An effective ventilation system for preventing indoor PM2.5 dispersion

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Abstract. Korean public housing ventilation systems mainly use natural ventilation and local exhausts. When a local exhaust is operated in a narrow space such as a kitchen, the air pressure loss can lack balance. A decrease in hood capture efficiency and ventilation effectiveness causes the problem that people in the living room can be exposed to PM2.5 generated by cooking. Therefore, it is necessary to develop an effective ventilation strategy for the local exhaust, considering the make-up air supply. In this study, a ventilation system that integrates the range hood and ventilation systems (e.g., heat recovery equipment and auxiliary air supply) was developed to resolve this issue. Multi point measurement was conducted using five low-cost sensors to determine the location of the sensors in the kitchen and living room. TSI-DustTrak 8532 and OPS3330 were performed with different ventilation system operating types. When the range hood was operated for one hour, the concentrations in the kitchen and living room were significantly high; 676 μg/m³ and 373 μg/m³, respectively. After the integrated operating algorithm was installed, the kitchen concentration was 185 μg/m³, and the living room concentration was 68 μg/m³. With an additional flow rate of 50 CMH through Heat recovery ventilator (HRV) the reduction in the concentration of PM2.5 was more effective. As a result, this advanced system was able to remove up to 60% of PM2.5 generated by cooking. The integrated system of the auxiliary air supply and range hood was evaluated to be effective in preventing the distribution of kitchen pollutants.

1. Introduction

Maintaining indoor air quality has become an important issue. Indoor particulate matter (PM) generated by cooking accounts for over 70% of daily PM generation in non-smoking households [1]. Gas cooking is known for PM-generating activity with the smallest particle size (≤0.1μm) [2]. The smaller the particle size, the more PM is suspended in the air, as little deposition occurs. The only solution is to remove indoor pollutants with a ventilation system.

In general, Korean public housing ventilation systems are designed to operate individually, mainly using local natural ventilation exhausts. Research has long been conducted to examine ventilation mechanisms and propose ways to improve ventilation performance in apartment buildings. However, the imbalance in room airflow due to the individual operation of the ventilation systems has not been resolved [3].

A range hood is installed in most Korean kitchens to prevent the dispersion of pollution sources. When the local exhaust is operated in a narrow space such as a kitchen, the pressure balance collapses. Modern buildings with high air-tightness do not satisfy the air supply corresponding to the exhaust air volume, so negative pressure is formed in the room. A 30% decrease in hood capture efficiency and ventilation effectiveness causes the problem that people in the living room can be exposed to PM2.5 generated from cooking [4]. Therefore, it is necessary to develop a range hood exhaust strategy considering the make-up air supply, since PM2.5 generated during cooking is rapidly dispersed in the living room. In addition, sensor-based operation strategies are unavailable in Korea.
In this study, a new ventilation system that integrates the range hood and ventilation system (e.g., heat recovery equipment and auxiliary air supply) was developed to improve the performance of the system. An effective sensor-based ventilation system for preventing indoor PM2.5 dispersion was developed and evaluated with field experiments.

2. Optimization of Sensor Location by Analyzing the PM2.5 Distribution

2.1 Indoor PM Characteristics

Outdoor PM enters the room through ventilation or infiltration. The larger the particle size, the faster the deposition rate [5]. The PM2.5 deposited by indoor air flow formation may be re-suspended or newly generated by the source. These processes may be expressed by the mass balance equation:

\[ V \frac{dC_i}{dt} = aPC_i - aVC_i - KV_i + \dot{S} \]

Here,

- \( V \): Volume of the room (m\(^3\))
- \( C_o \): Outdoor particle concentration (#/m\(^3\))
- \( C_i \): Indoor particle concentration (#/m\(^3\))
- \( a \): Air exchange rate (1/s)
- \( P \): Penetration coefficient
- \( K \): Particle deposition rate (1/s)
- \( \dot{S} \): Indoor particle emission rate (#/s)

The main factors involved in the inflow process of suspended particulate matter in the atmosphere are penetration coefficient, deposition rate, and air exchange rate. PM deposition is expressed using variables such as deposition rate, particle rate loss coefficient, and deposition velocity. When mechanical ventilation is used, PM may be affected by the filter efficiency and can be represented by the following equation:

\[ C_i = F_{in}C_o + C_s \]

Here,

- \( F_{in} \): Filter efficiency
- \( C_s \): PM concentration by indoor source (#/m\(^3\))

2.2 PM2.5 Sensor Fabrication and Calibration

The PM2.5 emission rate differs in cuisine, and the spatio-temporal distribution changes unexpectedly over time. Field measurement is essential for understanding the concentration distribution in the actual space. Five Arduino-based PM2.5 sensors were installed to perform multipoint measurements using the commercial instrument, TSI-DustTrak 8532. The sensor used GP2Y1010AU0F (sharp), which is relatively convenient for building software and hardware systems. The characteristics of the light-scattering sensor lead to ambient noise making the sensors value susceptible, which means that appropriate calibration is required. For the sensor calibration, measurement data from DustTrak and Sensor 1 in the kitchen were used. The linear regression model agreed well, and the R\(^2\) correlation values in the two cases were 0.97 and 0.98, respectively.

2.3 Field Measurement for the PM2.5 Distribution

A field test was conducted in the air quality management (AQM) test room in Korea (ACH50: 2.9 h\(^{-1}\)). The experiment space was limited to the living room and kitchen. A range hood was installed in the kitchen, along with a line diffuser on the kitchen ceiling, 1.5 m from the cook top.

Figure 1 shows the installation position of the PM2.5 sensors and measuring instruments. The two DustTrak 8532 were in the kitchen (\(D_k\)) and center of the living room (\(D_l\)). All sensors except Sensor 4 were sampled in the breathing zone (1.5 m), and Sensor 4 was installed near the ceiling. A pack of
smoked bacon (700 g) was broiling for 12 minutes. The measurement was performed over two hours, to evaluate the PM2.5 distribution. To analyze the influence of the living room distribution of the auxiliary air supply, the experimental cases are shown in Table 1.

### Table 1. Case study

| Case | Ventilation system                        | Operation time (min.) | Air flow rate (CMH) |
|------|------------------------------------------|-----------------------|---------------------|
|      |                                          |                       | Range hood | Auxiliary system |
| 1    | Range hood                               | 15                    | 320       | -               |
| 2    | Range hood + Auxiliary system            | 120                   | 320       | 133             |

**Figure 1. Description of the field measurement**

2.4 Analysis of the Spatio-temporal PM2.5 Distribution

The PM2.5 dispersion path of Case 1 was kitchen(S1)>ceiling of kitchen(S3)>between living room and kitchen(S4)>rear of living room(S5)>living room center (D1)>side of the living room(S2), as shown in Figure 2. For Case 2, on the other hand, the dispersion path was S1> S3> S2> S5> D1> S4.

Compared with Case 1, the results showed that S4 was the slowest in response due to the continuous supply of make-up air. The fastest detection was near the living room (S2) adjacent to the kitchen. The ceiling (S4), in particular, showed the auxiliary system affected to be clean supplying air. Case 2 measured relatively low concentration compared with Case 1 during cooking, because, the auxiliary air supply could increase the indoor flow mass.

The auxiliary system was operated together, and the concentration deposition rate was higher than when only the hood was operated. The auxiliary ventilation system directly affected the PM2.5 spatial distribution and L / K ratio. Sensor 3, located on the kitchen ceiling, detected that PM2.5 from the kitchen moved through the ceiling into the living room. This sensor had the highest rate of change among all the sensors. Higher concentrations of 1200 μg/m³ were measured in S3 (the ceiling) than in S4 (36 μg/m³). Case 2 showed a similar tendency, S3: 500 μg/m³ and S4: 200 μg/m³. In all cases, the fastest PM2.5 detecting sensor after the cook top was the ceiling. Therefore, it is necessary to locate IAQ sensors on the ceiling, a suitable position for PM2.5 distribution during cooking.
3. Introduction of the Integrated Ventilation System

3.1 Advanced Strategy Development

In general, ways to use supply air include the heat recovery ventilator (HRV) and auxiliary system (AS). To improve the performance of the range hood, a sensor-based operation strategy that integrates the range hood and AS was developed, as shown in Figure 3. IAQ sensors were positioned in the living room and kitchen ceiling, based on the results of the previous experiment. The integrated algorithm operates step by step based on a certain concentration of the sensors. The system is divided into three steps: the beginning stage, measuring stage, and end stage.

First, the cooktop IR sensor turns on, and the range hood level 1 operates. The HRV is always on to meet the air change rate (0.5/h). In the next step, concentration is measured every 10 seconds to determine the level of the range hood. If the kitchen concentration is 100 μg/m³ or higher, the auxiliary supply unit operates, and if the range hood is 300 μg/m³ or 500 μg/m³ or higher, it changes to level 2 or 3. When the sensor in the living room indicates 100 μg/m³ or less, and the kitchen detects 30 μg/m³, it enters the end stage, when level 1 of the range hood operates again. From then on, a timer of 20 minutes is activated. The system shuts down when certain conditions are much such when all 20 minutes have passed or the measurement is below 30μg/m³ in the living room. If the concentration increases again during re-cooking, the system returns to the measuring mode.

The AS and HRV cross-operate to prevent performance degradation due to overflow. All systems are designed to be switched off when the windows are open during cooking.

3.2 Field Measurement for Estimating the Performance of the Integrated Strategy

The environment for measurement was similar to that of Korean residential apartments (ACH50 2.9h⁻¹). The ventilation system was equipped with a range hood, HRV, and auxiliary supply system. The description of the case study is given in Table 2. The cooking phase involved three minutes of preheating, 12 minutes of cooking, and 45 minutes after cooking. The IAQ sensors and DustTrak 8532 were placed on the ceilings of the kitchen and living room, the most appropriate locations according to the previous experimental results. The measurement sensor used in the experiment was a light scattering sensor that scatters the material floating in the air using a laser built in the PMS5003. The maximum consistency errors were as follows: ± 10% (100 to 500 μg/m³), ± 10μg /m³ (0 to 100 μg/m³).
Table 2. Case Study

| Case | Ventilation system | Operation time (min.) | Air flow rate (CMH) | Range hood | Auxiliary system | HRV |
|------|--------------------|-----------------------|---------------------|-------------|-----------------|-----|
| 1    | Range hood         | 60                    | 150                 | -           | -               | -   |
| 2    | Range hood         | 60                    | 150                 | -           | -               | -   |
| 3    | Range hood + AS    | 60                    | 150/220/300         | 150         | -               | -   |
| 4    | Range hood + AS    | 60                    | 150/220/300         | 150         | -               | -   |
| 5    | Range hood + AS+HRV (constant) | 60           | 150/220/300         | 150         | 50              | 50  |

Figure 3. Integrated ventilation operating strategy

4. Results and Discussion

The PM2.5 concentrations in the kitchen and living room during cooking are shown in Figures 4 and 5. In Cases 1 and 2, the PM2.5 concentration was high in the kitchen and living room. Particularly after cooking, the dispersion in the living room reached a higher concentration than in the kitchen owing to buoyancy. The kitchen maximum value was 676 μg/m³, but the living room maximum value was 373 μg/m³. On the other hand, Cases 3 and 4 showed low overall concentrations in the kitchen and living room. The average concentration in the kitchen was measured as low as 200 μg/m³. The maximum concentration in the living room was measured as 54 μg/m³, and the concentration was hardly diffused (the background concentration was 34 μg/m³). This system was effective in preventing PM2.5 dispersing into adjacent space.
In Case 5, the effectiveness of HRV was evaluated with the range hood and AS, as shown in Figure 5. HRV operated constantly to achieve 0.5 times/hour for the minimum ventilation frequency. In this case, the kitchen concentration was 185 μg/m$^3$, and the living room concentration was 68 μg/m$^3$. With the additional flow rate of 50 CMH, the reduction in the concentration of PM2.5 was more effective. The integrated system of the auxiliary air supply and range hood during cooking was evaluated to be effective in preventing the distribution of PM2.5.

In further studies, the system will be applied to Korean residential apartments and verified through long-term experiments.

**Figure 4.** Range hood (150 CMH, constant) vs Range hood + AS

**Figure 5.** Range hood + AS vs Range hood + AS + HRV (50 CMH, constant)

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