When to open windows—a concept of balance-point outdoor concentration of particles

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ABSTRACT
Natural ventilation and infiltration are used for pollutant dilution and providing 'fresh' outdoor air supply in many buildings, in particular in residential buildings. Questions are often asked when natural ventilation should be encouraged. A balance-point outdoor concentration is proposed here using a simple steady-state model to represent the value of outdoor concentration at which the air exchange between indoor and outdoor does not affect the indoor and outdoor pollutant concentration ratios. When the outdoor particle concentration is higher than the balance-point outdoor concentration, an increase in the indoor and outdoor air exchange results in a higher indoor particle concentration level and vice versa. Ventilation should be encouraged only when the outdoor particulate concentration is lower than the balance-point outdoor concentration. This concept is similar to the concept of balance-point outdoor temperature used for energy consumption analysis based on degree-days.

INDEX TERMS
Air quality; Particulate matter; Natural ventilation; Indoor/outdoor ratio; Mass transfer

INTRODUCTION
Indoor particulate matter concentrations are complex combinations of many factors, such as indoor sources, ambient conditions, building materials, human behaviour and activities, ventilation and particle size distributions. Numerous measurements have been reported on the ratio between the indoor and outdoor particle concentrations (I/O), which to some extent indicates how well the building envelope protects us against outdoor particulate matter, or how well the ventilation system disperses the indoor-generated particles.

The building envelope does not necessarily provide us with good protection from exposure to certain types of pollutants. For pollutants with predominant indoor sources (such as formaldehyde and most other VOCs), the building envelope restricts the dispersion of pollutants, and air exchange between indoor and outdoor should be encouraged. On the other side, for pollutants with predominant outdoor sources (such as lead and pollens), a reduction in indoor and outdoor air exchange can reduce the indoor exposure level. For pollutants with origins both indoors and outdoors, e.g. particulate matters, nitrogen oxides and carbon monoxide, whether to encourage air exchange or not depends on the relative intensity of pollution between indoor and outdoor. However, so far there appears to be no simple quantitative index to measure the relative intensity of the pollution between indoor and outdoors, i.e. when should the air exchange between indoor and outdoor be encouraged. Li and Chen (2002) suggested a concept of balance-point outdoor concentration for this purpose. A brief description is given in this paper.

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THE CONCEPT OF BALANCE-POINT OUTDOOR CONCENTRATION

Assuming that the particle concentration in the building is uniform, the following simple macroscopic mass balance for particulate matter can be written for a naturally ventilated building:

$$\overbrace{V\frac{\mathrm{d}C_{\mathrm{i}}}{\mathrm{d}t}}^{\text{Transient}} = \underbrace{aPVC_{\mathrm{o}}}_{\text{Penetration}} + \overbrace{\dot{V}_{\text{source}}}^{\text{Indoorsource}} + \underbrace{RL_{\mathrm{fl}}A_{\mathrm{fl}}}_{\text{Resuspension}} - \overbrace{aVC_{\mathrm{i}}}^{\text{Airflow removal}} - \underbrace{KVC_{\mathrm{i}}}_{\text{Deposition}} - \overbrace{\dot{V}_{\text{sink}}}^{\text{Othersinks}} \tag{1}$$

where a is the air exchange rate per hour due to infiltration and natural ventilation (1/h), A_{fl} is the floor area (m^2), C_{i} is the indoor particle concentration (μg/m^3), C_{o} is the outdoor particle concentration (μg/m^3), K is the particle deposition rate (h^{-1}), L_{fl} is the mass loading of particles on accessible floor surfaces (μg/m^2), P is the particle penetration coefficient, R is the particle resuspension rate (h^{-1}), t is the time (h), V is the volume of the room (m^3), $\dot{V}_{\text{source}}$ is the indoor particle generation rate (μg/s), and $\dot{V}_{\text{sink}}$ is the removal rate of particles due to other sinks such as filtration (μg/s).

Equation (1) has been used in similar forms by a number of previous authors (Dockery and Spengler, 1981; Tichenor *et al.*, 1990; Mage *et al.*, 1999). All the parameters except V and A_{fl} are a function of both time and particle sizes. When the variations of these parameters are small, we obtain I/O as:

$$\frac{C_{\mathrm{i}}}{C_{\mathrm{o}}} = \frac{aP}{a+K} + \frac{RL_{\mathrm{fl}}A_{fl} + \dot{V}_{\text{source}}}{C_{\mathrm{o}}V\left(a+K\right)} \tag{2}$$

The balance-point outdoor concentration is obtained by simply setting I/O to be the value of the penetration coefficient P in Eqn (2).

$$C_{\mathrm{o,e}} = \frac{RL_{\mathrm{fl}}A_{\mathrm{fl}} + \dot{V}_{\text{source}}}{KVP} \tag{3}$$

A corresponding indoor particle concentration is defined as a balance-point indoor concentration:

$$C_{\mathrm{i,e}} = \frac{RL_{\mathrm{fl}}A_{\mathrm{fl}} + \dot{V}_{\text{source}}}{KV} \tag{4}$$

Equation (4) represents a balance between the indoor particle generation speed and particle deposition rate. I/O can also be written as:

$$\frac{C_{\mathrm{i}}}{C_{\mathrm{o}}} = P + \frac{KP\left(C_{\mathrm{o,e}} - C_{\mathrm{o}}\right)}{C_{\mathrm{o}}(a+K)} \tag{5}$$

From Eqn (5), it is seen that when the outdoor particle concentration is $C_{\mathrm{o,e}}$, the indoor particle concentration becomes $C_{\mathrm{i,e}}$ and is not affected by the infiltration of outdoor air. It can also easily be seen that the following relationships hold:

If $C_{\mathrm{o,e}} > C_{\mathrm{o}}$, then $\frac{C_{\mathrm{i}}}{C_{\mathrm{o}}} > P$; and If $C_{\mathrm{o,e}} < C_{\mathrm{o}}$, then $\frac{C_{\mathrm{i}}}{C_{\mathrm{o}}} < P$.

Thus, the balance-point outdoor concentration is a dividing point. From Eqns (3) and (4), it is seen that the indoor and outdoor balance-point concentrations are only functions of the indoor parameters such as particle sources, sinks, building geometry and filtration characteristics:

- For high indoor sources and human activity intensity, the indoor air is naturally dirtier in terms of particulate matter and is characterised by high balance-point indoor and outdoor concentrations.

- For buildings with low activity and no indoor sources, the indoor air is clean and the balance-point indoor and outdoor concentrations are close to zero. Consequently, $C_{o,e}$ and $C_{i,e}$ effectively quantify the intrinsic cleanness of the indoor environment by combining the effects of indoor activities, particulate sources and sinks, as well as the building envelop filtration characteristics.

The effectiveness of ventilation and infiltration on indoor particle concentration simply depends on whether the outdoor air is cleaner or dirtier than the air at the balance-point outdoor particle concentration, $C_{o,e,}$ High air exchange rates should be encouraged when outdoor particle concentrations are lower than $C_{o,e}$, and vice versa. Seen in Eqns (3) and (4), $C_{o,e}$ and $C_{i,e}$ are both particle size dependent.

However, our analyses here focus entirely on particulate matter alone. Natural ventilation needs to be controlled by many other physical and environmental parameters, such as air temperature and other ambient pollutants. For example, a decision to increase ventilation to reduce indoor PM levels might lead to an increase of indoor concentration of other pollutants, e.g. ozone, SO_2, etc. Thus, for a complete analysis of ventilation needs, other pollutants also need to be considered. From the derivations of $C_{o,e}$ and $C_{i,e}$, the concept of balance-point indoor and outdoor concentrations may be applied to other pollutant components. Indoor sinks for these pollutants need to be defined. If there are no indoor sinks or other mechanical removal mechanisms, the balance-point outdoor concentrations are zero for any pollutants and thus natural ventilation are needed.

The concept of the balance-point outdoor concentration is similar to the concept of balance-point outdoor temperature (Kreider and Rabl, 1994). The balance-point temperature is defined as the value of the outdoor temperature where, for a specified indoor air temperature, the total heat loss is equal to other indoor heat gains. With this concept, heating is needed only when the outdoor air temperature drops below the balance-point temperature. Although computers can now calculate the energy consumption of a building at the touch of a key with a transient analysis method, the concepts of balance-point temperature and degree-days still remain a valuable engineering tool (Kreider and Rabl, 1994). Similar to the concept of balance-point temperature, the balance-point concentration is a steady-state concept and a short-term balance-point concentration may also be used for certain short time period within which all the affecting parameters may be considered as a constant.

APPLICATION OF THE BALANCE-POINT CONCEPT

In the definition of balance-point indoor and outdoor concentrations, seven parameters have been involved, i.e. A_{fl}, K, L_{fl}, P, R, V and $\dot{V}_{source}$, within which the floor area, floor particle loading and building volume can be relatively easily estimated or measured. Many studies have contributed to the understanding of the particle penetration coefficient, resuspension rate, deposition rate and various indoor particle sources. A full discussion of these parameters is out of the scope of this paper. Table 1 lists the reasonable values for these affecting parameters obtained from literature, which are used in this paper.

Table 1 Parameters used in the model study

Parameter	Value	References
A_{fl}	15 × 8 m	–
C_o	30 μg/m^3 for $PM_{2.5}$ 50 μg/m^3 for PM_{10}	Chan *et al.* (2001)
K	0.4 h^{-1} for $PM_{2.5}$ 1.0 h^{-1} for PM_{10}	Thatcher and Layton (1995), Byrne *et al.* (1995), Fogh *et al.* (1997)
L_{fl}	100 μg/cm^2	Thatcher and Layton (1995)
$PM_{2.5}/PM_{10}$	0.6	–
P	0.9	Thatcher and Layton (1995), Wallace (1996), Tung *et al.* (1999)
R	1.0 × 10^{-5} h^{-1} for $PM_{2.5}$ 2.5 × 10^{-5} h^{-1} for PM_{10}	Thatcher and Layton (1995)
V	15 × 8 × 2.4 m	–
$\dot{V}_{source}$ (smoking)	14 mg/cigarette for $PM_{2.5}$ 22 mg/cigarette for PM_{10}	Wallace (1996)
$\dot{V}_{source}$ (cooking)	1.7 mg/min for $PM_{2.5}$ 4.1 mg/min for PM_{10}	Wallace (1996)
$\dot{V}_{source}$ (others)	2.8 mg/h for PM_{10} 0.95 mg/h for $PM_{2.5}$	Wallace (1996)

For buildings with low human activity and without indoor sources, the outdoor concentration is always higher than the balance-point outdoor concentration, which is nearly zero. Consequently, the most effective way of reducing indoor particulate matter concentration is to minimise the natural ventilation and air infiltration. However, *for buildings with normal activity and without major indoor sources*, but some typical indoor sources such as particles from loose construction materials and furnishings are considered, the balance-point outdoor $PM_{2.5}$ and PM_{10} concentrations defined by Eqn (3) are estimated to be 21 and 22 μg/m^3, respectively, using the data in Table 1; see Table 2. Figure 1 shows the I/Os for different air exchange rates at PM_{10} outdoor concentrations of 15, 25, 50 and 100 μg/m^3, respectively. It is seen that I/O decreases with an increase in the ambient particle concentration under otherwise the same conditions. This trend can be easily seen from Eqn (5) and has been observed by a number of authors, e.g. Funasaka *et al.* (2000) reported that the I/O for roadside houses is generally lower compared with those away from the roadside, due to an increase in the outdoor concentration for roadside houses.

At an outdoor PM_{10} concentration of 15 μg/m^3, the PM_{10} I/O increases with a decrease in the air exchange rate, while for outdoor PM_{10} concentrations of 25, 50 and 100 μg/m^3, the PM_{10} I/O decreases with a decrease in the air exchange rate. The outdoor PM_{10} concentration, which divides these two situations, is the balance-point outdoor PM_{10}, which is 22 μg/m^3 for the current case. Similarly, the dividing point for $PM_{2.5}$ is the balance-point outdoor $PM_{2.5}$, which is 21 μg/m^3 (the corresponding PM_{10} concentration is around 35 μg/m^3 if a $PM_{2.5}/PM_{10}$ of 0.6 is assumed). Most of the office buildings and residential houses are within this building category. The ambient particle concentration is generally in the range of 10–100 μg/m^3 in most of the cities. Consequently, the current simple modelling suggests that for buildings with normal activity and without major indoor sources as listed in Table 1, a high air exchange rate should not be encouraged in terms of particulate exposure in some moderately and highly polluted regions with a PM_{10} concentration higher than 35 μg/m^3. Conversely, in less polluted ambient regions with a PM_{10} concentration lower than 20 μg/m^3, a high ventilation rate is beneficial to reduce indoor $PM_{2.5}$ and PM_{10} concentrations.

For buildings with normal activity and major indoor sources such as cooking and cigarette smoking, which are the two major indoor particle sources, we consider a hypothetical example, it is assumed that (1) the intensities of particle generation due to cooking and cigarette smoking are the mean values, as listed in Table 1; (2) normal cooking duration is 30 min per day; and (3) smoking intensity is one pack of 20 per day, with each cigarette taking 10 min to burn.

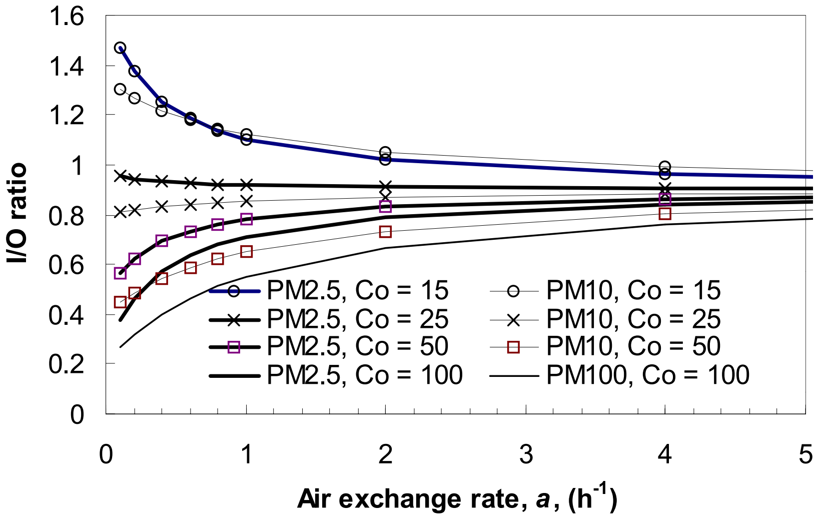

Figure 1 I/Os for a building with normal human activity and without major indoor sources.

Table 2 The balance-point outdoor particle concentration, $C_{o,c}$ (μg/m^3) for various conditions

Indoor sources	Daily mean $C_{o,e}$ for PM_{10}	Daily mean $C_{o,e}$ for $PM_{2.5}$	Short-term $C_{o,e}$ for PM_{10}	Short-term $C_{o,e}$ for $PM_{2.5}$
No major source	22	21	22	21
Cooking alone	42	41	1005	971
Smoking alone	93	133	831	532
Cooking and smoking	154	154	1815	925

Table 2 lists the balance-point outdoor particle concentrations for different conditions for PM_{10} and $PM_{2.5}$, respectively. Cooking and smoking significantly increase the daily mean balance-point outdoor concentrations due to the high indoor particle generation rate. The short-term balance-point outdoor concentrations (obtained from Eqn (3) during periods of smoking or cooking) are above 500 and 800 μg/m^3 for PM_{10} and $PM_{2.5}$, respectively, which are much higher than the outdoor particle concentration range of 10–100 μg/m^3 normally observed. Consequently, high air exchange rates during cooking and smoking can substantially reduce indoor particulate concentration levels.

CONCLUSIONS

The balance-point outdoor concentration is a simple index to quantify the cleanness of the building in terms of the outdoor particle concentration. When the outdoor particle concentration is less than the balance-point concentration, I/O is always smaller than the penetration coefficient, and introducing fresh air into the building should be encouraged and vice versa.

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