FLOW RATE AND CAPTURE EFFICIENCY OF DOMESTIC KITCHEN EXHAUST HOODS FOR CHINESE HOUSEHOLDS

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ABSTRACT

The building regulations of most countries require every kitchen to be provided with a window that opens into the external air. This alone is not an effective means for avoiding the contaminants generated during cooking from spreading into other parts of a residential flat. Many households equipped their kitchens with a range exhaust hood, with make up air drawn into the kitchen through an open window. Compared to other ventilation requirements in dwellings, the ventilation rate required for this purpose would be the highest, but would only need to be maintained for a relatively short time. The regulatory requirements pertaining to kitchen windows impose severe constraints on the layout design of buildings and increase the construction cost whilst the functions of the window can alternatively be fulfilled by the provision of artificial lighting and mechanical air supply and extraction systems. This paper reports the results of an experimental study on the capture efficiency of domestic kitchen exhaust hoods. The required parameters in a model for predicting the capture efficiency of such exhaust hoods were determined for application to typical Chinese cooking using a wok over a gas stove. The ventilation rate required for achieving satisfactory fume capture efficiency can then be determined, which is crucial to the design of the ventilation systems for the next generation of residential buildings with windowless kitchens.

1. INTRODUCTION

For the protection of human safety and health, maintaining adequate lighting and ventilation in dwellings, especially in kitchens, is essential and regulatory controls are often imposed to ensure the required provisions are duly made in building designs. Under the current Building (Planning) Regulation of Hong Kong [1], every room for habitation and every kitchen shall be provided with one or more windows that face directly into the "external air". The aggregate area of such windows (referred to as the prescribed window) shall not be less than one-tenth of the floor area of the room of which the portion that can be opened shall have an aggregate area not less than one-sixteenth of the floor area. No prescribed window shall be deemed to be facing into external air unless:

- it faces into a street which is not less than 4.5m wide; or
- it faces into the space above a rectangular horizontal plane (RHP) of dimensions that meet the minimum values as stipulated in the Regulation, which is uncovered and unobstructed, and;
- it is so placed such that a plane at an inclination angle of 76° protruding from the RHP at a position where the RHP intersects with the window sill is unobstructed. Where the RHP is intercepted by the site boundary, the inclination angle of the inclined plane can be increased up to 83°.

The requirements are often met by adopting layouts that form recessed spaces outside the building, as shown in Fig. 1. Such designs involve the use of more materials and are more costly to build. Furthermore, the difficulty involved in designing buildings that comply with the requirements would increase with the height of the building. To allow flexibility in planning and design of buildings, the Building Authority of Hong Kong is prepared to accept kitchen windows that do not fully comply with the requirements but will meet the requirements on the RHP, provided mechanical ventilation is also provided. This is an encouraging move from the sole use of rigid prescriptive requirements to the use of also performance-based requirements in regulating lighting and ventilation provisions in buildings in Hong Kong, which is being actively considered by the Government.

The contaminants that would be generated in a kitchen include particulate matters, moisture, heat, odours, and gases, which are typically produced at a high level of concentration over a short time [2]. The liquid particles, which are of particular concern, are generated when the water contained within the food is introduced into hot liquid grease or oil, which causes the water to flash over explosively into steam splattering the liquid oil, or when the oil is evaporated and subsequently condensed into fine liquid droplets. For those relatively large particles (with diameter in the range of 10 to 100 μm), it would not be possible to remove them by domestic ventilation equipment, but they would readily settle on nearby surfaces due to gravity. The smaller particles (with diameter in the range of 0.01 to 3 μm), however, could remain airborne for several hours and eventually settle on the floor, walls, furniture, drapes, and other surfaces in the kitchen and in other adjoining rooms, leading to soiling, odours and other problems.

The cooking process will also generate a large quantity of water vapour, which can quickly migrate to other parts of the dwelling, causing a high humidity level throughout the dwelling. Sustained high moisture content in an indoor space can promote mould growth, cause peeling of wallpaper off walls and even cause damage to the building structure, such as corrosion of reinforcement bars.

Chinese style cooking, such as stir-frying with a wok, would generate much more oil fume and moisture than Western style cooking, and would require a higher ventilation rate to be maintained for fume and moisture removal. It has been found that lung cancers figure highly among women's diseases in Taiwan, which is suspected to be due to regular exposure to the oil-aerosol and gaseous contaminants emitted during cooking [3].

Natural ventilation available from an open window or mechanical ventilation maintained by a wall/window mount propeller type exhaust fan can hardly effectively remove the oil-fume, moisture and smell generated during cooking. Furthermore, wind entering through a kitchen window can spread the contaminants to the adjoining rooms, rather than carrying them out of the window. The provision of a window is, therefore, not an effective solution for kitchens. A better means is to remove the fume at the spot it is generated by using an exhaust hood installed above the cooking range. This explains why kitchen exhaust hoods have become a common domestic appliance among households. Compared to other ventilation requirements in dwellings, the ventilation rate required for this purpose is the highest, but this need would only last for relatively short periods of time in a day.

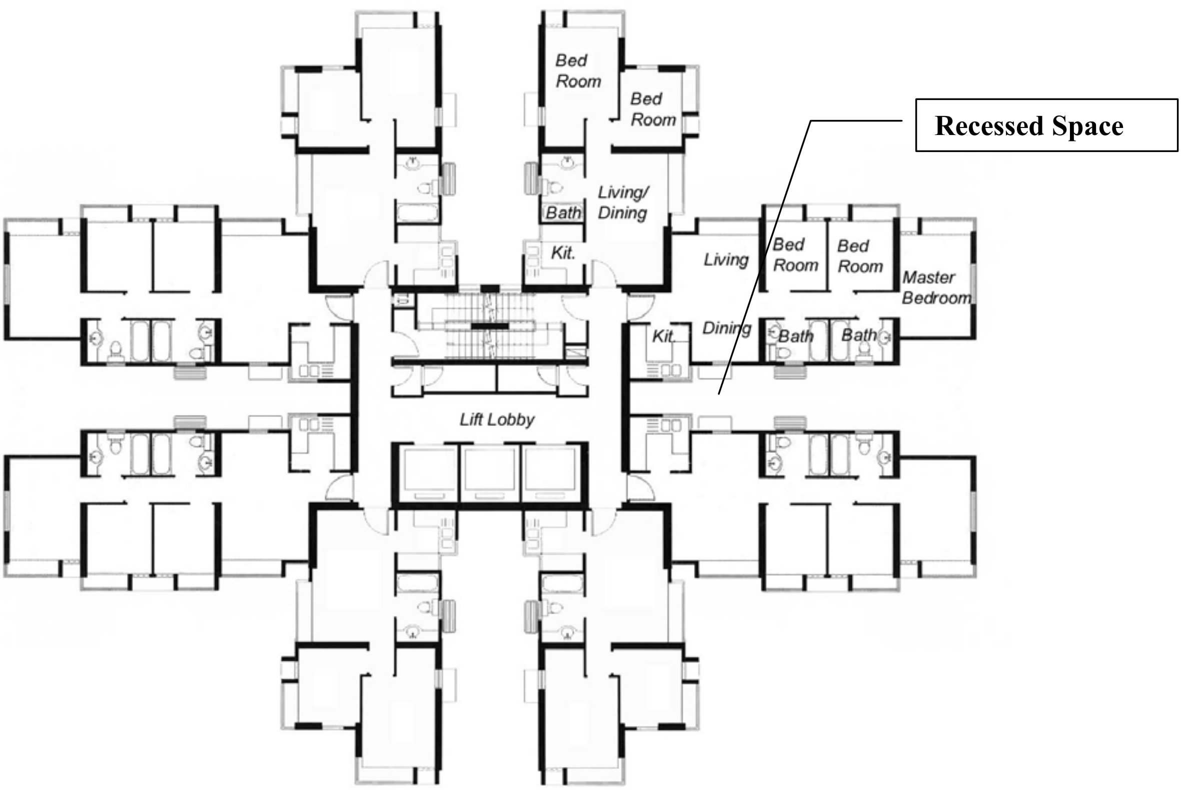


Fig. 1: Recessed spaces outside a high-rise residential building in Hong Kong

The performance of domestic exhaust hoods available in the market can be quite unsatisfactory [4], particularly for those that were designed for Western style cooking or when the hoods were poorly installed. Large reduction in the exhaust rate could result from long exhaust duct, excessive number of elbows in the ductwork, or when the exhaust fan in the hood is stalled by wind pressure. However, no guidance is available on the extraction rate required for effective control of the spread of contaminants generated from typical Chinese style cooking in households. A proper method for determining the extraction rate required to effectively capture the by-products of Chinese style cooking is needed, which would be crucial to the design of centralised supply and extraction systems when such systems become an acceptable alternative to prescribed windows in kitchens.

2. QUANTIFICATION OF THE PERFORMANCE OF KITCHEN EXHAUST HOODS

Fig. 2 shows the configuration of a typical installation of a kitchen exhaust hood. The capture efficiency of a kitchen exhaust hood, which equals the ratio of the fan exhaust flow rate to the total plume flow rate at the front canopy height, as shown in equation (1), is a performance index of the hood [5]. Combining equation (1) with a thermal plume flow rate equation (equation (2)) [6], yields a model for predicting the capture efficiency of a range hood, as shown in equation (3) [7].

$$\varepsilon = \frac{q_f}{q_p} \times 100\% \qquad (1)$$

$$q_p = k_v E^{1/3} (h + z_v)^{5/3} \qquad (2)$$

$$\varepsilon = \frac{q_f}{k_v E^{1/3} (h + z_v)^{5/3}} \times 100\% \qquad (3)$$

where q_f is the exhaust flow rate (m^3s^{-1}); q_p is the plume flow rate at the canopy hood entry level (m^3s^{-1}); E is the heat source power (W); h is the height from the heat source to the canopy hood entry (m); z_v is the distance between the heat source and the origin of the plume (m); and k_v is the coefficient describing the air entrainment by the plume.

The physical meanings of the parameters in the equations are as shown in Fig. 2.

Based on a review of the literature, Popiolek et al. [6] reported that the values for the coefficient k_v for thermal plumes, as used in different studies, varied between 0.0040 and 0.0082, and different methods have been suggested for the evaluation of z_v, including:

$z_v = D$; $z_v = 1.7D$; $z_v = 2D$; $z_v = 2.5D^{1.14}$; $z_v = 3D$

Due to the large variations in the suggested values for these two coefficients, results of calculations using different combinations of values for these coefficients can vary by several times. Thus, the values of k_v and z_v that would be applicable to typical Chinese style cooking in households need to be determined empirically to allow accurate determination of the capture efficiency of exhaust hoods based on typical settings in domestic kitchens.

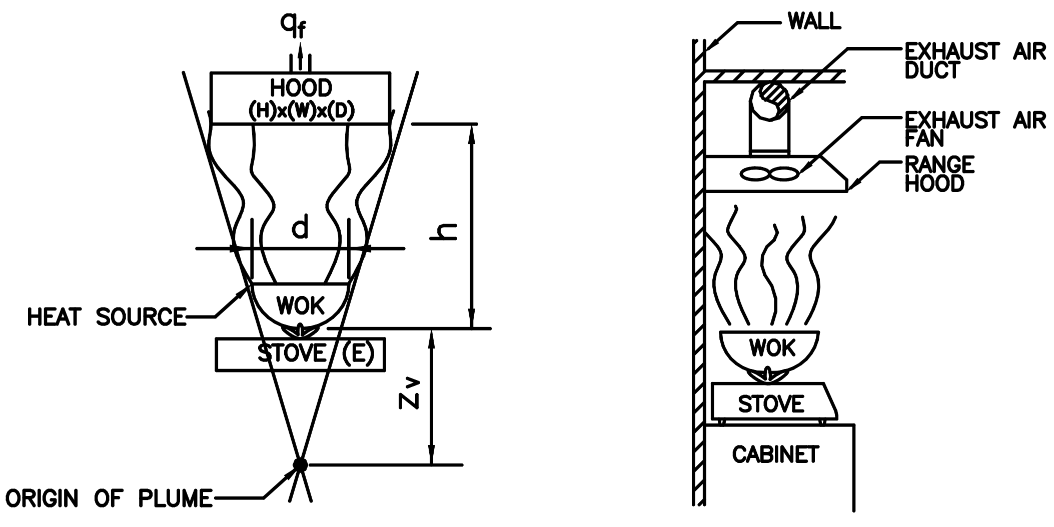


Fig. 2: Typical installation configuration of a domestic kitchen exhaust hood

3. LI AND DELSANTE'S DERIVATION

It has been shown [2,5] that the capture efficiency of a range exhaust hood, as defined in equation (1), can alternatively be expressed in terms of the concentrations of the contaminant in the kitchen and in the cooking zone. Li and Delsante's derivation [5] was based on a two-zone mixing model as shown in Fig. 3.

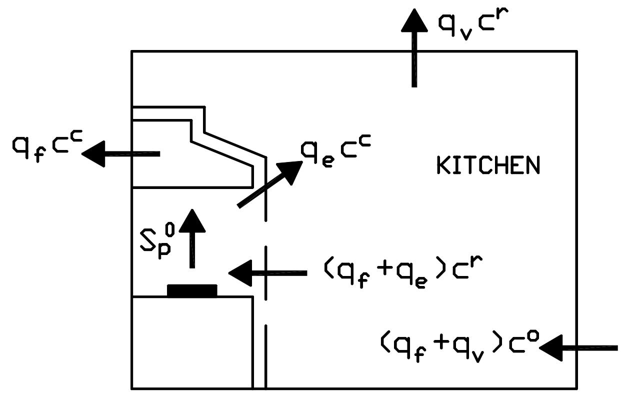


Fig. 3: A model for a kitchen range hood in a confined space

In Fig. 3, q_v is the general ventilation rate (m^3s^{-1}); $S^o{}_p$ is the contaminant generation rate at cooking source (kgs^{-1}); c^c is the concentration of contaminant in the exhaust (kgm^{-3}); c^r is the concentration of contaminant in the general area in the kitchen (kgm^{-3}); and c^o is the concentration of contaminant in the adjoining room.

By making the assumption that there were no other paths of airflow into and out of the kitchen other than the inflow from an adjoining space and the outflow through the exhaust hood (i.e. $q_v = 0$), the capture efficiency can simply be related to the concentrations of a gaseous contaminant in the exhaust (c^c), in the general area in the kitchen (c^r) and in the adjoining space (c^o), as shown in equation (4).

$$\varepsilon = 1 - \frac{c^r - c^o}{c^c - c^o} \tag{4}$$

Equations (3) and (4) are complementary to each other in that equation (3) can be used as a model for predicting the capture efficiency of a hood given the heat production rate and the exhaust flow rate maintained by the hood, whereas equation (4) is in a format that allows the capture efficiency to be determined from measurements of the contaminant concentrations.

Li et al. [7] later improved the derivation and compared the theoretical predictions against experimental measurements. They found that good agreement between the predictions made using equation (3) and those determined from the measured concentrations could be achieved only when the z_v value in equation (3) had been adjusted. Whilst Popiolek et al. [6] concluded from their experimental studies that 0.006 should be an appropriate value for k_v, Li et al. [7] opined that both k_v and z_v may vary with the strength and dimension of the heat source.

4. OBSERVATIONS OF THE PERFORMANCE OF SIX EXISTING KITCHEN EXHAUST HOODS

Six residential kitchens were visited to observe the performance of the exhaust hoods as found in those kitchens. Foods were stir-fried in a wok to mimic the normal cooking process in each site to observe the flow pattern of the plume and the performance of the hood in capturing the fume. In each visit, measurements were made of the size of the hood (H × W × D); the diameter of the exhaust air duct; the diameter of the wok (d); the height of the wok (bottom level) from the floor; the height between the hood canopy entry level and the wok (h); and the heat source power from the stove nameplate (E). The data pertaining to these six kitchens are summarised in Table 1.

Table 1: Summary of information pertaining to the range hoods and stove for six sites

Site	Hood size, H × W × D (mm)	Mounting height from wok, h (mm)	Exhaust duct diameter (mm)	Heat source power for hot-plate E (W)	Diameter of heat source, d (m)
1	100 × 710 × 510	850	140	6300	0.38
2	150 × 690 × 490	730	150	4920	0.45
3	130 × 720 × 520	780	152	5800	0.36
4	420 × 900 × 510	880	N/A†	6000	0.43
5	150 × 690 × 500	795	150	5800	0.45
6	135 × 700 × 500	860	145	4000	0.50

† The fan in this hood was a wall mount propeller fan that would discharge the fume directly through the opening in the window to outdoors.

The observation was made from the site inspections that with the exception of Site 4 (shown in Fig. 4), all the kitchen exhaust hoods failed to effectively capture the generated contaminants. The hood in Site 4 performed much better because it was a non-standard product that was significantly larger than the others, particularly in the width of the hood (900 mm c.f. ≈ 700 mm). It was also observed that the front-to-back dimension of the hood was critical to the exhaust performance. The hood should extend far enough forward to cover the thermal plume generated from the heat source but not so far forward that it would interfere with vision to food preparation. If the free area of the hood were small, a higher volumetric flow rate would be needed. Also, the hood should be located as close as possible to the source of contamination.

Fig. 4: Range hood at Site 4

The Hong Kong Consumer Council [4] advised that the range hood should be installed at a suitable height to avoid catching fire and reduction in the exhaust performance of the range hood. The recommended distance from the range is between 650 mm to 700 mm. However, the mounting levels of all the hoods (h) in the six sites were out of the range recommended by the Consumer Council (Table 1). This implies that the performance of many domestic exhaust hoods could be unsatisfactory for capturing the contaminants generated in cooking.

5. MEASUREMENTS CONDUCTED IN ONE OF THE SITES VISITED

The kitchen exhaust hood in Site 1 was selected for more detailed measurements. The dimensions of the kitchen were 3.2 m (W) × 1.6 m (D) × 2.5 m (H). The hood was installed against one of the walls above the cooking range. In this kitchen, the diameter of the wok, which was regarded as the size of the heat source (d), was 380 mm; the existing vertical distance between the bottom level of the wok and the hood canopy entry level (h) was 850 mm; and the heat source power was 6300 W. Measurements were carried out for each of the eight conditions summarised in Table 2. The value of h was adjusted in Experiment 6 to 8 by inserting sheets of polystyrene beneath the stove.

Although the focus of the study should be put on the efficiency of an exhaust hood in capturing the air-bone fine particles generated in cooking, direct measurement of the quantity of such particles would be difficult. Therefore, the simplifying assumption was made that those fine particles would move together with the air and the water vapour generated simultaneously. For ease of measurement, water vapour was taken as the “representative contaminant”, which was produced by boiling 2000 ml of water on the gas stove, at the fan centreline.

The concentrations of water vapour, quantified by the moisture contents of the air, in the exhaust air stream (c^c), the general area in the kitchen (c^r) and in the adjacent room from which make up air was drawn in (c^o) were determined based on measurements of the dry-bulb (t_d) and wet-bulb (t_w) temperatures at these locations. The water vapour contents were then calculated based on the measured dry- and wet-bulb temperature values [8]. The moisture content of air in the general area (c^r) was the average of the three values determined from the measurements at three sampling points in the kitchen. Measurements of c^c and c^o, however, were each made at only one sampling point; the former within the exhaust duct and the latter at the wall outside the kitchen nearby the entrance door to the kitchen. Six Hobo loggers were used to log the dry- and wet-bulb temperatures at 5-second intervals during each experiment (Fig. 5).

Prior to the moisture content measurement, the flow rate at the exhaust duct for each of the eight conditions shown in Table 2 was measured by traversing a Pitot tube along the duct diameter, at a distance 6-diameter downstream of the elbow at the hood outlet. The velocity pressure of the moving air in the duct was measured using an electronic manometer connected to the total and static pressure tappings of the Pitot tube. Five measurements were made in each of the two traverses across the duct at locations determined according to the equal area method [9]. The exhaust flow rate (q_f) for each fan operating condition was then calculated from the average of the velocities measured at each measurement point and the cross-sectional area of the duct. The measured water vapour contents in the air in the exhaust duct, the general area in the kitchen and in the adjacent room, and the hood capture efficiency calculated using equation (4) are summarised in Table 3.

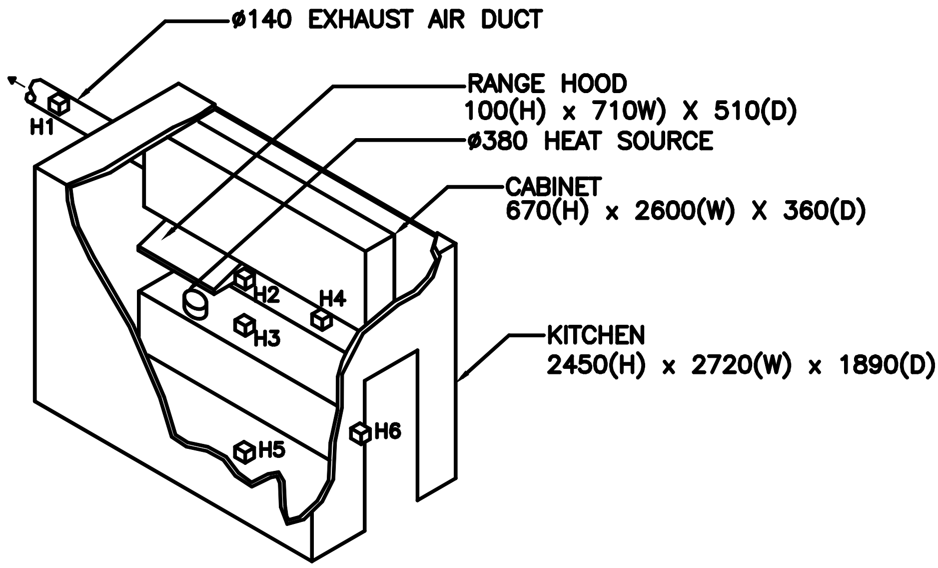
Table 2: Conditions of the 8 sets of experiments

Experiment No.	Condition
1	One fan on at high speed
2	One fan on at low speed
3	Two fans on, both at high speed
4	Two fans on, both at low speed
5*	Two fans on, one at high speed and one at low speed
6*	One fan on at high speed; distance between stove and hood reduced by 100 mm
7*	One fan on at high speed; distance between stove and hood reduced by 150 mm
8*	One fan on at high speed; distance between stove and hood reduced by 200 mm

*The high speed fan was directly above the heat source

Table 3: Capture efficiency of the exhaust hood calculated from measurements of moisture contents

Experiment No.	q_f (m^3s^{-1})	c^c ($kgkg^{-1}$)	c^r ($kgkg^{-1}$)	c^o ($kgkg^{-1}$)	ε (%)
1	0.199	0.00928	0.00893	0.00881	74
2	0.181	0.00925	0.00949	0.00960	68
3	0.257	0.01242	0.01148	0.01127	82
4	0.199	0.01159	0.01093	0.01065	70
5	0.247	0.00915	0.00771	0.00733	70
6	0.199	0.01094	0.01056	0.01045	78
7	0.199	0.01066	0.00917	0.00854	81
8	0.199	0.01043	0.01173	0.01203	79



H1	Exhaust air steam - c^c measurement
H2	Exhaust air steam - c^c measurement
H3	General area in kitchen - c^r measurement
H4	General area in kitchen - c^r measurement
H5	General area in kitchen - c^r measurement
H6	Outside the kitchen - c^o measurement

Fig. 5: Experimental setup

Among the series of experiments conducted, the achieved exhaust flow rate was the lowest in Experiment 2 (with only one fan running at low speed), and the corresponding capture efficiency of the hood was also the lowest (68%). The highest flow rate and the highest capture efficiency (82%) were achieved in Experiment 3 (with both fans running at high speed). It can be observed from the results of Experiments 1 to 5 that the capture efficiency would increase almost linearly with the exhaust flow rate, as shown in Fig. 6. On the other hand, the capture efficiency would increase with reduction in the level difference between the hood canopy and the source (h), as shown by the results from Experiments 1 and 6 to 8 (Fig. 7). These observations agree well with the trend suggested by equation (3).

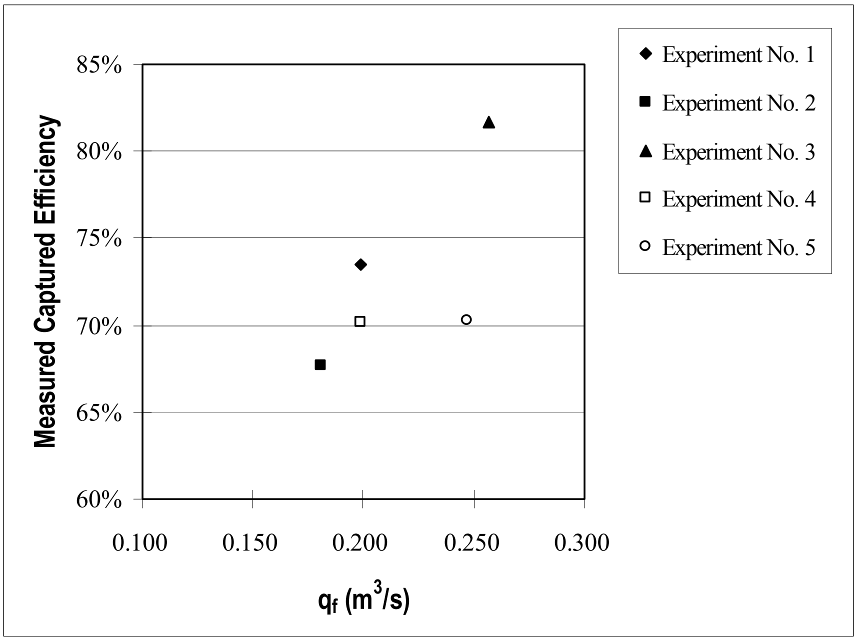


Fig. 6: Measured capture efficiency (ε) against the exhaust flow rate (q_f)

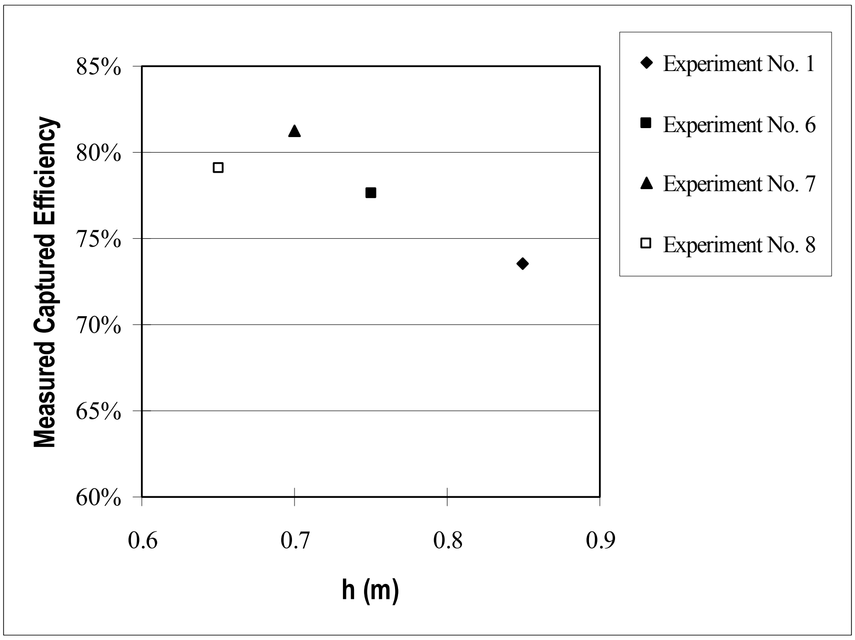


Fig. 7: Measured capture efficiency (ε) against the level difference between the hood canopy and the source (h)

Fig. 8 shows a plot of the k_v values calculated using the capture efficiency values evaluated from the measurements in the 8 experiments, as summarized in Table 3, and a range of assumed z_v values, including $z_v = D$; 1.7D; 2D; $2.5D^{1.14}$; and 3D. It can be seen from Fig. 8 that the values of k_v corresponding to these assumed z_v values range from 0.0044 to about 0.0135. The higher k_v values were pertaining to the smaller z_v values. Since the reasonable range of k_v should be from 0.004 to 0.0082 [6], it is highly unlikely that z_v would equal D or 1.7D. The best-fit values found were k_v = 0.0065, which is close to the value (0.006) recommended by Popiolet et al. [6], and z_v = 2.25D.

The values of k_v and z_v found from the above analysis of the results of the experiments conducted in Site 1 were taken as constant values and substituted into equation (3). The resultant equation is as shown in equation (5) below. Fig. 9 shows a comparison of the capture efficiency determined from experimental measurement with those predicted using equation (5).

$$\varepsilon = \frac{q_f}{0.0065E^{1/3}(h + 2.25D)^{5/3}} \times 100\% \quad (5)$$

It can be seen that using the selected constant values for the two coefficients (k_v = 0.0065) and (z_v = 2.25D) would allow the capture efficiency of the hood under different operating conditions to be predicted to a reasonable degree of accuracy.

6. CAPTURE EFFICIENCY OF THE EXHAUST HOODS IN THE SIX SITES VISITED

The model for predicting the capture efficiency of a kitchen exhaust hood (equation (5)) for cooking with a wok was applied to assess the performance of the hoods in the six visited sites. Here, the capture efficiency of a hood would be regarded as 100% if the predicted capture efficiency exceeds 100% [7]. Where the capture efficiency predicted was lower than 100%, the required exhaust flow rate for achieving a capture efficiency of 100% (q_{fs}), i.e. all the contaminants would (supposingly) be removed by the range hood, was also calculated. The results of these calculations were as summarised in Table 4.

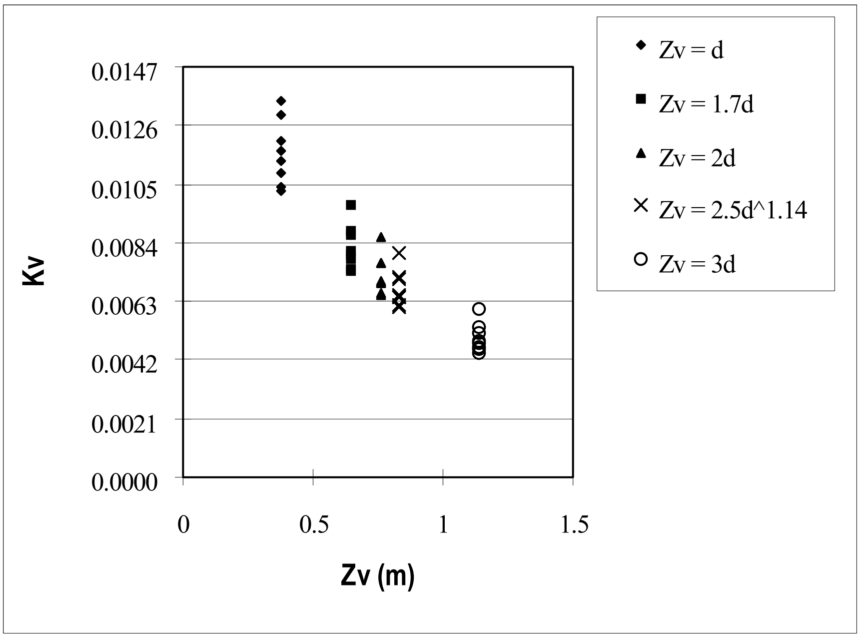


Fig. 8: Entrainment coefficient (k_v) against the distance from the heat origin (z_v)

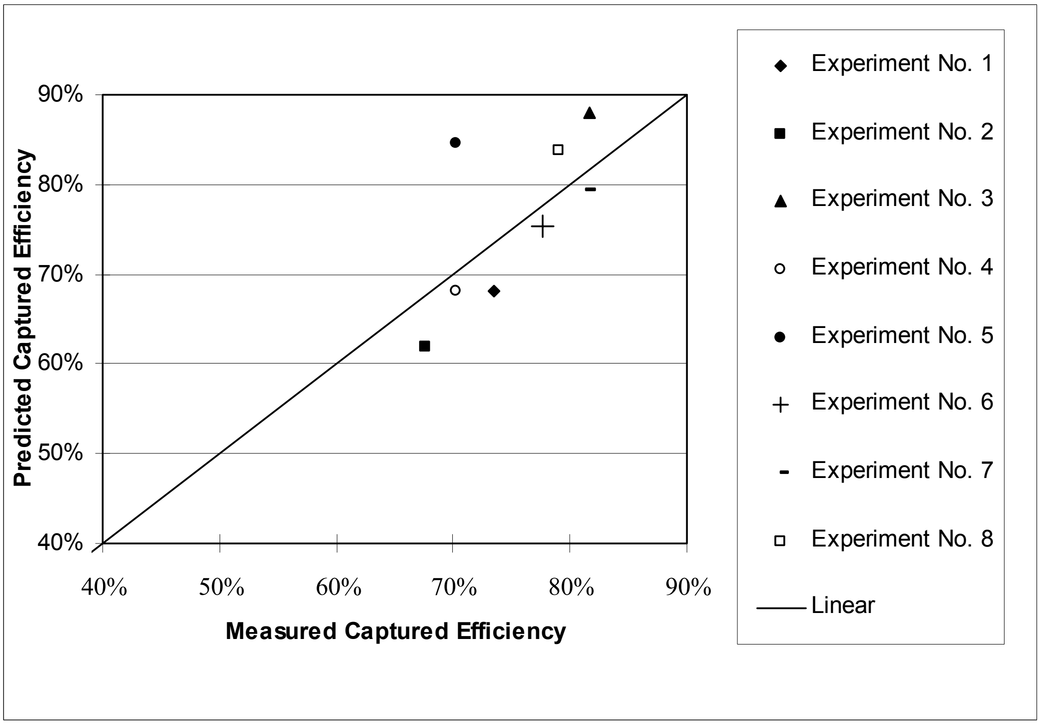


Fig. 9: Comparison of predicted and measured capture efficiency of the range hood at Site 1

Table 4: Comparison of the actual exhaust rate (q_f) and the required flow rate (q_{fs}) for idealistic performance of the exhaust hoods in the visited sites (with k_v = 0.0065 and z_v = 2.25D)

Site	Mounting height from wok, h (mm)	Heat source power, E (W)	Diameter of heat source, D (m)	Required exhaust flow rate, q_{fs} ($m^3 min^{-1}$)	Actual exhaust flow rate, q_f ($m^3 min^{-1}$)	Predicted capture efficiency, ε
Site 1	850	6300	0.38	17.5	11.9	68.1%
Site 2	730	4920	0.45	16.7	10.5	62.9%
Site 3	780	5800	0.36	15.2	10.6	69.8%
Site 4	880	6000	0.43	19.7	20.7	104.8%
Site 5	795	5800	0.45	18.8	9.0	47.9%
Site 6	860	4000	0.50	19.4	7.7	39.6%

It can be seen from Table 4 that except for Site 4, where a specially made hood was used, the flow rates maintained by the range hoods in all the visited sites were significantly lower than that required for achieving the idealistic capture efficiency of 100%. This may be taken as an indication that the performance of range hoods in many domestic kitchens could be rather poor. The fact that the residents at Site 4 equipped their kitchen with a specially made hood shows that they were aware of the deficiency of commercially available range hoods and, therefore, decided not to adopt such hoods. The exhaust flow rate that could be maintained was just slightly higher than that required for achieving 100% capture efficiency, which indicates that the residents at Site 4 did a good job in determining the capacity of the exhaust fan needed for satisfactory removal of cooking fumes (although this could just be incidental).

7. CONCLUSIONS

The study reported above, although was based on limited experimental data, provides a clear indication that it would be possible to equip a domestic kitchen with a range exhaust hood that can provide a sufficient extraction flow rate to achieve a high enough capture efficiency. The values of the entrainment coefficient k_v (= 0.0065) and the origin distance z_v (= 2.25D), as found from the experimental studies, provide a basis for determining the required extract and supply flow rate. Manufacturers of exhaust hoods should review the flow handling capacity of their products to cope with typical Chinese style cooking. Building developers may also consider equipping kitchens in residential developments with adequately designed range exhaust hoods as a standard provision, which would help ensure adequate exhaust rates would be achieved to meet the needs of Chinese style cooking in kitchens in residential buildings.

In the move toward relaxing or waiving the regulatory requirements on prescribed windows for domestic kitchens, it would be essential to require both centralised supply and exhaust systems be installed to ensure adequate removal of the fume and moisture that would be generated from cooking. Relying on an open window for intake of make up air would not be an adequate arrangement, as wind entering the window could lead to spreading of the fume and moisture to other parts in the dwelling. Furthermore, the centralised supply and exhaust systems should be designed with the ability to meet the intermittent needs for the ventilation air by different kitchens in the building.

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