The role of ventilation in the penetration of outdoor air pollutants

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ABSTRACT

Outdoor air is usually considered as a source of clean air in building ventilation principles. Although outdoor air quality has already improved in our cities, this principle may be challenged. Particulate matter remains especially problematic. This simulation study investigates the role that the mechanical ventilation system, with or without filtration, plays in the penetration of outdoor air pollutants, which may have adverse effects on indoor air quality and occupant health. Based on the Brussels $PM_{2.5}$ pollutant data, several configurations were examined using the CONTAM software. The influence of the airtightness of the building, the filter efficiency and the airflow rate of the mechanical ventilation system on the indoor air pollutant concentration were highlighted for a simple model, i.e. a single room housing, and afterwards extended to a complex model, i.e. a semi-detached house with several rooms. This influence was evaluated in terms of a total efficiency, taking into account filter effect and building envelope, as well as in terms of the occupant exposure to outdoor pollutants. Ventilation strategies based on outdoor pollutant concentration were implemented and assessed through exceedance days linked to World Health Organization (WHO) guidelines. On this basis, recommendations for managing the ventilation system in case of high concentrations of outdoor air pollutants can be discussed.

KEYWORDS

Indoor Air Quality, outdoor air pollutants, ventilation system, particulate matter, recommandations.

1 INTRODUCTION

Ventilation is a way to achieve a good indoor air quality by removing pollutants from the indoor air. Within the building ventilation principles, the polluted indoor air is replaced by outdoor air, which is considered as a source of clean air. Although the outdoor air quality already improved in cities like Brussels, some pollutants, especially particulate matter, remain problematic. This simulation study will highlight to what extent the penetration of polluted outside air can be limited depending on the ventilation system present (or not), its filtration level and its regulation. [4] The simulations were performed with the CONTAM software. Two practical aspects will be investigated; what is recommended to do with the ventilation system in case of important outdoor pollution (pollution peak) and if there is any point in regulating the ventilation system on a regular basis and therefore automatically, based on the outdoor concentration changes (that may be linked to traffic for example).

A first part will study the impact of few parameters on the penetration of outdoor pollutants, namely $PM_{2.5}$, with the help of multizone simulations. The focus is on three parameters : the building airtightness, the ventilation flow rate and the filter efficiency. It will help to understand how the penetration of outdoor pollutants depends on the characteristics of the ventilation system and the building envelope. By understanding what influences this penetration, strategies to try to control can be easier considered.

A second part will aim to elaborate recommendations on how to act in case of a pollution peak and to study if there is a real interest to add an automatic regulation on ventilation systems based on the outdoor air quality. A set of configurations will be analysed on specific days: days with a high 24-hour mean $PM_{2.5}$ outdoor concentration, days with a high variability in $PM_{2.5}$ outdoor concentration and days with a smog alert from the Belgian Interregional Environment Agency (IRCEL - CELINE). These first configurations will help generate interest in controlling the ventilation system based on outdoor pollutants. A second set of configurations implementing different ventilation strategies based on outdoor pollutant concentration will be studied in order to minimise the penetration of $PM_{2.5}$ outdoor pollutant.

2 INFLUENCE OF AIRTHIGHTNESS, VENTILATION FLOW RATE AND FILTER EFFICIENCY ON THE PENETRATION OF OUTDOOR POLLUTANTS

2.1 Methodology

Based on $PM_{2.5}$ outdoor pollutant data from Molenbeek-Saint-Jean (Brussels) in 2018, several configurations were examined using CONTAM software to determine which role the airtightness, the ventilation and the filter efficiency play on the penetration of outdoor $PM_{2.5}$. The simulations start with zero indoor $PM_{2.5}$ concentration. Two models were defined : a simple model and a complex model. The simple model refers to an one-room apartment suitable for 2 persons with a volume of 180 m^3 and a floor area of 60 m^2, see Figure 1. The complex model refers to a semi-detached house with 2 floors and several rooms, see Figure 2.

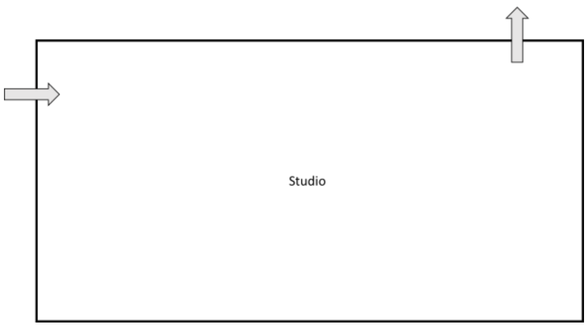

Figure 1: Simple model floor plan

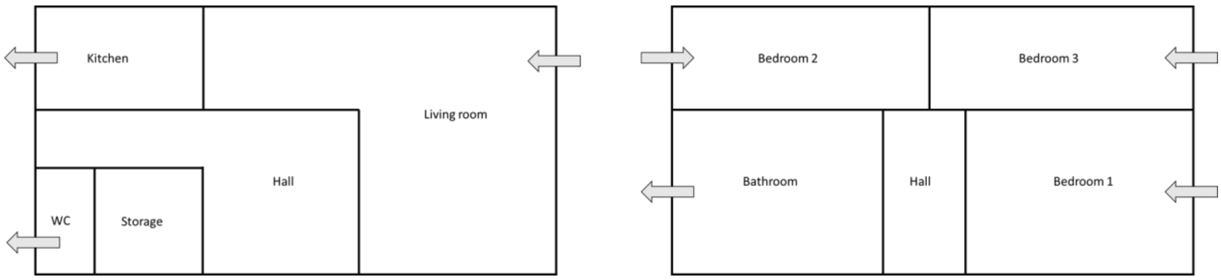

Figure 2 : Complex model ground and first floor plans

For each model, different airtightness, ventilation rates and filter efficiency were simulated:

- Airtightness expressed in terms of the air permeability v_{50} (m^3/hm^2) = 0, 1, 3, 6
- Filter efficiency against $PM_{2.5}$ (%) = 0, 30, 60, 80
- Ventilation flow rates (supplied and extracted air in balance) for the simple model, see Table 1

Table 1: Ventilation flow rates of the simple model

Air change rate (ACH or h^{-1})	**Volume (m^3)**	**Ventilation flow rate (m^3/h)**
0 (extracted and supplied)	180	0
0.028 (extracted and supplied)	180	5
0.14 (extracted and supplied)	180	25
0.28 (extracted and supplied)	180	50
0.42 (extracted and supplied)	180	75
0.55 (extracted and supplied)	180	100
0.69 (extracted and supplied)	180	125
1.39 (extracted and supplied)	180	250
2.78 (extracted and supplied)	180	500
5.55 (extracted and supplied)	180	1000

- Design ventilation flow rates for the complex model were determined using the following rules: 25 m^3/h per person, 1 bedroom for 2 persons and the others for 1 person, design number of persons for the living room equal to the total number of persons in bedrooms, extract flow rates in the services rooms based on NBN D 50-001 [1] and increased to balance the total supply and extract flow rates. In this complex model, the air is supplied to the bedrooms and living room, then transferred to the hallways and service rooms, and finally extracted from service rooms. From these design flow rates, see Table 2, two additional variants were simulated, namely halving or doubling them.

Table 2:Ventilation flow rates of the complex model

Room	**Air change rate (ACH or h^{-1})**	**Volume (m^3)**	**Ventilation flow rate (m^3/h)**
Kitchen	3.81 (extracted)	21	80
Living room	0.73 (supplied)	137	100
WC	8 (extracted)	5	40
Bedroom1	0.48 (supplied)	52	25
Bedroom2	0.47 (supplied)	53	25
Bedroom3	0.71 (supplied)	70	50
Bathroom	2.22 (extracted)	36	80

In order to evaluate the influence of a parameter on the penetration of outdoor pollutant, two indicators were proposed ; the total efficiency and the occupant exposure. As the simple model has only one room, the influence of the parameters on the indoor pollutant was evaluated based on a simple indicator, the total efficiency. For the complex model, as indoor concentrations may be heterogeneous, the influence of the parameters was evaluated in terms of occupant exposure, rather than based on the total efficiency. Occupant exposure indicates the cumulative concentration to which occupants are exposed.

The total efficiency was defined as:

$$\xi = 1 - \frac{C_{average,indoor}}{C_{average,\, outdoor}} \tag{1}$$

The total efficiency is equal to 1 if the average indoor concentration is zero. The total efficiency is equal to 0 if the average indoor and outdoor concentration are equal. The average values are computed on the simulated period, on basis of hourly data. It allows to take into account not only the effect of the filter but also other building features (e.g. the airtightness).

The occupant exposure was defined as :

$$Exposure = \int_{t_0}^{t_f} (C(t) - C_{threshold})\, dt \text{ with } C(t) > C_{threshold} \tag{2}$$

t_0 is the beginning of the study period
t_f is the end of the study period
C(t) is the indoor pollutant concentration
The occupant exposures are calculated above a threshold of 0 µg/m^3 (i.e. $C_{threshold} = 0$).

2.2 Results

2.2.1 Simple model

Figure 3 shows the total efficiencies evaluated for different airtightness, ventilation flow rates and filter efficiencies for January 2018. Without filtration, the total efficiency varies only very slightly with airtightness. With filtration, the higher the filter efficiency the more the total efficiency varies with both airtightness and ventilation rate.

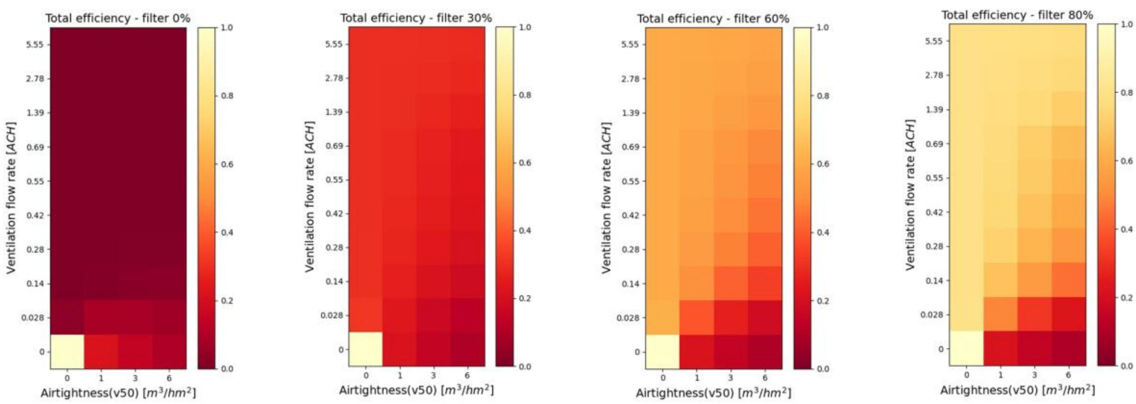

Figure 3: Total efficiencies for different ventilation rates, v_{50} and filter efficiencies. The highest total efficiency is one, in light yellow on the scale and the lowest is zero, in dark red.

Figure 4 shows the total efficiencies normalized by the filter efficiency. It confirms that with a higher filter efficiency the influence of airtightness and ventilation rate is increased. Indeed, it can be seen that the higher the filter efficiency, the more the leaks and the ventilation flow rate have an impact on the indoor concentration (more marked colour gradient). There is more potential to degrade the indoor air quality when you have a good filter. The ventilation rate has a greater impact on the overall efficiency when v_{50} is large (right column on the maps). Airtightness has a greater influence on total efficiency at low flow rates (bottom row on the maps).

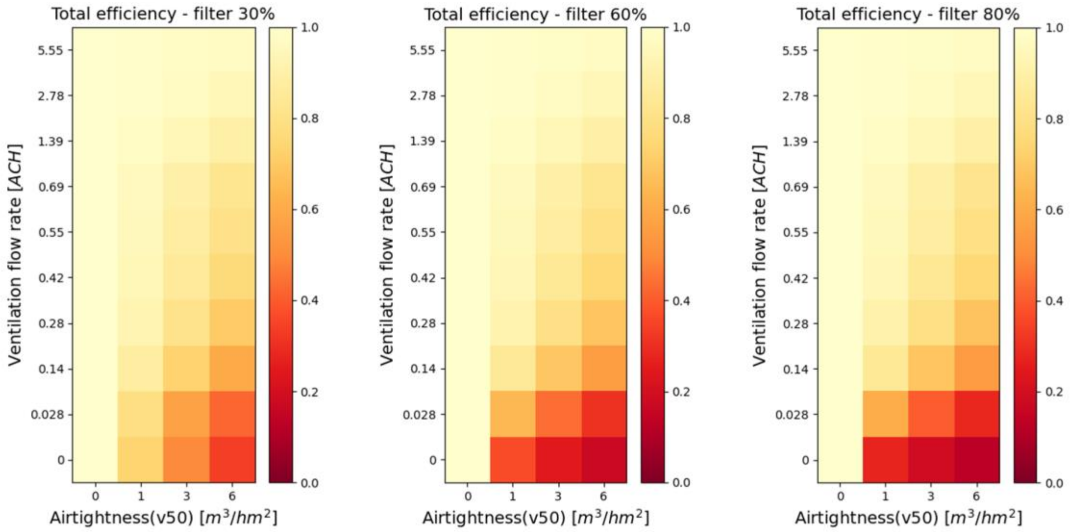

Figure 4 : Normalized total efficiencies for different ventilation rates, v_{50} and filter efficiencies

2.2.2 Complex model

This model shows similar trends to the simple model :

- the higher the filter efficiency, the lower the occupant exposure
- without filtration the occupant exposure is almost constant with non-zero ventilation rate
- with filtration the occupant exposure increases as leaks increase and ventilation flow rates decrease

2.3 Discussion

The results obtained provide a better understanding of the influence of filter efficiency, envelope airtightness and ventilation flow rate in the penetration of outdoor $PM_{2.5}$ inside. The filter efficiency has an important influence. It sets the lowest indoor $PM_{2.5}$ level that can be reached at the building level in the best conditions. The lowest level is the “plateau” colour in Figure 3 and Figure 4. Imperfect airtightness deteriorates this level : the indoor $PM_{2.5}$ concentration increases as leaks increase. Part of the outside air is filtered by circulating in the ventilation system and another part enters the house through the leaks by infiltration without filtration. The higher the leaks, the higher the percentage of unfiltered air entering the home. Increasing the ventilation flow rate is a way to reduce the impact of the infiltrations as the proportion of air filtered by the system increases in relation to the air flow through infiltrations. In order to achieve low indoor $PM_{2.5}$ concentrations, a tight building envelope, high filter efficiency and high flow rate are required.

The purpose of the complex model was to see if the above-mentioned conclusions were generalizable to a more elaborated model, composed of several rooms, a ventilation system with air transfer from some rooms to others, and occupants with a particular occupation profile of these spaces. The trends regarding the impact of airtightness, filter efficiency and ventilation are the same ones. Using the one zone model is thus sufficient to analyse the key phenomena.

Remark : These results are valid for other pollutants and for efficiencies corresponding to these pollutants. Here, $PM_{2.5}$ and the associated filter efficiencies were investigated. In practice, other pollutants such as finer PM or gaseous pollutants may not have as high a filter efficiency as $PM_{2.5}$.

3 INTEREST IN COTROLLING THE VENTILATION BASED ON OUTDOOR POLLUTANTS

3.1 Methodology

3.1.1 No ventilation control

Based on $PM_{2.5}$ outdoor pollutant data from Molenbeek-Saint-Jean in 2018, the evolution of indoor $PM_{2.5}$ concentration was studied for three types of days and different configurations. The analysed days were :

- Days with the highest 24-hour mean $PM_{2.5}$ concentration : 3/03/2018 and 21/04/2018
- Days with the highest variability in $PM_{2.5}$ concentration: 21/04/2018, 15/05/2018, 25/05/2018 and 26/05/2018
- Days with a smog alert: 21/02/2018 , 03/03/2018 and 15/05/2018 [3]

Table 3 shows the different studied configurations.

Table 3: Simulated cases with Molenbeek-Saint-Jean's $PM_{2.5}$ outdoor conditions 2018

Parameters	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5	Variant 6
Ventilation system	No system	No system	C or D	C or D	D	D
Flow rate (ACH)	0	0	0.28	0.28	0.28	0.28
$PM_{2.5}$ outdoor concentration (µg/m^3)	Molenbeek	Molenbeek	Molenbeek	Molenbeek	Molenbeek	Molenbeek
v_{50} (m^3/h m^2)	1	6	1	6	1	6
Filter efficiency (%)	0	0	0	0	80	80

As discussed in the previous section, the complex model shows similar trends to the simple model regarding the impact of airtightness, ventilation flow rate and filter efficiency on the penetration of $PM_{2.5}$ inside. Therefore, the studied configurations were only those of the simple model.

3.1.2 Ventilation control

From the specific days analysis, it was noticed that it may be useful in some configurations to switch off the ventilation system for a certain time period. Further investigation was carried out to determine, according to the available ventilation system and building envelope, how to act in case of a pollution peak and if there is a real interest for an automatic regulation of the ventilation systems based on the outside. Another set of cases was simulated in which the ventilation flow rates were partially (by 50 or 75%) or totally reduced when the exterior $PM_{2.5}$ concentration exceeded the WHO threshold. The WHO recommends that fine particulate matter does not exceed 15 µg/m^3 24-hour mean for more than 3-4 days per year. [2] The goal of these drafted guidelines is to reduce the health effect as much as possible.

The simulations were carried out for a full year, based on outdoor pollutant data from Molenbeek-Saint-Jean in 2018. These different ventilation strategies were assessed through exceedances days. An exceedance day is a day for which the 24-hour average exceeds 15 µg/m^3. Exceedance days were calculated for 80 simulation variants combining 5 filter efficiencies (0%, 15%, 30%, 60% and 80%), 4 values of v_{50} (0, 1, 3 and 6 m^3/h m^2) and 4 types of control (no control, reduction of the ventilation flow rate by 50%, by 75% or by 100% when the WHO threshold is reached).

3.2 Results

3.2.1 No ventilation control

Figure 5 shows time evolution of $PM_{2.5}$ concentration around 3rd March. Looking at the concentration peak as a whole, it can be seen that the simulation variants without filter (green curves) have a higher indoor concentration than the simulation variants without flow rate (orange and red curves) during the ascending phase of the peak. The variants with a 80% filter efficiency have the lowest indoor concentration during the pollution peak (blue curves).
The other specific days were analysed in another set of simulations and show similar trends to those mentioned for 3rd March.

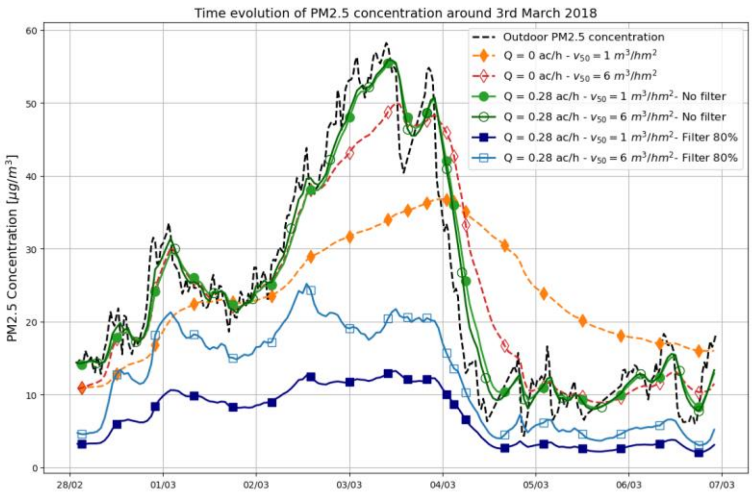

Figure 5: Time evolution of $PM_{2.5}$ concentration around 3rd March 2018 for different simulation variants. The black dotted line is the outdoor $PM_{2.5}$ concentration. The coloured lines are the simulation variants with different flow rates, airtightness and filter efficiencies.

3.2.2 Ventilation control

In general, it has been observed that the higher the filter efficiency, the fewer the number of exceedance days, see Figure 6. The number of exceedance days may decrease for variants without filter, with a 15% and 30% filter efficiency when the ventilation is controlled based on outdoor pollution. However, there are more days exceeding the threshold for variants with a 60% and 80% filter efficiency by trying to control the ventilation than by letting it run normally when the building envelope is not perfectly airtight.

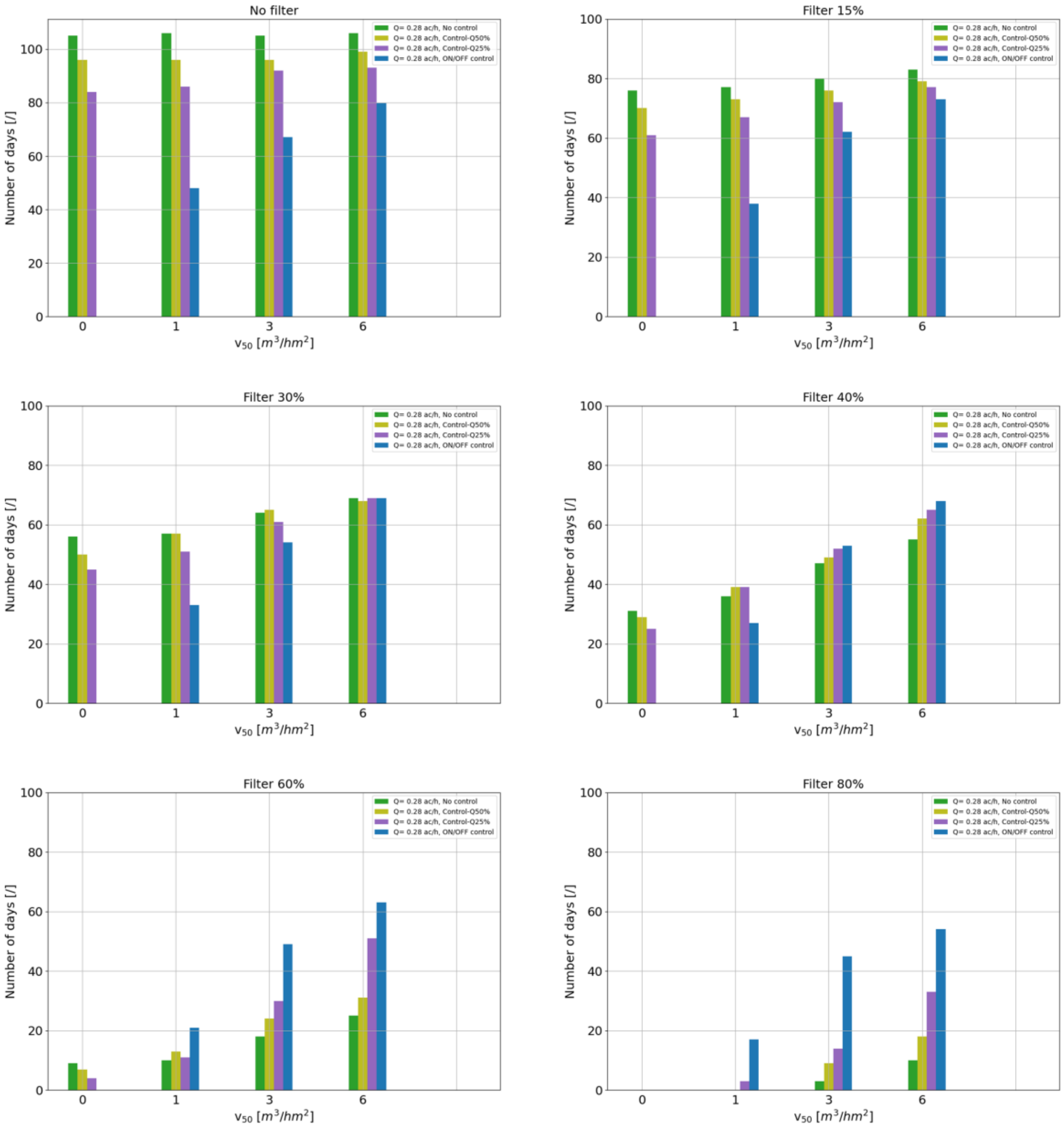

Figure 6 : Number of days exceeding the WHO $PM_{2.5}$ threshold for different control strategies, v_{50} and filter efficiencies

3.3 Discussion

Figure 5 shows a potential benefit of regulating the ventilation system to reduce the indoor $PM_{2.5}$ concentration (orange curve). Based on this, this section examines two questions that have practical applications :

- What recommendations can be given to act punctually in case of a pollution peak ?
- Would it be interesting to add automatic controls on ventilation based on outdoor air quality ?

The answer to these questions depends on the building airtightness, the filter efficiency and the ventilation flow rate, if there is a ventilation system. Two scenarios can clearly be distinguished: the case with a very efficient filtration and the case without filtration, i.e. with natural ventilation, fan assisted exhaust ventilation or even fan assisted balance ventilation but without filter.

For a ventilation system with a high filter efficiency, it is always preferable to keep the ventilation regardless of the level of airtightness. As seen in Figure 5 and in section 2, a good filtration strongly reduces a pollution peak and can even eliminate it completely with a good airtightness. In this scenario, the ventilation system should not be punctually switched off in case of a $PM_{2.5}$ pollution peak. The filter efficiency is so high that it allows the building to be supplied with clean air, diluting indoor air which may have a higher concentration of $PM_{2.5}$ due to leaks. In reality, the action to be taken also depends on the composition of the peak and the filter efficiency towards these pollutants. Here, only one pollutant and its related efficiency were studied. In the event of a chemical accident that releases $PM_{2.5}$ and gases, the filter may have no effect on the gases. Moreover, automatically regulating ventilation according to the outdoor $PM_{2.5}$ concentration does not seem relevant either in case of mechanical ventilation with a good filtration.

For a ventilation system without filter or with a low filter efficiency, it is interesting to cut off the ventilation system punctually in case of a $PM_{2.5}$ pollution peak. However, if the airtightness is too poor, the reduction effect on the indoor $PM_{2.5}$ concentration is limited. It should also be pointed out that when the peak is over it is necessary to ventilate again. Otherwise, the accumulated pollutants remain inside, see orange curve in Figure 5. An automatic regulation of the ventilation system based on the outdoor concentration (for example for a fan assisted exhaust ventilation system) could be relevant. The efficiency of this regulation decreases as leaks increases or with manual opening of windows and manually controlled grids.

For a ventilation system with a moderate filter efficiency, the control strategy to apply is less obvious. Results for the 30% filter efficiency and 60% filter efficiency show that there is a tipping point for filter efficiency that determines the strategy to be followed : turning off the ventilation system for a 30% filter efficiency does not deteriorate the indoor air quality compared to the 60% filter efficiency that may be worsened. This tipping point does not only depend on the filter efficiency but also on the airtightness. Section 2 highlighted that the penetration of outdoor pollutants is influenced by airtightness, filter efficiency and ventilation flow rate.

For a ventilation system with a filter (without knowing its efficiency), that it is not unwise to recommend letting the ventilation run. The cases with $v_{50} = 0$ m^3/hm^2 are theoretical cases and in practice for an automatic control it is difficult to completely stop the ventilation system. The improvement regarding the exceedance days is actually small for low and moderate filter efficiencies when reducing the ventilation flow rate by 50 or 75%. In contrast, for higher filter efficiencies, letting the ventilation run gives a relevant improvement.

4 CONCLUSIONS

This simulation study showed that the penetration of $PM_{2.5}$ outdoor pollutants can be limited by a good $PM_{2.5}$ filter efficiency, a tight building envelope and a high ventilation flow rate.

It also highlighted an interest in controlling the ventilation system based on the outdoor pollutant concentration when this one is not equipped with a filter. The indoor $PM_{2.5}$ concentration decreases when ventilation is partially or totally switched off. However, for cut-offs lasting several hours due to high outdoor $PM_{2.5}$ concentration, one might ask whether it is efficient to turn off the ventilation system : indoor $PM_{2.5}$ concentration will be lower but that air renewal will be insufficient, leading to an accumulation of other indoor pollutants. Further research is needed to find this trade-off between outdoor conditions and indoor air quality.

This simulation study finally discussed control strategies regarding ventilation systems equipped with a certain filter efficiency. The control strategy to adopt for the intermediate situation, i.e. a ventilation system with a moderate filter efficiency, is not straightforward. This leads to a general control strategy, namely letting the ventilation system run in case the filter efficiency is unknown. This general control strategy seems to be a good compromise as the number of exceedance days is significantly lower when letting the system run for high filter efficiencies than the reduction in exceedance days obtained when the system is cut-off for low filter efficiencies.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

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