Using Color Full-Scale Schlieren (CFSS) technique to improve kitchen exhaust hood performance

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Abstract: This article uses color full-scale Schlieren for heat flow visualization of the kitchen exhaust hood. Using grease filters with same percentage of opening but different forms for measurements the heat flow escaping rate, noise, and air velocity of the kitchen exhaust hood under conditions of different percentage masking. The results show that using different grease filters without masking has no escaping heat flow. Employing the rectangular filter with side masking has the worst heat flow escaping. The top masking has also no heat flow escaping and the form with circular opening has the strongest absorbability. In this work, the smallest noise level is 65dB which appears at the situation of top masking. Moreover, kitchen exhaust hood without masking the air flow rate increase 3.17% of the air velocity than side masking.

Keywords: Color Full-Scale Schlieren, Flow Visualization, Grease Filters

1. Introduction

Full-scale Schlieren technique was famous and especially developed for flow visualization with large area of test section. Neglecting three-dimensional effect, the full-scale Schlieren technique is suitable for flow visualizations of e.g. heating, ventilating, and air conditioning. It can directly and easily show heat flux distribution in a grand test size. In 1995, Settles et al. first presented the simple and large Schlieren optical system for qualitative visualization of the ventilation airflows, such as commercial kitchen griddle and exhaust hood, daily room, removing a frozen pizza, planar turbulent jet of heated air [1]. In 1999, Settles et al. further presented outdoor Schlieren and shadowgraph imaging, for visualization of outdoor thermal convection, combustion, and explosion phenomena, such as jet aircraft and high-speed flight [2].

In 2001, Settles et al. presented a very large Schlieren optical system with test section area of 2.3×2.9 m^2. The key element of the full-scale Schlieren system is the front illuminated source grid which is mounted by 12 pieces of aluminums sign panels that are assembled on a frame, where dimension of a single aluminum sign panel is 1.2m $\times 2.4$m $\times 2.5$mm. Upon the retroreflective material is silk-screened 5.08 mm wide vertical black grid lines spaced 5.08 mm apart. The author visualized many objects, such as heating and ventilation airflows, thermal plumes of people, aerodynamics of an explosive trace detection portal, gas leak detection, shock wave motion, and the discharge of firearms [3].

Full-scale Schlieren technique can be divided into two types in terms of different experimental arrangement. The one is retroreflective full-scale Schlieren which uses light projector to project penetration light through the test section on the retroreflection screen. The retroreflection screen shows first the shadowgraph image and the reflected light is focused through a condense lens on the camera. The most so far presented data in the references are captured by using the retroreflection method. The other one is background-oriented full-scale Schlieren which directly builds the background-oriented light source to project penetration light through the test section and be refocused through a convex lens on the camera. There are very few studies on the

background-oriented full-scale Schlieren. In 2011, C. C. Ting and C. C. Chen studied the rate of cutoff grid effect on the sensitive of imaging. The applied cutoff grids are with 50, 60, 70, 80, and 90% of the cutoff light percentage respectively. The test objects are burning candle, LPG flow ejecting into surrounding, and burning alcohol. The results show that the cutoff grid with 60% received the best flow visualization image [4 - 7].

In the research of the kitchen exhaust hood, present study focused on noise and heat flux of the kitchen exhaust hood. For the users who working in the kitchen, long - term inhalation the cooking smell will harm their body. Although setting kitchen exhaust hood can solve the cooking smell problem, it also bring noise problem too. Generally speaking, kitchen exhaust hood produces the sound when operating is low - frequency noise which is easy to affect the user's mood, so that users feel impatient and cause pressure. In addition, the low – frequency noise would affect to sleep and psychology, it may lead to neurasthenia or depression and other symptoms. Briefly speaking, long-term exposure to the environment with noise would harm the human body. In 2000, Chiang et al. investigated flow fields, temperature fields, and air contaminant of kitchen hood at indoor air environment by using numerical simulations [8]. Five years later, In 2005, Abanto et al. analyzed the number of blades and the twisting angle of kitchen hood system performance by using Computational Fluid Dynamics at operating conditions[9]. There are some articles focused on reducing noise by optical method or translation the noise to power energy[10-11]. In 2014, Young et al. using micro color Schlieren technique to visualize compressed diamond flow of nozzle[12].

Duct and motor are two major configurations of kitchen exhaust hood. Presently, noise values are between 60 and 80 dB which obtained at a distance from opening about 20 cm and most of kitchen exhaust hoods can reach the standards set by CNS [13-14]. After using kitchen exhaust hoods for a while the noise is usually greater than 70 DB and 69 dB low – frequency noise will make users feel uncomfortable. Based on above discussion the kitchen exhaust hoods still have some deficiencies which can be improved. Since using optical methods to visualization and improving heat flux of the kitchen exhaust hood is more directly, this paper make use of color full – scale Schlieren to visualize heat flux of the kitchen exhaust hood and discuss heat flux flowing situation with different grease filters and various masking conditions.

Full-scale Schlieren technique is a famous and especially developed for flow visualization with large area of test section. This work uses the optimal sensitive parameter of previous study to visualize the heat flow of the kitchen exhaust hood and observe the heat flux distribution.

2. Basic Theory

Full – scale Schlieren which make use of the light passing through the test section and imaging by penetrating through the convex lens is a convenient technique for optical visualization. Figure 1 shows schematic of the focusing Schlieren system. In addition, calculated the full - scale Schlieren sensitivity ε_{min}, the Weinstein's contribution model was be used [3] as shown in the following figure.
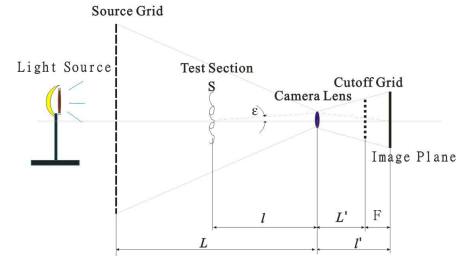

Figure 1. *Schematics of the focusing Schlieren system*

$$\varepsilon_{min} = \frac{2}{k}\frac{\Delta E}{E}\frac{L}{L'(L-l)}$$
$$= a\frac{\Delta E}{E}\frac{L}{L'(L-l)} \quad \text{(radians)} \tag{1}$$

Where k is a number of line-pairs per millimeter and $\Delta E/E=0.1$ is a 10% detection threshold. Equation (1) can therefore be rewritten as follow:

$$\varepsilon_{min} = 20626a\frac{L}{L'(L-l)} \quad \text{(arcseconds)} \tag{2}$$

Where 1 radian = 20625 arcseconds.

The parts of knife – edge and source grid can be as the imaging of objects with lines width, then imaging on the cutoff grid by the light passing through the convex lens. By means of the geometrical optics, the distance between cutoff grid and lens can be calculated and then derive the scale to get the size and position of the image on cutoff grid. If the lines width of the cutoff grid is b, then the distance between brightness width and darkness width can be derived from different cutoff rate. That is, brightness width is b – (b × cutoff-rate) and darkness width is b + (b × cutoff-rate). Table 1 shows the distance to different cutoff grids.

Table 1. *Band distances of the cutoff grid*

Focal length, f = 501.3 mm, Band width, b = 0.546 mm, L=6m, l=3m			
Brightness width (mm)	0.273	0.218	0.163	0.109
Darkness width (mm)	0.819	0.874	0.929	0.983
Cutoff rate (%)	50	60	70	80

In this study, assuming the cavity is infinite, so that the cavity can be considered as a constant pressure situation. The leakage of gas flowing through the heat exchanger and after a period of time, the temperature of gas will be equal to the ambient temperature. According to Bernoulli's law:

$$p_1 + \frac{1}{2}\rho v_1^2 + \gamma z_1 = p_2 + \frac{1}{2}\rho v_2^2 + \gamma z_2 \tag{2}$$

Assuming that z1 = z2, v1 = 0 and p2 =0, then the fluid velocity of outlet as shown below:

$$v_2 = \sqrt{\frac{2p_1}{\rho}} \qquad (3)$$

When applied v2 (m/s) ×A2, then can get the leakage rate Q (m3/s) as shown below:

$$Q = A_2 v_2 \qquad (4)$$

This work uses homemade Pitot tubes with U –shaped tubes to measure the wind velocity. The homemade Pitot tube is combined with two tubes, inner tube and outer tube. The inner tube which opening faces the fluid direction is used as stagnant tube. The outer tube has a small opening can connect to side tube. The fluid speed can be derived from the pressure difference between inner and outer tube as shown in Fig. 2. Assuming that the tip of Pitot tube as the stagnant point, the fluid speed is equal to zero and flow field is unaffected by Pitot tube. That is, p1 = p2, due to point 1 and point 2 have same height, then z1 = z2. According to Bernoulli's law from equation (3), v1 can be written as follow:
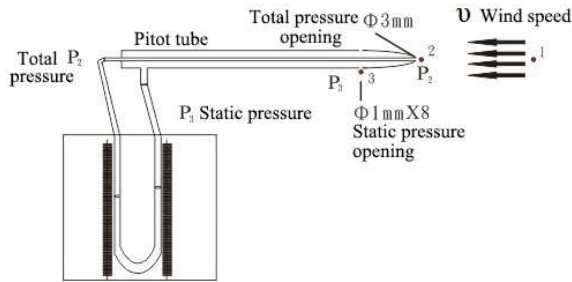
Figure 2. *Schematics of the air velocity and wind speed measurement*

$$v_1 = \sqrt{\frac{2\Delta p}{\rho}} \qquad (5)$$

Where Δp is defined as pressure difference and γw is defined as liquid specific gravity and Δh is defined as the height difference of the liquid in the U – shaped tube. The air velocity Q can be obtained by the cross – section area multiplying wind speed. Thus, Q can be written as follow:

$$\Delta p = \gamma_w \Delta h \qquad (6)$$

$$Q = 60\pi r^2 v \qquad (7)$$

3. Experimental Setup

This study uses 28 full spectrum fluorescent lamps (Philips-865) as the matrix light source for the measurements. These lamps separate equally each other and its light source section is 2×2 m². When light passing through the atomizing film, it will be scattered the propagation direction and then pass through the color mask,

finally the light focusing by convex lens and receiving by CCD camera. Fig. 3 shows photo of the background-oriented light source detail setup. Fig. 4 exhibits photo of the source grid with color light source. Fig. 5 shows the spectrum distribution of the fluorescent lamps.
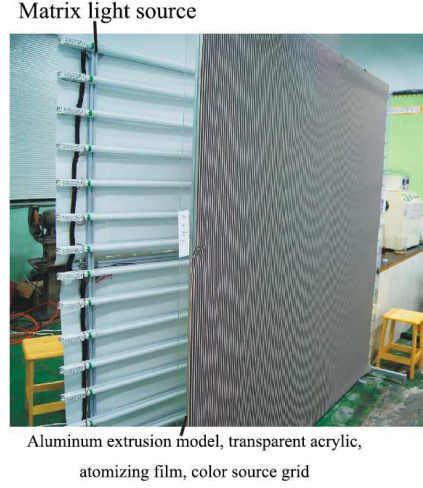
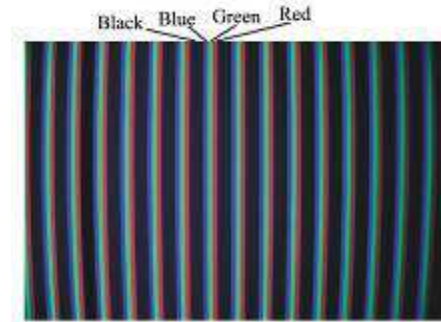**Figure 3.** *Setup photo of the background-oriented light source*

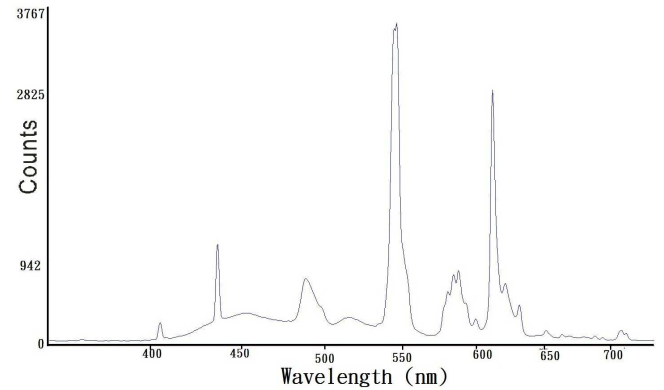**Figure 4.** *Source grid with color light source*

Figure 5. *Spectrum distribution of the fluorescent lamps*

Color full-scale Schlieren system is composed of background-oriented light source and photographical room. The photographical room is built for the photographical purpose and it is made up by condense lens, the cutoff grid, image plane, and the CCD camera. Fig. 6 shows setup photo of photographical room.
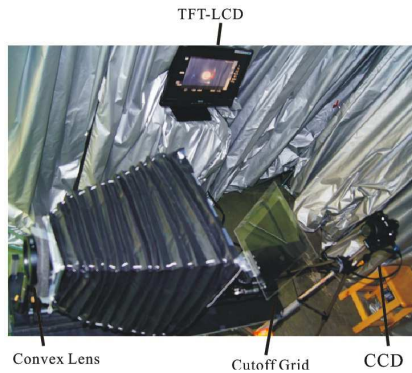
Figure 6. Setup photo of photographical room

Due to find the influence of noise and exhaust on the kitchen exhaust hood, this study using filters and support frame setting up the kitchen exhaust hood then cutting openings on top filter and side filter. Fig. 7 shows setup photo of the testing kitchen exhaust hood. On grease filters side, Fig. 8 shows photo of different type grease filters, type1 grease filters using diameter with 4cm circular openings, type 2 using 2×23 cm rectangular openings, and type 3 using 69cm2 trapezoid openings. All of the openings have same percentage of the aperture rate. Furthermore, this work uses burning candles as heat source which its fumes is used to simulate the cooking smell.
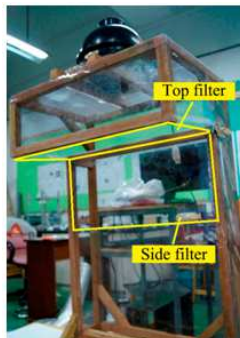

Figure 7. Experimental setup photo of the testing kitchen exhaust hood
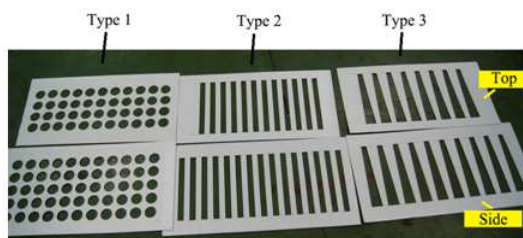

Figure 8. Three different type grease filters

The experimental setup detail of noise measurement is based on the standards of Chinese National Standard (CNS) 3805 and 3765-31 as shown in figure 9. The setup of air velocity measurement is based on the standards of American Society for Testing and Materials (ASTM) D3154-00 [15]. Each Pitot tubes total length is 1m. The diameter of the total pressure opening is 3 mm and the diameter of the static pressure openings is 1mm. Fig. 10
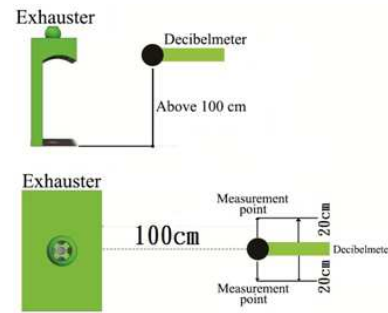
shows the setup of the air velocity measurement.

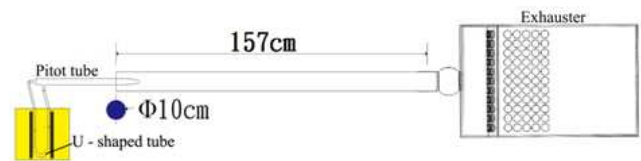*Figure 9. Schematics of the noise measurement*

Figure 10. Schematics of the air velocity measurement

4. Results and Discussion

This study discusses the influence of different cutoff rate on color full-scale Schlieren system. For obtaining more colorful effect and more sensitivity during different various refraction index field of the image, we divide the source grid into transparent part and non-transparent part. The transparent part composed by three equal segments and print three primary colors, R, G, and B serving as red, green, and blue which are the basic color components of visible white light. Fig. 11 shows color full-scale Schlieren image photo of turning on stove to generate heat flow. Figs. 11(a) – (d) show photos of cutoff grid under 50, 60, 70, and 80% cutoff rate respectively. The results show that the Fig. (b) has the best sensitivity, namely, full-scale Schlieren with 60% cutoff rate could be used in further study.
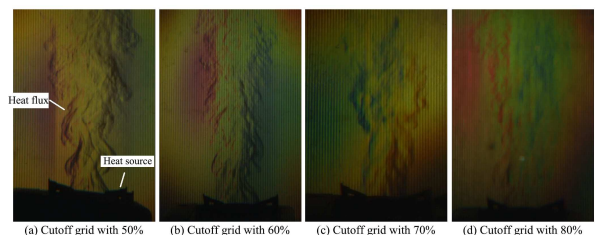

(a) Cutoff grid with 50%   (b) Cutoff grid with 60%   (c) Cutoff grid with 70%   (d) Cutoff grid with 80%

Figure 11. Cutoff grid with various cutoff rates

In this work, the color full-scale Schlieren experimental setup bases on the optimal conditions from previous discussion. That is, this work uses light band width 6 mm of source grid and cutoff rate under 60% which is used for observing the heat flow of the kitchen exhaust hood with different type grease filters. All of the grease filters have same open holes rate but different shapes. Fig. 12 shows photo of heat flow visualization with different type grease filters, namely, the gas inlet located at top and side of kitchen exhaust hood are open. Fig. 13 shows photo of heat

flow behavior under blocking side inlet and puts grease filters on top inlet of kitchen exhaust hood. Fig. 14 shows photo of heat flow performance under blocking top inlet and puts grease filters on side inlet of kitchen exhaust hood.

Fig. 12 shows photo of kitchen exhaust hood heat flow with different type grease filters by using color full-scale Schlieren technique. Fig. 12(a) shows photo of heat flow visualization with type 1 grease filter. Fig. 12(b) shows photo of heat flow behavior with type 2 grease filter and fig. 12(c) shows photo of heat flow behavior with type 3 grease filter. The results show that there has no heat flow escaping by kitchen exhaust hood. All waste gas with poison could be captured.
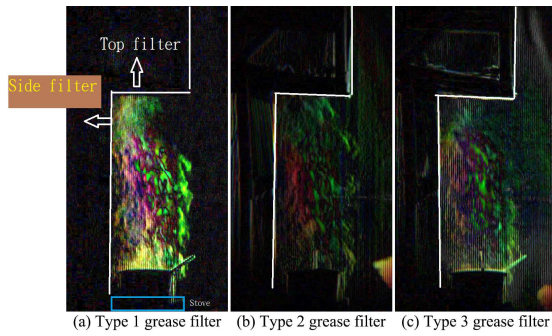

(a) Type 1 grease filter   (b) Type 2 grease filter   (c) Type 3 grease filter

Figure 12. *Photo of heat flow without any blockage*

Fig. 13 shows photo of heat flow behavior under blocking side inlet and puts grease filters on top inlet of kitchen exhaust hood by using color full-scale Schlieren method. Fig. 13(a) shows photo of heat flow distribution with type 1 grease filter. Fig. 13(b) shows photo of heat flow behavior with type 2 grease filter. Fig. 13(c) shows photo of heat flow performance with type 3 grease filter. The results show that the heat flow can't be completely captured by kitchen exhaust hood with three type of grease filters. Fig. 13(a) shows the best capturing performance of kitchen exhaust hood in fig. 13. As the fig. 13 shows that the escaping waste gas of heat flow in fig. 12(a) is less than fig. 12(b), and the escaping waste gas of heat flow in fig. 12(c) is also less than fig. 12(b). Namely, type 1 grease filter under block side inlet and puts grease filters on top inlet of kitchen exhaust hood by using color full-scale Schlieren technique owns the best result.
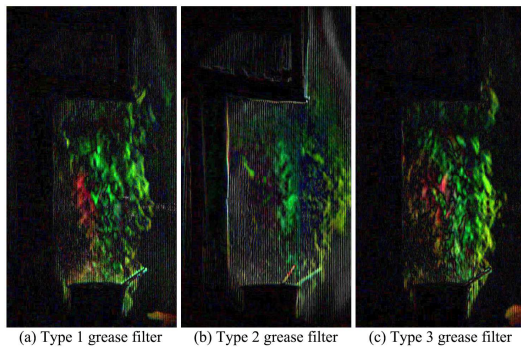

(a) Type 1 grease filter   (b) Type 2 grease filter   (c) Type 3 grease filter

Figure 13. *Photo of heat flow with side blocking and puts different type of grease filters on top inlet*

Fig. 14 shows photo of heat flow performance under blocking top inlet and puts different grease filters on side inlet of kitchen exhaust hood by using color full-scale Schlieren. Fig. 14(a) shows photo of heat flow with type 1 grease filter. Fig. 14(b) shows photo of heat flow with type 2 grease filter. Fig. 14(c) shows photo of heat flow with type 3 grease filter. The results show that there has no heat flow escaping and the absorbability of different grease filters in sequence are Fig. 14(a) > Fig. 14(c) > Fig. 14(b). In other words, blocks top inlet and puts different grease filters on side inlet of kitchen exhaust hood obtains the best flow field without any escaping waste hot gas and poison gas. Comparing to fig. 15, the noise level also shows that blocking top inlet and putting type 1 grease filters on side inlet of kitchen exhaust hood obtains the smallest noise 65dB and best flow behavior.
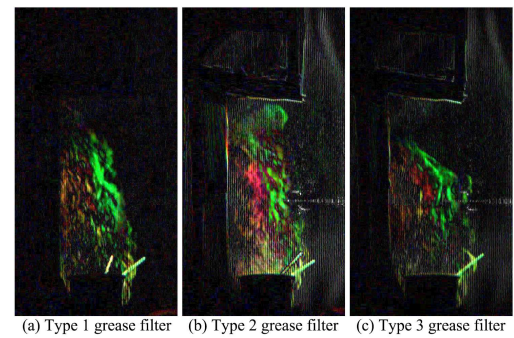

(a) Type 1 grease filter   (b) Type 2 grease filter   (c) Type 3 grease filter

Figure 14. *Photo of heat flow blocking top inlet and puts different grease filters on side inlet*
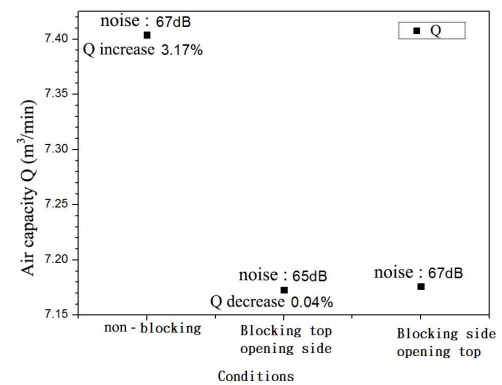

Figure 15. *Air capture efficiency and noise values with several masking conditions*

The images of heat flow show that using diameter 4cm circular opening with top of 44 circular openings, side of 55 circular openings has the best absorbability. From the noise side, the noise which has reduced to ca. 65 dB is reaching the standards set by CNS. Fig. 15 shows air velocity and noise values with several masking conditions. To investigate the reason, it is because the motor on shelter which has the effect of reducing noise. The result can be further used as the basis of designing the kitchen exhaust hood. That is, add side exhausting method can reduce the motor's power to decrease the harming of noise. According to fig. 16, the higher distance (Z) between stove and exhaust hood the

more waste hot gas will occur [16]. Reducing the distance between stove and exhaust hood could be exhaust efficiently, but the shorter the distance of Z will limit chef operation area. This study uses side exhausting method to keep the advantage of short distance Z and keeping chef operation area.
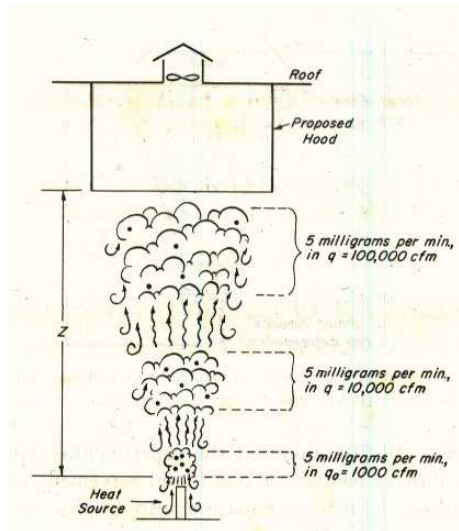

Figure 16. The relationship between distance of Z and waste gas generation [16]

5. Conclusions

This study employed color full-scale Schlieren method to visualize kitchen exhaust hood flow behavior. Using optical method can directly exhibit the performance of kitchen exhaust hood. This research also pointed some significant results. Using side exhausting method can reduce the motor's power consumption and fan noise generation. Blocking top inlet and puts type 1 grease filters on side inlet of kitchen exhaust hood obtains the best flow field without any escaping waste hot gas and poison gas.

Acknowledgements

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