles, USA, car; AC: air condition, nAC: windows open; X: small streets; Y: freeway
Rim et al., 2008	6-35	bus	Austin; USA; 6 busses; 2006
Wallace & Ott, 2011	29-34 (-)	car	USA; 17 trips; 2005-2009
Knibbs & de Dear, 2010	11 9	bus car	Sydney; Australia; 40 trips; 2004
Zhang & Zhu, 2010	7.3-34	bus	Texas; USA; school buses; 2008

a: median; b: mean of three cycles

Table 4. Particle number concentrations (PNC) in indoor air of transportation systems (10^3 of particles/cm^3)

4.5.2 PM in underground transportation systems

Studies in this micro environment show that the exposure is significantly above the values measured in above ground transportation systems. In the Berlin underground mean PM_4 contents of 141 (124-169 µg/m^3) were measured in winter and 153 µg/m^3 (121-176 µg/m^3) in summer (Fromme et al., 1998). Similar results were obtained in the London underground with mean $PM_{2.5}$ concentrations of 247 µg/m^3 (105 – 371 µg/m^3) (summer) and 157 µg/m^3 (12 – 263 µg/m^3) (winter) (Adams et al., 2001). In a more recent study conducted in London mean values of 180 - 200 µg/m^3 ($PM_{2.5}$) were measured (Hurley et al., 2004). By contrast, significantly lower mean pollutions were observed in Boston (70 µg/m^3 $PM_{2.5}$), Los Angeles (13.7 µg/m^3) and Helsinki (21 µg/m^3) (Levy et al., 2002; Aarnio et al., 2005; Kam et al., 2011). In the underground of Mexico City the mean values amounted to 61 µg/m^3 (31 - 99 µg/m^3)

(Gómez-Perales et al., 2004). Measurements in the Seoul underground and in a Chinese city, resulted in concentrations of 148 µg/m³ (Sohn et al., 2005) and 67 µg/m³ (26-123 µg/m³), respectively (Chan et al., 2002).

In the Berlin underground stations the PM_4 contents ranged between 128 and 311 µg/m³ during operation (Fromme et al., 1998), and in London the average $PM_{2.5}$ contents were 270 - 480 µg/m³ (Hurley et al., 2004). In Boston 130 µg/m³ were measured at the underground station (Levy et al., 2002). On the other hand the contents in Taipei were on average only 25-40 µg/m³ (Cheng & Yan, 2011) and in Paris (Raut et al., 2009) the contents were 61 µg/m³ (normal hours) and 93 µg/m³ (rush hours) correspondingly lower.

At present only a few measurements on ultrafine particles are available. In three underground lines in London 17,000 – 23,000 particles/cm³ (>50 nm) were measured on average whereas on the platforms of the three underground stations the average contents determined were 14,000 – 29,000 particles/cm³ (Hurley et al., 2004). Similar results were reached by measurements at the underground of Boston with mean values of approximately 21,000 particles/cm³ (Levy et al., 2002) and in Helsinki, with 27,000 particles/cm³ (14,000-50,000 Pt./cm³) (Aarnio et al., 2005).

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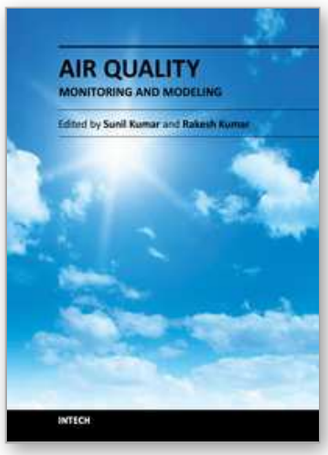

Air Quality - Monitoring and Modeling

Edited by Dr. Sunil Kumar

ISBN 978-953-51-0161-1
Hard cover, 230 pages
Publisher InTech
Published online 29, February, 2012
Published in print edition February, 2012

The book reports research on relationship between fungal contamination and its health effects in large Asian cities, estimation of ambient air quality in Delhi, a qualitative study of air pollutants from road traffic, air quality in low-energy buildings, some aspects of the Sentinel method for pollution problem, evaluation of dry atmospheric deposition at sites in the vicinity of fuel oil fired power, particles especially PM 10 in the indoor environment, etc.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Hermann Fromme (2012). Particles in the Indoor Environment, Air Quality - Monitoring and Modeling, Dr. Sunil Kumar (Ed.), ISBN: 978-953-51-0161-1, InTech, Available from: http://www.intechopen.com/books/air-quality-monitoring-and-modeling/particles-in-the-indoor-environment

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