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A NUMERICAL AND EXPERIMENTAL STUDY OF LOCAL EXHAUST CAPTURE EFFICIENCY

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Abstract—Direct capture efficiency of a local exhaust system is defined by introducing an imaginary control box surrounding the contaminant source and the exhaust opening. The imaginary box makes it possible to distinguish between contaminants directly captured and those that escape. Two methods for estimation of direct capture efficiency are given: (1) a numerical method based on the time-averaged Navier–Stokes equations for turbulent flows; and (2) a field method based on a representative background concentration. Direct capture efficiency is sensitive to the size of the control box, whereas its location is less important for the case studied. The choice of sampling strategy to obtain a representative background concentration is essential as substantial differences on direct capture efficiency are found. Recommendations are given.

NOMENCLATURE

A	area
C_1, C_2, C_μ	constants in turbulence model
D	diffusion conductance
G	turbulence generating source term
P	source term in Equation (4)
S	flow rate of contaminant
U	velocity
c	concentration
k	turbulent kinetic energy
n	normal of the surface
p	pressure
q	flow rate of air
u, v, w	velocity
x, y, z	Cartesian co-ordinates
Greek symbols	
ϕ	variables in Equation (4)
Γ	diffusion coefficient
ε	turbulence dissipation rate
η	capture efficiency
μ, μ_{eff}, μ_t	dynamic viscosity (laminar, effective and turbulent, respectively)
ρ	density
σ	turbulent Prandtl number
τ	local mean age of air
Subscripts	
S	refers to contaminant source
b	background
c	refers to contaminant
ge	refers to general exhaust
in	into the control volume
i, j	vector directions
k	refers to turbulent kinetic energy

le	refers to local exhaust
n	normal of the surface
occ	occupied zone
out	out of the control volume
s	refers to air supply
ϕ	variables in Equation (4)
ε	refers to turbulence dissipation rate

Superscripts

C	convection
D	diffusion
d	direct
tot	total
1, 2, 2a, 2b, 2c, 2d	concepts of the capture efficiency

INTRODUCTION

LOCAL exhaust ventilation is widely used to control contaminants in buildings with localized emissions. A simple exhaust system consists of an exhaust opening connected to a fan by a duct, and is intended to provide an air movement that will carry contaminants from where they are released to the exhaust opening. The capture velocity, defined as the air velocity needed at the point of release to overcome opposing air currents and to capture the contaminants into the hood, is an important parameter in the design of local exhuast opening (ACGIH, 1984).

The usefulness of the capture velocity as an index of contaminant removal performance has been questioned (ELLENBECKER *et al.*, 1983; FLETCHER and JOHNSON, 1986), and JANSSON (1982) and ELLENBECKER *et al.* (1983) suggested the use of a capture efficiency concept instead. The capture efficiency is defined as the ratio between the flow rate of contaminants directly captured and the total flow rate of contaminants released from the source. The capture efficiency of a local exhaust is a useful design parameter in situations where it is functionally related to breathing zone concentrations, but no consistent approach for estimating it seems available.

The aim of this study is three-fold: (a) to introduce a definition of contaminants direct captured by a local exhaust; (b) to develop a method for estimation of direct local exhaust capture efficiency using a numerical model; and (c) to compare the method developed with previously reported methods.

LOCAL EXHAUST CAPTURE EFFICIENCY

Consider a local exhaust opening (flow rate q_{le}) at a source of constant emission rate, S, there, being only one source in the room. At steady state the capture rate of the exhaust is S_{le} and concentration at the exhaust duct is c_{le}. Then the total capture efficiency is

$$\eta_{\mathrm{le}}^{\mathrm{tot}} = \frac{S_{\mathrm{le}}}{S} = \frac{q_{\mathrm{le}} \times c_{\mathrm{le}}}{S}. \qquad (1)$$

As pointed out by Jansson (1982) S_{le} should include only contaminants being direct captured. Let this 'direct' efficiency be denoted $\eta_{\mathrm{le}}^{\mathrm{d}}$. An estimate of $\eta_{\mathrm{le}}^{\mathrm{d}}$ can be obtained from a mass balance of an imaginary control box containing the source and the exhaust opening. By definition pollutants kept within the control box are considered to be captured directly (Fig. 1).

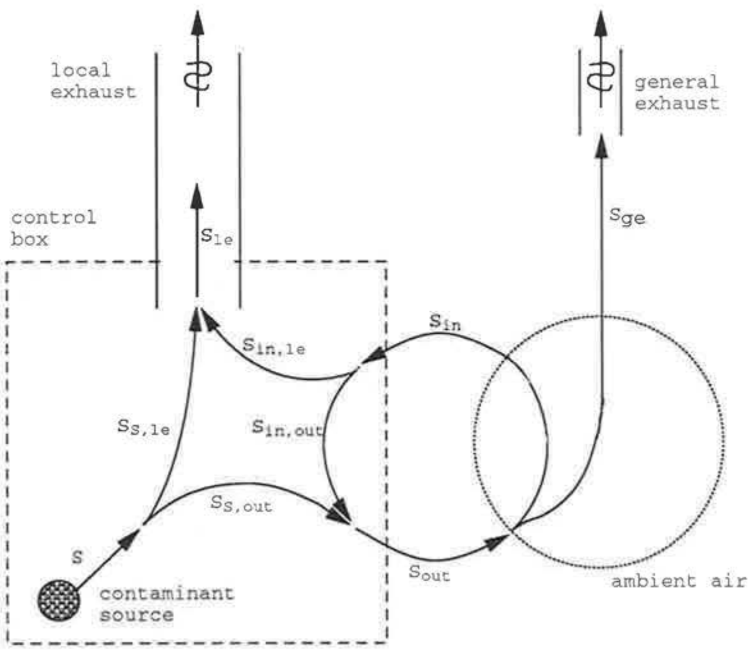

FIG. 1. Control box to distinguish between direct captured and escaped contaminants. The circle to the right represents room air exclusive the control box.

Part of the contaminant generated, S, is captured directly by the local exhaust, $S_{S.le}$, and the remainder, $S_{S.out}$, escapes out of the control box. Of what escapes some may return into the control box, S_{in}, the rest being entrained in the general exhaust, S_{ge}. Part of S_{in} is captured by the local exhaust, $S_{in,le}$, and the rest escapes out of the control box, $S_{in,out}$. With reference to Fig. 1 the following mass balance applies to the control box:

$$S+S_{in}=S_{le}+S_{out}, \tag{2a}$$

where

$$S=S_{S.le}+S_{S.out} \tag{2b}$$

$$S_{in}=S_{in.le}+S_{in.out} \tag{2c}$$

$$S_{le}=S_{in,le}+S_{S.le} \tag{2d}$$

$$S_{out}=S_{ge}+S_{in}=S_{S,out}+S_{in,out}. \tag{2e}$$

By definition the direct capture efficiency, η^{d}_{le}, is derived from

$$\eta^{d}_{le}=\frac{S_{S,le}}{S}=\frac{S_{le}-S_{in,le}}{S}=\eta^{tot}_{le}-\frac{S_{in,le}}{S}. \tag{3}$$

The emission rate S is assumed known, and S_{le} is obtained from exhaust duct data. Consistent estimates of $S_{in.le}$ and $S_{S.le}$ require detailed recording of trajectories of all fluid elements of contaminants.

In this study two experimental methods for estimation of η^{d}_{le} are given: a numerical method and a field method. As can be seen from Equation (3) and Fig. 1 an estimate of η^{d}_{le} depends on size of the box, but no data on this relationship seem to be available in the literature. As Fig. 1 shows, η^{d}_{le} also depends on the position of the box relative to the contaminant source and the local exhaust opening. In this study capture efficiency is estimated for a selected range of box sizes and positions.

EXPERIMENTAL TECHNIQUES

Test case

The configuration and dimensions of the test chamber are shown in Fig. 2. For all tests air flowed in to the chamber at $q_s = 427$ m^3 h^{-1}, and flows out at $q_{ge} = 327$ m^3 h^{-1} at the general exhaust and at $q_{le} = 0.3 \times q_{ge} = 100$ m^3 h^{-1} at the local exhaust.

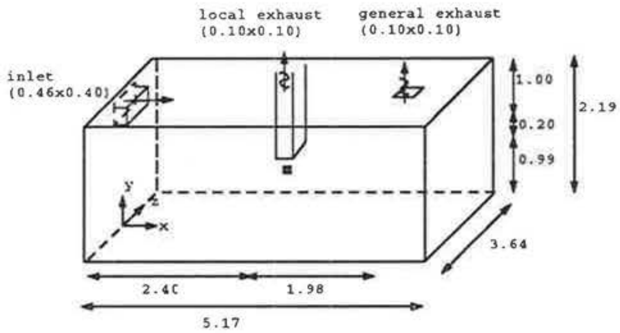

FIG. 2. Configuration of the test chamber. Lengths in metres.

The contaminant was slowly released on the centre line of the local exhaust. For such a configuration ACGIH (1984) recommends a capture velocity of 0.25–0.50 m s^{-1}. If the capture velocity is $v = q_{le}/(10\ d^2 + A_{le})$, where A_{le} is the hood area, this is equivalent to a distance, d, not greater than 0.1 m between the exhaust opening and the source. However, in this study the distance between them was extended to $d = 0.20$ m (0.99 m above the floor).

Numerical method

The TEACH-code is used for the three-dimensional calculation of isothermal, turbulent and stationary flow using the standard two-equation k–ε turbulence model (LAUNDER and SPALDING, 1974). The model was originally developed for describing the flow patterns of air at room level, and later it was extended to include the performance of a local exhaust opening. The concentration field of a contaminant is obtained by treating the contaminant as a scalar quantity which does not affect the air velocity field.

By expressing them in finite difference form the TEACH code solves equations of the following type:

$$\mathrm{div}(\rho U \phi) = \mathrm{div}(\Gamma_\phi\ \mathrm{grad}\ \phi) + \mathrm{P}_\phi. \tag{4}$$

In this study the dependent variables ϕ in Equation (4) take the forms of air velocity (u, v, w), turbulent kinetic energy (k), turbulent energy dissipation rate (ε), continuity (1), concentration (c) and local mean age of air (τ), respectively. The corresponding diffusion coefficients (Γ_ϕ) and source terms (P_ϕ) are listed in Table 1, which also

TABLE 1. TERMS OF THE TURBULENCE MODEL*

Equation	Variable ϕ	Diffusion coefficient Γ_ϕ	Source term P_ϕ
Continuity	1	0	0
u-momentum	u	μ_{eff}	$\frac{-\partial p}{\partial x}$
v-momentum	v	μ_{eff}	$\frac{-\partial p}{\partial y}$
w-momentum	w	μ_{eff}	$\frac{-\partial p}{\partial z}$
Turbulent kinetic energy	k	$\frac{\mu_{eff}}{\sigma_k}$	$G-\rho\varepsilon$
Turbulence dissipation rate	ε	$\frac{\mu_{eff}}{\sigma_\varepsilon}$	$\frac{\varepsilon}{k}(C_1G-C_2\rho\varepsilon)$
Concentration	c	$\frac{\mu_{eff}}{\sigma_c}$	P_c
Local mean age of air	τ	$\frac{\mu_{eff}}{\sigma_c}$	1

$$G=\mu_{eff}\frac{\partial U_i}{\partial x_j}\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right);\quad \mu_{eff}=\mu+\mu_t;\quad \mu_t=C_\mu\rho k^2/\varepsilon$$

P_c = production rate at source points, elsewhere $P_c=0$

Constants in the turbulence model

$C_1=1.44$ $C_2=1.92$	$C_\mu=0.09$	$\sigma_k=1.0$ $\sigma_\varepsilon=1.22$	$\sigma_c=0.9$

*The symbols are defined in the Nomenclature.

includes the constants of the turbulence model. ρ is the density of air and U is the air velocity. The age of a fluid element of air is defined as the time that has passed since it entered the room. The local mean age of air is the mean of the ages of all fluid elements within a small volume centered at that point and can be obtained by integrating the time-dependent form of Equation (4) with $\phi=c$ and $P_\phi=0$ from time $t=0$ to $t=\infty$ (SANDBERG and SJÖBERG, 1983). This gives a numerical method for computing the local mean age of air from a steady-state concentration distribution with contaminant sources uniformly distributed in the calculation domain. The model is applied to an actual test room with a local exhaust system (Fig. 2): the boundary conditions of the model are summarized in Table 2. The wall-function introduced by LAUNDER and SPALDING (1974) is used at the walls as well as at the local exhaust duct.

The numerical model cannot distinguish directly captured contaminants $S_{S,le}$ from the total amount of captured contaminants S_{le}, nor $S_{in,le}$ from S_{in}. Therefore, as an approximative solution the pollutant flow, S_{in}, into the imaginary control box is substituted for $S_{in,le}$. The flow S_{in} is computed as the sum of convective flow S_{in}^{C} and diffusive flow S_{in}^{D}, the latter including turbulent as well as laminar diffusion. Consider a

TABLE 2. BOUNDARY CONDITIONS FOR THE NUMERICAL MODEL*

	Walls including duct walls	Inlet	Local exhaust (opening)	General exhaust
Velocity	†	$u=u_s$ $v=w=0.0$	$v=v_{le}$ $u=w=0.0$	$v=v_{ge}$ $u=w=0.0$
Turbulence	†	$k=(1.0\,u_s)^2$ $\varepsilon=\rho C_\mu k^2/(20\mu)$	$\frac{\partial k}{\partial y}=\frac{\partial \varepsilon}{\partial y}=0.0$	$\frac{\partial k}{\partial y}=\frac{\partial \varepsilon}{\partial y}=0.0$
Concentration	$\frac{\partial c}{\partial \mathrm{n}}=0.0$	$c=0.0$	$\frac{\partial c}{\partial y}=0.0$	$\frac{\partial c}{\partial y}=0.0$
Local mean age of air	$\frac{\partial \tau}{\partial \mathrm{n}}=0.0$	$\tau=0.0$	$\frac{\partial \tau}{\partial y}=0.0$	$\frac{\partial \tau}{\partial y}=0.0$

*The symbols are defined in the Nomenclature.
†Wall function as given by LAUNDER and SPALDING (1974).

surface element of area $\mathrm{d}A$. The mean air velocity at the normal of an element is v_n, contaminant concentration is c and gradient of contaminant concentration is $\partial c/\partial \mathrm{n}$. Let D denote the diffusion conductance. The contaminant flow into the control box is computed as

$$S_{\mathrm{in}}=S^{\mathrm{C}}_{\mathrm{in}}+S^{\mathrm{D}}_{\mathrm{in}}=\sum\left(\rho_c v_n c+D\frac{\partial c}{\partial \mathrm{n}}\right)\mathrm{d}A, \tag{5}$$

where $v_n=|v_n|$ for air velocity into the box, and $v_n=0$ for air velocity out of the box $\partial c/\partial \mathrm{n}=|\partial c/\partial \mathrm{n}|$ for diffusion into the box, and $\partial c/\partial \mathrm{n}=0$ for diffusion out of the box $\rho_c=$density of contaminant.

Note that in Equation (5) the summation is taken over the total surface of the control box. Let capture efficiency derived from S_{in} be denoted η^1_{le}. From Equations (2c) and (3) it follows that the following relation applies

$$\eta^1_{\mathrm{le}}=\frac{S_{\mathrm{le}}-S_{\mathrm{in}}}{S}=\frac{S_{\mathrm{le}}-(S_{\mathrm{in,le}}+S_{\mathrm{in,out}})}{S}=\eta^{\mathrm{d}}_{\mathrm{le}}-\frac{S_{\mathrm{in,out}}}{S}. \tag{6}$$

In this study η^1_{le} is calculated for the set of box sizes and locations listed in Table 3.

Techniques for validation

Validation is performed in a laboratory using a test chamber with the configuration shown in Fig. 2. The performance of the numerical model is validated in terms of air velocity and the local mean age of air. For validation of air velocity, the local exhaust is at ceiling level. Data on air velocity are obtained using calibrated omni-directional probes with characteristics meeting an accepted standard (ISO, 1982). The local mean age of air is obtained using a step-up stimulus–response tracer gas technique. A mixture of air and tracer gas (SF_6) at a concentration of 500 ppm simulates contaminant delivered with the air supply at constant flow rate. Tracer gas concentrations against time are obtained using a sensitive, rapid response measuring system (BREUM and SKOTTE, 1991).

TABLE 3. BOX SIZES AND LOCATIONS FOR COMPUTATION OF CAPTURE EFFICIENCY. ORIGIN AND ORIENTATION OF THE CO-ORDINATES ARE GIVEN ON FIG. 2

Control box Position	No.	Co-ordinates (m) x_1	x_2	y_1	y_2	z_1	z_2	Volume (10^{-3} m^3)
A	1	2.25	2.45	0.75	1.22	−0.19	0.19	35.7
	2	—	2.47	—	—	—	—	39.3
	3	—	2.50	—	—	—	—	44.7
	4	—	2.55	—	—	—	—	53.6
	5	—	2.65	—	—	—	—	71.4
	6	—	2.85	—	—	—	—	107
	7	—	3.10	—	—	—	—	152
	8	—	3.45	—	—	—	—	214
B	9	2.35	2.55	0.75	1.22	−0.19	0.19	35.7
	10	2.33	—	—	—	—	—	39.3
	11	2.30	—	—	—	—	—	44.7
	12	2.15	—	—	—	—	—	71.4
	13	1.95	—	—	—	—	—	107
	14	1.55	—	—	—	—	—	179
C	15	2.35	2.45	0.90	1.22	−0.05	0.05	3.2

Field method

From an experimental point of view the approach of Equation (3) is far from obvious. However, for field applications $S_{\text{in,le}}$ can be obtained from knowledge of airflow patterns and concentrations of air contaminants at surfaces of the control box. Only part of the air entering the control box leaves the box by the local exhaust. As an analogy to $S_{\text{in,le}}$ (see Fig. 1) this flow rate of air is denoted $q_{\text{in,le}}$. Let $\langle c_b \rangle$ be the average contaminant concentration (background) of $q_{\text{in,le}}$. As exhausted air has to cross the surface of the control box, $q_{\text{in,le}}$ equals q_{le}. $S_{\text{in,le}}$ is then given as $<c_b> \times q_{\text{le}}$. Let the derived direct capture efficiency be denoted η^2_{le}:

$$\eta^2_{\text{le}} = \frac{(c_{\text{le}} - \langle c_b \rangle) \times q_{\text{le}}}{S}. \tag{7}$$

In general no information on the distribution of $q_{\text{in,le}}$ or on the background concentration, c_b, over the surfaces of the control box is available, and a strategy is needed to find representative locations for measuring concentrations for the estimation of $\langle c_b \rangle$. In this study four alternative strategies to obtain $\langle c_b \rangle$ are applied:

(a) sampling in the general exhaust duct (c_{ge}), η^{2a}_{le}
(b) sampling in the occupied zone (c_{occ}), η^{2b}_{le}
(c) sampling at the centres of control box surfaces, η^{2c}_{le}
(d) sampling at the control box surfaces (area weighted mean value), η^{2d}_{le}.

The basic ideas of the strategies are summarized below:

(a) the contaminant concentration in the general exhaust is used as an estimate of the background concentration, assuming the escaped contaminants being fully mixed with room air;
(b) the sampling is conducted at different distances from the contaminant source in the central plane of the room, 0.99 m above floor level. Note that the contaminant source is also located 0.99 m above the floor;
(c) the mean of contaminant concentrations at the six centre points of the surfaces

of the control box is used for $\langle c_b \rangle$, assuming that $q_{in,le}$ is equally distributed over these surfaces, and that the concentration at the centre of a surface is representative of that surface;

(d) an area-weighted mean of contaminant concentration at the surfaces of the control box is used for $\langle c_b \rangle$, assuming that $q_{in,le}$ is equally distributed over the surface of the control box.

For comparison η_{le}^{2c} and η_{le}^{2d} are calculated for the same set of box sizes and locations of the control box as for η_{le}^{1} (see Table 3). In field studies concentrations of true contaminants are measured, but in this study contaminant concentrations are computed by the numerical model.

RESULTS

The numerical model is validated in terms of air velocity field and local mean age of air. Profiles of data obtained are given in Fig. 3 (air velocity) and Fig. 4 (local mean age of air). For clarification only results from the central plane are shown but similar results are obtained in other selected planes of the room (Madsen, in preparation).

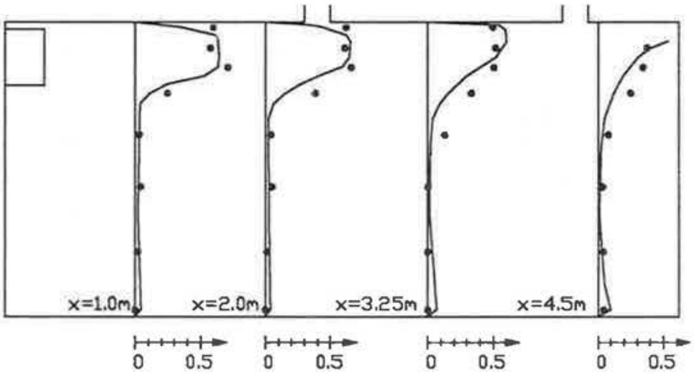

FIG. 3. Results from validation of the velocity field. For practical reasons high air velocities (>0.7 m s^{-1}) at the general exhaust opening ($x=4.5$ m) are excluded from the figure.

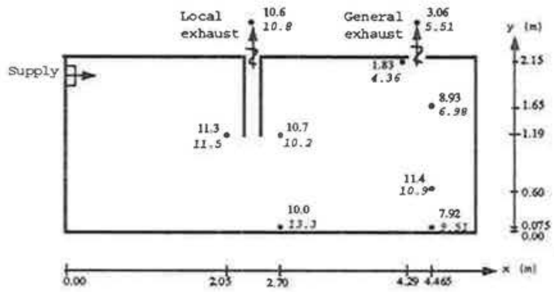

FIG. 4. Results (given in minutes) from validation of the local mean age distribution. Numerical values are bold and experimental values are in italics.

The calculated local exhaust capture efficiencies, η^1_{le}, η^{2c}_{le} and η^{2d}_{le} in relation to size and location of the control box are given in Fig. 5. Although without any physical reality for box No. C15 (Table 3) η^1_{le} comes out to be negative (-8.8%): this finding is considered further in the discussion. η^{2b}_{le} is computed for a range of sampling locations in the occupied zone, at the centre line 0.99 m above floor level. The results are shown in Fig. 6.

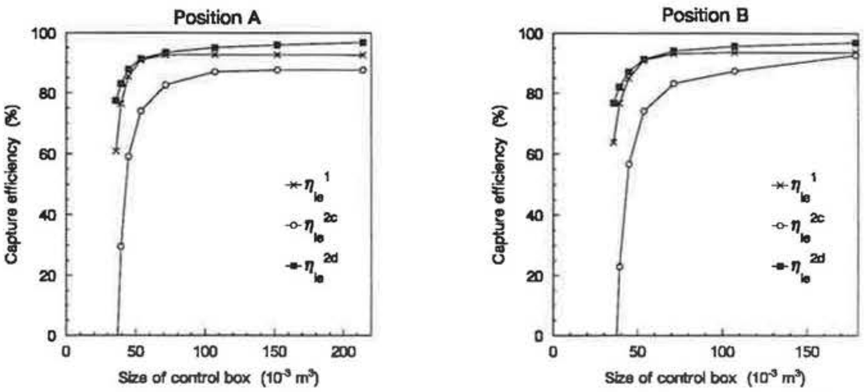

FIG. 5. Relationship between size and location of the control box and the captue efficiencies, η^1_{le}, η^{2c}_{le} and η^{2d}_{le}. A and B are the test series given in Table 3.

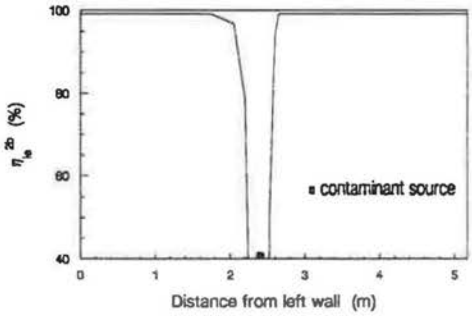

FIG. 6. η^{2b}_{le} as a function of distance from the contaminant source.

TABLE 4. ESTIMATED LOCAL EXHAUST CAPTURE EFFICIENCIES FOR CONTROL BOX NO. B12

Sampling strategy	η^{tot}_{le}	η^1_{le} Numerical	η^{2a}_{le} General exhaust	η^{2b}_{le} Occupied zone	η^{2c}_{le} Centre points	η^{2d}_{le} Area weighted mean
$\langle c_b \rangle$*	0	—	0.001	0.004†	0.16	0.05
η_{le}	99.6	93.2	99.5	99.2	83.2	94.1

*Concentrations nomalized with a reference to local exhaust air concentration.
†$x = 4.0$ m is used as sampling location in the far field.

For a fixed size and location of the control box the estimated local exhaust capture efficiencies, η_{le}^{tot}, η_{le}^{1}, η_{le}^{2a}, η_{le}^{2b}, η_{le}^{2c} and η_{le}^{2d} are given in Table 4. Box No. B12 (see Table 3), with the dimensions $0.40 \times 0.47 \times 0.38$ m is chosen for this comparison. The computed background concentrations are included in the table.

DISCUSSION

From Figs 3 and 4, a fair agreement between measured and calculated air velocity and local mean age of air has been obtained. The agreement is at a level reported in previous studies (MURAKAMI *et al.*, 1992; DAVIDSON and OLSSON, 1987). The disagreement at floor level is caused by imperfect isothermal conditions. In this study the floor is slightly colder (by about 0.7°C) than room air temperature. As computation of the concentration field from a contaminant source is similar to computation of the local mean age distribution a validation of both is not necessary (SANDBERG and SJÖBERG, 1983). Experiments with local mean age are relatively easy to perform and this approach is used in the study.

The potential flow theory is widely used to predict the velocity field in front of a local exhaust hood, but turbulence and general room air movements are not accounted for. This is a shortcoming of the theory when computing dispersion of contaminants and local exhaust capture efficiency (ALENIUS and JANSSON, 1989). FLYNN and ELLENBECKER (1986) introduced a spread parameter for the distribution of contaminants about streamlines, and an empirically corrected distance to the dividing streamline. Empirical formulae are given by CONROY and ELLENBECKER (1989), but no detailed information is given about the dependence on turbulence intensity.

The numerical model used in this study computes the air velocity field and contaminant concentration from the time-averaged Navier–Stokes equations including a turbulence model. The model includes a method to compute direct capture efficiency, η_{le}^{1}, for a local exhaust system based on the concept of an imaginary control box. In Fig. 5, η_{le}^{1} is given as a function of box size for two different positions of the control box. η_{le}^{1} is in general positively correlated to box size. As $S_{S.le}$ increases with increasing box size [Fig. 1 and Equation (3)] the true direct capture efficiency, η_{le}^{d}, is expected to be positively correlated to box size. However, for large boxes (>0.15 m^3) η_{le}^{1} is negatively correlated to box size. As the size of the control box diminishes, η_{le}^{1} becomes rather sensitive to box size and can even become negative (Table 3, box No. C15). The negative correlation to box size and negative values for small boxes indicate the shortcomings in approximating the polutant flux $S_{in.le}$ by S_{in}. An improved numerical model computing the trajectories of genrated contaminant fluid elements is needed. It is noted that η_{le}^{1} is an underestimate of η_{le}^{d} [Equation (6)].

For field studies, it is common practice (ELLENBECHER *et al.*, 1983) to use total capture efficiency (η_{le}^{tot}) as an index of contaminant removal performance of a local exhaust system. The concept allows a straightforward testing of exhaust systems and gives a rough indication of sensitivity to cross flows for example (FLETCHER and JOHNSON, 1986). It is noted that η_{le}^{tot} is an overestimate of direct capture efficiency [Equation (3)]. TAPOLA and KULMALA (1986) and FARNSWORTH *et al.* (1989) estimated capture efficiency from data obtained by sampling from locations in a grid (η_{le}^{2}). However, no sampling strategy is descibed. NIELSEN *et al.* (1991) used contaminant concentration in the general exhaust duct c_{ge} as background concentration. In this study four different sampling strategies to obtain a useful background concentration $\langle c_b \rangle$ are applied: sampling in the general exhaust (η_{le}^{2a}), sampling in the occupied zone (η_{le}^{2b}), sampling at centres of control box surfaces (η_{le}^{2c}), and sampling at control box surfaces (area weighted mean) (η_{le}^{2d}). For comparison total capture efficiency is computed as well.

In Fig. 6, η_{le}^{2b} is given for sampling points in the occupied zone at different distances from the contaminant source. The curve is steep for sampling points near the source (± 0.5 m) because of steep gradients in the concentration field. It is noted that the curve is not symmetrical about the source, which indicates a cross flow from the right to the left. In the far field, the concentration field and η_{le}^{2b} are relatively uniform.

In Fig. 5, η_{le}^{2c} and η_{le}^{2d} are given as functions of control box size. The two sets of curves for position A and B are rather similar, indicating a tendency towards a symmetrical contaminant distribution about the source point. However, the curves differ for large box sizes due to a weak cross flow. For all control boxes investigated η_{le}^{2d} is greater than η_{le}^{2c}. The contaminant source is located approximately at the centre of the box. Therefore contaminant concentrations at the centre points are elevated as compared to a surface area weighted mean concentration. With small boxes η_{le}^{2c} can become negative (Fig. 5), indicating that the concentration in the local exhaust duct is lower than at the centre points of the control box.

As mentioned above, η_{le}^{1} underestimates the true capture efficiency, η_{le}^{d}, and the total capture efficiency, η_{le}^{tot} is an overestimation of η_{le}^{d}. As the distributions of $q_{in,le}$ and c_b over the surfaces of the control box are unknown, η_{le}^{2c} and η_{le}^{2d} can be either greater or less than the true capture efficiency, η_{le}^{d}. The relationship between capture efficiency, η_{le}^{d}, and size of the control box for a given position of the box will be a positively correlated curve above η_{le}^{1} and below η_{le}^{tot}, starting at zero and ending at η_{le}^{tot}.

In Table 4 the methods developed for estimating local exhaust capture efficiency are compared for control box No. B12 (Table 3). It is noted that η_{le}^{tot}, η_{le}^{2a} and η_{le}^{2b} do not depend on the selected control box, as the concentration field is not influenced by the control box. A high total capture efficiency, η_{le}^{tot} is achieved, 99.6%. However, as can be seen from the alternative efficiency concepts, part of the captured contaminants is not directly captured.

In this study the general exhaust is located at the wall jet of supplied air, which implies some short-circuiting of supply air. As expected, contaminant concentration in the general exhaust duct, c_{ge}, is lower than room mean contaminant concentration. Using c_{ge} as an estimate of background concentration the capture efficiency η_{le}^{2a} is 99.5%. When using as background concentration a contaminant concentration in the occupied zone far from the contaminant source capture efficiency η_{le}^{2b} becomes 99.2%, which still is very high. Sampling at surfaces of the control box gives remarkable lower direct capture efficiencies owing to increased concentrations near the contaminant source.

No method to obtain a consistent estimate of direct capture efficiency is achieved in this study. However, sampling in a fine grid, η_{le}^{2d} has the same characteristics as the true capture efficiency, η_{le}^{d}. η_{le}^{2d} is positive correlated to box size and approaches η_{le}^{tot} for large box sizes. To obtain a true estimate of direct capture efficiency, $\langle c_b \rangle$ should be the average contaminant concentration of $q_{in,le}$. MADSEN *et al.* (1993) suggested a method to obtain the distribution of $q_{in,le}$ over the surfaces of the control box by a smoke test but the method is not fully developed. It is emphasized that the results of the present study are obtained for a single contaminant source in a room. The results may not be valid for a situation of several sources operating simultaneously in a room.

The approach for estimation of local exhaust capture efficiency depends on the purpose of the study. For intervention studies, total capture efficiency, η_{le}^{tot} provides an index of improvement. Sampling in a grid is aplicable for standardized testing of exhaust systems. To improve the estimate of direct capture efficiency, η_{le}^{d}, sampling in a fine grid obtained numerically or experimentally is necessary. Methods available at the design stage of local exhaust systems include numerical computation, full-scale testing in the laboratory, knowledge obtained from similar systems and recommendations based on capture velocity.

CONCLUSION

A fair agreement between measured and calculated air velocity and local mean age of air has been obtained by the numerical model used in this study.

The introduction of an imaginary control box to distinguish between direct captured and escaped contaminants allows a consistent definition of direct capture efficiency for a local exhaust system. Methods need to be improved to obtain an estimate of direct capture efficiency. However, sampling in a fine grid (η_{le}^{2d}) has characteristics similar to the true capture efficiency.

Direct capture efficiency depends greatly on size of the control box, whereas the position of the box turned out to be less important for the case studied. The sampling strategy to obtain a representative background concentration is essential.

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