Journal of Hazardous Materials 163 (2009) 454–462

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Particulate pollution in ventilated space: Analysis of influencing factors

Bin Zhao*, Jun Wu

Department of Building Science, School of Architecture, Tsinghua University, Beijing, China

ARTICLE INFO

Article history:
Received 7 May 2008
Received in revised form 27 June 2008
Accepted 27 June 2008
Available online 6 July 2008

Keywords:
Particle pollution
Ventilation
Indoor air quality (IAQ)
Influencing factor

ABSTRACT

Particle pollution has been identified to be a major indoor air pollution problem as many epidemiologic evidences have indicated that the particle exposure affects the occupant health. In common practice, mechanical ventilation is introduced to maintain a satisfactory indoor air quality for the occupant, which includes the area of particle control within the space. In order to have an effective control to the indoor particle pollution, it is important to understand the major factors influencing the indoor particle concentration in the breathing zone. This study employs a previously proposed approach to study the particle pollution in a typical ventilation system. The model simultaneously takes into account the interactions between particle transport in ventilation ducts and rooms and particle spatial distribution. It has been proven that an entire ventilation system, including filters, ducts and rooms, can be regarded as a serial of filters in steady-state cases, hence the name "particle filter group model". The particle concentration in the breathing zone is calculated under different conditions, and the result is then validated by experimental data. Based on the results, four main factors that affect the particle concentration in the breathing zone are identified, they are fresh air rate, particle filter efficiency, the type of the ventilation duct (roughness) and ventilation modes. Their degrees of influence are analyzed and then the possible measures to improve/control the indoor particle pollution are suggested.

1. Introduction

Epidemiologic evidence has supported a strong association between exposure to fine particles and adverse health effects including aggravation of respiratory and cardiovascular disease, lung disease, decreased lung function, asthma attacks, heart attacks and cardiac arrhythmia [1]. Since people spend most of their time indoors, special attention should be paid on indoor particle pollution. Due to the relatively high concentration of particle in China, it makes the research on particle pollution even more important than the other countries comparatively. In order to have a better control on the indoor particle pollution, it is worthwhile to understand how the major factors influence the indoor particle concentration in breathing zone.

Meanwhile, mechanical ventilation systems are widely used to maintain thermally comfortable environment and with satisfactory indoor air quality (IAQ) for the occupants. In common practice, a certain percentage of recycled air is recirculated into the mechanical ventilation system and its particle concentration level is related to the couple effect of the particle deposition in ventilation ducts and dispersion inside rooms. On the other hand, the inlet particle concentration depends on both indoor particle generation rate and also the atmospheric particle coming in with the fresh air. These complex relations make it very difficult to compute the particle concentration in each part of the system. In order to simplify the calculation, most of the existing studies used zero inlet particle concentration as the boundary conditions for indoor particle distribution calculation, for example, Holmberg and Li [2], Holmberg and Chen [3] and Zhao et al. [4].

The main objective of this paper is to adopt the previous proposed approach – particle filter group model [5] – to study the indoor particle concentration in a mechanical ventilation system. The advantage to employ this model is that it simultaneously takes into account the interactions between particle transport in ventilation ducts and rooms and particle spatial distribution. The influence of fresh air rate, the particle filter efficiency, the type of ventilation duct (roughness) and the ventilation modes on particle pollution in the breathing zone is further analyzed, and then the possible measures to improve/control the indoor particle pollution are suggested based on the analysis.

* Corresponding author. Tel.: +86 10 62779995; fax: +86 10 62773461.
E-mail address: binzhao@tsinghua.edu.cn (B. Zhao).

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doi:10.1016/j.jhazmat.2008.06.118

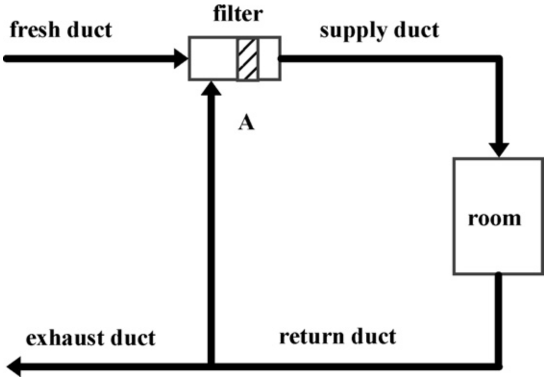


Fig. 1. Schematic diagram of the studied ventilation system.

2. Methodology

2.1. Particle filter group model

The particle filter group model is employed in this study. This approach is based on the fact that the entire ventilation system, including filters, ventilation ducts and ventilation rooms, could be regarded as a serial of filters in steady-state cases. The penetration coefficients of each part of the ventilation system remain constant with the intake particle concentration, which are similar to the real filter. The particle phase is too dilute to have any effect on indoor airflow, thus satisfying the linear superposition theorem in the calculation for indoor particle concentration. This issue has been proved both theoretically and experimentally [5].

For a simple ventilation system with one AHU and one ventilation room, as shown in Fig. 1, the particle concentration at point A (after the fresh air mixed with the recycled air) can be calculated with the following equations in accordance to the particle mass conservation principle:

$$C_{\text{in,fresh}} = \frac{Q_{\text{fresh}} C_{\text{out}} P_{\text{fd}}}{Q_s - Q_{\text{r,returm}} P_{\text{sd}} P_{\text{room,s}} P_{\text{rd}}} \tag{1}$$

$$C_{\text{in,sp}} = \frac{(Q_{\text{r,returm}}/Q_s) \sum_{i}^{B} (\text{Sp}_i P_{\text{room,sp},i} P_{\text{rd}})}{Q_s - Q_{\text{r,returm}} P_{\text{sd}} P_{\text{room,s}} P_{\text{rd}}} \tag{2}$$

Here $C_{\text{in,fresh}}$ is the concentration of the particles from the outdoor air at point A. $C_{\text{in,sp}}$ is the concentration of the particles from the indoor particle source at point A. Q_{fresh} is the fresh airflow rate. C_{out} is the atmospheric/outdoor particle concentration. P_{fd} is the penetration coefficient of the fresh duct. Q_s is the airflow volume of the ventilation room. $Q_{\text{r,returm}}$ is the recycled airflow rate. P_{sd} is the penetration coefficient of all ventilation parts from point A to the inlet of the ventilation room. $P_{\text{room,s}}$ is the penetration coefficient from the inlet to the outlet of the room. P_{rd} is the penetration coefficient of the return duct. $P_{\text{room,sp},i}$ is the penetration coefficient from the particle source i to the outlet of the room. Sp_i is the generating rate of indoor particle source i. The detail of the calculation method for the penetration coefficient of each part of the ventilation system could be found in Ref. [5] and thus not repeated here.

When the particle concentration at point A is calculated, the particle concentration at the inlet of the ventilation room could also be determined by multiplying the particle concentration at point A with the penetration coefficient from point A to the inlet of the ventilation room. Thus the particle concentration of the entire ventilation system could be analyzed.

2.2. Experimental validation of the particle dispersion calculation

The two main key points for applying particle filter group model is the correct prediction of particle deposition in ventilation ducts and particle dispersion in ventilation rooms, which are used to calculate the penetration coefficient of ventilation ducts and rooms. The previous study has validated particle deposition calculation [6,7], whereas the calculation of particle dispersion in indoor environment is validated by the experiment in a test chamber.

Drift flux model is employed to calculate indoor aerosol particles distribution. This model is a Eularian method that integrates the gravitational settling effects of particles into the concentration transportation equation. It is an improvement of the traditional transportation model of contaminant concentration by adding the drift flux term into the particle concentration equation, which is caused by the velocity slippage of particle and air due to drag force and gravity. Especially, the particle deposition boundary conditions for walls are developed based on the analytical expression of deposition velocity by Lai and Nazaroff [8]. This treatment is just like the wall functions for particle concentration governing equation [4].

The particle deposition and the concentration measurement were carried out in a cubic test room ($L(X) \times H(Y) \times W(Z) = 4\,\text{m} \times 3\,\text{m} \times 2.5\,\text{m}$). A mechanical ventilation system was installed to simulate different indoor environments. The air change rate of the test room was maintained at 8.0 ACH in this study, which was controlled by an electronic fan speed controller and measured by a nozzle flowmeter, as shown in Fig. 2(a). A high efficiency particle filter was used to prevent incoming particles from outdoor, so that the particle concentration of the supply air could be regarded as zero and thus neglected the background particle influence. The configuration of the ventilation mode (bottom supply) is shown in Table 1 and Fig. 2(b). The inlet and outlet were symmetrical with the center plane ($Z = 1.5\,\text{m}$). The measurements were performed under isothermal condition. A condensation mono-disperse aerosol generator (TSI 3475, TSI Inc.) was used to generate fine DEHS particles. The density of the generated particles is $914\,\text{kg/m}^3$, approximately equal to the density of water and thus the diameter of particles is approximately equal to aerodynamic diameter. The tested particle sizes were $0.75\,\mu\text{m}$, $1.5\,\mu\text{m}$ and $10\,\mu\text{m}$, representing fine, accumulation and coarse mode particles, respectively. The size of the particle generator was $L(X) \times H(Y) \times W(Z) = 0.3\,\text{m} \times 0.56\,\text{m} \times 0.3\,\text{m}$, and it was also symmetrical with the center plane, as shown in Fig. 2(b). Two optical particle counters (FLUKE 983, FLUKE Inc.) were used to measure the particle concentration on three vertical lines

Table 1
Configuration of the validated ventilation mode (inlet/outlet locations)

Ventilation modes	Inlet						Outlet					
	X_s [a]	X_e [a]	Y_s [b]	Y_e [b]	Z_s [c]	Z_e [c]	X_s [a]	X_e [a]	Y_s [b]	Y_e [b]	Z_s [c]	Z_e [c]
Bottom supply	1.82	2.18	0	0	1.32	1.68	2.22	2.4	2.5	2.5	1.41	1.59

[a] X_s and X_e denote the start and end location in X axis, respectively.
[b] Y_s and Y_e denote the start and end location in Y axis, respectively.
[c] Z_s and Z_e denote the similar meaning in Z axis, respectively.

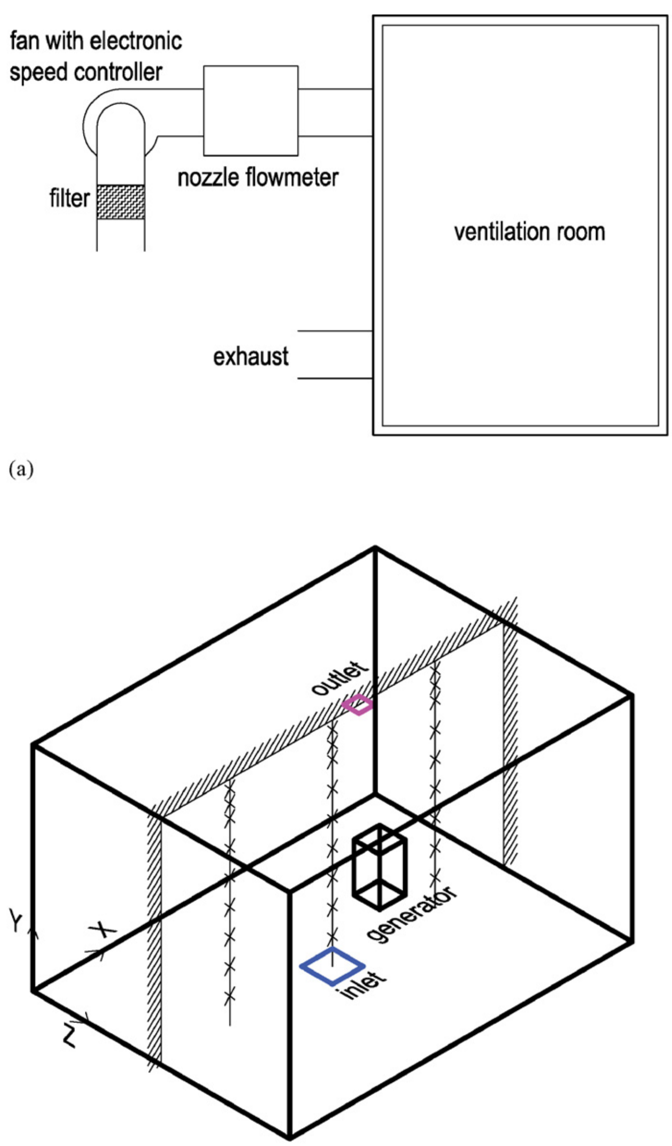
in the room, which were all on the center plane (Z = 1.5 m) and the X location was 0.8 m, 2 m and 3.2 m, respectively.

In this study, the predetermined airflow rate of the ventilation system was fixed at 8.0 ACH. The aerosol generator generated particles of certain volume continuously throughout the measurement (the ventilation system was started 30 min earlier than the TSI 3475). The particle counter was used to count the particle concentration at the outlet automatically until the particle concentration in the room remained constant. The number of samples in each measured point was 6 and the duration of measurement at each point was 15 min (detailed set of the sampling points could be found in the results, Fig. 2(c)). When other measured points were required, the experimenter would have to enter the test room to relocate particle counters. To avoid experimental errors, the measurement would not resume until 15 min after the experimenter had left the room. This was to ensure that the test room would return to a steady-state condition in accordance to the ventilation rate. The ventilation room was sealed up as the door has rubber sealing strip installed at the edges, which could seal the only crack between the door and wall well. Nobody was inside the room during the experiment. Thus the particle resuspention could be neglected. The comparison was presented in Fig. 2(c). It indicated that the calculated particle concentration of different sizes has a good agreement with the measurements.

3. Cases analysis

3.1. Cases

The mechanical ventilation system shown in Fig. 2(a) is studied since it is similar to the real ventilation system used in many actual engineering. It has fresh air supply duct, return duct and exhaust duct with the corresponding supply airflow rate at 8 ACH, which is also the popular value in actual engineering applications. However, this value may be a bit high for “bottom supply” case. It should be noted that we want to incorporate the influence of ventilation strategies on particle pollution, thus we maintain the same supply airflow rate for different ventilation strategies so that we can



(a)

(b)

Fig. 2. (a) Experiment setup, (b) schematic diagram of the validated ventilation mode, (c) comparison of measured and calculated particle concentration.

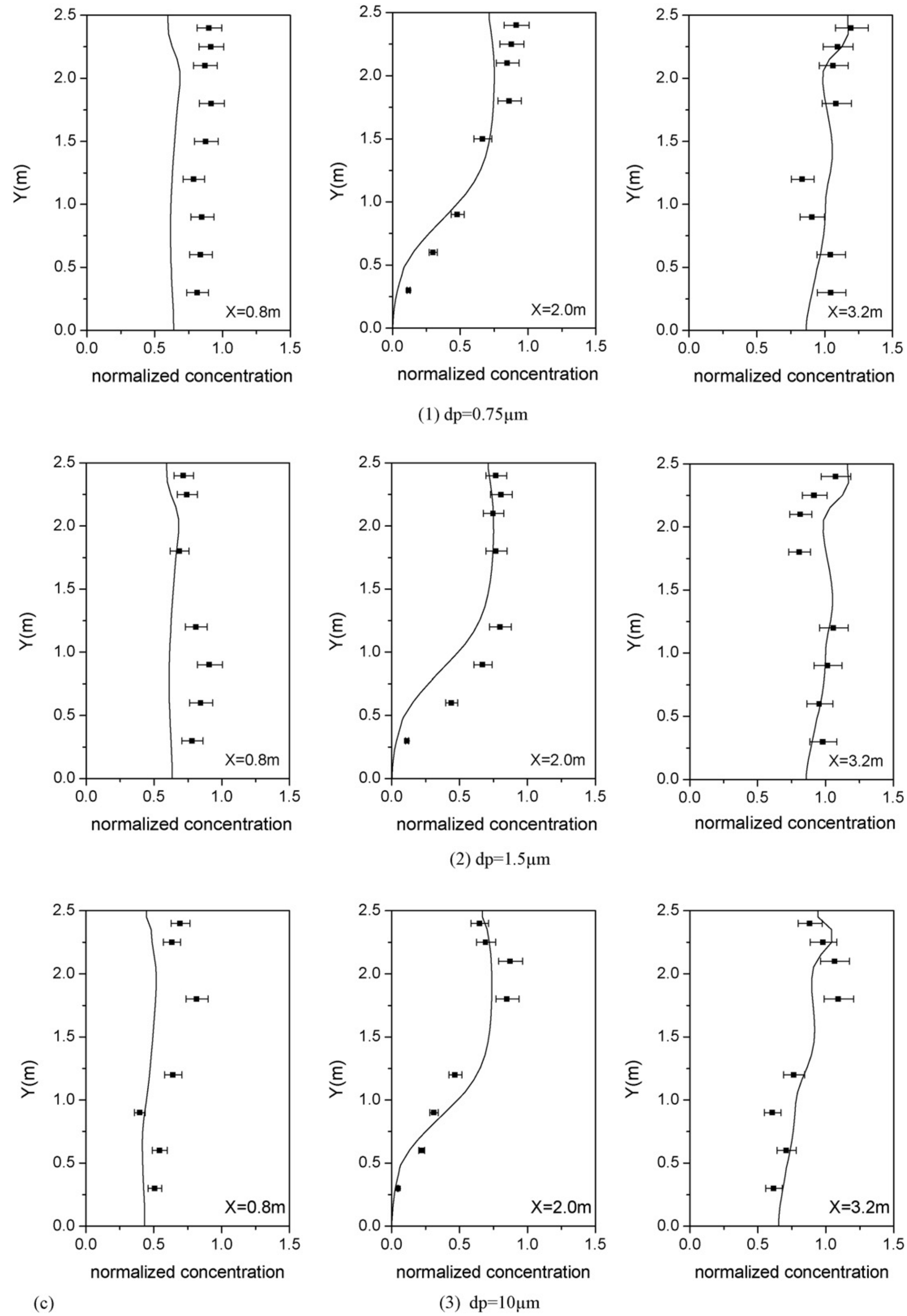


Fig. 2. (*Continued*).

focus on the effect of ventilation modes themselves. This is the main reason why we keep 8.0 ACH for "bottom supply" case. The configurations of ventilation ducts are listed in Table 2 and the sketch map of the ventilation system is shown in Fig. 1.

To study the influence of different parameters of the ventilation components on indoor particulate pollution, four influencing factors are studied in this case, that is, different fresh air rate (10%, 50% and 100%, respectively), two different types of the ventilation ducts (steel duct with smooth inner surface and slag gypsum board duct with rough inner surface, whose effective rough height is 1000 μm (micron)), three different types of filters (ASHRAE 40% filter, ASHRAE 85% filter and zero efficiency filter, that is, no fil-

Table 2
Configuration of the ventilation ducts

Ventilation ducts	Cross section (mm × mm)	Length of horizontal duct (mm)	Length of vertical duct (mm)	Number of bends
Fresh air duct	120 × 120	2000	0	1
Supply duct	120 × 120	5000	2000	4
Return duct	120 × 120	5000	2000	4
Exhaust duct	120 × 120	2000	0	1

Table 3
Filter efficiency of the different filters [10]

Particle diameter (μm)	ASHRAE 40% filter	ASHRAE 85% filter
0.25	3.6%	50.4%
0.75	9.1%	78.7%
2	32.4%	95.1%
4	97.3%	100.0%
7.5	100.0%	100.0%
20	100.0%	100.0%

ter; the filter efficiency of different particle diameters is shown in Table 3) and four different ventilation modes that could stand for the most commonly used ventilation modes (ceiling supply, side-up supply, side-down supply and bottom supply). All the inlets and outlets are symmetrical with the center plane (Z = 1.5 m). The configuration of the four ventilation modes is shown in Table 4 and Fig. 3. The particle source is the same as that used in the experiment above.

Here the particles of six different sizes (0.25 μm, 0.75 μm, 2 μm, 4 μm, 7.5 μm and 20 μm in diameter) are analyzed. These particle size distributions are the same as the size distribution of the outdoor air observed in Beijing, China [9].

A standard case is assumed with a ventilation system that has 10% fresh air rate, ASHRAE 40% filter, steel ventilation duct and side-up supply ventilation mode. This is for the analysis of basic characteristics of indoor particulate pollution in the entire ventilation system. When analyzing one of the four influencing factors (fresh air rate, the filter efficiency of the filter, the type of the ventilation duct and ventilation modes), the other influencing factors are assumed to be as same as the standard case.

3.2. Results

3.2.1. Indoor particulate pollution of the standard case

The penetration coefficient at each part of the ventilation system should be determined first in order to obtain the particle concentration at the inlet of the ventilation room. With a method suggested by Zhao and Wu [5], the penetration coefficient at each part of the standard case can be calculated. The results are shown in Table 5.

Then with Eqs. (1) and (2), the particle concentration of different particle sizes after the fresh air mixed with the recycled air can be calculated. Since the particle concentration of the fresh air and the generating rate of indoor particle source might be quite different in real case, the absolute value of the particle concentration after

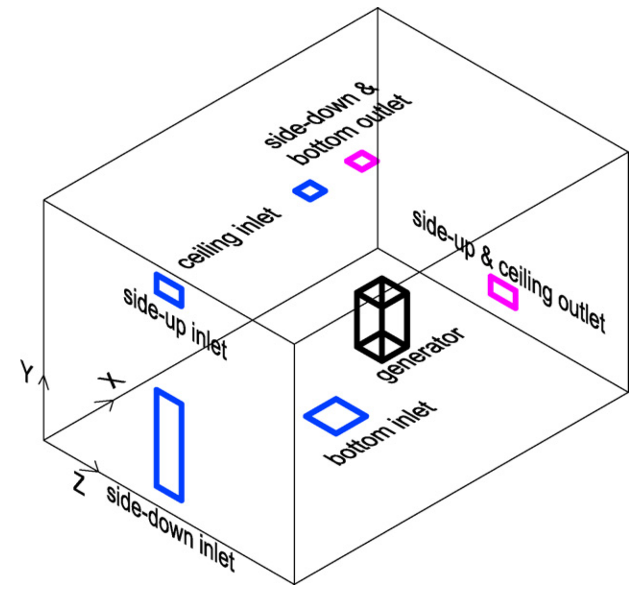


Fig. 3. Schematic diagram of the different ventilation modes.

the fresh air mixed with the recycled air makes little sense. This also suggests that the particle filter group model satisfies the linear superposition theorem and the penetration coefficients of each part of the ventilation system do not vary with the intake particle concentration. Therefore, the relative value of the particle concentration after the fresh air mixed with the recycled air, $(C_{in,fresh})/C_{out}$ and $(C_{in,sp}Q_s)/Sp$, is adopted, as shown in Table 6.

With the results listed in Table 6, the particle concentration at the inlet of the ventilation room can be calculated and then the indoor particle concentration can be determined. The average particle concentration in the breathing zone (in this case, the breathing zone is defined as the indoor space with the height range between 1.0 m and 1.8 m) is analyzed, as the concentration in this zone is regarded as the most important to human health. Table 7 lists the results.

In this table, $C_{breath,fresh}$ is the concentration in breathing zone of the particles from the outdoor air, $C_{breath,sp}$ is the concentration in breathing of the particles from the indoor particle source.

Table 7 shows that the coarse particles in breathing zone are almost entirely coming from the indoor particle source, as most

Table 4
Configuration of the four ventilation modes (inlet/outlet locations)

Ventilation modes	Inlet						Outlet					
	X_s[a]	X_e[a]	Y_s[b]	Y_e[b]	Z_s[c]	Z_e[c]	X_s[a]	X_e[a]	Y_s[b]	Y_e[b]	Z_s[c]	Z_e[c]
Ceiling supply	1.6	1.78	2.5	2.5	1.41	1.59	4	4	0.2	0.38	1.35	1.65
Side-up supply	0	0	2.22	2.4	1.41	1.59	4	4	0.2	0.38	1.35	1.65
Side-down supply	0	0	0.2	1.2	1.35	1.65	2.22	2.4	2.5	2.5	1.41	1.59
Bottom supply	1.82	2.18	0	0	1.32	1.68	2.22	2.4	2.5	2.5	1.41	1.59

[a] X_s and X_e denote the start and end location in X axis, respectively.
[b] Y_s and Y_e denote the start and end location in Y axis, respectively.
[c] Z_s and Z_e denote the similar meaning in Z axis, respectively.

Table 5
Penetration coefficient at each part of the standard case

Particle diameter (μm)	Fresh air duct (%)	Supply duct (%)	Return duct (%)	Exhaust duct (%)	Filter (%)	Room $P_{room,s}$ (%)	Room $P_{room,sp}$ (%)
0.25	99.98	99.95	99.95	99.98	96.40	99.88	99.89
0.75	99.92	99.93	99.93	99.92	90.90	99.63	99.64
2	99.53	99.65	99.65	99.53	67.60	97.88	97.93
4	98.03	98.60	98.60	98.03	2.70	92.30	92.55
7.5	93.57	94.48	94.48	93.57	0.00	77.62	78.43
20	64.04	57.86	57.86	64.04	0.00	41.34	44.44

Table 6
The particle concentration after the fresh air mixed with the recycled air

Particle diameter (μm)	0.25	0.75	2	4	7.5	20
$(C_{in,fresh}/C_{out})$	0.74	0.54	0.24	0.10	0.09	0.06
$(C_{in,sp}Q_s)/Sp$	6.69	4.82	2.15	0.84	0.67	0.20

coarse particles from outdoor air are filtered and deposited in the ducts. The small penetration coefficient of the ducts and the filter plays an important role as the particles from the outdoor air initially flow through the fresh air duct and then through the particle filter.

3.2.2. The influence of the fresh air rate

Fig. 4 shows the influence of fresh air rate on the indoor particle concentration in the breathing zone, including the particles from the outdoor air and the indoor particle source. It is found that as the fresh air rate increases, the concentration of the fine particles from the outdoor air increases while that of the fine particles from the indoor particle source decreases. The reason is that when the fresh air rate increases, the ratio of the particles circulated in the ventilation system decreases. Therefore, it is difficult to determine the influence of fresh air rate on the total fine particle concentration in the breathing zone. However, for coarse particles, whether it is from the outdoor air or from the indoor particle source, the concentration in the breathing zone varies little with the fresh air rate as most of the coarse particles deposited in ducts and filters.

3.2.3. The influence of the filter efficiency

Fig. 5 shows that as the particle filter efficiency increases, the particle concentrations of both from the outdoor or indoor particle source decrease in the breathing zone. This is easy to understand since the particles from the outdoor air and the particles from the indoor particle source will both flow through the filter before they enter into the indoor environment.

3.2.4. The influence of the type of the ducts

As shown in Fig. 6, when the inner surface of the duct changes from smooth to rough, the particle concentration in the breathing zone decreases, for both the particles from the outdoor air and the particles from the indoor particle source. This change is more obvious for the fine particles than that for the coarse ones. This is due to the fact that the roughness of the duct affects the deposition velocity of the fine particles much more than that of coarse particles [7]. This indicates that the penetration coefficient of the ducts change more obviously for the fine particles. When the particle size is sufficiently big, the particle concentration in the breathing zone does not change with the roughness of the inner surface. As in this case, the penetration coefficient of the filter is so small that few particles could reach to the inlet of the ventilation room.

Table 7
The particle concentration in the breathing zone of the standard case

Particle diameter (μm)	$(C_{breath,fresh}/C_{out})$	$(C_{breath,sp}/(Sp/Q_s))$
0.25	0.6950	7.0789
0.75	0.4710	5.0550
2	0.1551	2.1828
4	0.0024	0.7823
7.5	0.0000	0.6321
20	0.0000	0.2590

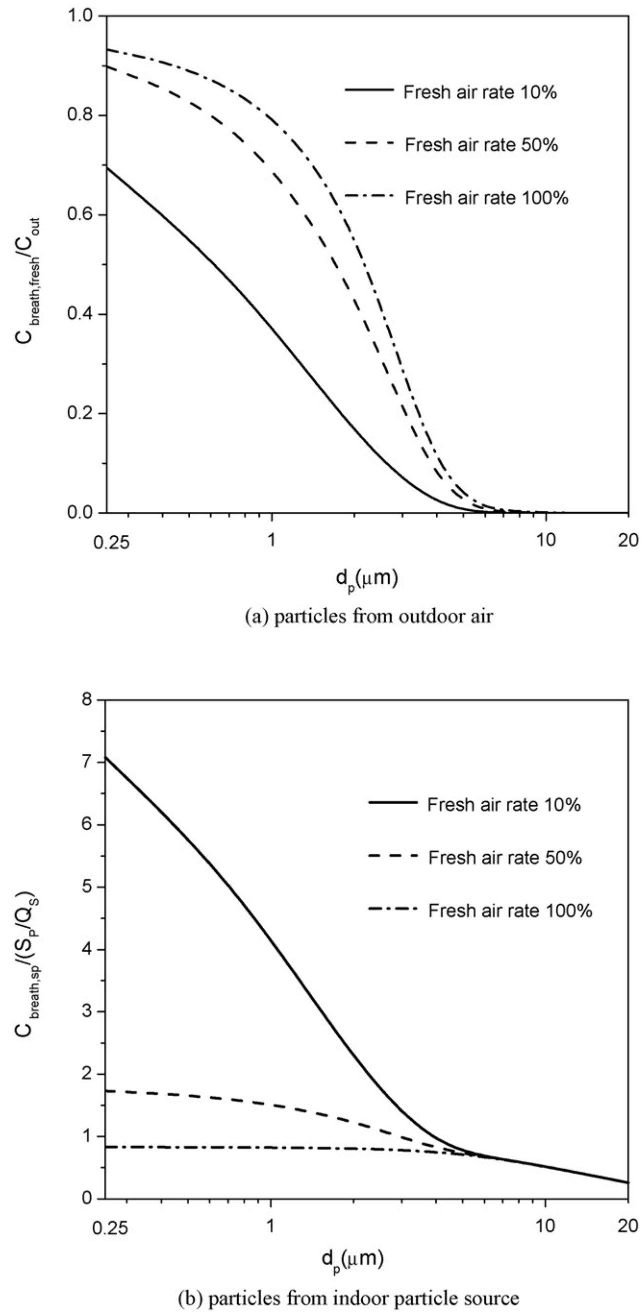


Fig. 4. The influence of the fresh air rate on particles from outdoor air and particles from indoor particle source.

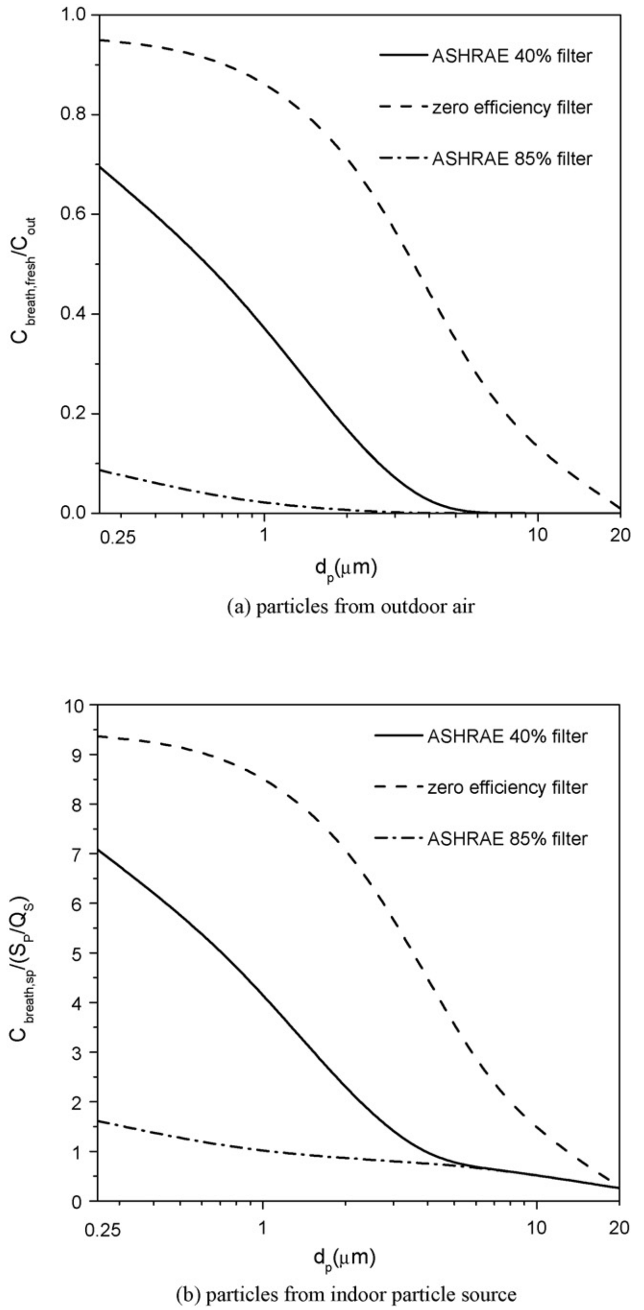


Fig. 5. The influence of the filter efficiency on particles from outdoor air and particles from indoor particle source.

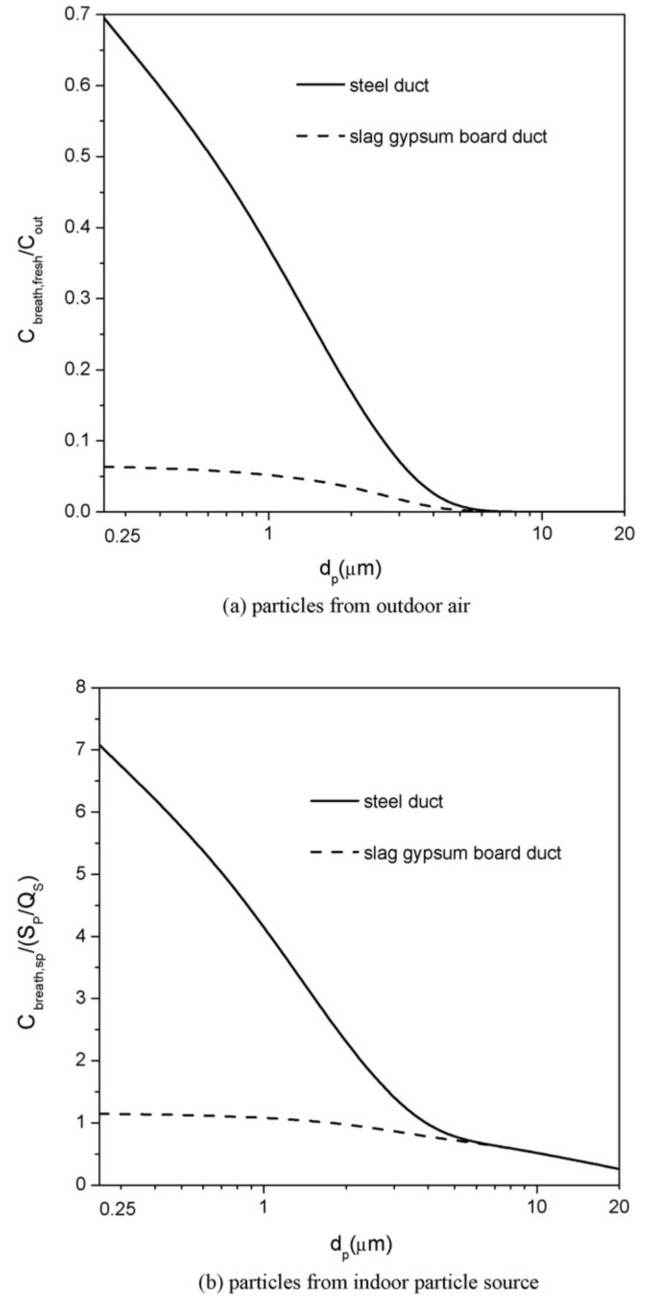
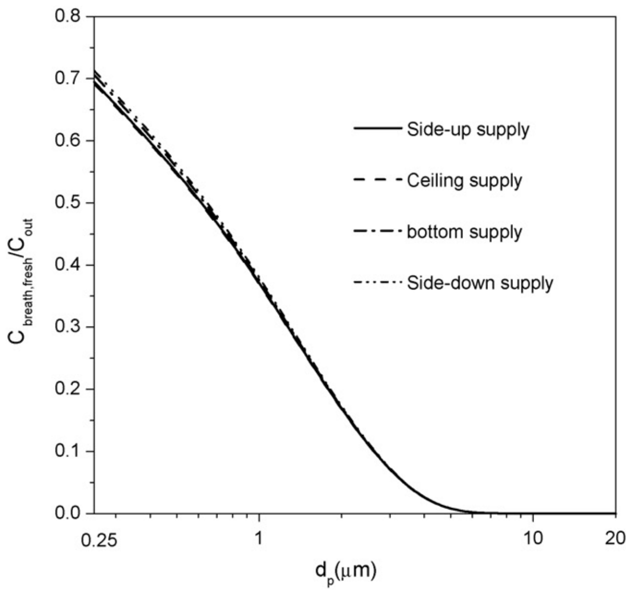


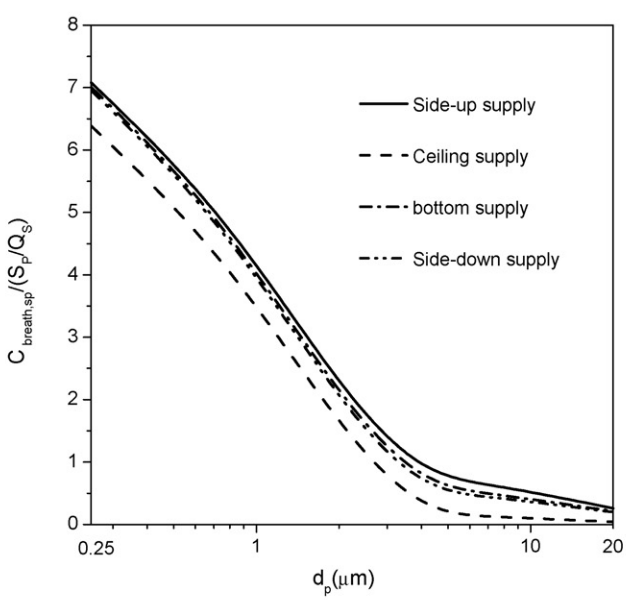
Fig. 6. The influence of the type of the ducts on particles from outdoor air and particles from indoor particle source.

3.2.5. The influence of the ventilation modes

As shown in Fig. 7, when the ventilation modes change, the concentration in the breathing zone of the particles from the outdoor air varies little. This is because the ventilation modes have little effect on the particle concentration at the inlet of the ventilation room. For fine particles, the ratio of concentration in the breathing zone at the inlet concentration differs little for the four ventilation modes, while few coarse particles could reach to the inlet of the ventilation room. However, when the ventilation modes vary, the concentration in breathing zone of the particles from the indoor particle source varies much. Among the four ventilation modes, the side-up supply mode has the highest particle concentration in breathing zone and ceiling supply mode has smallest particle concentration. The difference in particle concentration between the bottom supply and side-down supply is not obvious. This is because the side-up supply mode allows air to mix well within the ventilation room, while the side-down and bottom supply modes make the airflow in the ventilation room similar to a “piston” flow. The smallest concentration of the ceiling supply mode is related to the location of the indoor particles source, which forces the air flow, along with the particles, directly to the outlet of the ventilation room. Therefore, the best ventilation mode was not always the same, it is strongly related to the location of the indoor particle sources.



(a) particles from outdoor air



(b) particles from indoor particle source

Fig. 7. The influence of the type of the ducts on particles from outdoor air and particles from indoor particle source.

3.3. *Measures to control particle pollution in ventilated spaces*

Based on the above analysis, potential measures are suggested for controlling indoor particle pollution, especially the particle concentration in breathing zone indoors.

By reducing the fresh air rate, enhancing the filter efficiency, and increasing the roughness of the ventilation ducts can all reduce the outdoor fine particle concentration in the breathing zone, while the influence of these three factors is not obvious for the coarse particles. Surely, the amount of fresh air rate, the filter efficiency, and the ducts roughness should be determined by many other factors. The analysis in this paper is just from the view-point of particle pollution control. The ventilation modes could hardly influence the outdoor particle concentration in breathing zone. Similarly, by increasing the fresh air rate, enhancing the filter efficiency, and increasing the roughness of ducts could also reduce the indoor fine particle concentration in the breathing zone, while the influence of these three factors is also not obvious for the coarse particles. However, the ventilation modes and the location of the indoor particle source can have a big influence on the indoor particle concentration for both fine and coarse particles.

Together, for the particles from the outdoor air and indoor particle source, enhancing the filter efficiency, and increasing the roughness could both reduce the indoor particle pollution. However, the most suitable fresh air rate should be based on the relationship between the outdoor particle concentration and the indoor particle generating rate. Generally, when designing a ventilation mode, the possible location of the indoor particle source should be decided first and the outlet should be close to the particle source for the airflow to effectively take the particles away from the breathing zone. If possible, the user should place the possible particle sources near the outlet and away from the breathing zone when using the room.

4. Discussion

Due to the dynamic accumulating characteristic of deposited particles on the wall surfaces, it is hard to consider the roughness caused by the previous deposited particles in present models. The roughness may be decided by the size of deposited particles and deposition rate. And the most important is that the roughness may become larger as more particles are deposited onto the wall surfaces. The effect of roughness caused by the previous deposited particles needs to be further explored.

As discussed by Zhao and Wu [5], the heat exchangers can be treated as filters based on the work by Siegel and Nazaroff [11]. Therefore, the particle filter group model can be easily extended to incorporate the heat exchangers or coils by adding one "filter" into the filter groups. However, the present study does not include dampers. The particle deposition rate onto different kind of dampers is another issue waiting for further study.

Besides the four influencing factors discussed in this paper, the supply airflow rate would also affect the concentration in the breathing zone significantly for both particles from the outdoor air and the indoor particle source. The reason is that different airflow rates lead to different air velocities in the ventilation ducts, which may change the penetration coefficient of the duct. And supply airflow rate decides the indoor airflow pattern and the particle spatial distribution. This would influence the particle pollution level coupled with particle source location. Therefore, the influence of the supply airflow rate on the concentration in the breathing zone needs further study by combining the influence of particle source location.

5. Conclusion

Particle filter group model is employed to predict the particle concentration in breathing zone with a typical ventilation system. The ventilation system studied is assumed to have one AHU within a room, which is simplified for analysis to grasp the main characteristics of particle concentration in ventilation system and its influencing factors. Four typical influencing factors are also analyzed with the particle filter group model. The following conclusions may be drawn:

(1) In a standard case, (10% fresh air rate, ASHRAE 40% filter, steel ventilation duct and side-up supply ventilation mode is setup for a standard case in this study), the coarse particles in the breathing zone are almost entirely coming from the indoor

particle source, as most coarse particles from outdoor air are filtered and deposited in the ducts.

(2) As the fresh air rate increases, the concentration in breathing zone of the fine particles from the outdoor air increases while that of the fine particles from the indoor particle source decreases. However, for coarse particles, the concentration in breathing zone from both the outdoor air and the indoor particle source varies little with the fresh air rate.

(3) When the filter efficiency of the filter increases, the particle concentration in the breathing zone decreases, for both the particles from the outdoor air and the particles from the indoor particle source.

(4) When the inner surface of the duct changes from smooth to rough, the particle concentration in the breathing zone decreases, for both the particles from the outdoor air and the particles from the indoor particle source. This change is more obvious for fine particles than that for coarse particles. When the particle size is big enough, the particle concentration in breathing zone does not vary with the roughness of the inner surface.

(5) When the ventilation modes change, the concentration in breathing zone of the particles from the outdoor air varies little. However, when the ventilation modes vary, the concentration in this zone of the particles from the indoor particle source varies greatly.

(6) For the particles from the outdoor air and indoor particle source, enhancing the filter efficiency, or increasing the roughness can reduce the indoor particle pollution, while there may be a more suitable fresh air rate. Generally, when designing a ventilation mode, the possible location of the indoor particle source should be decided first and the outlet should be close to the particle source so that the airflow can effectively take the particles away from the breathing zone.

Acknowledgements

This study is supported by National Key Technology R&D Program (no. 2006BAJ02A10) and the Fundamental Research Foundation of Tsinghua University (Grant no. Jcqn 2005002).

References

[1] U.S. Environmental Protection Agency (EPA), Review of the National Ambient Air Quality Standards for Particulate Matter: Policy Assessment of Scientific and Technical Information, OAQPS Staff Paper, 2005.
[2] S. Holmberg, Y. Li, Modelling of the indoor environment-particle dispersion and deposition, Indoor air 8 (1998) 113–122.
[3] S. Holmberg, Q. Chen, Air flow and particle control with different ventilation systems in a classroom, Indoor air 13 (2003) 200–204.
[4] B. Zhao, X. Li, Z. Zhang, Numerical study of particle deposition in two different kind of ventilated rooms, Indoor and Built Environment 13 (2004) 443–451.
[5] B. Zhao, J. Wu, Modeling particle fate in ventilation system—Part I: model development, Building and Environment 44 (2009) 605–611.
[6] B. Zhao, J. Wu, Modeling particle deposition from fully developed turbulent flow in ventilation duct, Atmospheric Environment 40 (2006) 457–466.
[7] B. Zhao, J. Wu, Modeling particle deposition onto rough salls in ventilation duct, Atmospheric Environment 40 (2006) 6918–6927.
[8] A.C.K. Lai, W.W. Nazaroff, Modeling indoor particle deposition from turbulent flow onto smooth surfaces, Journal of Aerosol Science 31 (2000) 463–476.
[9] Z. Xu, Theory of Air Cleaning Technology, Tongji University Press, Shanghai, P.R. China, 1998 (in Chinese).
[10] W.J. Riley, T.E. McKone, A.C.K. Lai, W.W. Nazaroff, Indoor particulate matter of outdoor origin: importance of size dependent removal mechanisms, Environmental Science and Technology 36 (2002) 200–207.
[11] J.A. Siegel, W.W. Nazaroff, Predicting particle deposition on HVAC heat exchangers, Atmospheric Environment 37 (2003) 5587–5596.