EXPERIMENTAL EVALUATION
OF KITCHEN HOODS PERFORMANCE

G.V. Fracastoro, M. Perino

Dipartimento di Energetica - Politecnico di Torino, Turin, ITALY

ABSTRACT

This paper presents an original protocol to measure the fluodynamic performance of hoods in the laboratory. Results are presented both in terms of contaminant removal efficiency and flow field.

The measuring campaign has been performed in order to assess how the hood performance is influenced by the boundary conditions, the hood geometry, and the heat power released by cooking appliances.

KEYWORDS

Kitchen ventilation, measuring techniques, full-scale experiments, air quality.

INTRODUCTION

Relatively little attention has been paid insofar to efficient ventilation of residential kitchens, where a large fraction of typical indoor pollutants (water vapour, carbon monoxide, nitrogen oxides and VOC's) is released, and may often cause poor air quality problems. The ability of commercially available range hoods to remove these pollutants is generally unknown, both to the producers and to the users.

The performance of a hood may be described by a number of parameters, such as volume flow rate, capture velocity, delta-p vs. flow rate curve, contaminant capture efficiency (CCE), etc. In spite of its importance, the CCE value is generally unknown, and even its definition is not generally agreed upon. The following paragraphs will show how it is possible to define and measure CCE with respect to gaseous pollutants, i e, "passive" pollutants, whose mass allows them to follow the airflow induced by the hood.

CONTAMINANT CAPTURE EFFICIENCY OF THE HOOD

With reference to figure 1, in this paper the CCE has been defined (Wolbrink & Sarnosky, 1992, Cardinale et al., 1993) as:

$$E = \frac{q_c}{q} \tag{1}$$

where q_c is the amount of contaminant directly captured by the hood.

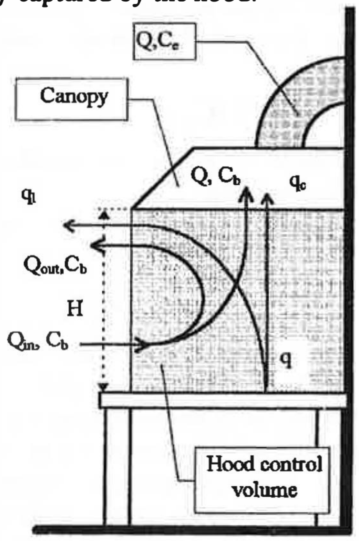

Figure 1 Description of main symbols.

CCE is influenced by geometrical features (distance of cook top from the hood canopy), physical quantities (flow rate of the hood, heat released by the cooking appliance), and by a number of "disturbing factors" such as local drafts induced by persons moving around, thermal boundary conditions, type of contaminant released, etc..

The aim of this paper is to define a procedure for a reliable and repeatable laboratory measurement of CCE, which is not a trivial task as it may appear (Madsen et al., 1994).

To this aim it is important to stress that q_c represents the fraction of the emitted contaminant which is *directly* captured by the hood: the part of that leaks out of the control volume of the hood (dotted area in figure 1), and is afterwards sucked through the hood together with the room air, *should not* be included in the term q_c. Otherwise, when all the room air is exhausted through the hood, the CCE would in the long term always tend to one.

Laboratory assessment of CCE has been made using the ***tracer gas technique***.

Continuity equation written for the tracer gas in the canopy (see figure 1 for the meaning of symbols) under the hypothesis of non compressible fluid, isothermal field, steady state, and uniform concentration[1] yields:

$$q_c = Q \cdot (C_e - C_b) \qquad (2)$$

where Q is the net volume air flow entering the hood.

From (2) and (1) one gets at once

$$\boxed{E = \frac{Q \cdot (C_e - C_b)}{q}} \qquad (3)$$

which is the basis for experimental evaluation of CCE. However, there are two considerations to be made about C_b:

a) it is difficult to measure the mean value C_b over the hood boundary, also because not all the air crosses such boundary from the room to the hood, ***but in the opposite direction*** as well. In fact, the continuity equation written for the air in the control volume under the hood yields:

$$Q_{in} = Q_{out} + Q \qquad (4)$$

a) C_b varies (slowly) with time, due to progressive accumulation of the contaminant not exhausted by the hood.

To take into account these factors, two different "models" of the surrounding room may be adopted:

1. The room is a "large enclosure"
2. The room is a "confined space"

Measurements in a "large enclosure"

If the experimental apparatus is located in a large enclosure (volume > 500 ÷ 1000 m^3), it may suffice to measure the initial and final values of the background concentration near the hood, and, calling C_0 its average value, one may assume:

$$C_b = C_0 \qquad (5)$$

In this case, from (3) and (5) one gets:

$$\boxed{E = \frac{Q \cdot (C_e - C_0)}{q}} \qquad (6)$$

Measurements in a "confined space"

If the experimental apparatus is located in an ordinary room (volume in the range 20 ÷ 100 m^3), one may assume that

$$C_b = \langle C \rangle \qquad (7)$$

where <C> is the room average concentration

Under the hypothesis that air is exhausted only through the hood, and that contaminant concentration in outdoor air is zero, <C> will theoretically vary during the test according to the following law:

$$\langle C \rangle = \frac{q \cdot (1-E)}{Q} + e^{-\frac{t}{\tau}} \cdot \left(\langle C \rangle_i - \frac{q \cdot (1-E)}{Q} \right) \qquad (8)$$

where:

$\langle C \rangle_i$ = initial concentration in the room

$\tau = V/Q$ nominal room time constant

Now, since <C> varies slowly during the measurement period, it may be considered constant "at intervals" ($C_b = \langle C \rangle$). Therefore:

$$\boxed{E = \frac{Q \cdot (C_e - \langle C \rangle)}{q}} \qquad (9)$$

It may be observed that in steady-state conditions eqn (8) yields

$$E = 1 - Q \cdot \langle C \rangle_\infty / q\,, \qquad (10)$$

correctly implying, by comparison with (9), that at steady state

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[1] these hypotheses will be considered valid throughout the whole paper.

$$q = Q \cdot C_{e,\infty}.$$

Both equations (9) and (10) could be used to assess CCE, but eqn (9) has been preferred to (10) because it leads to a smaller measurement error, being $\langle C \rangle_{\infty} \ll C_{e,\infty}$.

EXPERIMENTAL APPARATUS

The experimental apparatus needed to measure the capture efficiency, as defined in the previous paragraph, is shown in figure 2.

The tracer gas (SF_6) is released 15 cm above the cook top by means of a metallic duct '5'. The emission point is located on the vertical axis passing through the centre of the hood. This last is mounted on a suitable bracket system that allows an easy adjustment of the distance between the cook top and the hood canopy. The heat source is a commercial cooking burner working either with natural gas (hood #2) or liquid petrol gas (hood #1). Temperature of the fumes is continuously monitored in order to prevent that it exceeds 800° C and oxidation of the tracer gas may occur[2]. Tracer and combustion gas flow rates are measured by means of volumetric meters '1' and '17'. Exhaust air flow rate is measured by a thin plate orifice '8'. A centrifugal fan connected at the end of the exhaust pipe offsets, by means of damper '12', the pressure drop due to the orifice and to the other measuring instruments.

The tracer gas concentration has been sampled at two points: on the exhaust air duct upstream the orifice ('7'), and inside the test room, where a network of Rilsan pipes samples the air over 8 points to measure the average room concentration. An automated pneumatic scanner ('13') switches between these two channels automatically, and sends the air samples to a photoacoustic gas analyser '15' Bruël & Kjaer 1302. The whole measurement cycle is managed by a PC ('14'). A Solomat MPM 4000 monitor acquires the fume and room temperature, while the tracer gas flow rate is measured by means of a volumatric flow rate.

Error analysis

Since the capture efficiency may be written, whatever the test procedure adopted, with the same mathematical structure (eqn. 6 or 9) there is only one expression for the measurement uncertainty ΔE. This is due to both systematic, $|\Delta E_s|$, and random, $|\Delta E_c|$, components, and is cautiously calculated as:

$$|\Delta E| = |\Delta E_s| + |\Delta E_c| \quad (11)$$

The systematic error is given by:

$$|\Delta E_s| = \left|\frac{Q}{q}\right| \cdot \left(|\Delta C_{1,s}| + |\Delta C_{2,s}|\right) \cdot + \left|\frac{E}{Q}\right| \cdot |\Delta Q_s| + \left|\frac{E}{q}\right| \cdot |\Delta q_s| \quad (12)$$

where the Δ's represent the instruments nominal uncertainties, and subscripts 1 and 2 refer to exhaust and room concentrations.

The absolute value of random errors is computed as: $|\Delta E_c| = \sqrt{\sum (\Delta E_c)^2}$, that is, neglecting the mixed product of error components, and random errors on Q and q (measured with a 'spot' procedure):

$$|\Delta E_c| = \sqrt{\left(\frac{Q}{q}\right)^2 \cdot \left[(\Delta C_{1,c})^2 + (\Delta C_{2,c})^2\right]} \quad (13)$$

In their turn, ΔC_1 and ΔC_2 are given by

$$\Delta C_{1,c} = t_{C_1} \cdot \frac{\sigma_{C_1}}{\sqrt{n_{C_1} - 1}} \quad \Delta C_{2,c} = t_{C2} \cdot \frac{\sigma_{C2}}{\sqrt{n_{C_2} - 1}} \quad (14)$$

where t is Student's parameter, σ_c is the standard deviation of the concentration samples and n_c is the numerousness of the samples. Hereafter it will be assumed a confidence interval of 99% for the t-value estimate.

EXPERIMENTAL PROCEDURE AND DATA PROCESSING

Measurements in large enclosures

For the development of this procedure (eqn 6) no particular care for data post-processing is required. Thanks to the small time constant of the system (only C_e is a time

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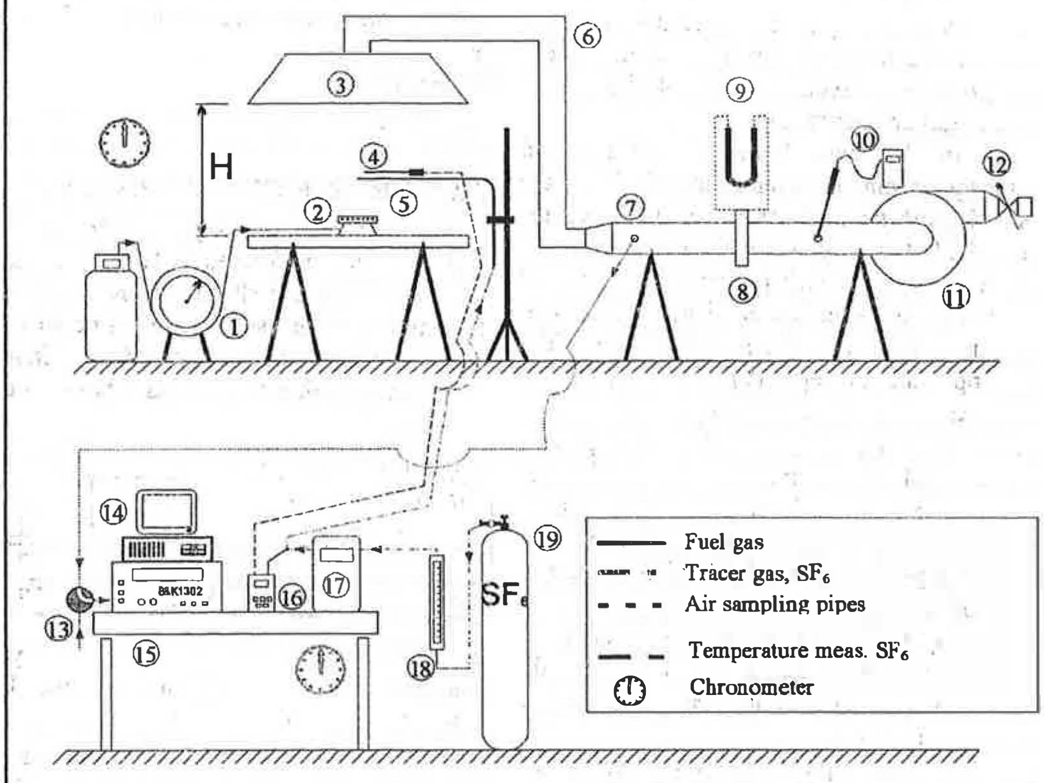
[2] Temperature of the fumes may also be considered as a suitable indicator of the perturbing air draft that tends to decrease the hood efficiency.



①	Volume meter (fuel gas) (± 0.2%)	11	Centrifugal fan
②	Commercial cooking burner	12	Damper
③	Hood	13	Multi channel pneumatic scanner
④	K-Thermocouple (± 0.2 °C)	14	Computer
⑤	Tracer gas duct	15	B&K1302 ® gas analyser (± 1%)
⑥	Flexible duct	16	Solomat ® MPM 4000 monitor
⑦	Sampling point - $C_{exhaust}$ measurement	17	tracer gas flow-meter (± 2.5 %)
⑧	Baffle	18	Rotameter (tracer gas flow rate)
⑨	Differential micromanometer (±1% or, if greater, ± 1 Pa)	19	SF_6 bottle
⑩	K-Thermocouple (± 0.2 °C)		

Figure 2 Experimental set-up and instruments accuracy.

varying parameter) the measurement period is reduced to about ½ hour.

The experimental procedure is easy and quick to perform. However, the results are affected by large random fluctuations due to perturbing air drafts. This leads to poor repeatability of measurements, as unstable (high solar radiation, wind...) atmospheric conditions lead to systematically lower values of efficiency and large scattering of data. A useful information about the reliability of the measurement is the fume temperature: when the cross air drafts perturb the measurement the mean fume temperature during the test shows values 30% lower than those measured with "still" indoor air.

Measurements in confined spaces

In this case eqn (9) has been adopted. Measurements were performed inside a thermostatic room[3] of (3.5 x 4.5 x 3)m. The hood is leaned against one of the boundary walls and a network of pipes is set up in order to provide an average value of the indoor tracer gas concentration.

In this case both the exhaust and average room concentration of SF_6 vary slowly with time. Three different procedures may be followed for the data processing:

1. to assume, adopting a strategy borrowed from the ventilation efficiency assessment, that all the time-varying quantities appearing in eqn. (9) are evaluated at steady-state: $C_e(\infty)$, $<C(\infty)>$.
2. To apply eqn. (9) to single time step, after the end of the initial short transient of concentration within the hood control volume, and to assume CCE as the average over a sufficiently high number of points.
3. To apply eqn (9) not to *flow rates* but to *volumes* of tracer gas removed by the hood, i e, integrating eqn. (9) over a reasonable time.

The development of procedures 2 and 3 does not present particular problems.

The first approach appears theoretically more solid than the others, but its drawback is the large amount of time required to reach steady-state conditions (2-3 hours). In order to overcome this limitation, a forecast numerical technique has been applied, which allowed to stop all the experiments after ½ - 1 hour. The values of $<C(\infty)>$ and $C_e(\infty)$ have been derived best-fitting the measured data by means of a non linear least-square method. The calculation procedure provides also the standard deviation for the predicted concentration values and the t-Student parameter corresponding to 99% probability. Some care must be taken in the processing of C_e data. Since these concentrations show large fluctuations, the numerical method may not always converge. In this case, the moving averages of the exhaust concentration have been calculated before the best-fit application, in order to smooth down the scattering and to enhance the mean trend of the C_e. Whenever even this method did not converge it has been assumed:

$$C_e(\infty) = C_e(\tau_{final}) + [< C(\infty) > - < C(\tau_{final}) >]$$

CAPTURE EFFICIENCY RESULTS

Due to the poor repeatability of the measurements performed in large enclosures the related results will not be presented and, hereafter, the analysis will be restricted only to the *confined space* tests. Two different commercial kitchen hoods have been investigated (see table 1).

Table 1 - Hood features.

Hood	Flow rate m^3/h	Canopy size cm	no. of tests
# 1	100-180	50 x 60	27
#2	80-120	52 x 60	27

A parametric analysis was performed, varying the cook top to hood distance (H), the flow rate of the hood (Q), and the fire thermal output. CCE has been evaluated adopting the three procedures described in the previous paragraph. The results of procedures 2 and 3 show a good agreement (differences lower than 3%), while those derived from procedure 1 show a greater spread and differences with the others may reach 12% (figure 3).

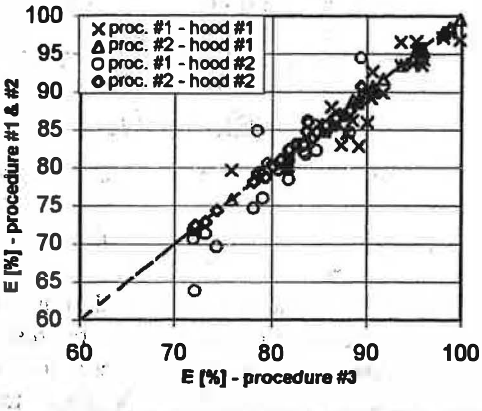


Figure 3 CCE measurements for hood #1 and #2. Comparison between procedures.

The CCE values shown in figures 4 and 5 were obtained using procedure #3. Since the

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[3] Indoor air temperature has though not been controlled during the tests.

fire output did not show a well defined effect[4] on CCE, its influence has been neglected. Each point is then the average of three values, obtained with 800 W, 1200 W and 1800 W fire output. The error analisys, performed by means of procedure described in previous paragraph, has pointed out that for hood #1 the maximum uncertainty (over the 27 tests) is 11 %, with a mean value of 8 %. For hood #2 these values are respectively 13% and 7%.

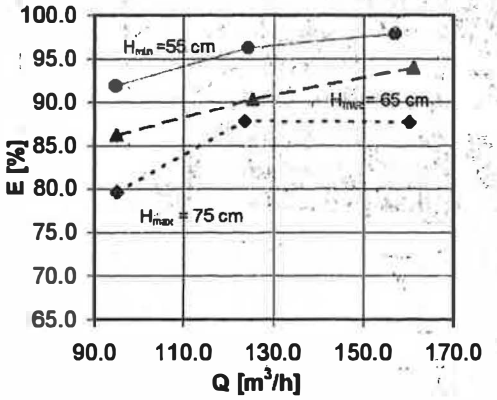

Figure 4 Contaminant removal efficiency for hood #1 as a function of flow rate and cook top-to-hood distance.

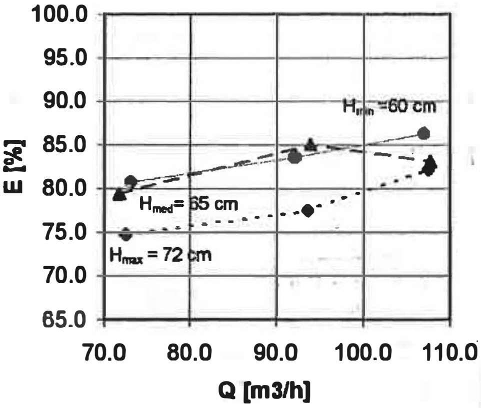

Figure 5 Contaminant removal efficiency for hood #2 as a function of flow rate and cook top-to-hood distance.

In both cases, CCE has a systematic tendency to decrease with distance H (with one exception at mean flow between 60 and 65 cm for hood #2), and to increase with air flow rate Q. This may be considered, *per se*, an evidence of the reliability of the measuring protocol.

The CCE values may be calculated as the ratio between the air flow rate of the hood to the air flow rate induced by the plume, as suggested by Li and Delsante (1997):

$$E = \frac{Q}{Q_p} \tag{15}$$

where Q_p is the flow rate of the plume, in its turn given by (Awbi, 1991):

$$Q_p = 21.96 \cdot S_p^{\frac{1}{3}} \cdot (H+d)^{\frac{5}{3}} \tag{16}$$

with:

S_p = heat source power [W]
d = diameter of the heat source [m]

However, the calculated values appear strongly underestimated respect to measured values, as shown by figure 6.

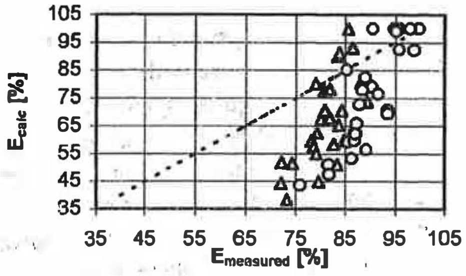

Figure 6 Comparison between measured (proc. #3) and calculated CCE.

FLUODYNAMIC CHARACTERISTICS

Hood #1 has also been characterised in terms of velocity field inside the control volume of the hood. Velocity has been monitored by means of an ultrasonic anemometer (Gill Windmaster: resolution = 1 cm/s, accuracy = ± 1.5%, 3 axes components with 1 or 4 Hz frequency). The measurements have been performed without any fire output over a grid made up of 8 different planes (4 horizontal planes parallel to the hood canopy, 4 vertical planes, 2 lateral, one frontal and the last

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[4] Apparently, the fire power output has an "on-off" influence on CCE, that is, a minimum output is sufficient to enhance the capturing effect of the hood. Efficiency falls dramatically at zero power output.

passing through the hood axis) containing, each, a total of 24 uniformly spaced sampling points.

The matrices of measured values have been processed with MatLab® in order to obtain a finer grid; adopting a biarmonic interpolation. The tests have been developed for three different air flow rates (min, med, max) and for H = 65 cm. An example of the measured data is shown in figure 7.

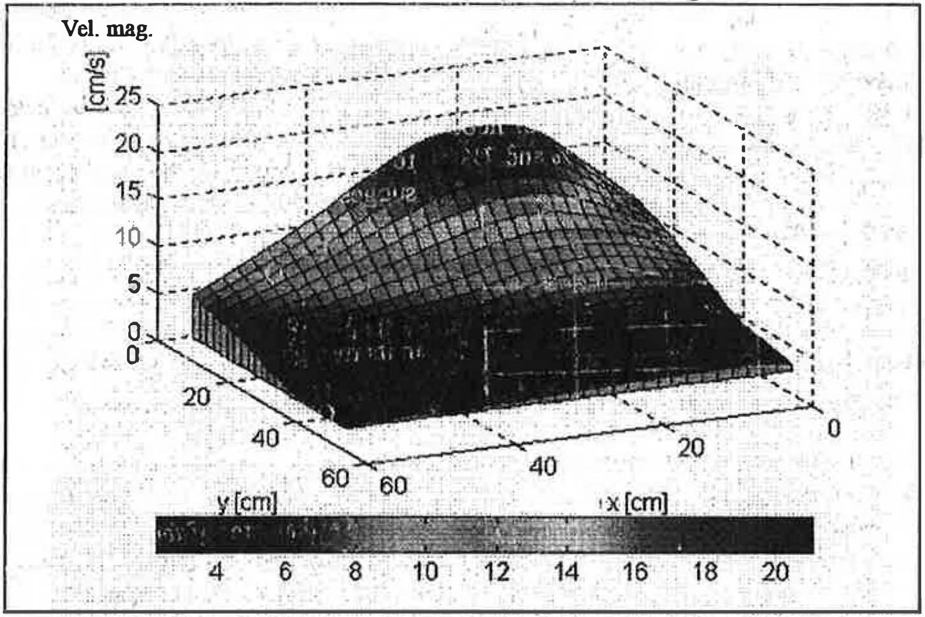

Figure 7 Velocity field on a vertical plane along hood #1 axis.

From the analysis of the complete set of data it has been concluded that:

- the flow field is quite asymmetric,
- there is a qualitative agreement between the shape of measured and theoretical (available for grilles) iso-kinetic lines,
- at distances greater than 0.6-0.7 equivalent diameters from the intake section the air velocity becomes so low that it has the same magnitude of random turbulent fluctuations,
- the structure of the flow field is practically independent of the air flow rate, as it is shown in figure 8.

Finally, a comparison between measured velocity profiles and those predicted using Della Valle (1952) formula and Drkal formula, quoted by Recknagel and Sprenger (1980) along the hood axis has been performed (see figure 9). Della Valle formula seems to approximate more realistically the velocity decay along the hood vertical axis.

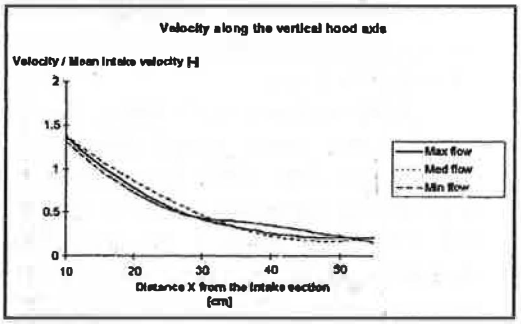

Figure 8 Non-dimensional velocity profiles for different air flow rates.

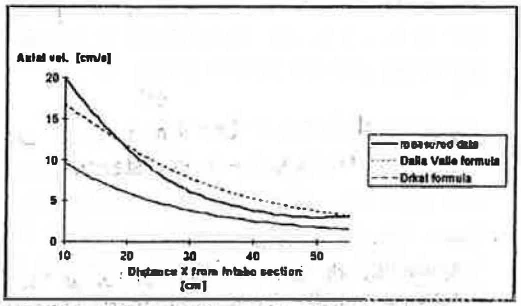

Figure 9 Measured and predicted velocity profiles.

although the measured values decrease more rapidly with the distance from the canopy.

CONCLUSIONS

Two protocols have been proposed in this paper to measure the contaminant capture efficiency of hoods.

The experimental campaigns have shown that tests performed inside a *large enclosure* are poorly repeatable, with the values of CCE largely influenced by boundary conditions. Critical factors are meteorological conditions (wind, high solar radiance), casual disturbances and turbulence, cross drafts. Therefore, even if this method is easy and quick to carry on it should not be recommended to determine CCE.

On the opposite, the *confined space* procedure allows a more reliable and repeatable measure of CCE, but requires a heavier data processing in order to take into account the time variation of background tracer concentration C_b. To this purpose three different methods have been proposed and tested.

#1. steady-state extrapolation
#2. average of instantaneous values
#3. integrated values

All procedures yield comparable results (for the two hoods tested differences are always lower than 12%). In particular, there is a striking agreement between method #2 and #3, while method #1 shows larger deviations, and requires a more complex data post-processing for a reliable forecast of the steady-state exhaust concentrations.

Therefore, the authors have found advisable to use the integral method, which seems to be stable, insensitive to stochastic perturbations and easy to carry on.

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