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Residential Kitchen Range Hoods – Buoyancy-Capture Principle and Capture Efficiency Revisited

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Abstract A buoyancy-capture principle is firstly revisited as the most important fluid dynamics mechanism in kitchen range hoods. A recent new derivation of the capture efficiency of a kitchen range hood, which eliminates the inconsistencies and inadequacies of existing derivations, shows that the capture efficiency equals the ratio of capture flow rate to total plume flow rate in a confined space. The result is applied here, together with the buoyancy-capture principle, to derive a simple formula for determining capture efficiency. A computational fluid dynamics (CFD) program is adapted to study the capture efficiency of range hoods in a residential kitchen and the predicted results are used to evaluate the accuracy of the simple formula. It is shown that the simple capture efficiency model performs reasonably well for the range hoods considered in this paper.

Key words Range hoods; Kitchen ventilation; Capture efficiency; Capture principle; CFD; Indoor air quality.

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Introduction

Unlike general ventilation, residential kitchen ventilation is generally intermittent. High levels of various contaminants are generated during cooking over a short period. The contaminants must be removed quickly and totally if possible. Kitchen range hoods have been introduced as a solution to these problems. There is an increasing demand for improved capture efficiency of range hoods in Australia due to the availability of new cooking appliances (such as grills and barbeques), and because occupants are increasingly sensitive about indoor air quality. In some residential buildings, where other types of ventilating, heating or cooling system are installed, this demand may be even higher, because contaminants escaping from the kitchen area will be dispersed throughout the rest of the building. However, a literature review shows that investigations into kitchen range hoods are very limited. Many existing design methods are based on experience, and some of them are even based on a wrong ventilation principle.

The purposes of this investigation are threefold:

- to re-emphasize the buoyancy-capture principle in range hood ventilation of kitchens;
- to present a simple formula for calculating capture efficiency based on the buoyancy-capture principle and the new derived result of Li and Delsante (1996); and
- to develop a methodology for determining capture efficiency by using the contaminant concentration fields calculated by the computational fluid dynamics programs. The CFD simulated results will be used to evaluate the simple formula based on the buoyancy-capture principle.

Ventilation Principle of Kitchen Range Hoods

There are three main characteristics of kitchen contaminants, namely that they are released at high concentrations over a short period, the released contaminants are of various types, and the contaminants and heat are usually generated simultaneously. In terms of density of the contaminants, they can be grouped as:

- *"active" contaminants*, including heavy solid particles and large liquid particles. They are generally heavier than air and do not follow the airflow. These contaminants generally cannot be removed by the normal action of exhaust fans. Fortunately, most of them do not usually travel far from the cooking area.

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- *"passive" contaminants,* including some of the small liquid particles, odours, most of the gases, and heat. They (except heat) do not interact with the flow fields. Some (excluding heat) have a density slightly different from that of the air, but as they travel a relatively short distance (the distance from cook-top to exhaust inlet is about 0.75 m) with a high speed (≥0.5 m/s), the assumption of "passivity" will not cause large errors in evaluating capture efficiency.

In the present definition of capture efficiency and CFD analysis, *only passive contaminants are considered.* However, the concepts and the solution procedure might be extended to include "active" contaminants in a future study.

A range hood over a cook-top without buoyant forces (velocity-capture principle) is considered in Figure 1a. The air approaches the range hood from all directions, i.e. the upstream flow volume (area) is large. Thus, the air velocity decreases rapidly with the distance from the hood. The air velocity near the cook-top (e.g. point P in Fig. 1a) is very low. Now consider a cook-top producing heat sources which, in turn, generate thermal plumes. The plumes bring the passive contaminants upwards into the high-velocity territory of the range-hoods and thus the contaminants are captured and exhausted (i.e. the buoyancy-capture principle) (see Fig. 1b.)

It is reasonable to argue that any design methods or kitchen hood analyses that do not use the buoyancy capture principle will not produce very meaningful results. As a design/application engineer, Fritz (1989) summarized the three most common methods for determining the proper level of exhaust for cooking hoods. Two of them are relevant to the capture principles discussed above. The third method is based on so-called Underwriters Laboratories (UL) tests, where the results depend on the test environment and the cooking equipment. The first method (claimed to be the best known) is based on maintaining a velocity of 0.6 to 0.8 m/s into the hood capture area. It is easy to understand that this is based on the velocity-capture principle. Experience shows that the exhaust quantities predicted by this method are far greater than necessary (Fritz, 1989). The second method is based on estimating the amount of heated air produced by each piece of equipment (buoyancy capture). Generally the various cooking appliances are grouped into classes, this method being claimed to give the most reliable results. However, it has not been incorporated into any applicable codes. Though the two capture principles were not used by Fritz (1989) to explain the differences between the methods, his experiences clearly support the buoyancy-capture principle.

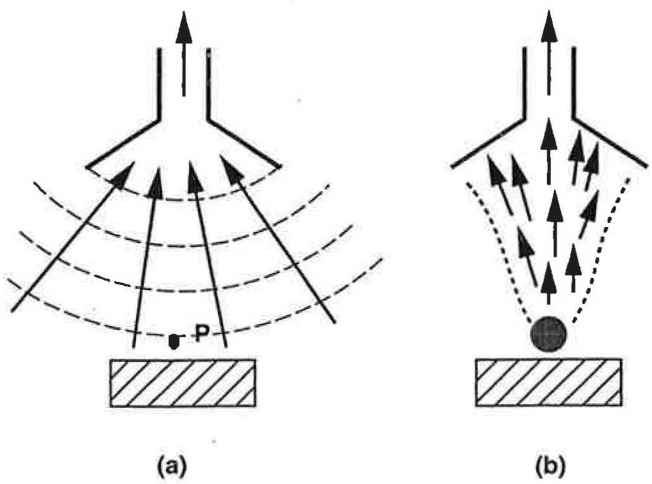

Fig. 1 Two ventilation principles of range hoods. (a) velocity-capture principle, in which the air approaches the range hood from all directions; (b) buoyancy-capture principle,in which a thermal plume is generated from the heat source and the hood captures the plume, thus the contaminants

Based on the buoyancy-capture principle, it is proposed that the two range hood parameters of most importance are the *exhaust flow rate and the horizontal dimensions* of the hood. If the hood covers the thermal plumes generated, then a 100% capture efficiency requires that the exhaust flow rate must be greater than the total plume flow rate. If the exhaust flow rate is smaller than the total plume flow rate, the difference will escape into the room. If the hood does not cover the thermal plumes, some of the cooking-polluted air can still escape even if the exhaust flow rate equals the total plume flow rate. The extra air needed for air mass conservation in the hood must be provided by room air entrainment. To have a 100% capture efficiency, the exhaust flow rate must be sufficiently high to introduce high velocity in the opening area to "suck" the escaping air into the hood. Thus the velocity-capture principle works together with the buoyancy-capture principle in this situation.

In reality, there are some other factors influencing the hood capture performance, such as:

- room airflow, sometimes termed "side draught";
- disturbances by the cook (e.g. moving hands);
- cooking types, e.g. steam jetting out of a side gap in the lid; and
- room geometry.

The first three factors can dominate, since they directly affect the thermal plumes, which may then flow beyond the hood, and thus reduce the capture efficiency. However, these factors are very difficult to quantify experimentally and numerically. A more realistic ılation would include a representative level of disturbances. They are not included in the present ›stigation. It is easy to show that a wall-mounted .llation helps to reduce their influence. Cook-tops range hoods are commonly installed adjacent to a in residential buildings, and this configuration is ›idered in the present study.

finition of Capture Efficiency

ecent study by Li and Delsante (1996) presented a derivation of capture efficiency. They showed that existing derivation of capture efficiency (Wolbrink l Sarnosky, 1992) of a kitchen range hood in a con-›d flow system is inconsistent and inadequate. In existing derivation, the capture efficiency of kit-n range hoods is defined as the ratio of the contami-its captured by the hood to the total contaminants oduced at the source.

As discussed, cooking introduces heat sources. The w rate of plumes rising from the heat sources varies th the size, shape of the heat sources and surround-g airflow. The plume from the cooking heat source reads while it rises, and entrains secondary air into e plume. If the net flow rate in the plume is greater an the exhaust flow rate at the canopy entry level, e difference escapes into the rest of the room, thus troducing contaminants into the room (see Fig. 2). By ntinuity, the entrained airflow rate must equal the ım of the exhaust flow rate and the escaped flow rate. should be noted that the entrained air also carries ıe contaminant concentration of the room zone if the

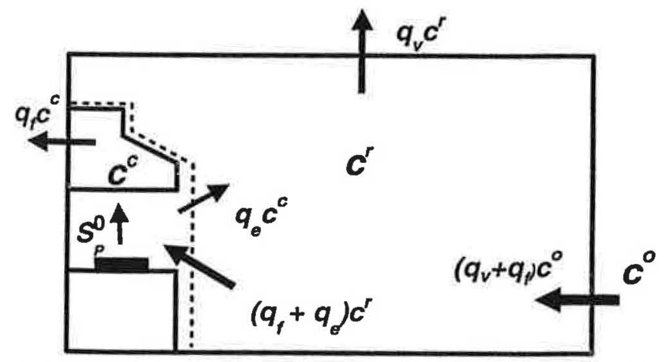

Fig. 2 A simple two-zone model for kitchen airflow, in which the airflow between the cooking zone and the room zone is considered, where c^r is the concentration in the room zone (kg/m^3), c^c is the concentration in the cooking zone, which equals that at the exhaust outlet (kg/m^3) assuming a well-mixed cooking zone, c^0 is the concentration in the ambient air (kg/m^3), q_e is the escaped flow rate (m^3/s), q_f is the exhaust flow rate (m^3/s), which also equals the supply flow rate to the kitchen due to continuity, S^0_p is the contaminant source generated during cooking (kg/m^3) and q_v is the general ventilation flow rate (m^3/s)

rest of the room is well mixed. A consistent and useful definition and derivation of the hood capture efficiency must take these flow rates into account.

Such a consistent definition and derivation were provided by Li and Delsante (1996). By this derivation, they showed that the capture efficiency ε_c can be calculated as either

$$\varepsilon_c = 1 - \frac{c^r - c^o}{c^c - c^o} \quad (1)$$

or

$$\varepsilon_c = \frac{q_f}{q_f + q_e} \quad (2)$$

where
c^r concentration in the room zone (kg/m^3),
c^c concentration in the exhaust outlet (kg/m^3),
c^o concentration in the ambient air (kg/m^3),
q_e escaped flow rate (m^3/s) ($q_e>0$),
q_f exhaust flow rate (m^3/s).

The new derivation gives the same final formula as does the Sarnosky derivation in terms of the concentrations, but the inconsistencies in the original derivation are avoided. In addition, in the new derivation, it is also proved that the capture efficiency equals the ratio of capture flow rate to the total plume flow rate, which also indicates that the capture efficiency does not depend on the ambient concentration, although it is included in equation (1). The latter conclusion is considered to be particularly important.

Both equations (1) and (2) are simple, and only two or three quantities are involved. In equation (1), three averaged concentrations are needed for evaluating the capture efficiency. This result is particularly useful in experimental testing and CFD analysis of capture efficiency. In equation (2), only two flow rates are needed. It should be noted that q_f+q_e equals the plume flow rate at the canopy entry level. In the next sections, equation (1) will be used in our CFD analysis of capture efficiency and equation (2) will be used to develop a simple formula for predicting the capture efficiency.

It is interesting to point out that the defined capture efficiency equals the direct capture efficiency of Jansson (1982, 1990) and Madsen et al. (1994), if we assume that the hood captures a contaminant directly from the source as efficiently as it captures a contaminant that is entrained from the room (Li and Delsante, 1996).

A Simple Formula for Estimating Capture Efficiency

As discussed earlier, although the capture efficiency is mainly governed by two parameters of the hood, namely, the exhaust flow rate and the hood horizontal dimensions, and details of the cooking heat source, there are many other factors that influence the hood performance. It is a difficult task to find a simple formula for the hood capture efficiency without determining/simulating the indoor air distribution, as can be seen from the previous discussion of a confined flow system.

The following analysis is based on the assumptions that the hood horizontal dimensions extend sufficiently to cover the plume size, and the plume flow rate depends only on the power of the heat source and other geometrical parameters. It should be mentioned that design of a kitchen range hood may also be constrained by other considerations than capture efficiency, e.g. thermal comfort in the kitchen. However, this investigation concentrates only on the capture efficiency of the hood.

The flow arising from a cooking process can be simplified as a plume generated from a heat source. The plume is generally turbulent. Due to its importance in many flow situations, such as fires and dispersion of pollutants from industrial chimneys, the plume flow has been recognized as a very important basic flow. A classical publication about plumes is that of Morton et al. (1956). An extensive review of plume study was provided by Chen and Rodi (1980). The flow rate of a plume rising from a circular heat source with surrounding air at 22°C is predicted to be (Awbi, 1991)

$$q_p = 0.0061 S_p^{1/3} (h+d)^{5/3} \tag{3}$$

where

q_p plume flow rate at the canopy entry level (m^3/s) ($=q_f+q_e$),

S_p heat source power (W),

h height from the heat source to the hood (m),

d diameter of the heat source (m).

If the heat source is a rectangle with length l (m) and depth w (m), an equivalent diameter d is calculated as

$$d = \sqrt{\frac{4lw}{\pi}} \tag{4}$$

If the exhaust flow rate is q_f (m^3/s), the capture efficiency is calculated, according eq. (2), as

$$\varepsilon_c = \frac{q_f}{q_p} \tag{5}$$

Eq. (5) is valid only if $q_p \geq q_f$. The capture efficiency equals 100% if $q_p \leq q_f$. Eq. (5) will be referred to as the simple formula in this paper.

It should be mentioned that the simple formula here considers only the effect of convective transport, not the diffusive transport, including the turbulent fusion which can also disperse contaminants from cooking zone to room areas.

Examples

The Ventair code is used for CFD analysis in this pa, it was originally developed for simulating three mensional turbulent flows using the SIMPLEC num

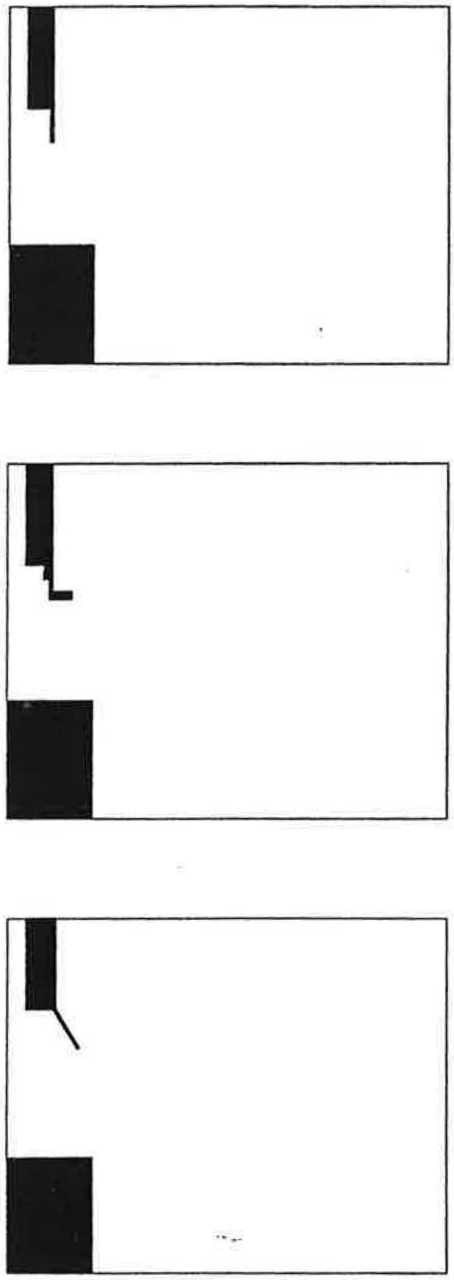

Fig. 3 Three types of range hood used in this study, (a) Type H includes HA50 and HA80, (a) Type HB includes HB60 and HB and (c) Type HC includes HC60 and HC90. Each type is inves gated for two widths, as indicated by the suffix to the mo code: e.g. HA50 denotes a hood 0.5 m wide

cal algorithm and the standard κ-ε turbulence model (Li et al., 1993). The second-order accurate convection schemes are described in Li and Rudman (1995). The code has been used for a displacement ventilation flow, incorporating both convection and thermal radiation models (Li et al., 1993). A common feature in displacement ventilation airflows and kitchen airflows is that plumes are developed from heat sources in both cases. Comparisons between detailed full-scale measurements and *Ventair* simulations have been presented in Li et al. (1993). Generally, good accuracy has been obtained with the Ventair code. This result, in addition to more than 20 other tests, establishes confidence for applying the code to the kitchen flows in this paper. From the CFD-simulated concentration fields, the capture efficiency is evaluated from equation (1). This result is then used to evaluate the result predicted by the simple formula.

The model room used in the *Ventair* code for this study has dimensions of 3 m×3 m×2.5 m. Three types of range hood (HA, HB and HC) are considered (see Figure 3), that are the products of an Australian hood manufacturer. Each type is investigated for two widths, as indicated by the suffix to the model code: e.g. HA50 denotes a hood 0.5 m wide. The installation of these range hoods is the same as that in Li and Delsante (1996). No other ventilation system exists in the room. A cupboard and a bench are built against one rear wall, with the range hood located in the middle of the cupboard. The rectangular heat source is 0.15 m high and located over the cook-top. For contaminant calculations, a contaminant source is introduced in the same space as the heat source. The depths of the cupboard and the bench are 0.3 m and 0.6 m, respectively. Offset of the heat source from the cook-top/hood edge is .05 m. To reduce the influence of side draught, the opposite boundary is completely open with a uniform inflow of air.

In this study, only steady-state situations are considered. The exhaust outlet concentrations and the room concentrations are calculated, and each is space-averaged, in order to evaluate the capture efficiency from equation (1).

The capture efficiencies, which are calculated by using CFD and the simple formula of equation (5), are plotted in Fig. 4–6 for each range hood and defined power level.

From equation (5), the capture efficiency is proportional to the exhaust flow rate. This is clearly shown in Fig. 4–6. It should be mentioned again that equation (5) was developed based on very simplified assumptions. The most important assumption is in the calculation of the air entrainment into the plume. The CFD results do not show a strict linear relationship between the capture efficiency and the exhaust flow rate. This is because the flow situations considered in our CFD calculations are more complex, and the simulated plume develops in a confined space. However, the results calculated by the simple method agree very well with the CFD results.

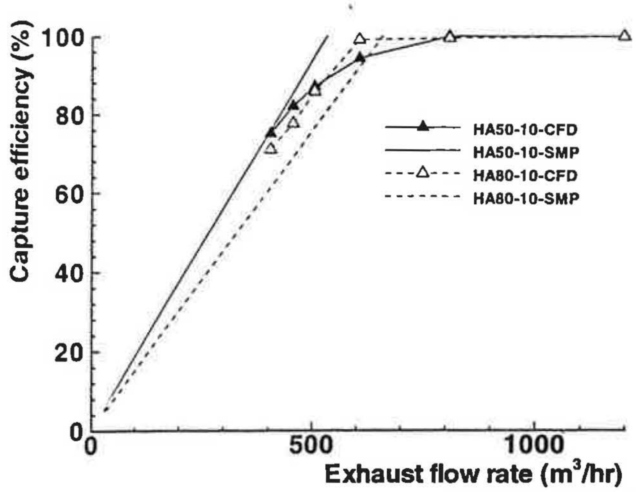

Fig. 4 Calculated capture efficiencies of the hood HA50 and HA80 for a heat power level of 10 kW. SMP means the result of the simple formula and CFD means the result with the CFD simulation

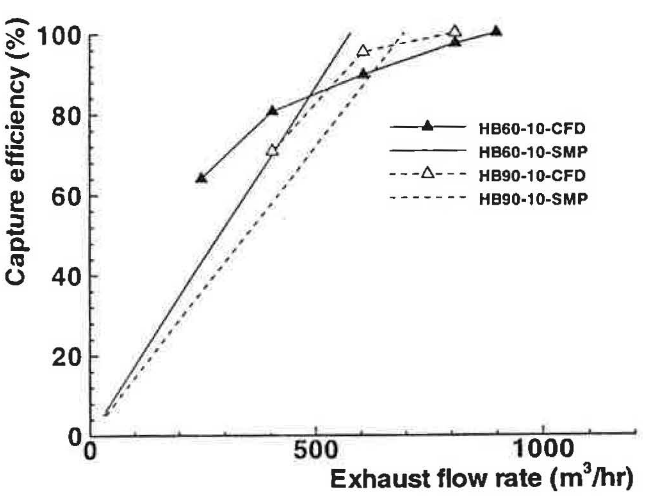

Fig. 5 Calculated capture efficiencies of the hood HB60 and HB90 for a heat power level of 10 kW. SMP means the result of the simple formula and CFD means the result with the CFD simulation

This agreement clearly confirms that buoyancy-capture is the dominant mechanism in kitchen range hoods. Buoyancy capture is one of the assumptions in the simple formula. The CFD method makes no assumption at all regarding buoyancy capture or velocity capture, since the CFD calculation itself will identify the relevant physical processes. The calculations performed in this paper have demonstrated the role of

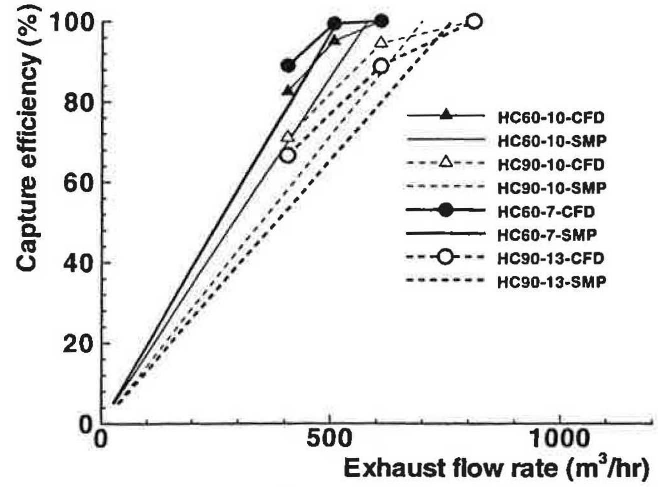

Fig. 6 Calculated capture efficiencies of the hood HB60 and HB90 for a heat power level of 10 kW. SMP means the result of the simple formula and CFD means the result with the CFD simulation. The bold lines are the results with a heat power level of 7 kW for HC60 and 13 kW for HC90

CFD in understanding the physical transport of contaminants in a kitchen.

From these results, it can be seen that a 100% capture efficiency is achieved for exhaust flow rates between 500 and 900 m^3/hr, depending on the range hood design and power levels. This result agrees well with the flow rates recommended by the hood manufacturer. Various details of cook-top arrangements are not fully considered in this study, simply because different combinations can result in an extremely large number of cases. We have instead considered a more general case in which the heat power is distributed in a defined area which is generally smaller than the range hood.

However, the area of the heat source plays an important role in the capture efficiency. For example, if the heat source is concentrated in a much smaller area, the capture efficiency will increase; however, if the size of heat source is larger, the capture efficiency will decrease. It should be noted that the large hood has a lower capture efficiency than that of a short HC hood in Figure 6 for the same heat power level. This is due to a larger size of the heat source used in the large hood evaluation. The larger the heat source, the greater the plume flow rate at the hood canopy level, as shown by equation (3).

It appears that for the same heat power and exhaust flow rates, different designs lead to rather similar results. This can be again explained by the buoyancy-capture principle. However, there are still some differences in different hood designs, as shown by the CFD results. Unfortunately, such a difference cannot be predicted by the simple formula. If different designs are to be compared, then the CFD approach has to be used.

To use the present simple model for engineering sign of kitchen range hoods, it will be necessary to velop further the plume model. One way to do thi: to group the cooking appliances into various types a then to develop the plume model for each type. C may be used to study and paramaterise the si draught effect in the new plume model.

The minimum exhaust flow rate at which the c ture efficiency reaches 100% can be estimated from F 4–6 from both the CFD results and those of the sim formula. This estimated flow rate has to be multipl by some safety factor (≥1) in order to achieve a 10 capture efficiency in real situations. The choice of t safety factor will depend on a knowledge of other fluencing factors in the system. When a weak mu room type of plume is generated below a hood wh the heat power is low, e.g. during the first few minu of cooking or after the power is off, the buoyancy-ca ture concept may not be valid any longer. C methods can be applied to study these factors, e.g. si draught, room geometry and other ventilation/heati systems in the house. In addition, a time-depende solution may be sought in order to study the effect the assumption of steady-state in this investigation.

It may be mentioned that CFD simulations can al provide a complete picture of the flow fields in the k chen, which help to further understand the system, shown by Li and Delsante (1996). CFD can be a go design method except that it requires detailed softwa experience and a good computer, and it can be ve expensive. CFD can also be used to assist in develo ing an engineering design tool as has been done her

Concluding Remarks

Kitchen ventilation using range hoods is shown to governed mainly by the buoyancy principle. It is a vised that any hood design methods for kitche should follow this principle in order to obtain an op mum design. The present investigation has identifi two important parameters which influence the captu efficiency of a range hood, the exhaust flow rate an horizontal dimensions of the hood. Although this m be well known by range hood design engineers, t importance of the results in this paper is their link wi the buoyancy capture principle. Determining an ad quate exhaust flow rate and hood horizontal dime sions should first be based on the heat power, t physical size of the heat source and the distance b tween the heat source and the hood.

A new derivation of capture efficiency has been a plied in this study. The new concept is consistent an can be represented either by the concentrations or t pture/plume flow rates. A simple formula for determining capture efficiency has been developed based on e buoyancy-capture principle and the new derivation. The model performs reasonably well in the oblems considered in this paper, as compared to the FD predicted results.

Iomenclature

concentration (kg/m^3)
concentration of contaminant in the exhaust (kg/m^3)
concentration of contaminant in the rest of the room (kg/m^3)
concentration in the outdoor ambient air (kg/m^3)
diameter of the heat source (m)
height from the heat source to the hood (m)
length of the heat source (m)
escaped flow rate at front canopy level (m^3/s)
airflow rate through the exhaust duct (m^3/s)
net flow rate in the plume at front canopy level (m^3/s)
general ventilation rate (m^3/s)
capture efficiency of kitchen range hoods
plume flow rate (m^3/s) ($=q_f+q_e$)
heat source power (W)
width of the heat source (m)

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