The effect of make-up air system on the performance of oil fume collection in commercial kitchen

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Abstract. Make-up air and exhaust system dominates the airflow pattern in the commercial kitchen. In this paper, the numerical simulations were performed to analyze and compare the effect of different make-up air modes on the flow field characteristics, the temperature and concentration of C₁₉H₃₀ distribution and the collection efficiency of fume particles. It was shown that air curtain supply can prevent oil fume from spreading out more effectively than ceiling supply (CS) mode. It improves primary collection efficiency when the exhaust airflow rate is less than 4500 m³/h in upward air curtain supply (UACS) and 4000 m³/h in downward air curtain supply (DACS) mode, respectively.

1. Introduction
Cooking oil fume is one of the important pollution sources of the particulate pollutants in the urban atmosphere [1], especially in commercial kitchens as a result of large quantities of oil required during the cooking process [2]. Health concerns on cooking oil fume in commercial kitchen have increased in recent years. It is reported that cumulative exposure to cooking oil fume has been considered as a significant risk factor for the cancer [3]-[4]. Therefore, to improve the indoor air quality of commercial kitchen, a reasonable and complete make-up air system is required. The dispersion of airflow depends highly on the make-up air mode [5]. Gao et al. [6] analyzed the influence of the oil fume in human breathing zone under the condition of natural ventilation when the windows and doors is opened and closed in kitchen, and found that the air supply position of different mechanical ventilation has greater impact on the collection performance. A similar result was found by Kosonen et al [7]. In their paper, the floor air supply system is proposed as the best air supply mode, and the ceiling air supply at a low velocity as the second.

A new make-up air mode, air curtain supply is proposed by some investigators. In order to verify and quantify the usefulness of the air curtain supply, this study focuses at the commercial kitchen make-up air system, which include CS, UACS and DACS modes.

2. Material and methods

2.1. Modeling description
The kitchen model shown in figure 1 is a typical commercial kitchen of canteen in Beiyang Yuan campus at Tianjin University. The size of the kitchen is 10.32m(L)×8.07m(W)×2.78m(H). In the case study of kitchen, there is no window and two closed doors on the north and south sides. Simplified mannequins were designed in the two cooking zones on the west and east sides (Zone 1 and Zone 2).
The air curtain supply is the effective measures to improve the collection efficiency of the oil fume, so the UACS mode and DACS mode were introduced to compare the traditional CS mode. During the simulation, the air curtain jet velocity is 0.5 m/s, jet angle is 90° and jet slot is 3 mm [8].

2.2. Simulation method
The numerical simulations were conducted by using the commercial CFD software Fluent 15.0. A standard k-ε turbulence model was adopted here to predict airflow and turbulence. The SIMPLE algorithm was applied for the pressure and velocity coupling. The discretization scheme for all variables was the second order upwind except that the pressure was used PRESTO scheme.

Airflow rate from 3000 to 5000 m³/h in each zone was set at the outlet of the exhaust hood for each case. It is assumed that the flow velocity at each point on the outlet surface is evenly distributed, and different airflow rates can be obtained by changing the flow velocity. The case with a reference exhaust airflow rate of 4000 m³/h is the base case. For other boundary surfaces, the settings are listed in Table 1.

Table 1. Boundary conditions used in the simulation.

| Boundary name         | Settings       |
|-----------------------|----------------|
| Door                  | Wall           |
| Supply                | Velocity-inlet |
| Pollutant source      | Velocity-inlet |
| Jet-air slot          | Velocity-inlet |
| Wall                  | Wall           |

2.3. Definition of collection efficiency
The particle trajectory was tracked by Lagrangian model. The fuel-oil-liquid (C₁₉H₃₀) material was selected instead of the fume particle. The collected pollutants are divided into two parts, one part is directly collected by exhaust hood, and the other disperses in the kitchen at first and then it is collected by exhaust hood, which are defined as the primary and secondary collection of particles, respectively. Based on the particulate residence time on the inlet of hood, the primary and secondary collection efficiencies of fume particles are computed to evaluate the performance of range hood.

The collection efficiency of fume particles is determined by the residence time distribution histogram of fume particles, in which the abscissa coordinate is the residence time of particles and the ordinate coordinate is the proportion of the number of particles in the residence time interval to the total number of particles. Choosing the appropriate abscissa interval makes the distribution of particle proportion at the inlet of the hood more continuous with the residence time. Assuming that the minimum residence time of particles in the histogram is S and the median X of the time interval in which the number of particles accounts for the largest part is X, it is defined that the primary particle trapped by the range of residence time is between S and 2X-S, and the remaining particles with
residence time greater than 2X-S are considered as secondary particles trapped. The collection efficiency is defined as follows:

$$\eta_{pc} = \frac{n_{pc}}{n_p}$$

$$\eta_{sc} = \frac{n_{sc}}{n_p}$$

where, $n_p$ is the total amount of fume particles generated by cooking; $n_{pc}$ and $n_{sc}$ is the amount of particles collected by the primary and secondary collection, respectively; $\eta_{pc}$ and $\eta_{sc}$ are the ratio of primary collected particles and secondary collected particles, respectively.

3. Results and discussion

To investigate the effects of different make-up air system, five cases under three kinds of make-up air modes are studied by numerical simulation. We analyze the flow field characteristics, the distribution of temperature and $C_{19}H_{30}$ concentration and fume particles collection efficiency in zone 1 and zone 2 with the reference exhaust airflow rate of 4000m$^3$/h in this section.

3.1. Ceiling supply

The contour plots of two cooking zones are presented in figure 2 and figure 3 with the reference exhaust airflow rate of 4000m$^3$/h, respectively. It can be obviously seen that a large amount of oil fume escapes from the front edge of the hood and spread around, which contribute to the accumulation of pollutants near the ceiling and at the corner of the cooking zone.

In zone 1 and 2, the supply air is totally from the north and south air supply inlets on the ceiling and the collection efficiency is therefore highly affected by the location of two inlets. From figure 2, the supply air from the south air supply inlet pushes the oil fume to the left in the zone 1, and air temperature on the left side of the hood is high, which accelerates the fume diffusion.

![Figure 2 Contour plots on Y-Z axis, X=0.5m in zone 1. (a) Flow field. (b) Temperature distribution. (c) $C_{19}H_{30}$ concentration distribution.](image1)

![Figure 3 Contour plots on Y-Z axis, X=7.573m in zone 2. (a) Flow field. (b) Temperature distribution. (c) $C_{19}H_{30}$ concentration distribution.](image2)
3.2. Upward air curtain supply
Upward air curtain supply device is applied with three slots on the hearth. Although UACS adds a part of the fresh air, the kitchen is still in the negative pressure state. The outdoor air is sent into the kitchen from the north and south air supply inlets under the pressure difference between the kitchen and outdoors. Figure 5a shows the supply air at the lower edge of the hearth. Compared with figure 3a, the air velocity decreases to about 0.6m/s. The results indicate that UACS plays an important role in providing comfortable airflow pattern in the kitchen. In addition, an improvement in the fume diffusion is achieved in figure 4c and figure 5c when compared with figure 2c and figure 3c, respectively. However, the C_{10}H_{30} concentration is remain relatively higher on the left size of the hood, especially in zone 2. The mass fraction of C_{10}H_{30} on the left size of the hood inlet lies in the range of 0.00025 to 0.000288. Thus, the risk of the spillage from the hood may be increased if the exhaust outlet could not discharge oil fume in time or the amount of oil fume increase suddenly.

![Figure 4](image1.png)
Figure 4. Contour plots on Y-Z axis, X=0.5m in zone 1. (a) Flow field. (b) Temperature distribution. (c)C_{10}H_{30} concentration distribution.

![Figure 5](image2.png)
Figure 5. Contour plots on Y-Z axis, X=7.573m in zone 2. (a) Flow field. (b) Temperature distribution. (c)C_{10}H_{30} concentration distribution.

3.3. Downward air curtain supply
The same as the UACS, the installation of the downward air curtain provides a lot of fresh air to the whole ventilation system, reducing the air supply volume of the north and south air supply inlets, as shown in figure 7a. At the same time, in contrast to the case of CS (seen in figure 2c and figure 3c), it also prevent oil fume from flowing into the non-working area in the kitchen. Conversely, in figure 7c, although the phenomenon that the oil fume is biased towards the left still exists, the mass fraction of C_{10}H_{30} on the left size of the hood inlet decreased less than 0.00025 and the fume gas can be effectively controlled in the cooking zone.

![Figure 6](image3.png)
Figure 6. Contour plots on Y-Z axis, X=0.5m in zone 1. (a) Flow field. (b) Temperature distribution. (c)C_{10}H_{30} concentration distribution.
3.4. Collection efficiency of fume particles

The fume collection efficiencies of exhaust hood with different make-up air systems are studied in the case-study kitchen. Figure 8a illustrates that the UACS shows a significant improvement in primary collection efficiency in zone 1 compared with the CS. The primary collection efficiency in the zone 1 is increased to more than 64% under all exhaust airflow rate cases and the difference between the CS and UACS can be up to 9.8%. However, the primary collection efficiency of UACS in the zone 2 is found to go up slightly less than that of the CS when the exhaust airflow rate exceeds 4500 m$^3$/h. It should be noted that the primary collection efficiency begin to decline at the exhaust airflow rate of 4000 m$^3$/h, so UACS and DACS may be counterproductive under excessive airflow rate.

4. Conclusions

This paper investigates the effects of different make-up air systems on the collection performance of exhaust hoods. Simulation results show that UACS and DACS can prevent oil fume from spreading out more effectively than CS. Air curtain is also the key to improvement of primary collection efficiency, but adverse effects in primary collection efficiency may occur when exhaust airflow rate exceed 4500 m$^3$/h and 4000 m$^3$/h in UACS and DACS modes, respectively.
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