Capture efficiency of combustion gases from gas fired cooking-stoves - implications for exposure to nitrogen dioxide in homes

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ABSTRACT
The indoor level of nitrogen dioxide in homes with a gas fired cooking stove is a complicated function of several factors including cooking habits, the capture effectiveness of the range hood, the extract flow rate, the ventilation and air distribution in the dwelling etc.

The paper reports the results of an experimental study of the way in which the capture efficiency of a cooking range hood varies with the extract flow rate, the heating power and which burner on the range is used.

The result shows that the range hood capture efficiency varies between 0 and 90% depending on use and extract flow rate. The capture efficiency has a strong effect on the NO_2 concentration.

In order to analyse the importance of different factors on nitrogen dioxide exposure, the result of a mathematical simulation is presented, including outdoor NO_2-concentration, reactive decay constant of NO_2, emission rate, capture efficiency and ventilation.

INDEX TERMS
Capture efficiency, Kitchen exhaust hood, Nitrogen dioxide, Exposure assessment

INTRODUCTION
Several investigations indicate that the exposure to nitrogen dioxide is considerably higher in homes with gas fired stoves, than in those with electric stoves. The recently adopted WHO long term air quality guideline for nitrogen dioxide of 40-50 $\mu g/m^3$ is mainly motivated from the observation that children exposed to a 30 $\mu g/m^3$ average increment of exposure (due to indoor sources) show an increase in the incidence of lower respiratory illnesses.

CAPTURE EFFICIENCY
The purpose of the range hood is to capture and transport away contaminants emitted during cooking, in order to minimise their spreading to the occupation zone. The effectiveness of the hood is quantified by its capture efficiency. The capture efficiency can be defined in different ways. The two most frequently used definitions are:

1 The ratio between the total amount of contaminants transported away through the hood and the total amount of contaminants emitted during cooking.
2 The ratio between the amount of contaminants *directly* transported away through the hood and the total amount of contaminants emitted during cooking.

The second definition has also been called direct capture efficiency" (Madsen *et al.* 1994).

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According to the first definition those contaminants, which first leak out to the occupation zone and then return to the hood, are also counted as captured. In contrast the second definition does not count those contaminants, which contribute to the exposure in the occupation zone, as captured. Therefore, compared with definition 2, the capture efficiency is overestimated using definition 1.

In spite of the shortcomings, definition 1 has been used and continues to be used in standardised test procedures for range hoods. For example the Swedish standard SS 435 05 01 (1981), the French standard NF E 51-704 (1986) and even the new European standard IEC 61591 (1997) use definitions similar to definition 1, though the latter standard uses the concept ”odour reduction factor” instead of capture efficiency.

However, using definition 2 may introduce some delicate measurement problems (Madsen *et al.* 1994, Fracastore and Perino 1998, Li *et al.* 1996, 1997). This paper reports a simple technique to measure the direct capture efficiency, using the second definition, which is useful not only in laboratories, but also in the field.

The direct capture efficiency of a range hood depends on several factors.

The position of the burner on the range
The power of the burner
The extract flow rate in the hood
The height of the hood above the range
The design of the hood
The temperature of the pots and pans used
Air movements in the kitchen

The paper reports an investigation on the way in which the direct capture efficiency depends on the four first factors, while the last three factors are kept relatively constant.

METHODS

Although we are interested in the air contamination by nitrogen dioxide from the burners, the capture efficiency of the hood is determined using a sulphur hexafluoride (SF_6) tracer gas. The main reasons are the various chemical reactions which NO_2 can undergo and the essentially more complicated analysis technique. An alternative would be to use the carbon dioxide, also generated by the burner. It was however, judged better to use SF_6 as a tracer due to the better control of emission and background concentration.

The experimental layout is schematically displayed in Figure 1. Referring to Figure 1 the direct capture efficiency (ε) can be written as

$$\varepsilon = \frac{Q_e\left(C_e - \langle C_b \rangle\right)}{\dot{m}_{SF_6}} \tag{1}$$

where Q_eC_e is the amount of tracer extracted per time unit through the hood, $Q_e\langle C_b \rangle$ is that part of the extracted amount, which is supplied to the range hood from the kitchen and $\dot{m}_{SF_6}$ is the mass flow rate of supplied tracer gas.

Thus, when determining the capture efficiency, the following quantities must be known:

Q_e	Extract flow rate of air [m^3/h]
C_e	Concentration of tracer gas in the extract [mg/m^3]

$\langle C_b \rangle$ The average tracer concentration in the air supplied to the hood from the kitchen [mg/m^3]
$\dot{m}_{SF_6}$ The injection rate of tracer SF_6 [mg/h]

The only quantity, which cannot be controlled or measured directly (in field trials), is the extract flow rate Q_e . However, if the same mass flow rate of tracer gas is injected directly into the extract, the capture efficiency is by definition 100% so that

$$Q_e\left(C_0 - \langle C_b \rangle\right) = \dot{m}_{SF_6} \quad (2)$$

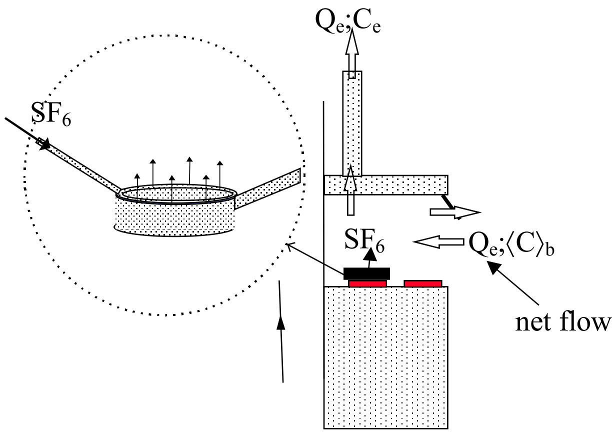

Figure 1. Principle of the measurement of hood capture efficiency. Q_e is the hood extract flow rate, which is also equal to the net flow of air from the kitchen to the hood. During cooking the tracer gas is injected around the circumference of the cooking pan as illustrated in the inset.

Experimental design
The experiment is carried out in an indoor test house with a kitchen, 2 rooms, a bathroom and a hall. The house is extract ventilated with the extract points in the bathroom (15 *l*/s) and in the kitchen's range hood (variable). Air inlets are situated in the two rooms. All internal doors are open during the experiments. A low speed oscillating fan in the kitchen secures some air movements. The fan is directed so that the air jet is not directly hitting the space above the stove.

The gas stove is fuelled with propane and has four burners and a gas fired oven. The extract flow in the range hood is adjustable with the fan speed. During the laboratory experiments the extract flow rate is measured with a measurement flange in the exhaust duct. The burner power is calculated from weighing of the fuel consumption.

The following parameters are varied during the experiment.
- The position of the burner on the range (back, front, oven)
- Height of the hood above range (no hood, 50 cm, 65 cm)
- Extract air flow rate in the hood (10.5 *l*/s, 20 *l*/s, 40 *l*/s)
- Burner power (back burner: 2 kW and 0.33 kW, front burner: 1.3 kW and 0.25 kW)

The cooking pan used during the experiments is 25 cm wide and covered with a welded lid. It is cooled with water circulation inside to keep the temperature of the water to 70-90 ºC.

Tracer gas dosing and analysis
SF_6 tracer gas analysis and injection is performed using an INNOVA (Brüel & Kjær) infrared gas analyser 1302 and doser 1303.

Air samples are taken using 4 mm polypropylene plastic tubes. A tracer gas sampling point is situated in the hood extract duct, approximately 1 m above the opening in the range hood. Other air samples are taken in the kitchen at a height of approximately 1 m and at a distance of 80 cm from the front of the stove. These samples are collected from six positions, evenly spaced on a length of 1.5 m.

The tracer concentrations are measured as a function of time for the four different modes illustrated in Figure 2. The first two modes of the experiment aim at determining the extract airflow rate in the hood. In mode 1 the background concentration (equal to the SF_6 concentration in the kitchen) is measured without tracer injection. In mode 2 constant tracer injection is made directly into the extract opening, securing 100 % capture efficiency. In mode 3 the burner is on and the injection (with the same injection rate) is made in a specially designed cooking device (see Figure 1). In mode 4 both burner and tracer injection is off yielding once again the background concentration in the kitchen.

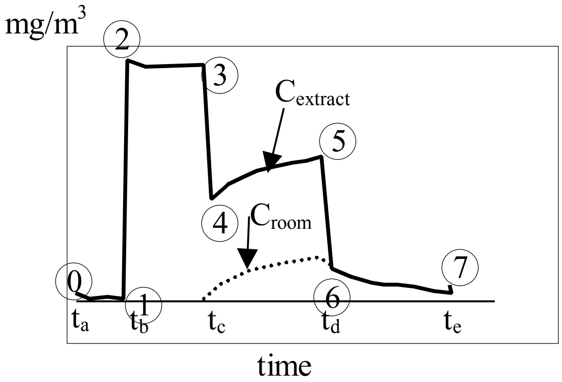

Figure 2. Schematic illustration of how the tracer concentration in the hood extract and room air changes with time when shifting the injection points.

mode 1 t_a-t_b : 0-1 no injection, burner off
mode 2 t_b-t_c : 2-3 injection in extract, burner off
mode 3 t_c-t_d: 4-5: injection in cooking pan, burner on
mode 4 t_d-t_e: 6-7: no injection, burner off

CALCULATIONS

The calculation of the capture efficiency is performed using equation 1. The extract flow rate Q_e is calculated from the known tracer emission rate $\dot{m}_{SF_6}$ and the measured concentrations in the extract during mode 2 (C_0) and the room concentration during mode 1 ($\langle C_b \rangle$):

$$Q_e = \frac{\dot{m}_{SF_6}}{\left(C_0 - \langle C_b \rangle\right)} \tag{3}$$

(note: if the room concentration decays during mode 1 due to ventilation, an extrapolated value of $\langle C_b \rangle$ should be used in order to represent its true value during mode 2.)

If the room concentration during mode 3 is measured then the difference between the extract concentration and the room concentration is calculated as a function of time and an average value of C_e - $\langle C_b \rangle$ calculated during mode 3. As an alternative, useful if the room concentration is not measured, two values of $\langle C_b \rangle$ can be calculated from measurements in the extract, one by extrapolation to point t_c from mode 1, and the other from back-extrapolation to t_d from mode 4 (see Figure 1). Then two values of C_e - $\langle C_b \rangle$ can be calculated, valid at the endpoints of mode 3, and an average taken. Both calculation techniques have been tested in this work and shown to yield comparable results. Finally the capture efficiency is calculated using equation 1.

RESULTS

The results of the determinations of the direct capture efficiency for different burner power, hood heights, extract flow rates and position of used burners are graphically displayed in Figure 3.

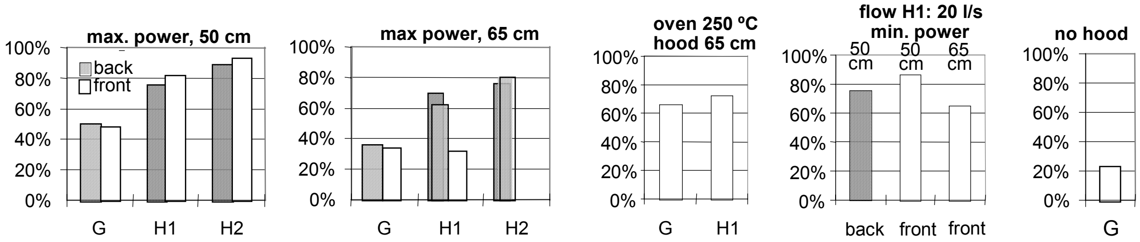

Figure 3. Results from determination of the capture efficiency. Range hood extract flow rates: G= 10.5 *l*/s, H1= 20 *l*/s, H2= 40 *l*/s (double bars indicate duplicate experiments).

DISCUSSION

Capture efficiency

The result of the measurement of capture efficiency shows that it increases strongly with increasing hood extract flow. It also increases significantly when lowering the height of the hood above the range. At a height of 50 cm the efficiency increases from 50% at a flow rate of 10.5 *l*/s to 90% at 40 *l*/s. If the hood is removed completely, the extract duct itself yields 20% capture efficiency. The difference when using back or front burner is usually small. However, one measurement with 65 cm height and the front burner at max. power breaks the trend and indicates a very low efficiency of 30%. A reasonable explanation may be that the strong thermal plume affects the capturing in this case. Unfortunately, only two measurements are performed with front burners at max. power with that hood height, so it is difficult to tell if this value is due to an unfortunate faulty measurement or a real effect. At 65 cm height and at min. power with the front burner, approximately the same efficiency is found as that at max. power.

Nitrogen dioxide exposure

In order to assess the importance of the capture efficiency for nitrogen dioxide exposure in homes with gas stoves a mathematical model is required. The concentration of nitrogen dioxide in a multi-zone dwelling can be modelled with a system of differential equations:

$$(1-\varepsilon)\dot{\boldsymbol{m}} + \boldsymbol{QC}_{in} - \boldsymbol{QC} - k_r\boldsymbol{VC} = \boldsymbol{V}\frac{d\boldsymbol{C}}{dt} \qquad (4)$$

where the bold letters refer to matrices of NO_2 emission rates ($\dot{\boldsymbol{m}}$), air flows ($\boldsymbol{Q}$), ambient concentration ($\boldsymbol{Q}_{in}$), room air concentrations ($\boldsymbol{C}$) and room volumes ($\boldsymbol{V}$) respectively. ε denotes the capture efficiency and k_r the reactive rate constant for NO_2.

It is beyond the scope of this paper to discuss mathematical modelling and simulation of nitrogen dioxide exposure (Stymne 2001). However, an idea of the relative importance of a gas stove installation can be gained from the single zone calculation of NO_2 during a day with a typical pattern of stove use shown in Figure 4. The following parameters are assumed - NO_2 emission rate: 36 [mg,h^{-1},kW^{-1}], outdoor NO_2 concentration: 40 [µg/m3], volume of the dwelling: 175 m^3, air change rate: 0.5 [h^{-1}], rate constant for reactive removal of NO_2 1.0 [h^{-1}]. It should be noted that in particular the assumed reactive rate constant for NO_2 is very uncertain. It is strongly dependent on the type of materials indoors. Literature values vary from 0.2 h^{-1} to 2 h^{-1}.

The simulation shows that the daily average exposure to NO_2 with ”normal” cooking on a gas stove can vary between 15 µg/m^3 (with 90% capture efficiency) and 33 µg/m^3 (without hood) in a normally ventilated urban dwelling (with ambient NO_2 concentration of 40 µg/m^3). Peak concentrations vary between 40 µg/m^3 and 160 µg/m^3 under the same circumstances.

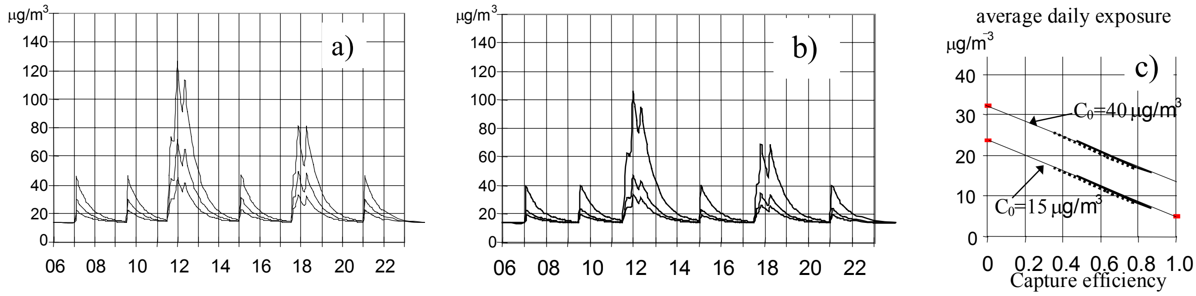

Figure 4. Simulation of NO2 concentration during a day with normal use of the stove. a) displays the result for a hood height of 65 cm and diagram b) for 50 cm. The curves refer to extract flows of 10 *l*/s, 20 *l*/s and 40 *l*/s respectively. Diagram c) displays the daily average (24 h) exposure as a function of capture efficiency at two different outdoor NO2 concentrations.

CONCLUSIONS

A simple and useful technique for measurement of the direct capture efficiency (ε) of a kitchen hood using tracer gas is demonstrated. It can be concluded that the capture efficiency of a kitchen hood can vary between 30% and 90%, depending in particular on the extract flow rate and the height of the hood above the range. Simulation shows that the average indoor NO_2 concentration due to gas cooking under a ventilated hood may increase between 12 $\mu g/m^3$ (at ε=0.3) and 2 $\mu g/m^3$ (at ε=0.9) above that emanating from outdoor air in a normally ventilated dwelling with ”normal” cooking habits. In order to avoid unacceptable levels of nitrogen dioxide, it is recommendable to use special means for securing a hood extract flow during gas fired cooking.

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