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Publication date:
1994

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Madsen, U., Aubertin, G., Breum, N. O., Fontaine, J. R., & Nielsen, P. V. (1994). *Tracer Gas Technique Versus a Control Box Method for Estimating Direct Capture Efficiency of Exhaust Systems*. Dept. of Building Technology and Structural Engineering. Indoor Environmental Technology Vol. R9457 No. 47

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INDOOR ENVIRONMENTAL TECHNOLOGY
PAPER NO. 47

Presented at Ventilation '94, the 4th International Conference on Ventilation for Contaminant Control, Stockholm, Sweden, September 1994

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Tracer gas technique versus a control box method for estimating direct capture efficiency of exhaust systems

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Summary
Numerical modelling of direct capture efficiency of a local exhaust is used to compare the tracer gas technique of a proposed CEN standard against a more consistent approach based on an imaginary control box. It is concluded that the tracer gas technique is useful for field applications.

Introduction
For situations with localized contaminant emission, local exhaust ventilation is a widespread solution to contaminant control. Local exhaust capture efficiency has proven to be a useful index of contaminant removal performance of such systems (1). By definition total capture efficiency (η^{tot}) is given as contaminant capture rate at the exhaust in proportion to output rate at the source. To become an even more useful index Jansson (2) pointed out that a capture efficiency should include only contaminants being directly captured. However, for application of such a direct capture efficiency (η^{d}) a quantification of the term "directly" is needed. Madsen et al. (3) suggested to use an imaginary control box to distinguish between directly captured and escaped contaminants. Such an approach proved to be useful in numerical calculations (4) but for field applications other techniques are needed. CEN (Comité Européen de Normalisation) is preparing a European standard for safety of machinery and a working group has prepared a draft proposal for measuring the capture efficiency of an exhaust system (5). The purpose of the present study is to compare capture efficiency (η^{CEN}) obtained by the proposed CEN-method against η^{d} as derived from numerical computations. The models used are summarized first.

Local exhaust capture efficiency
Consider a local exhaust opening 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}. Then the total capture efficiency is

$$\eta^{tot} = \frac{S_{le}}{S} \qquad (1)$$

As pointed out by Jansson (2) S_{le} should include only contaminants being directly captured. Let this direct capture efficiency be denoted η^{d}. Madsen et al. (3) estimated η^{d} from a mass balance of an imaginary control box containing the source and the exhaust opening (Fig. 1). By definition contaminants kept within the control

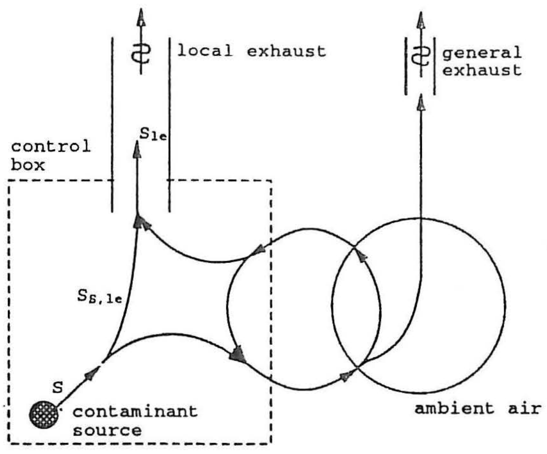

Figure 1. Control box to distinguish between direct captured and escaped contaminants. The circle to the right represents room air exclusive the control box.

box are considered to be captured directly and the rate is denoted $S_{S,le}$. Then direct capture efficiency is defined as

$$\eta^d = \frac{S_{S,le}}{S} \quad (2)$$

Emission rate S is considered to be known, but a consistent estimate of $S_{S,le}$ requires detailed recording of trajectories of all fluid elements of contaminant.

Numerical method

Trajectories of fluid elements of contaminant can be obtained by a numerical method, treating the particles individually through solving the particle motion equation. The model is described in detail by Lu et al. (6) and will only briefly be presented here.

The motion of a spherical and rigid particle in a turbulent fluid flow is governed by the following simplified equation, where inertia equals drag and gravity forces:

$$\rho_p \frac{dV}{dt} = -\frac{3}{4 d_p} \rho_f C_D (V-U) |V-U| + (\rho_p - \rho_f) g \quad (3)$$

where V and U are instantaneous particle and fluid velocity vector, respectively; ρ_p and ρ_f are particle and fluid density, respectively; d_p is particle diameter; g is acceleration vector due to gravity and C_D is the drag coefficient.

It is assumed that the particle mass-loading is low so that the presence of particles does not modify the fluid motion, nor is interaction between particles taken into account. The particle trajectories are obtained by solving Eq. 3 for successively small time steps Δt (0.005 s), assuming U constant within each time step. Direct capture efficiency, η^d, of the local exhaust is computed by following each particle trajectory and reckon if the particle escapes the control box, averaging over a large number of particles, in this study 5000. The particles deposit when they reach a surface. To simulate gaseous contaminants 1 µm particles of unit density are chosen.

To solve Eq. 3 the instantaneous velocity of the fluid is required at location of the particle. The mean velocity is computed by the CFD-code EOL (7) under isothermal and steady conditions, using the two-equation k-ε turbulence model and the wall functions introduced by Launder and Spalding (8). The fluctuating velocity of the fluid is modelled from a random process and knowledge of the turbulent kinetic energy.

CEN-method

The proposed method for the measurement of capture efficiency of an exhaust system is as follows (5):

A tracer of similar aerodynamic behaviour as the real contaminant is selected. The tracer is emitted at a constant rate S into the exhaust duct. S is then given as the exhausted air flow rate q_{le} times the concentration of the tracer C_2 in the duct. The rate of directly captured tracer is obtained by emitting, from time t=0, the tracer at rate S at a characteristic emission point of the real pollutant. The tracer concentration, C_3, versus time is measured at the exhaust duct. C_3 rises progressively as a function of time and shows roughly two time constants:

- the first is relatively small and corresponds to the accumulation of tracer in the volume directly under the influence of the exhaust system;
- the second corresponds to the accumulation of tracer in the rest of the room. A part of the tracer, escaping from the zone of direct influence of the exhaust system, is secondarily and indirectly collected over a longer period of time.

The efficiency is now defined on the basis of C_3 recorded within a period following the first time constant but before the second time constant influences C_3. In practice, the time constant of the room is much larger than the time constant of the local exhaust system and the measurement may be facilitated by averaging C_3 over a time interval of a few minutes when arriving at the first quasi equilibrium state.

Assuming a constant exhaust air flow rate capture efficiency is

$$\eta^{CEN} = \frac{C_3 - C_1'}{C_2 - C_1} \qquad (4)$$

where C_1 and C_1' are the ambient concentration of the tracer measured in the exhaust duct before the tracer emission and when the background level is stabilized after the tracer emission, respectively. It is noted that C_1' decreases with time. As there are no other sources in the room, C_1 and C_1' equal zero for this study.

η^{CEN} can be obtained from the numerical model, computing the age of the captured particles. $C_3 \times q_{le}$ can be interpreted as the number of captured particles of age less than the time t corresponding to the end of the first quasi equilibrium state. $C_2 \times q_{le}$ is the number of emitted particles.

Test cases

The configuration of the room under testing is shown in Fig. 2. The air supply rate is 427 m^3/h for all tests (air exchange rate of 10 h^{-1}). The exhausted flow rates are 327 m^3/h at the general exhaust and 100 m^3/h at the local exhaust. The contaminant is released in the center line of the local exhaust, 0.20 and 0.30 m below the exhaust opening, respectively. The two source positions, in the following denoted Position 20 and Position 30, are chosen as being representative for a high and a fair capture efficiency, respectively.

Direct capture efficiency, η^d, depends on size and location of the imaginary control box in relation to the contaminant source and the exhaust opening (3). In this study η^d is calculated for nine centered and roughly cubic control boxes of which three examples are listed in Table 1. Capture efficiency, η^{CEN}, depends on the time t selected to conclude the first quasi equilibrium state. η^{CEN} is calculated versus t.

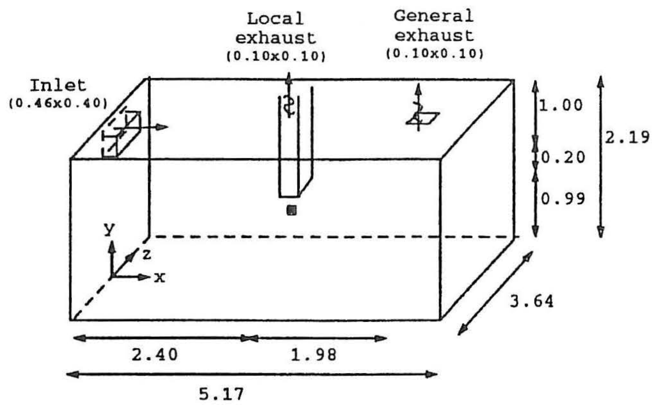

Figure 2. Configuration of the test chamber. Dimensions are given in meter.

Table 1. Examples of selected imaginary control boxes for computation of direct capture efficiency, η^d. Origin and orientation of the coordinates are given in Fig. 2.

Box	Coordinates (m)						box volume	$\sqrt[3]{volume}$
No.	x1	x2	y1	y2	z1	z2	(m^3)	(m)
1	2.35	2.45	0.85	1.22	-0.05	0.05	0.0037	0.155
4	2.20	2.60	0.70	1.35	-0.20	0.20	0.104	0.470
8	1.40	3.40	0.00	2.00	-1.00	1.00	8.00	2.00

Results

The calculated direct capture efficiency, η^d, versus size of the imaginary control box is given in Fig. 3 for the two positions of the contaminant source. The calculated capture efficiency, η^{CEN}, versus time t is given in Fig. 4. Total capture efficiency, η^{tot}, is included in the figures and is 92.7 % for source Position 20 and 73.7 % for Position 30. The relation between size of the control box and time t, giving identical capture efficiencies, η^d and η^{CEN}, is shown in Fig. 5.

Control box No. 8 and a value of t=70 sec give identical capture efficiencies (91.6 % for Position 20 and 67.9 % for Position 30). The ratios of emitted particles fulfilling both criteria of being directly captured are 91.5 % (Position 20) and 67.9 % (Position 30) for this particular control box and time t, respectively.

Discussion

It appears from Fig. 3 that direct capture efficiency, η^d, increases with increasing size of the imaginary control box. η^d approaches total capture efficiency, η^{tot}, for large control boxes. For practical applications, the control box is chosen to include areas where contaminants are acceptable. From Fig. 4 it appears that η^{CEN} increases with increasing choice of the time t and that η^{CEN} approaches η^{tot} for large values of t. For small control boxes as well as for small values of t, the

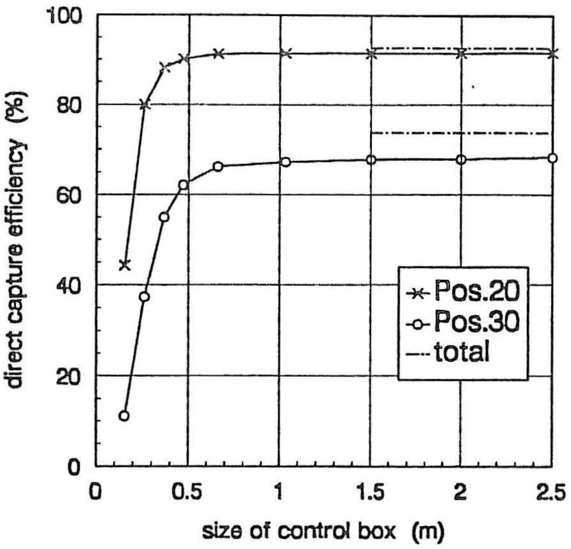

Figure 3. Direct capture efficiency η^d versus size of the imaginary control box.

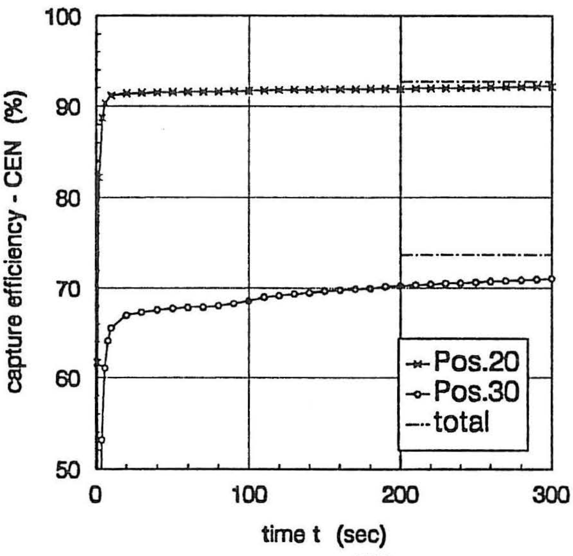

Figure 4. Capture efficiency η^{CEN} versus time t.

capture efficiencies η^d and η^{CEN} approach zero. No data on direct capture efficiency seem available from the literature for comparison.

The curve for Position 30 in Fig. 4 shows two time constants as assumed in (5). Position 20 shows the same behaviour if a more detailed scale is used. The first quasi equilibrium state during which η^{CEN} is to be "measured", is obtained after 30 sec and lasts only 40 sec. η^{CEN} is 91.6 % and 67.9 % for the source Positions 20 and 30, respectively. It is noted that in field applications the fluctuating behaviour of C_3 does blur the conclusion of the first quasi equilibrium state.

Figure 5 allows a comparison of the two capture efficiencies, η^d and η^{CEN}. For the two positions of the contaminant source, Fig. 5 shows paired data of time and box size giving identical capture efficiency. The relation is nearly linear. Note that η^{CEN} for t=70 sec corresponds to a cubic box of side length 2.0 m! This box is nearly identical to the volume directly under the influence of the local exhaust as almost all particles captured within 70 sec also are kept within this box.

The difference between the two definitions of local exhaust capture efficiency is that for η^d only contaminants kept within a defined volume is considered directly captured. For η^{CEN} only contaminants captured within a defined time is considered directly captured. η^d is flexible in its definition as areas where contaminants are acceptable can be included in the box. Using the CEN-method

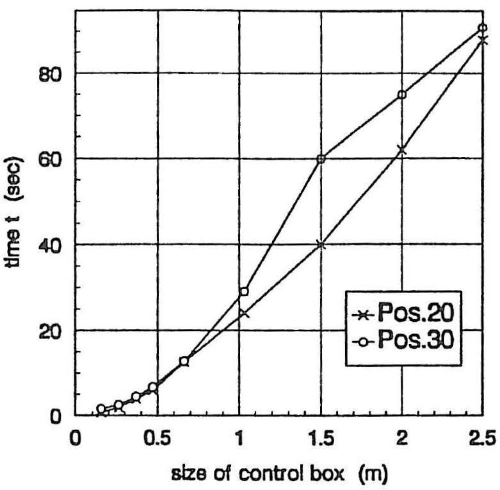

Figure 5. Relationship between size of the imaginary control box and time t, giving identical capture efficiencies η^{d} and η^{CEN}. Time t is from start of tracer emission.

the corresponding volume is determined by the air flow induced by the local exhaust.

At present no consistent experimental method based on the control box definition of directly captured contaminants is available and approximative methods have to be used. If q_{le} is small compared with other exhausted air flows from a room the main part of the escaped contaminants is captured by the other exhausts. Consequently, a minor difference between η^{CEN} and η^{tot} is to be expected. However, measurement of η^{CEN} and η^{tot} is nearly identical, and the proposed CEN-method has proven useful in testing local exhaust systems (9). From this study η^{CEN} is recommended for field applications.

References

1. Ellenbecker MJ, Gempel RF and Burgess WA. Capture efficiency of local exhaust ventilation systems. Am. Ind. Hyg. Assoc. J. 44 (1983) 752-755.
2. Jansson A. The capture of contaminants by exhausts. [Translation of the Swedish original "Utsugs infångning av föroreningar."] Arbete och Hälsa 11 (1982).
3. Madsen U, Breum NO and Nielsen PV. A numerical and experimental study of local exhaust capture efficiency. Ann. occup. Hyg. 37 (1993) 593-605.
4. Madsen U, Fontaine JR, Nielsen PV, Aubertin G and Breum NO. A numerical study of dispersion and local exhaust capture of aerosols generated from a variety of sources and air flow conditions. Am. Ind. Hyg. Assoc. J. (to be submitted)
5. CEN TC 114/WG 15 Safety of machinery - Evaluation of the emission of airborne hazardous substances - Part 4: Capture efficiency of an exhaust system - Tracer method. (draft) (1993).
6. Lu QQ, Fontaine JR and Aubertin G. Particle motion in two-dimensional confined turbulent flows. Aerosol Sci. Tech. 17 (1992) 169-185.
7. Fontaine JR, Braconnier R, Rapp R and Sérieys JC. EOL: A computational fluid dynamics software designed to solve air quality problems. In Hughes RT, Goodfellow HD and Rajhans GS (Ed.) Ventilation'91, Proceedings of the 3rd international symposium on ventilation for contaminant control. ACGIH, Cincinnati (1993) 449-460.
8. Launder BE and Spalding DB. The numerical computation of turbulent flows. Comp. Meth. appl. Mech. Engng. 3 (1974) 269-289.
9. Vavasseur C, Muller JP, Aubertin G and Lefevre A. Application of tracer gas methods to the measurements of ventilation parameters in nuclear power plants and various industrial sectors. In Goodfellow HD (Ed.) Ventilation '85, Proceedings of the first international symposium on ventilation for contaminant control. Elsevier Sci. Pub., Amsterdam (1986) 785-796.

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