PROBE-PM—A CODE TO SIMULATE PARTICLE TRANSPORT IN VENTILATION SYSTEM

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ABSTRACT

Scientific studies have linked particulate matter with a series of significant health problems. In ventilation systems, indoor particle concentration and dust load on air duct surfaces are two concerns for human health. PROBE-PM (Predicting code for building environment-particulate matter transport simulation), a code to simulate the particle transport in the whole ventilation system is developed. PROBE-PM is employed to predict indoor particle concentration and dust load on duct surfaces by taking into the dynamic characteristic of the ventilation system and the effects of penetration through ducts on indoor concentration. The simulation models are introduced and a case study is analyzed.

KEYWORDS

Particle, ventilation system, indoor air quality

INTRODUCTION

Particulate matter is the term used for a mixture of solid particles and liquid droplets found in the air. Scientific studies have linked particulate matter, especially fine particles, with a series of significant health problems, including aggravated asthma, acute respiratory symptoms, chronic bronchitis and decreased lung function (EPA 1995). Many countries have set standards that regulate indoor particle concentration. Besides, if not properly installed, maintained and operated, components of ventilation systems may become contaminated with particles of dust, pollen or other debris. Combined with moisture, the potential for microbiological growth is increased and spores from such growth may be released into the room, causing allergic reactions or other symptoms and diseases in people exposed to them. In China, “hygiene norms of air conditioning and ventilation systems in public places” has made specific requirements on dust load on duct surfaces, which is 1g/m^2.

Particles could enter the room both from outdoors and indoor activities such as cooking, cleaning, smoking, or human movements. In the mechanical ventilation mode, assuming that air enters and exits the room only via ventilation systems, particles in outdoor air are drawn into the room through fresh air ducts and filters and some of indoor particles recycle into the room via return air, also passing through ducts and filters. Particles will deposit on duct surfaces and be captured by filters. Therefore, in order to know the indoor particle concentration and dust load on duct surfaces, particle transport in the whole ventilation system should be considered. The published work by Sippola and Nazaroff (2003) might be the only one that could be found, which combines the indoor particle concentration with particle transport in ventilation ducts and filters. However, the dynamic characteristic is negelected, which is actually important for real ventilation systems.

PROBE-PM (Predicting code for building environment-particulate matter transport simulation), a program to predict the particle transport in the whole ventilation system is developed in this study, including three basic components that affect the particle transport in ventilation systems. They are ventilation ducts, filters and ventilated rooms. The program is based on the model of each component of ventilation systems, which establishes the particle mass balance equation for each part. Particle deposition for each part is taken into account by fitting a series of empirical equation based on the previously proposed theoretical models or measured data, and the dynamics characteristic of outdoor concentration, indoor sources and ventilation modes are also considered. The particle concentration of any point in the ventilation system and amount of particle deposition of any component could be analyzed by this program. However, since the indoor particle concentration and dust load on duct surfaces are of the greatest concern, they will be analyzed as an example of the function of PROBE-PM in this paper.

SIMULATION MODEL

The models of three main components of ventilation systems that affect particle transport are introduced in this chapter. Indoor particle concentration and dust load on duct surfaces are simulated based on these models in PROBE-PM.

Filters

Particles will be captured when air passes through filters. Define the penetration factor P_{filter} of filters as:

$$P_{filter} = 1 - \eta \qquad (1)$$

where, η is the efficiency of the filter. Then the particle concentration after the filter C could be calculated as:

$$C = C_0 P_{filter} \qquad (2)$$

Here, C_0 is the particle concentration at the entrance of the filter.

Ventilation ducts

When ventilation ducts transport air through ventilation systems, particles in the air will deposit on duct surfaces governed by mechanism of diffusion, gravitational sedimentation, thermophoresis, electrostatic force and turbophoresis. The duct could also be treated as a filter by defining the penetration factor, the fraction of particles penetrating a duct, to calculate the particle concentration at the outlet of an air duct.

The penetration factor of a straight duct, defined as the ratio of the outlet concentration to the inlet concentration, could be calculated by the following equation:

$$P_{straight} = \exp\left(\frac{-pLV_d}{AU_{ave}}\right) \qquad (3)$$

Here, U_{ave} is the average air speed in the axial direction, A is the cross sectional area of the duct, L is the duct section length and p is the perimeter of the duct normal to the flow direction, V_d is the area-weighted average deposition velocity which takes Brownian and turbulence diffusion, gravitational sedimentation, and turbophoresis into account. More details including how to calculate V_d could be found in Zhao and Wu (2006).

Penetration factor of duct bends could be calculated by means of empirical model presented by McFarland et. al. (1997)

Penetration through an entire duct, P_{duct}, could be calculated by multiplying the calculated penetration rate for straight ducts and bends:

$$P_{duct} = \prod_{i=1}^{n_s} P_{straight,i} \prod_{j=1}^{n_b} P_{bend,j} \ . \qquad (4)$$

Here n_s is the total number of straight ducts and n_b is total number of bends.

The average dust load of an entire duct N could be calculated as follows:

$$N = \frac{C\left(1 - P_{duct}\right)Qt}{A_{duct}} \qquad (5)$$

Here C is the particle concentration at the duct inlet, Q is the flow rate, A_{duct} is the area of the duct surfaces and t is the time.

Room

Assuming that the air is well mixed and the particle concentration is uniform inside a single room, the mass balance of particulate matter in the indoor air could be presented as the following equation:

$$V\frac{dC}{dt} = aPVC_{out} + nVC_{\sup} + \dot{S}c + RL_{fl}A_{fl} - (a+n)VC - KVC \qquad (6)$$

Here V is the volume of the room, C is the indoor particle concentration, t refers to the time, a is the air exchange rate due to infiltration and nature ventilation per hour, P is outdoor particle penetration factor, C_{out} is outdoor particle concentration, n is the air exchange rate (sum of fresh air exchange rate and re-circulated air exchange rate), $C_{\sup}$ is the supply air particle concentration, $\dot{S}c$ is the indoor particle source, R is the particle resuspension rate, L_{fl} is mass loading of particles on accessible floor surfaces, A_{fl} is floor area and K is the particle deposition rate in the room.

For the commonly used primary return air system with a single room, particle concentration of supply air is calculated as follows:

$$C_{\sup} = \left[n\varepsilon C_{out}P_{fr} + n(1-\varepsilon)CP_{re}\right]P_{\sup}P_{fil} \quad (7)$$

Here ε is the fraction of fresh air, P_{fr} is the penetration factor of fresh air duct, P_{re} is the penetration factor of return duct, $P_{\sup}$ is the penetration factor of supply duct and P_{fil} is the penetration factor of filter.

This model emphasizes the dynamic characteristic of indoor particle concentration and the effect of penetration through ducts on indoor particle concentration. The differential equation of room particle concentration is solved in PROBE-PM.

CASE STUDY AND RESULT ANALYSIS

The simulation of a primary return air system with one room is conducted by PROBE-PM as a case study. A schematic of the case studied is shown in Figure 1.

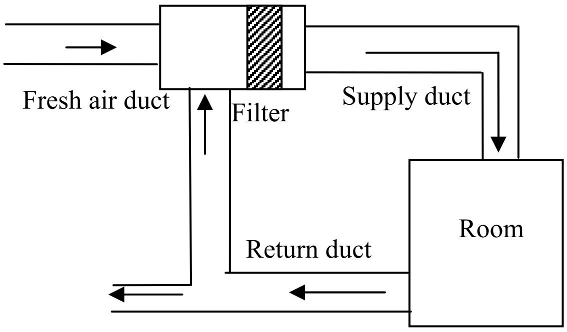

Figure 1 Schematic of the case studied, arrows indicate the air flow path

Parameters

The parameters used in this case are shown in the following tables. Outdoor concentration, indoor source and ventilation mode change hourly and have a schedule. Parameters concerning particulate matter take particle size distribution into account. However, the result of simulation sums up the mass of different diameter groups and is expressed in the form of PM_{10}.

The room size is 5m×4m×3m. The fraction of fresh air is 10% of the total supply air. Lack of outdoor concentration data, the simulation period is three days and outdoor concentration of each day is the same, which were measured (Wang and Zhang 2002). Mass proportion of each particle group is given in table 1.

Table 1 Particle diameter distribution in Beijing's Atmosphere

PARTICLE DIAMETER (μm)	**MEAN PARTICLE DIAMETER** (μm)	**MASS PROPORTION**
0-0.5	0.25	0.014
0.5-1	0.75	0.028
1-3	2	0.083
3-5	4	0.153
5-10	7.5	0.722

Table 2 lists the penetration factor of the filter. The efficiency of the filter is 40%.

Table 2 Penetration factor of the filter

PARTICLE MEAN DIAMETER (μm)	**PENETRATION FACTOR** P_{fil}
0.25	0.61
0.75	0.60
2	0.24
4	0.06
7.5	0.04

Table 3 lists particle deposition rate in the room (Lai and Nazaroff 2000) and outdoor particle penetration factor under infiltration (Liu and Narzoff 2003). The outdoor particle penetration factor under natural ventilation when air exchange rate is 5 h^{-1} in the simulation is approximately 1 for all groups of particle diameter.

Table 3 Particle deposition rate in the room and outdoor particle penetration rate

MEAN PARTICLE DIAMETER (μm)	**P**	**K**
0.25	0.96	0.005
0.75	0.99	0.025
2	0.96	0.155
4	0.83	0.596
7.5	0.42	2.055

The parameters of ducts which were used to calculate the penetration rate of ducts are give in table 4. And penetration rate of ducts are given in table 5 according to method mentioned above.

Table 6 gives the estimation of indoor source strength. The indoor resuspention is neglected in this simulation.

Table 4 Parameters of ducts

	DUCT SIZE (mm×mm)	**LENGTH OF HORIZONTAL STRAIGHT DUCTS** (m)	**LENGTH OF VERTICAL STRAIGHT DUCTS** (m)	**NUMBER OF BENDS**
Fresh air duct	120×120	2	0	1

	DUCT SIZE (mm×mm)	**LENGTH OF HORIZONTAL STRAIGHT DUCTS** (m)	**LENGTH OF VERTICAL STRAIGHT DUCTS** (m)	**NUMBER OF BENDS**
Supply duct	160×120	5	2	4
Return duct	120×120	5	2	4

Table 5 Penetration factor of ducts

PARTICLE MEAN DIAMETER (μm)	**FRESH AIR DUCT** P_{fr}	**SUPPLY DUCT** $P_{\sup}$	**RETURN DUCT** P_{re}
0.25	99.95%	99.90%	99.89%
0.75	99.94%	99.91%	99.90%
2	99.59%	99.40%	99.38%
4	98.47%	97.46%	97.19%
7.5	94.20%	89.07%	87.44%

Table 6 Estimation of indoor source strength

PARTICLE MEAN DIAMETER (μm)	**2 PHOTOCOPIER** (μg/h)	**SMOKING** (μg/h)	**HUMAN SITTING** (μg/h)	**ROOM CLEANING** (μg/h)
0-0.5	0	700	0	0
0.5-1	890	4600	20	1500
1-3	1714	10000	60	3000
3-5	2996	19000	80	9000
5-10	0	0	0	0

The simulation period is 3 days, and the schedule of ventilation modeand indoor source are shown in table 7 and 8.

Table 7 Schedule of ventilation mode

TIME	**VENTILATION MODE**
0:00~8:00	Infiltration a=0.5h^{-1}
8:00~18:00	Day 1 & 2: Mechanical ventilation n=5 h^{-1} Day 3: Natural ventilation a=5h^{-1}
18:00~24:00	Infiltration a=0.5h

Table 8 Schedule of indoor source

SOURCE	**SCHEDULE**
photocopier	8:00~12:00,13:00~17:00
smoking	12:00~13:00 (Only second day)
human sitting	8:00~18:00
cleaning	17:00~18:00

Results

The indoor particle concentration PM$_{10}$ in 3 days is shown in figure 2. In this case, if the filter functions well and there is no significant indoor source, indoor particle concentration is controlled well below the outdoor concentration in the mechanical ventilation mode. However, the indoor source such as smoking increases the indoor concentration greatly. When windows are open (natural ventilation), indoor concentration is affected mainly by outdoor concentration.

Figure 3 shows the dust load on fresh air duct surfaces, based on which the number of air conditioning operation days when dust load per m^2 reaches 1 g/m^2 could be estimated. According to China’s “hygiene norms of air conditioning and ventilation systems in public places”, air ducts should be cleaned that time. For this case, fresh air duct should be cleaned after approximately 100 air conditioning operation days, supply duct should be cleaned after about 2800 days and return duct 440 days. The results are listed in table 9.

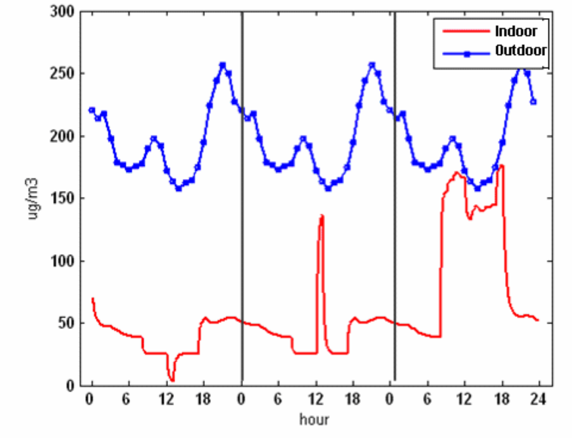

Figure 2 Indoor and outdoor particle concentration

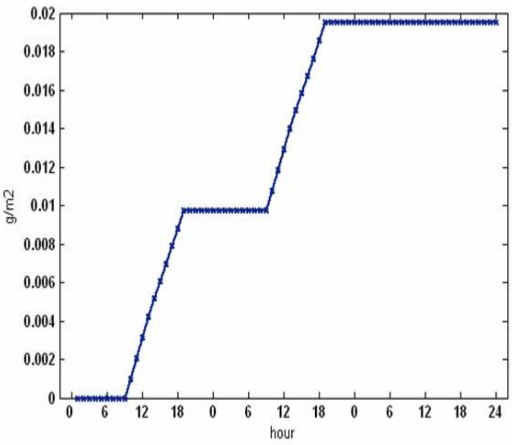

Figure 3 Dust load on fresh air duct surfaces

Table 9 Duct cleaning period (day)

Fresh air duct	100
Supply duct	2800
Return duct	440

CONCLUDING REMARKS

PROBE-PM is a code to predict indoor particle concentration and dust load on duct surfaces by taking into the dynamic characteristic of the ventilation system and the effect of penetration through ducts on indoor concentration. A case study has shown the results by PROBE-PM. Since cleaning periods of different types of air ducts are distinct, and indoor particle concentration change greatly with outdoor concentration, indoor source strength and ventilation mode, PROBE-PM shows the advantage of taking these factors into account.

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