Static pressure reset control strategy for roof fans in centralized cooking exhaust systems

Yanlei Yu, and Jun Gao

1School of Mechanical Engineering, Tongji University, 200092 Shanghai, China

Abstract. Excessive static pressure and inadequate flow rate at each terminal of the centralized cooking exhaust systems contribute to poor indoor air quality in kitchens. Roof fans can improve the ventilation performance of centralized cooking exhaust system, but the optimal control strategy for roof fans is currently unavailable. This paper proposes a static pressure reset control strategy for variable frequency operation of roof fans that follows the law of normal distribution of simultaneous operating rate. The effect of the roof fan on the static pressure and flow rate distribution in a centralized cooking exhaust system with multiple power sources of range hoods is investigated. The relationship between simultaneous cooking rate and the appropriate set point of the roof fan is determined using experimental and simulation methods. The results show that the proposed static pressure reset control strategy for roof fans has improved control performance and significant potential for energy savings.

1 Introduction

Large amounts of toxic cooking gases are produced throughout the cooking process, and good ventilation control is essential for maintaining healthy indoor air quality [1, 2]. The most popular local exhaust equipment for eliminating cooking emissions is the range hood. The effectiveness of eliminating pollutants from indoor air is determined by the hood's capture efficiency and exhaust flow rate [3]. In scenarios such as high-rise residential and large commercial kitchens, multiple hoods are connected through centralized exhaust shaft to provide centralized filtration and purification of captured cooking pollutants before being centrally discharged into the outside environment. Thus, a centralized cooking exhaust system consists of multiple hoods, branches, connections, central shaft, dampers, and centralized purification units, etc [4, 5].

In fact, the centralized cooking exhaust system is an air distribution system with multiple decentralized fans. The pressure head and flow rate of each decentralized fan is governed by the fan characteristic curve, and the exhaust air resistance for each exhaust terminal is matched to the pressure head of each fan [6]. As a result, the exhaust terminal with a higher exhaust resistance has a lower flow rate, making it difficult to meet the pollutant elimination requirements. For the conventional residential Chinese cooking characteristics, the recommended range of the flow rate is 300-500m³/h. However, several researches show that the actual exhaust flow rate in kitchens of high-rise residential buildings is much lower than the recommend range, and the exhaust flow rate of higher households can be more than twice that of lower floors [7].

To address the issue of uneven flow rate distribution in centralized cooking systems, adding a centralized fan at the exhaust system's outlet can provide additional power. Han et al. [8] investigated the effect of various system parameters including the building height, shaft dimension, fan characteristics, and concurrent hood usage on the distribution of static pressure. The results showed that the roof fan could minimize the pressure build-up. Park et al. [9] proposed a novel exhaust cowl, which can improve the ventilation performance of the centralized exhaust system with the help of wind pressure.

The development of centralized roof fan has been promoted as a solution to meet the adequate flow rate demands in part by reducing the static pressure distribution; however, the characteristics and control strategy of the roof fans in the centralized cooking exhaust system should be properly evaluated and compared with the alternative solutions. Conventional static pressure reset strategies have a large energy saving potential, but they are difficult to apply to centralized cooking exhaust systems, due to the difficulty of controlling end decentralized fans (hoods) and in-home monitoring. There has been little research into the interaction of variable airflow control strategies for roof fans and cooking behaviour characteristics.

This work aims to develop a static pressure reset strategy for roof fans in centralized cooking exhaust systems. The influence of the negative pressure at the outlet on the static pressure and flow distribution was investigated and the reasonable static pressure set point for the roof fan was determined based on the cooking behaviour characteristics.

* Corresponding author: gaojun-hvac@tongji.edu.cn

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2 Method

2.1 Centralized cooking exhaust system model

In order to obtain the flow characteristics and construct a reasonable control strategy for the roof fan in the centralized exhaust system with decentralized fans, a theoretical model of the centralized exhaust system is developed in MATLAB. Various system parameters affect the distribution of static pressure and flow rate in the centralized exhaust system, and the factors considered in the model mainly include:

(1) Structure parameters: building height (78m, 26-story), centralized shaft size (300mm × 300mm), branch size (180mm × 180mm), shaft material (concrete and hot-dip galvanized steel).

(2) Operation parameters: simultaneous operating rate and location distribution. The simultaneous operating rate is defined as the ratio between the number of hood fans running simultaneously and the number of all hood fans. The location distribution of operating hoods is set to uniform to reflect the most typical location distribution in actual centralized cooking systems.

(3) P-Q curve of fans. The range hood is mainly composed of an exhaust fan and a damper for adjusting the exhaust flow rate. Since there is a polynomial relationship between the static pressure jump \( P_i \) and the flow rate \( V_i \) through the fans, the characteristic curve of the fan is expressed as follows:

\[
P_i = c_0 + c_1 V_i + c_2 V_i^2 + c_3 V_i^3
\]

(4) Static pressure resetting point of the roof fan. The control goal with the roof fan power \( P_{rooffan} \) is to ensure that each decentralized fan has a flow rate of at least 400 m³/h while minimizing energy costs.

![Diagram of the centralized cooking exhaust system.](image)

In this work, the numerical nodes are located at the connections between branches and the shaft, as shown in Fig. 1. Based on the continuity of flow, the flow rate in the shaft is equal to the sum of the airflow at each exhaust terminal from the downstream to the upstream floors, as below:

\[
Q_{m, i} = \sum_{j=1}^{n} Q_{b,j}
\]  

(2)

According to Bernoulli’s theorem, the exhaust resistance of the \( i \)th terminal can be calculated from the hydraulic analysis, as shown in equation (3). The resistance loss of the branch pipe \( \Delta P_{b,j} \), the convergence loss of the tee at the connection between the branch pipe and the main pipe \( \Delta P_{tee,con,i} \), the straight-through resistance loss at several tee locations downstream \( \Delta P_{along,m,j} \), the resistance loss of several sections of the shaft \( \Delta P_{tee,dir,i} \), and the local resistance loss at the outlet \( \Delta P_{outlet} \) contribute to the flow loss of each terminal \( \Delta P_i \).

\[
\Delta P_i = \Delta P_{b,j} + \Delta P_{tee,con,i} + \sum_{j=1}^{n} \Delta P_{along,m,j} + \sum_{i=1}^{n} \Delta P_{tee,dir,i} + \Delta P_{outlet}
\]  

(3)

When the roof fan is turned on, the exhaust resistance to be overcome of each terminal is provided by the pressure head of both the hood fan and the roof fan, as below:

\[
\Delta P_i = P_i + P_{rooffan}
\]  

(4)

The flow rate at each terminal is initialized to solve the proposed mathematical model. The exhaust resistance and pressure head provided by the hood fan and roof fan of each terminal are calculated and compared. Root mean square error (RMSE) is used as an indicator to determine the calculation error between the exhaust resistance and the pressure head provided by the fans. The air flow at each terminal of the system is updated to reduce RMSE, and the calculations process are repeated until the resistance matches the power to obtain the flow and pressure distribution for a specific operating condition.

2.2 Experimental platform

Fig. 2 shows a full-scale experimental platform of a centralized cooking exhaust system. The experimental platform is made up of 26 completely duplicated units. The range hoods are connected to the central shaft via flexible pipes, reducers, and manual adjustment valves, etc. The cross-sectional size of the shaft is 400 mm × 500 mm, and the total length of the system is 78 m. The cross-sectional size of the branch is 180 mm × 180 mm, and the branch length is 1.5 m. The experimental system is made of hot-dip galvanized steel.
Fig. 2. Experimental platform of the centralized cooking exhaust system: (a) full-scale platform; (b) roof fan.

3 Results and discussion

3.1 Verification of the theoretical model

The dependability of the theoretical model is validated by comparing it to experimental measurements taken under representative condition, as shown in Fig. 3. In general, the tendencies of calculation results and experimental measurements were consistent. The maximum relative error in airflow rate was 10.88%, and the maximum relative error in static pressure was 8.87%.

The differences between the numerical calculation and the experimental results were caused by a variety of factors, the most significant of which was the unavoidable air leakage of the experimental platform. The velocity of the ambient air also had an effect on the actual operating state of the decentralized fans. Because the difference between experiment and calculation was less than 12%, the theoretical results were reasonable in predicting the flow characteristics in the central exhaust system. As a result, the proposed model is used for the subsequent computational analysis of the performance of the centralized cooking exhaust system.

Fig. 3. Comparison of experimental data and theoretical model results at each branch: (a) exhaust flow rate; (b) static pressure.

3.2 Effect of the simultaneous operating rate

The operating parameters of the centralized cooking system are related to the distribution patterns of the airflow rate and static pressure in the shaft. The simultaneous operating rate responds to the number of households in an apartment building where cooking takes place simultaneously. The effect of simultaneous operating rate on the flow characteristics of the centralized cooking exhaust system is shown in Fig. 4. It can be seen that under large opening rate, the static pressure accumulates and the problem of insufficient flow is serious at the bottom. Taking the flow rate of the hood on the lowest floor to reach 400m$^3$/h as the control target, the roof fan needs to provide sufficient auxiliary power when the simultaneous operating rate is greater than 40%.

Fig. 4. The flow characteristics at each branch under different simultaneous operating rates: (a) exhaust flow rate; (b) static pressure.

3.3 Determination of static pressure reset value

The roof fan can significantly increase total system flow due to the negative pressure created at the shaft outlet, which changes the pressure distribution in the system. Take the simultaneous operating rate of 60% as an example, the correlations between static pressure reset point and flow characteristics of the shaft are shown in Fig. 5. The greater the negative pressure provided by the roof fan at the shaft outlet, the greater the decrease in static pressure value on the top floor; however, the decrease in static pressure value on the lower floors is insignificant. When the static pressure of the roof fan at the outlet is set to -431Pa, the flow rate of the lowest floor hood is exactly 400m$^3$/h.

Fig. 5. The correlations between static pressure reset point and flow characteristics of the shaft: (a) exhaust flow rate; (b) static pressure.
Fig. 5. The correlations between static pressure reset point and airflow distribution in the system: (a) exhaust flow rate; (b) static pressure.

Similarly, the appropriate static pressure values at the shaft outlet corresponding to various operating conditions characterized by the simultaneous hood opening rate are determined as shown in Fig. 6.

Fig. 6. The appropriate static pressure values of the shaft outlet under various operating conditions.

3.4 Control strategy based on the cooking behaviour characteristics

Since the simultaneous operating rate of decentralized fans in the shaft of high-rise residential buildings is difficult to monitor in each home, the conventional static pressure reset method is difficult to implement. Given that the distribution of a large number of random cooking behaviours over time has a statistically significant feature, i.e., the operating rate exhibits a normal distribution with cooking time.

The peaks of these waveforms correspond to times slightly earlier than the daily breakfast, lunch and dinner meal times, and the three peaks on weekdays correspond to 07:47, 11:59 and 17:32, respectively [10]. This paper establishes a relationship between the simultaneous operating rate and time in order to control the reset point of the roof static pressure over time as shown in Fig. 7.

Fig. 7. Control strategy based on the cooking behaviour.

4 Conclusion

This paper proposes a new static pressure reset control strategy for roof fans based on cooking behaviour characteristics in centralized cooking exhaust systems. The proposed strategy changes the variable frequency of roof fan in response to system load changes and circumvents indoor monitoring of simultaneous operating rates.

A qualitative parametric analysis is conducted in MATLAB to investigate flow characteristics with roof fans in the shaft, followed by experiments for validation. Guidance of the static pressure reset value is given based upon the normal distribution of simultaneous operating rates with cooking time.

This work provides theoretical support for the application and rational control of roof fans in centralized cooking exhaust systems.

References