RESEARCH ON EVALUATION INDEX OF INDOOR PM$_{2.5}$ PURIFICATION EFFECT

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Abstract. PM$_{2.5}$ has been associated with negative health impacts in studies performed throughout the world. Inevitably, the occupants are exposed to PM$_{2.5}$ that was brought in from the outdoor environment by ventilation airflow. Natural ventilation (NV) is commonly used in apartments. However, the purification methods and their effects were different for different NV apartments. The main evaluation indexes were indoor PM$_{2.5}$ mass concentration and I/O ratio. But some deficiencies have been found in the practical applications of the two indicators. This study analyzed the limitations of PM$_{2.5}$ concentration and I/O ratio in evaluation based on field measurement. The indoor PM$_{2.5}$ concentration was not suitable for large-scale, long-term evaluation. The I/O ratio had limitations in both the short-term and long-term evaluation process. In the short-term, it is mainly the impact of the lag effect. In the long-term, it is due to the difference in the influencing factors of indoor and outdoor concentration, leading to inaccurate evaluation results of I/O ratio. To this end, this study established a new effect evaluation index—the percentage of purification time up to standard (PPTS). The new evaluation index has strong operability and advantages in practical application.

1 Introduction

In the last two decades, the health impacts of PM$_{2.5}$ have been under increasing scrutiny. In China, one of the countries with the highest PM$_{2.5}$ levels [1], studies indicate that PM$_{2.5}$ was the cause of nearly 1.4 million deaths due to stroke, acute pulmonary infection (33%), ischemic heart disease (27%), and lung cancer (24%) [2]. The ever-growing urban population is exposed to the indoor PM$_{2.5}$ that is brought in from the outdoor haze environment by ventilation airflow [3]. Since most people spend 85-90% of their time indoors, understanding the purification effect is important for understanding the impact of particle pollution on occupant health.

It’s necessary to determine the appropriate evaluation index for the widely used natural ventilation methods (NV), to make a reasonable judgment on the pros and cons of the purification strategy. At present, the evaluation indicators of the purification effect are mainly indoor PM$_{2.5}$ mass concentration [3] and I/O ratio [4]. Therefore, extracting appropriate feature indicators and making reasonable judgments on the purification effect become the key to determining a reasonable operation strategy. This study analyzed the limitations of PM$_{2.5}$ concentration and I/O ratio in the evaluation of purification, and thus explores the establishment of a new index of PM$_{2.5}$ purification evaluation.

2 Methodology

Continuous field measurements are used in data acquisition. Measurement items include indoor and outdoor PM$_{2.5}$ mass concentration, external window status, and operation status of the portable air cleaners (PAC). Choose 3 naturally ventilated apartments in Beijing. Information about the apartments was depleted in Table 1. CADR stands for Clean Air Delivery Rate. The PM$_{2.5}$ recorders were placed in the well-ventilated position. Two recorders were placed in each room and the average of their measurements was taken as the PM$_{2.5}$ concentration of the room at the moment.

Table 1. Basic information of the NV apartments

| Code | Year of built | Floor/Total | Area /m$^2$ | Window opening frequency | PAC Quantity | CADR/m$^3$·h$^{-1}$ | Operational state |
|------|---------------|-------------|------------|--------------------------|--------------|----------------------|-------------------|
| N1   | 2000          | 14/15       | 72         | Less                     | 1            | 130                  | Intermittent      |
| N2   | 2010          | 8/12        | 80         | Normally                 | 1            | 400                  | Intermittent      |
| N3   | 2007          | 3/6         | 76         | Less                     | 1            | 230                  | Intermittent      |

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window action time was instantaneous, and the data recording interval of PM2.5 concentration recorder and smart electricity meter was 10 min.

3 Results and discussion

3.1 Limitations of indoor PM$_{2.5}$ concentration

The hourly average indoor and outdoor PM$_{2.5}$ concentrations were collected. Fig. 1 showed a scatter plot drawn using their values. In most apartments, as shown in Table 2, the correlation coefficients of indoor and outdoor concentrations were above 0.6. Under the influence of wind and heat pressure, particles in the outdoor environment are brought indoors by airflow through the doors and windows of the building envelope, and the gaps between the pipe holes. It can also directly enter the room through the occupants' independent window opening behavior. On the other hand, low indoor particle sources, coupled with the low frequency of the PAC, make the intensity of indoor PM$_{2.5}$ sources and sinks small. As a result, for the NV system without the influence of internal sources and PAC, the indoor concentration was dominated by the outdoor concentration, as indicated by the high correlations between both concentrations.

| Statistics     | N1   | N2   | N3   |
|----------------|------|------|------|
| N              | 3728 | 1986 | 2566 |
| Pearson’s r    | 0.151| 0.866| 0.631|
| p-value        | 0.000| 0.000| 0.000|

In this way, in addition to the indoor concentration, the influence and role of the outdoors should be considered for the evaluation of the purification effect of NV apartments. Ignore the correlation, and simply take indoor PM$_{2.5}$ concentration as the evaluation index, which may cause misjudgment on the effect of purification.

3.2 Limitations of I/O ratio

3.2.1 Limitation in short-term evaluation

Given the strong correlation between indoor and outdoor PM$_{2.5}$ concentration of natural ventilation apartments, researchers then proposed to evaluate the purification effect by the Indoor-to-Outdoor ratio (I/O ratio). This method uses the outdoor concentration as a reference value to evaluate the indoor purification effect. However, due to the hysteresis effect of indoor concentration relative to outdoor concentration, the I/O ratio fluctuates greatly in a short time. It was found that many of these inconsistent data occurred when the ambient concentrations dropped rapidly to very low levels near the end of a heavy pollution episode, while the indoor PM$_{2.5}$ concentrations responded slowly to this change and remained relatively high due to the indoor-outdoor lagging effect [6].

Fig. 1. Relationship between the simultaneously measured hourly average indoor and outdoor PM$_{2.5}$ concentrations in apartments (A). Frequency distributions of outdoor and indoor measurements were shown as histograms on the top (B) and right side (C).

3.2.2 Limitation in long-term evaluation

For long-term evaluation, the I/O ratio also has a problem that cannot be ignored: the influencing factors of indoor and outdoor concentrations are different. The I/O ratio is determined by the indoor and outdoor concentrations. However, it was found that their influencing factors are quite different. The indoor concentration was mainly affected by the occupants’ timetable, and the outdoor concentration mostly depended on the traffic and meteorological conditions. Indoor PM$_{2.5}$ can be affected by internal sources, such as cooking, smoking, and even secondary organic aerosol formation [6]. Indoor emissions due to human activities are important reasons. We analyzed the daily indoor PM$_{2.5}$ change of NV apartments.
Fig. 2. Daily cycle of indoor PM$_{2.5}$ concentrations by month

Fig. 2 revealed the daily trend of indoor concentration. In general, the peak matched with cooking time. For NV households, indoor PM$_{2.5}$ concentration usually had an obvious daily cycle, and it had a great relationship with the members' work and rest time.

Another factor that directly determines the I/O ratio is the outdoor PM$_{2.5}$ concentration. In most circumstances, it was found that the outdoor PM$_{2.5}$ peaks appear at around 8 a.m., and 8 p.m. to 1 a.m. The peak matched with transportation rush hours. Nevertheless, the PM$_{2.5}$ levels were not only driven by primary emissions but were also affected by other factors such as meteorological conditions. Because of the daily rhythm of public behavior and relatively stable rush hour, the factors affecting outdoor concentration have a daily cycle to a certain extent.

These apartments were used as examples to illustrate the limitations of the I/O ratio in long-term evaluation (Fig. 3). The I/O ratio evaluation results of the N2 apartment are in the best position among the three apartments. However, from the perspective of the daily variation of indoor PM$_{2.5}$ in these apartments (See Fig. 2), no matter the concentration or its stability, the purification effect of N2 is not good. The reason why the I/O ratio evaluation of N2 was better than other apartments was probably that its indoor and outdoor PM$_{2.5}$ concentrations show consistency and synchronization of changes in time. The similar daily cycles made the changes in their ratios stabilize.

If the peaks and valleys of the daily changes in indoor and outdoor concentration were similar in time, then the I/O ratio will be relatively stable. Conversely, if there was a discrepancy in the peaks or valleys, the I/O ratio will become larger over a period of time. The data during this period of time, on the one hand, will cause a large number of extreme values in the final evaluation result, which will affect the average value of the I/O ratio. On the other hand, the appearance of such outliers affected the stability of the I/O ratio and increased the standard deviation. The consequence of the I/O ratio evaluation method was to overestimate the purification effect of apartments with similar indoor and outdoor concentration cycles while underestimating the effect of apartments with different cycles. In general, there was no direct correlation between the I/O ratio and the degree of internal pollution. It showed the limitation of simply using the relative value of indoor and outdoor concentration, that is, the I/O ratio.

Fig. 3. Daily cycle of I/O ratios by month

### 3.3 The Percentage of Purification Time up to Standard (PPTS)

#### 3.3.1 Principles for Determining the Long-term Index

In the evaluation of the long-term purification, due to the correlation between indoors and outdoors, the statistical data should be classified according to the outdoor level. It can avoid the impact of sudden changes in ambient concentration on the evaluation results. At the same time, problems caused by inconsistent test time should be avoided, and the impact of time lag should be minimized. Finally, it is ideal to use a single indicator to reflect the combined effects of the outdoor levels, indoor sources, the PAC, and ventilation.
3.3.2 Definition of the PPTS

This research proposed the Percentage of Purification Time up to Standard (PPTS) of indoor PM$_{2.5}$ under each outdoor PM$_{2.5}$ level. That is, for each outdoor PM$_{2.5}$ level, the total measurement duration was used as the denominator, and an indoor PM$_{2.5}$ mass concentration less than 35μg/m$^3$ was used as the numerator. The ratio of the two values is defined as the percentage of purification time up to standard (PPTS) of indoor PM$_{2.5}$ for each outdoor PM$_{2.5}$ level, and the definition of the formula is expressed as follows:

$$P_d = \frac{N_d}{M_d}$$  \(1\)

Where $P_d$ is the Percentage of Purification Time up to Standard (PPTS) of indoor PM$_{2.5}$; $M_d$ is the total measurement duration of an outdoor PM$_{2.5}$ level, h; $N_d$ is the duration of indoor PM$_{2.5}$ mass concentration less than 35μg/m$^3$ under a certain outdoor PM$_{2.5}$ pollution level, h. The higher the PPTS, the better the purification effect, which means that the current purification strategy was appropriate. Conversely, the lower the PPTS, the less effective the purification, which signifies the need to optimize and adjust the strategy.

![Fig. 4. The PPTS of indoor PM$_{2.5}$ in NV apartments](image)

Fig. 4 showed the PPTS of tested apartments. Under different outdoor PM$_{2.5}$ levels, the PPTS was obtained through calculation. When the outdoor level was excellent, the PPTS of whole subjects were all greater than 0.7, which means the purification effect was ideal. However, as the outdoor PM$_{2.5}$ deteriorated, the PPTS of N2 and N3 showed a clear and rapid decline. When the level was fine, the PPTS of the N2 apartment dropped to 0.315, while the PPTS of N1 and N3 were much higher than 0.5. At the level of slight, medium, and serious, the gap between the N1 apartment and others had become larger. The PPTS of the N1 apartment remained above 0.34, while the PPTS of the N2 and N3 apartments had become less than 0.1. The PPTS results revealed that N1 had the best purification results. And the N2 had the worst purification effect. It is contrary to the result of the I/O ratio evaluation. We reviewed the daily variation of indoor and outdoor PM$_{2.5}$ concentration and I/O ratio (in Section 3.2.2). Due to the influence of the daily cycle of indoor and outdoor concentration, the evaluation result of the I/O ratio is inaccurate. By observing the law of concentration changes, it is believed that the evaluation results of PPTS are more reasonable and accurate.

4 Conclusion

As for the evaluation of the purification of indoor PM$_{2.5}$, the evaluation method based on indoor PM$_{2.5}$ concentration and I/O ratio had limitations in its application to large-scale and long-term purification evaluation of indoor PM$_{2.5}$ environments due to the following reasons: 1) For NV apartments, there was a strong correlation between the indoor and outdoor PM$_{2.5}$ concentration. 2) In short-term evaluation, the I/O ratio had a lagging effect. In the long-term evaluation, the I/O ratio will also cause misjudgment due to the inconsistency of the daily circulation pattern of indoor and outdoor concentrations. And this kind of misjudgment makes the evaluation results have a close relationship with the daily cycle rules.

Because of the above limitations, this research established a new evaluation index of the indoor PM$_{2.5}$ purification effect: the percentage of purification time up to standard (PPTS). Compared with the current evaluation, the PPTS has strong operability for the comprehensive evaluation of the long-term purification effect of large-scale indoor PM$_{2.5}$ environments. At the same time, it can also play an effective guiding role when optimizing the purification strategy.

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