EFFECT OF BUILDING AND INSTALLATION DESIGN ON $PM_{2.5}$

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ABSTRACT

People spend more than 80% of their time indoors. In contrast to ambient air, no (legal) limits for indoor particulate matter exist, although there are WHO guidelines. In the Netherlands a measurement protocol to determine the $PM_{2.5}$ in office buildings has been developed including 5 quality classes. However at the moment no simple guidelines or models are available which can support the design and in-use phases to predict the $PM_{2.5}$ concentration in office buildings and schools. This paper describes the results of a mass balance model which predicts the effect of building and installation design parameters on $PM_{2.5}$ concentration. Three experimental case studies are used to fit two parameters in the model and to validate the overall model. For Dutch buildings air tightness, ventilation flow and the filter quality prove to be critical factors. In the US, due to high recirculation rates, increasing the ventilation flow or reducing the infiltration flow has only a minor effect. There it is more effective to increase the filter quality. The results of our model further indicate that it is well possible for modern offices equipped with F7 filters to be below the WHO air quality guideline for annual mean $PM_{2.5}$ of less than 10 $\mu g/m^3$. It would be interesting to further validate the model with regard to deposition losses in offices and to include PM_{10} in the model for schools.

KEYWORDS

$PM_{2,5,}$ Office building, School, Air tightness, filter quality

1 INTRODUCTION

People spend more than 80% of their time indoors. However, unlike ambient air, no legal limits exist for particulate matter inside. Because there is no convincing evidence that the hazardous nature of particulate matter differs from indoor sources as compared to outdoor sources the steering group assisting in WHO indoor air quality guidelines concluded that the 2005 air quality guidelines for particulate matter are also applicable to indoor spaces (WHO 2010). In the Netherlands a measurement protocol to determine the $PM_{2.5}$ in office buildings has been developed [VLA 2014]. However at the moment no simple guidelines are available which can be referred to in the design and the use phase to predict the $PM_{2.5}$ in an office building. In EN 13779 (2007) different Outdoor Air (ODA) and Indoor Air (IDA) classes have been defined to facilitate filter selection for buildings. Firstly these classes are difficult to interpret as they are relative to the outdoor air quality. Secondly the effect of infiltration, by which untreated air enters the building, is not incorporated. Field studies (Jacobs, 2014) show that open windows, open doors and infiltration through cracks can have a major influence on the indoor $PM_{2.5}$ concentration. Thirdly the EN 13779 does not take into account internal sources of $PM_{2.5}$. These may have a significant effect on the indoor concentration at schools as reported by Blondeau et al. (2004) and Alves et al. (2014). Therefore this paper describes the results of a model to predict the effect of three building and installation design parameters (ventilation flow, airtightness and filter quality) on $PM_{2.5}$ concentrations in office buildings and schools.

2 METHODS

As a marker for the indoor fine dust, $PM_{2.5}$ has been chosen. The measurement protocol for $PM_{2.5}$ is published in Dutch (VLA 2014) and in English [Jacobs 2015]. In short the measurement protocol consists of the following steps. The indoor $PM_{2.5}$ concentration at the work place, see figure 1, is measured by a calibrated optical particle counter during a working week. The indoor concentration largely depends on the outdoor concentration and is corrected for low or high concentrations during the measurement week. The hourly outdoor concentration is derived from an outdoor station of the Dutch air quality monitoring network. Based on the one week measurement data an estimation of the yearly averaged $PM_{2.5}$ concentration is made. This estimate is then compared to the WHO (2006) annual advisory value of 10 $\mu g/m^3$ according to the VLA methodology class A , 15 $\mu g/m^3$ corresponding to class B and the Dutch limit value of 25 $\mu g/m^3$, in force since1-1- 2015, corresponding to class C. Buildings with $PM_{2.5}$ concentrations above 25 $\mu g/m^3$ are classified as D. To stimulate good building and installation designs an A+ class has also been defined: < 2.5 $\mu g/m^3$.

Figure 1: optical particle counter placed in suitcase in an office room.

A mass balance model has been established of a typical office building and a class room. The model contains three input parameters:

- Air exchange rate: the number of air changes per hour;
- Specific airtightness, this is the air leakage at 10 Pa pressure difference per m^2 floor area;
- Filter quality according to EN779:2012.

The indoor $PM_{2.5}$ is calculated by equation 1 similar to Chan (2015).

$$PM_{2.5} = \frac{PM_{2.5\ \mathrm{ambient}}\ [I+V(1-\eta)]+s}{I+V+d} \qquad (1)$$

$PM_{2.5}$ and $PM_{2.5\ \mathrm{ambient}}$ are the indoor and outdoor $PM_{2.5}$ concentrations (µg/m^3), I and V are the infiltration and ventilation air exchange rates (1/h).

The filter efficiencies η with regard to $PM_{2,5}$ have been estimated in consultation with filter suppliers and the results of the field studies, see table 1.

Table 1: assumed filter efficiencies.

Filter quality according to EN779	Estimated $PM_{2.5}$ removal fraction η
G4	0.50
M5	0.60
M6	0.90
F7	0.95
F9	0.99

In the model the effect of desorption on surfaces has been taken into account by a first order deposition loss d = 0.15 1/h as found by Zaatari (2014) for retail stores. The effect of internal sources has been taken into account. The internal source s (µg/(h m^3)) is based on the intercept b of the XY plots of the results of two office building case studies (Jacobs 2015). By assuming $PM_{2.5\ \mathrm{ambient}}$ is zero, from equation (1) it follows:

$$S = (I + V + d) * PM_{2.5} = (I + V + d) * b \qquad (2)$$

The intercept for offices is typically 1,5 µg/m^3, the internal source S is then about 5 µg/(h m^3). The internal source in class rooms has been estimated 4 times higher than offices due to the higher occupation.

To determine the infiltration rate a yearly average pressure difference of 3 Pa with the outside is assumed. Based on this average pressure difference and the airtightness levels used in the model the infiltration rate ranges from 0.1 to 0.9 air changes per hour. For reference, the Dutch Building decree specifies a minimum air tightness of 1.2 $dm^3/(s\ m^2)$ at 10 Pa pressure difference. This corresponds with an infiltration rate of about 0.7 air changes per hour.

3 RESULTS

3.1 Model study

The results of the mass balance model with regard to $PM_{2,5}$ in an office building and a class room are given in table 2 and 3. In the tables the $PM_{2,5}$ concentration is expressed according to the classification described under the method section. Offices equipped with F7 filters are well below the WHO air quality guideline for annual mean $PM_{2.5}$ of less than 10 µg/m^3 (class A). In schools, due to the higher internal sources, sufficient air flow is required to achieve class A.

Table 2: offices, indicative effect of filter efficiency, air tightness and ventilation rate on $PM_{2.5}$ in offices according to VLA classes

Air Exchange rate [ACH]	Airtightness [dm^3/(s m^2)] @10Pa	without filter	G4	M5	M6	F7	F9
< 1	> 1,2	B	B	B	B	B	B
1 – 2	> 1,2	B	B	B	A	A	A
2 – 3	< 1,2	B	B	A	A	A	A
> 3	< 0,8	B	A	A	A	A	A
> 3	< 0,4	B	A	A	A	A	A+
> 4	< 0,1	B	A	A	A	A+	A+

Table 3: indicative effect of filter efficiency, air tightness and ventilation rate on $PM_{2.5}$ in classrooms according to VLA classes

Air Exchange rate [ACH]	Airtightness [dm^3/(s m^2)] @10Pa	without filter	G4	M5	M6	F7	F9
1	> 1,2	C	C	C	B	B	B
2	> 1,2	C	B	B	B	B	B
3	< 1,2	C	B	B	A	A	A
4	< 0,8	C	B	B	A	A	A
5	< 0,4	C	B	A	A	A	A
6	< 0,4	C	B	A	A	A	A

3.2 Comparison model with case studies

Three case studies have been carried out, these have been described in detail by Jacobs (2015). The results are summarized in table 4 and compared with the model results. Note that the case study results are used for the prediction of the internal source S and the filter efficiency η. Two of the three classes have been predicted well. With regard to the third building class A is predicted while the measurement indicates a class A+ (<2.5 µg/m^3). The lay-out of the last building acts as a guard ring which ensures a very low infiltration of ambient air. With only an M6 filter the lowest $PM_{2.5}$ concentration is achieved. These results clearly show that not only the filter quality but also the infiltration flow relative to the ventilation flow is an important parameter.

Table 4: comparison case studies with model prediction $PM_{2.5}$ [µg/m^3]

Case study	**Measured (µg/m³) / VLA class**	**Model (µg/m³) / VLA class**
1. Office building Rotterdam (F7)	4.4 / class A	3.5 / class A
2. TNO Office building (F7)	5,8 / class A	5.3 / class A
3. Office with guard ring (M6)	1 / class A+	2,6 / class A

3.3 Comparison with literature

Chan et al (2015) has performed a similar model study for the United States. The predicted $PM_{2.5}$ concentrations of Chan and by this study are listed in table 5. Especially in the situation without filters, large deviations between the two models can be seen. With regard to buildings equipped with F7/MERV 13 filters the models are quite close. Explanations are:

- Ambient air quality: for the US an average outdoor $PM_{2.5}$ of 10.8 and for the Netherlands 15 µg/m^3 is assumed;
- The filter efficiency used by Chan is much lower than assumed in this paper;
- The air infiltration rate used by Chan for schools and offices is 0.2 and 0.1 /h respectively which is much lower as assumed in this paper.
- Chan assumes a relative low ventilation rate of 0.5 – 1.0 and a recirculation rate of 3 /h while in the Netherlands the ventilation rates are in the order of 1 – 4 /h and no recirculation is applied.

Table 5: predicted mean indoor concentration $PM_{2.5}$ [µg/m^3]

	Chan (2015)	TNO model
Office without filter	6.6	15.8
Office G4/MERV 8	5.9	10.3
Office F7/MERV 13	3.5	5.3
School without filter	8.3	19.3
School G4/MERV 8	8.3	13.3
School F7/MERV 13	5.2	8.0

It can thus be concluded that there exists large differences in air handling between the US and the Netherlands. This also has an effect on the strategy for $PM_{2,5}$ reduction. In the US, due to the high recirculation rates used, it is most effective to increase the filter quality. Increasing the ventilation flow or reducing the infiltration flow has only a minor effect. In the Netherlands, recirculation is not applied, therefore a higher ventilation flow and a better air tightness have a relatively large effect.

3.4 Future research

The estimate for the deposition d is derived from research in retail stores. This loss may be too low for offices. A better estimate may be derived from research in naturally ventilated offices where no filters are applied. Further, more research in schools is required to validate the model calculations with regard to schools and to also include PM_{10}.

4 CONCLUSIONS

A mass balance model has been set up to calculate the $PM_{2.5}$ concentration in office buildings and schools. The model provides a straightforward method to classify buildings with regard to the indoor $PM_{2.5}$ concentration and enables estimation of the effect of measures to improve the air quality. For the Netherlands air tightness in combination with the ventilation flow and the filter quality are critical factors. In the US, due to the use of recirculation, increasing the ventilation flow or reducing the infiltration flow has only a minor effect. More research in naturally ventilated offices could improve the estimate for the deposition rate. Also more research in schools is required to include PM_{10} in the model.

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