AIR CHANGE RATE MEASUREMENTS USING INDOOR/OUTDOOR RATIO OF PM2.5

Lingshan Li1,Xiaofeng Li*2, Pok Lun Cheng 1

1 Tsinghua University
Dept. Of Building Science, School of Architecture, Tsinghua University
Beijing, 100084, China

2 Tsinghua University
Dept. Of Building Science, School of Architecture, Tsinghua University
Beijing, 100084, China
**Corresponding author: xfli@tsinghua.edu.cn*

Abstract

According to past researches, most people spend 80%-90% of their time indoors. The ventilation is very important to people's health and the comfortable surroundings around us. From the viewpoint of energy saving, mechanical ventilation will consume a large amount of additional energy. So variety of ways measuring natural ventilation is worth considering. In fact, in real life, many people tend to have their windows shut rather than open, and the reasons are complex.

Some reasons are due to safety, maintaining a good thermal environment, harmful outdoor pollutants, shielding from outside noise etc. Thus, it is necessary to set an index of low ventilation rate, in order to simulate the situation of windows shut or slightly opened. The ACH is controlled between 0.5 and 1, by adjusting the window openings. As measurement technique, the constant injection method can be used to measure the infiltration rate of natural ventilation. One useful way is the dry ice method, in which dry ice in an insulated container is used as a constant injection of tracer gas. Apart from dry ice method, the PM2.5 is considered to be another kind of tracer gas. The main sources of PM2.5 come from burning of fossil fuels. If there are no indoor sources, e.g. smoking or waste-combustion, we can assume that there are no initial indoor sources of PM2.5, where all sources come from outdoors. Then the I/O ratio of PM2.5 can be used to determine different ventilation rates.

In this study, the ACH from tracer gas method and I/O ratio of PM2.5 was compared. The relevance between ACH and I/O ratio will be verified through a specific equation to get further conclusion, through which we can get ACH directly by means of measuring I/O ratio of PM2.5.

Keywords

ACH; PM2.5; Natural ventilation; Constant injection; Dry ice method; I/O ratio

1 INTRODUCTION

Evidence indicates that most people spend 85~90% of their time indoors, and the quality of air is decided by the concentration of all particles. Natural ventilation is an important way to improve IAQ, while the extent of the windows' opening has a great influence on the ventilation rate.

Concerning about the measurement of natural ventilation, many researchers have summarized many kinds of methods. Many of them are used to measure the air changes per hour (ACH), such as simulation, tracer gas methods, etc.

Many studies have introduced the background, theory, usage conditions and economic benefits to measure ACH by tracer gas, such as Heidt and Werner (1986), Sherman (1990), Roulet & Vandaele (1991) and McWilliams J. (2003)

The decay method is widely used in past researches, using only the decay period of the tracer gas to get the ACH, where the time interval depends on the ACH. Since the measured ACH range is lower than 1.0, the time to change all the air in room is more than an hour, so this method is not suitable for low unsteady ventilation rates. When measuring unsteady ventilation, only the constant injection method is applicable.
Recent years, PM2.5 becomes the hot spot of scientists. Especially in Beijing, the outdoor concentration of PM2.5 is high. According to weather statistics of Beijing Municipal Environmental Protection Bureau, 58 days in 2014 and 45 days in 2013 are heavy polluted, in which the concentration of PM2.5 is higher than 150 mg/m3.days when the concentration is over 100mg/m3 are nearly 30%. So it is an excellent tracer source to use in field measurements.
Chen and Zhao studied the possibility of using particles such as PM10, PM2.5 to get a relevance between indoor and outdoor (I/0) ratio of PM and ACH both unsteady- and steady-state differential equations were put forward in their study
Assuming there's no indoor sources of PM2.5, where particles on surfaces and clothes being negligible, it can be considered that all particles are from outdoors to indoors by natural ventilation.
Our aim is to measure the ACH with a constant injection method by using CO2 released from dry ice, and get the I/0 ratio of the PM2.5 concentration at the same time. Then, the relevance between these two parameters can be compared.

2 METHODOLOGY

This part will explain the two methods used in the comparison for the calculation of ACH. A well-known tracer gas method was used to prove the ACH calculated with the PM2.5 method. Since the reliance of PM2.5 method is unknown, the ACH taken from the tracer gas method is set as standard and regarded as a-true. So in this experiment, it is vital to get the correct result of a-true with great caution, or the standard error will be large.

2.1 Tracer gas method

2.1.1 ACH calculation method

The constant injection method using a steady release rate of tracer gas can be expressed as:

$$\Delta C = \frac{\Delta \tau}{V_{zone}}(F - NV_{zone}(C_1 - C_e)) \qquad (1)$$

ΔC:Change of tracer gas concentration,
Δτ :Time interval,
Vzone :Zone volume
F :Tracer gas injection rate
N :number of ACH
C1 :indoor tracer gas concentration
Ce :outdoor tracer gas concentration.
The only unknown parameter is N, with all the rest as input values. The calculation was repeated for each consequent time interval to get a theoretical curve.
Between the measured and theoretical values, a curve fit equation was used, by using the solver tool in Excel:

$$\mathrm{Error}\left(C_{i,t}\right) = \left(C_1 - C_{i,t}\right)^2 \qquad (2)$$

The calculated sums of the errors were small due to this method, and varied between 1-5%, so the curve fit had an error of 1-5%. This calculation method is applicable with a variable tracer gas concentration, when the ACH is unsteady for the constant injection.

2.1.2 Tracer gas CO2

The dry ice in an insulated box works as a constant injection tracer source. The sublimation rate of dry ice is affected by the insulation of the box and indoor temperature. If the dry ice is placed in an insulated box, the heat transfer will eventually reach steady state.
The weight loss of the dry ice box was used to calculate the emission rate of CO2 with the following formula:

$$F_{CO_2} = \dot{m}\frac{V_m}{M_m} \qquad (3)$$

FCO2: Volumetric release rate of CO2
Vm : Molar volume of CO2
Mm : Molar mass of CO2.

In this study, the dry ice box was positioned in the center of the room and weighted twice every day (night and morning). The weight has an accuracy of ±1 g.
CO2 concentrations were measured with Telaire 7001. Measuring range of the CO2 sensors was between 0-2500 ppm with an accuracy of ±5%. The CO2 concentration was measured with a time interval of 1 min. Two sensors were positioned inside in the different places in the office. The average was used between the two sensors, with a position difference of less than 5 %. One CO2 sensor was used to measure the outdoor concentration, positioned on the rooftop.

2.2 PM2.5 method

2.2.1 ACH calculation

According to the conservation of mass, the differential equation can be written as follow:

$$V\frac{dC_{in}}{dt} = aPVC_{out} - aVC_{in} - KVC_{in} + S \qquad (4)$$

V: Room volume
T: Time
A: ACH
P: Particle penetration factor
K: Particle deposition rate
S: Indoor particle emission rate.
It should be noted that the suspension of particles is neglected in this equation.
The steady-state equation can be simplified as:

$$\frac{C_{out}}{C_{in} - C_s} = \frac{K}{P}\left(\frac{1}{a}\right) + \frac{1}{P} \qquad (5)$$

Bennett and Koutrakis (2006) developed an alternative method for calculating the infiltration factor using time-dependent indoor and outdoor particle concentrations and ACH. Assuming there are no indoor particle sources:

$$C_{in,t} = \frac{aP}{K+a}C_{out}\left(1 - e^{-(K+a)\Delta t}\right) + C_{in,t-\Delta t}e^{-(a+K)\Delta t} \qquad (6)$$

The two important parameters in the equation are P and K. They are discussed as follow.

2.2.2 The particle penetration factor——P

P is the particle penetration factor, defined by the ratio of the last and former concentration. It can be changed by the different kind of windows and opening angle, or even by the air flow rate.

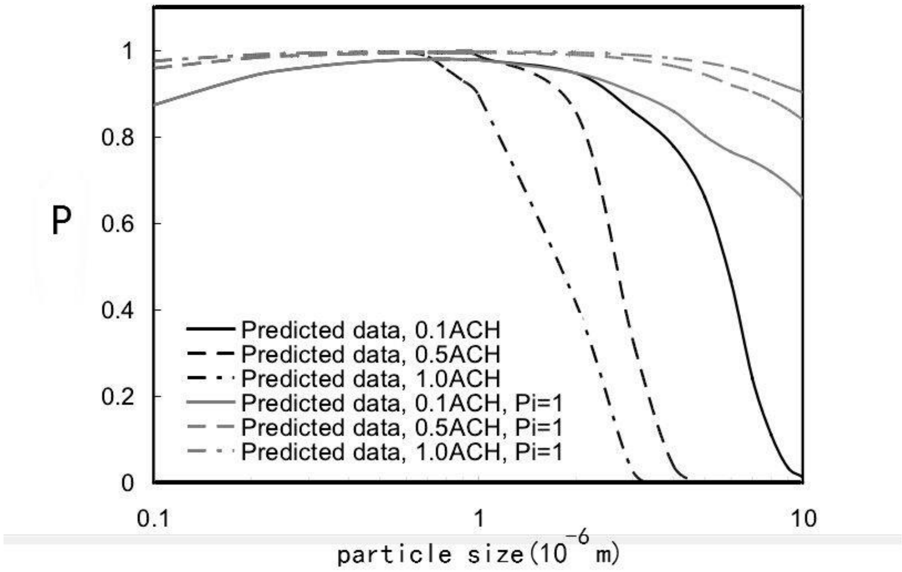

Figure 26: P for different ACH

Chun Chen gives the common distribution of P for small rooms, shown in Fig. 1.
It can be seen that when the ACH is in the range of 0.5~1.0, predicted data for P is close to 1.0. So in the beginning, P is set as 0.9/0.95/1.0 for individual calculation for analyzing.

2.2.3 The particle deposition rate——K

Influencing parameters of K is complex. The most important aspect is particle size. Others like airflow distribution, temperature, humidity, surface of the table and wall also influences K.
Due to other researches can't be decided by a constant value to become a parameter of the formula, but statistics show that K always is between 0.05~0.5.
Now, the very important task is to get a proper single value K from the experiment. Constant value doesn't mean that K is not changeable. It is just for the convenience of calculation method.
During the calculation process, the ACH from the dry ice method is set as a-true. So the perfect result is when the ACH from PM2.5 method is the same as a-true. The error can also be used to judge if the relevance is conceivable. By comparison of different K, we can get the most accurate one to be the parameter of the formula.

2.2.4 Indoor and outdoor (I/O) ratio of PM2.5

The I/O ratio is defined as：

I/O Ratio = $\frac{C_{in}}{C_{out}}$ (7)

To get the PM2.5 concentration, the instrument AM510 was used with a logging interval of 1 min. The sensor was zero calibrated every 24 hours.
The error contains two parts: one is the mechanical error, and another part is caused by the temperature. For the mechanical part, the instrument has a preset correction factor. Comparing with the standard concentration of meteorological observatory, we can set one certain factor for PM2.5. The factor is not accurate for many reasons, so error comes. For the temperature part, the standard temperature is set during zero calibration when the temperature change and error appears. Taking into account these errors, only the concentrations more than 100mg/m3 was considered.
After getting both the indoor and outdoor concentration of PM2.5, the I/0 ratios can directly be used in the iterative calculation to get the ACH. The calculation part was executed with the help of MATLAB.

2.3 Test room chosen for experiment

The test room chosen is a 3 story office building on the second floor, in Beijing, China. The room faces north-west, with two windows facing both north and west direction, as shown in Fig 2.

The room volume is 57.4 m^3, (4.35m x 3.30m x 4.00m) which is an important parameter of tracer gas method. Most of the surface is white wall or smooth wooden desks, knits are little. So the deposition rate K is not so big in this occasion.

The air flow rate was controlled by changing the angle of the windows 3 and 4. The remaining openings were sealed by transparent adhesive tape to avoid multi-zone condition. So all the windows use single-sided ventilation, where windows are faced towards one direction. When the windows are opened, the influence of window frames is negligible, making P equal to 1.0.

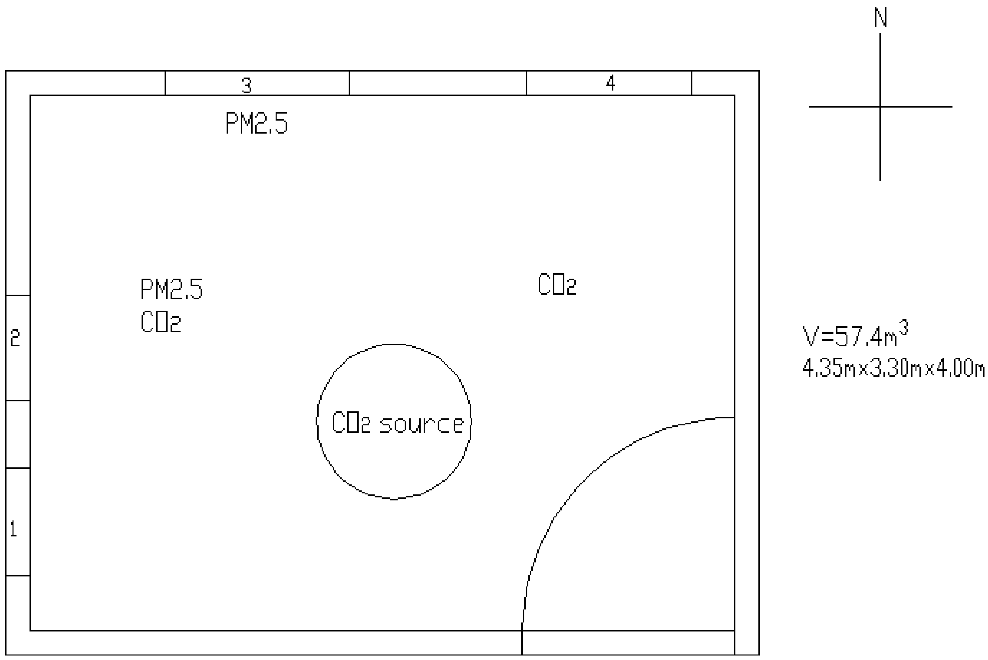

Figure 2: Room dimensions

3. RESULTS

This part shows the results from the experiments, which was conducted between April to May 2015.

3.1 Calculation of ACH using tracer gas method

The indoor CO2 graph was divided between: step-up, constant and decay, for the calculation of ACH (shown in Fig. 3).This was done in order to calculate the ACH with minimal curve fit errors. The calculated ACH is shown directly next to the indoor CO2 concentration graph, with brackets representing the time interval chosen for the calculation part.

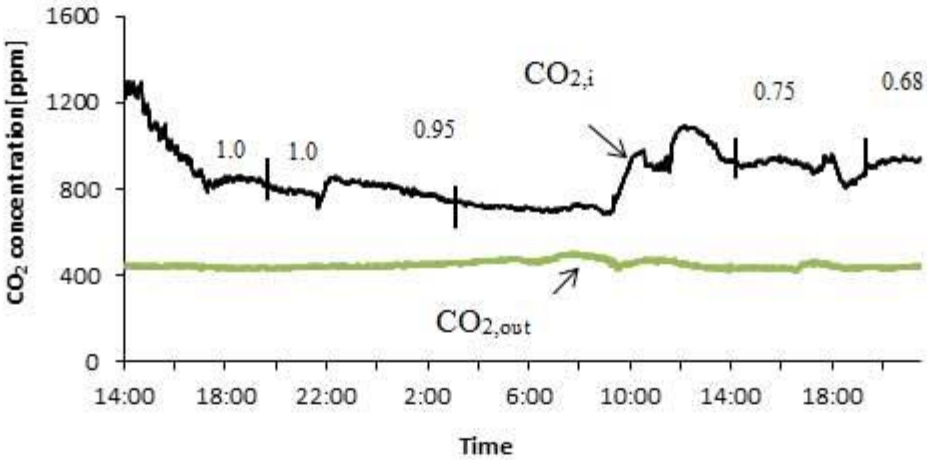

Figure 27: Calculation of ACH using dry ice method

There were no people or other disturbances present during the measurements, except two times per day weighting the dry ice which only took half minute per time. This short amount of time of disturbance was considered to have no effect on the calculated ACH.

3.2 Calculation of ACH using PM2.5

The indoor and outdoor PM2.5 concentration for a typical day is shown in Fig. 4.

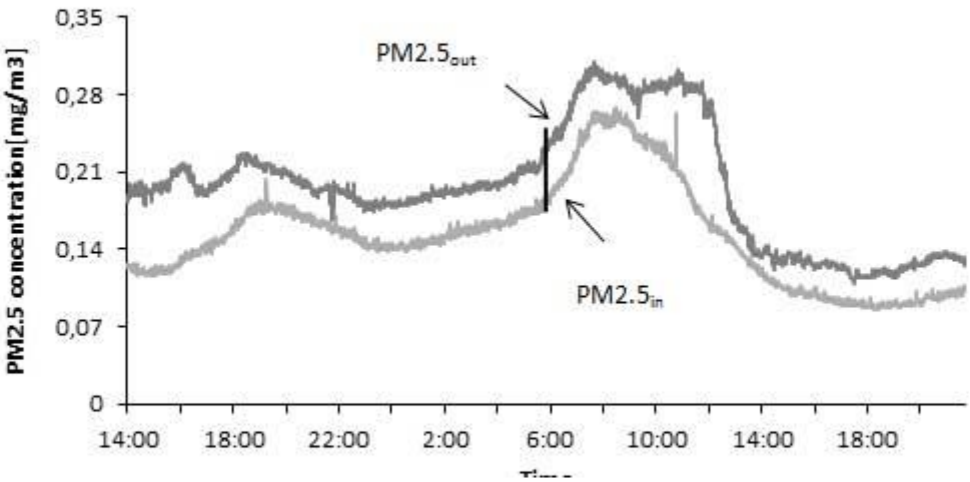

Figure 28: Concentration of PM2.5

When the indoor and outdoor concentrations have a nearly parallel trend, the data can be used for the calculation of a(PM2.5). Also, when the ACH is under 1.0, the PM2.5 concentration should be steady for at least one hour.
Similar to the calculation of dry ice method, the calculation part was divided into parts. The time intervals chosen were 2 hours during to the consideration of accuracy.

3.3 Verification of PM2.5 method

When P is constant, the only unknown parameter remaining is K, which can be found through statistical method.
For the comparison of the two methods, the ACH from the dry ice and PM2.5 method is set as a-true and a(PM2.5), respectively.
The aim at first is to figure out which combination of P and K can serve the most reliable formula. So the data points where P and K can measure closest to a-true in one period of time

was chosen, as shown in Fig 5. In this figure, different combinations of P and K are shown, which needs further analyzing for the most rational P and K.

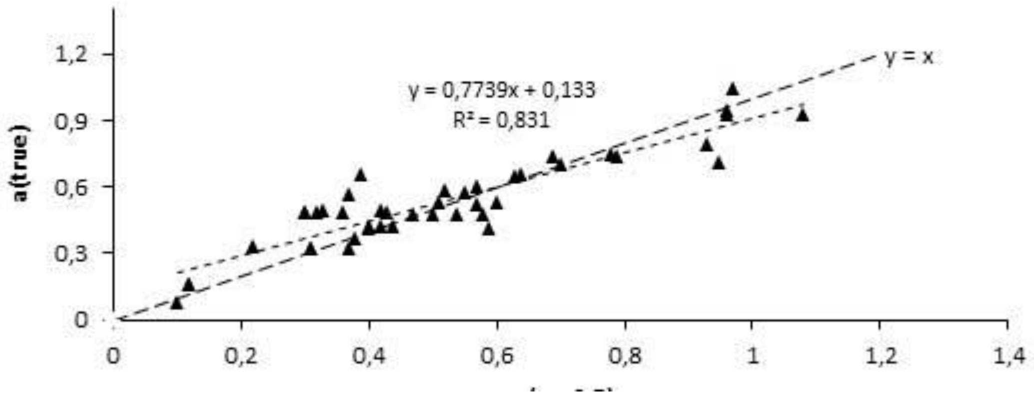

Figure 29: Comparison of the two methods with different K.

The data was further divided between ACH<0.4 and ACH>0.4, with the statistics of P and K for ACH<0.4 shown in Table 1 and 2. The ACH below 0.4 was excluded, due to inconsistent relevance. It would also take too long time for the indoor air to change 1 time and getting a steady I/O ratio of PM2.5.

Table 1: Statistics of P and K

P	1	0.95	0.9
Occurrences	27	11	12
K	0.05~1	0.1(not included)~0.2	0.2(not included)~0.5
Occurrences	8	33	9

For the value of K, the most occurrences appears between 0.1~0.2, which is used in the calculations further on.

When we set P=1.0 and K=0.15, and left out the points who's ACH<0.4, and get a figure:

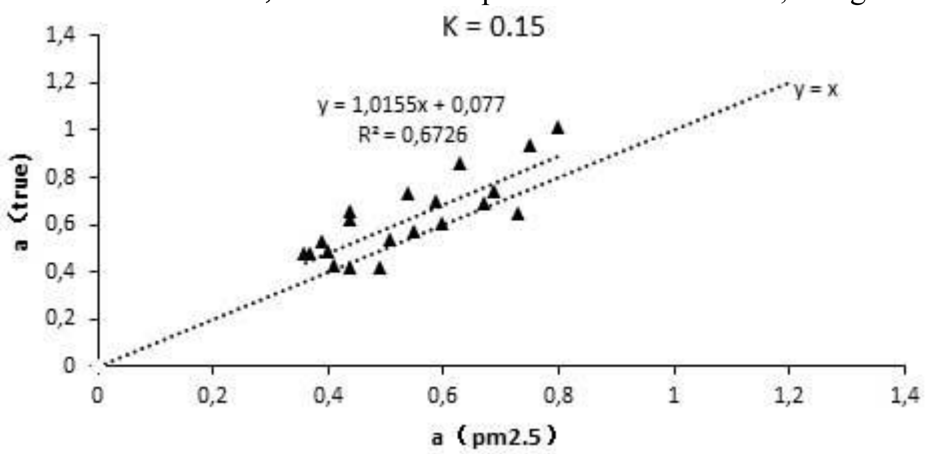

Figure 6 Comparison of ACH from the tracer gas and PM2.5 method.

The result is acceptable for most users. In the 21 points, six of them are located close to y=x, others stay parallel with the standard line, and show a good linear relationship.
But other values of K give not so good relevance, as shown in Fig. 7 .

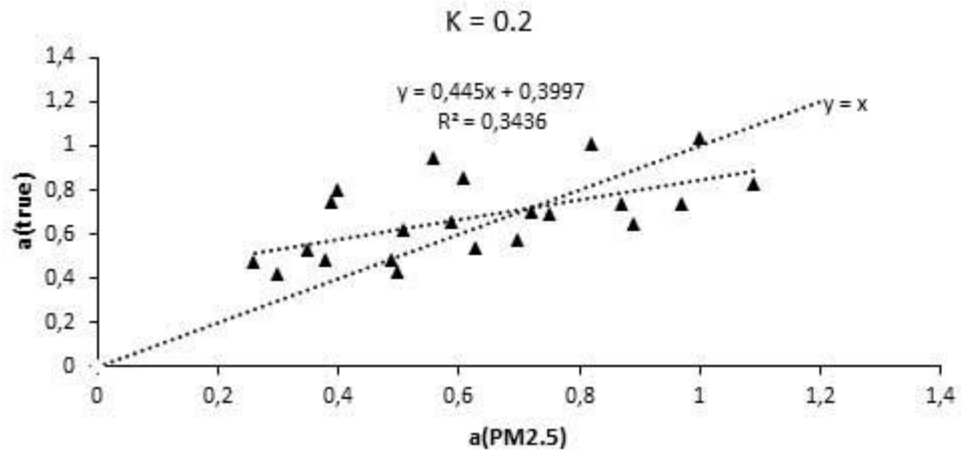

Figure 7:K=0.2

After analyzing, it was decided to use K= 0.15, and P = 1.0, so the final equation can written as follow:

$$V\frac{dC_{in}}{dt} = aVC_{out} - aVC_{in} - 0.15VC_{in} + S \quad (8)$$

And the calculation formula becomes:

$$C_{in,t} = \frac{a}{0.15+a}C_{out}\left(1 - e^{-(0.15+a)\Delta t}\right) + C_{in,t-\Delta t}e^{-(a+0.15)\Delta t} \quad (9)$$

Iterative methods can get a solution with certain programs. The suitable "a" is between 0.4 and 1.0. By measuring the concentration of PM2.5 both indoors and outdoors, we can get conceivable ACH.

4 DISCUSSION

The field experiment of the ventilation rate measurement can have several deviations, because K is decided by different reasons, which are too complex. And the influence of K on a is not linear. In most occasions, the airflow is always changing so the deposition rate changes. Also, the concentration of PM2.5 in the surroundings can't be controlled easily by people. Thus, when it is windy or rainy this method is limited, because the concentration will show a sharp decline.
According to the statistics of Beijing Municipal Environmental Protection Bureau, the result can be used 30% days of a year in Beijing area to get the approximate ACH.
Other people can use this formula to get ACH without producing tracer gas on purpose when windows open only a little (AHC between 0.4 and 1.0). This will help a lot with financial and physical reasons.
This experiment only uses one value of K. Future research can add more parameters influencing it, by including , the roughness of indoor surface. Then K can be decided more accurately.

5 CONCLUSIONS

People are searching for different methods to know more about our surroundings, including the natural ventilation rate, so PM2.5 is considered. The concentration of PM2.5 indoors and outdoors was used to get ACH, compared with a traditional tracer gas method. The relevance between these two methods was compared, and a new formula with constant K and P was found. Thus, the formula can be used to measure ACH directly with the help of high concentrations of PM2.5, especially occasions with windows slightly open.
In most developing industrial cities China, PM2.5 is especially outstanding issue. With the high concentration of PM2.5 in such area like Beijing, it can be a free source of tracer source to use anytime for great convenience. This method is also easy to use, due to the easy measure steps.

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