Ann. occup. Hyg., Vol. 30, No. 4, pp. 497–513, 1986.
Printed in Great Britain.
0003–4878/86 $3.00+0.00
Pergamon Journals Ltd.
© 1986 British Occupational Hygiene Society.

Downloaded from https://academic.oup.com/annweh/article-abstract/30/4/497/165659 by Centers For Disease Control user on 21 July 2020

CAPTURE EFFICIENCY OF FLANGED CIRCULAR LOCAL EXHAUST HOODS

MICHAEL R. FLYNN* and MICHAEL J. ELLENBECKER†
Department of Environmental Sciences and Physiology, Harvard School of Public Health, 665 Huntington Avenue, Boston, MA 02115, U.S.A.

Abstract—The concept of capture efficiency as a design parameter for Local Exhaust Ventilation systems is presented. A theoretical model, based on computer-generated streamline maps, is developed for predicting the capture efficiency of a flanged circular hood operating with a cross-draught blowing perpendicular to the centreline. The model assumes a low flow, point source of gaseous contaminant located on the hood centreline. Measured values of capture efficiency are presented and compared with the theory. Potential applications of capture efficiency to the design and improvement of Local Exhaust Ventilation systems are discussed.

INTRODUCTION

LOCAL EXHAUST VENTILATION (LEV) systems are used primarily to control worker exposure to toxic airborne contaminants, either gas, vapour or aerosol. Optimally designed hoods of LEV systems will enclose the contaminating process to as great an extent as is feasible. The ultimate enclosure might be the glove box, where the contaminant is emitted completely inside of the hood. This study is primarily concerned with exterior hoods, i.e. hoods which, for various reasons, are required to exert an influence out into the work place and capture the contaminant. Often these hoods are associated with processes that require a considerable degree of control, since the contaminant may be carcinogenic or otherwise highly toxic, thereby precluding general room ventilation. LEV systems with exterior hoods (hereafter the term LEV will be used to refer to such systems) have been designed since the 1930s according to the principle of capture velocity. Capture velocity is defined in an unfortunate tautology as: 'the velocity at any point in front of the hood necessary to overcome opposing air currents and capture the contaminated air by causing it to flow into the hood' (ACGIH, 1984).

The determination of this velocity is largely a matter of trial and error, as no specific methodology is available for evaluating the necessary and sufficient capture velocity for a given set of conditions. In addition, the prediction of the velocity that a hood can generate at 'any point in front of the hood' has always been restricted to empirically determined centreline velocity gradients formulated by DALLAVALLE (1930), SILVERMAN (1943), FLETCHER (1977) and others. As a design parameter capture velocity is not an adequate measure of how well the hood performs. A more direct index of hood performance is the capture efficiency, defined (ELLENBECKER *et al.*, 1983) as the fraction

* Present address: Department of Environmental Sciences and Engineering, School of Public Health, University of North Carolina at Chapel Hill, Chapel Hill, NC 27514, U.S.A.
† Present address: Mechanical Engineering Department, University of Lowell, Lowell, MA 01854, U.S.A.

of contaminant generated per unit time that is captured per unit time, or mathematically:

$$\eta_e = \frac{G'}{G}, \tag{1}$$

where G' is the capture rate of the hood and G is the contaminant generation rate.

The rate of escape of contaminant into the work place, and perhaps the worker's breathing zone, is given by:

$$G'' = (1 - \eta_e)G, \tag{2}$$

where G'' is the effective generation rate into the room atmosphere. Obtaining this information is the first step in constructing estimates of worker exposure to contaminants generated by processes under the control of LEV systems.

The concept of capture efficiency is not new and has received some attention in the literature (BURGESS and MURROW, 1976; JANSSON, 1980; ELLENBECKER *et al.*, 1983; FLETCHER and JOHNSON, 1986); however, a comprehensive theoretical treatment does not exist and the evaluation of significant factors is incomplete. This paper presents an idealized theoretical model of capture efficiency and its subsequent empirical examination. The approach is based on the intuitive idea that capture efficiency depends upon the interaction of three flow fields: (1) the flow field generated by the hood; (2) the flow field generated by the contaminating source; and (3) the flow field due to any perturbing cross-draughts. The complex interactions of these vector fields ultimately determine whether the contaminant is captured or escapes into the general room air. It is useful to consider each the three velocity fields as being composed of deterministic and stochastic elements. Each field will have average values for velocity magnitudes and directions that can be determined by mathematical functions. In addition, each field will contain a certain amount of variability about these average values owing to turbulence; this comprises the stochastic portion.

A validated model of the three-dimensional velocity field around a flanged circular hood (FCH) either with or without a uniform cross-draught blowing perpendicular to the hood centreline has been developed from a modified potential flow solution (FLYNN and ELLENBECKER, 1985, 1986). The model allows for the addition of various contaminating flow fields, but most easily that of a point source of gaseous contaminant issuing radially in all directions. Such a point source may be unrealistic; nevertheless, it is useful in identifying the way in which the three fields interact to capture the airborne contaminant.

THEORY

The model of the interaction of the flow fields previously described is deceptively simple; a closer look reveals the complexity of capture efficiency. The velocity field around the FCH depends on the flow into the hood (Q), and the hood diameter (D). These quantities, along with position, are sufficient to define the deterministic portion of the field. The stochastic field is not quantified; no attempt was made to evaluate turbulence intensities or scales; and possible boundary layer effects due to the flange were not considered. These are both important in describing capture efficiency in a complete way (ROACH, 1981), but a comprehensive treatment is beyond the scope of this paper.

Downloaded from https://academic.oup.com/annweh/article-abstract/30/4/497/165659 by Centers For Disease Control user on 21 July 2020

The flow field generated by a source will be determined by the source flow (Q_s), shape, area over which the contaminant is generated, the direction in which it is generated, whether the contaminant is gas or particulate, any buoyant forces due to density differences, and boundary layers due to flow past the source's surfaces. The modelling of such generalized sources is beyond the scope of this paper. By assuming a 'point' source emitting gas at low velocity, a simple model for contaminant generation can be developed.

The perturbing cross-draught is perhaps the most complex and variable of the three flow fields. Such airflows may be entirely random, unsteady in time, accelerating in space, of high or low turbulence, or cyclonic (e.g. from cooling fans). The worker and/or the process may also generate complex eddies and draughts. The assumption of a steady uniform cross-draught perpendicular to the hood centreline is an idealization: in reality, more complex flows may be expected. In addition, the assumption of steady state has been made for all fields; if necessary, time variation in the flows may be suitably approximated by using time intervals small compared with the period of variation.

The model of capture efficiency derived here assumes incompressible air flow Q into an FCH of diameter D, a uniform cross-draught of velocity V_c blowing perpendicular to the hood centreline, and a point source of isothermal non-buoyant gas releasing at flow Q_s some distance Z along the hood centreline. The cylindrical co-ordinate system is used: the hood centreline is the Z-axis, and the cross-draught blows from the $\theta = 180°$ half plane to the $\theta = 0°$ half plane. A BASIC computer program has been developed for the IBM XT personal computer (FLYNN and ELLENBECKER, 1986), which maps the streamlines for the flow described above. A visual plot of these streamlines for the plane parallel to the direction of the cross-draught is shown in Fig. 1. All streamlines off this plane are three-dimensional space curves.

If inviscid flow is assumed (i.e. frictional forces are neglected), capture efficiency should depend only on the variables mentioned above. In this case, application of the

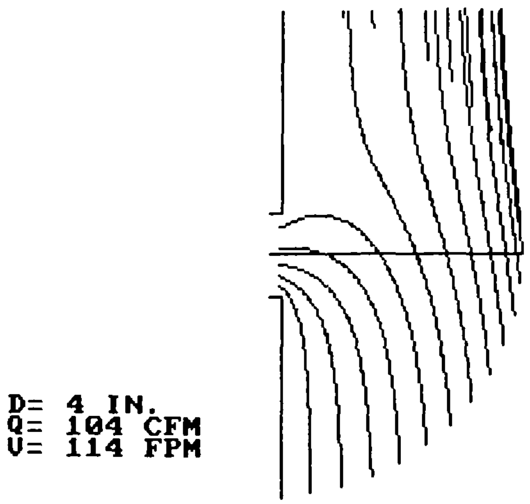


Fig. 1. Streamline map for a 10.16 cm (4 in.) FCH at 0.049 m^3 s^{-1} (104 cfm) and a cross-draught of 0.579 m s^{-1} (114 fpm).

Downloaded from https://academic.oup.com/annweh/article-abstract/30/4/497/165659 by Centers For Disease Control user on 21 July 2020

Buckingham pi theorem (WHITE, 1982) suggests that the dimensionless parameters Q_s/Q, Z/D, and V_f/V_c where V_f is the hood face velocity, should adequately describe the process. The functional relationship between these variables cannot be specified explicitly from the theorem. The first dimensionless group, Q_s/Q, is the ratio of contaminant flow to hood flow. This ratio can have a profound effect on capture efficiency. If $Q_s/Q \to 1$ the contaminating process will exert a major influence on the flow field and the three-dimensional distribution of the pollutant. If $Q_s/Q \ll 1$ the contaminant, from a point source, will behave much as a single streamline and be confined to the centreline base plane (plane of the cross-draught).

The second dimensionless group, Z/D, is the ratio of the hood-source separation to the hood diameter. As Z/D grows large, the hood flow field influence becomes less and the effects of the cross-draught and source fields are more pronounced. The final group, V_f/V_c, is the ratio of the hood face velocity to the cross-draught velocity. It takes into account the relative strength of the cross-draught compared with that of the hood. By reducing $Q_s/Q \ll 1$ the contaminant field may be treated as a single streamline, at least from the deterministic perspective, and the influence of turbulence on capture efficiency may be observed.

Computer models can be used to visualize the contaminant issuing from the source. The simplest model assumes that the contaminant is an infinitely small element of fluid and that the contaminating flow field is negligible. The streamline representing the contaminant flow is termed the 'idealized contaminant streamline' or ICS; it either enters the hood ($\eta_e = 1$) or does not ($\eta_e = 0$) and, hence, capture efficiency for $Q_s/Q \ll 1$ is, theoretically, a step function. For an FCH of specified diameter, flow and cross-draught there will be one ICS that will just enter the hood; this streamline is the critical streamline (CS). The Z/D value for each CS is identified as $[Z/D]_{50}$, or the critical distance.

If the contaminant did not disperse as it travelled toward the hood, it would remain on the ICS. For a point source, capture efficiency as a function of distance would be a step function, i.e. $\eta_e = 1.0$ for $Z/D < [Z/D]_{50}$, and $\eta_e = 0$ for $[Z/D]_{50} < Z/D$. In reality, of course, the contaminant does disperse around the ICS. Based on the assumption of a symmetric distribution, $[Z/D]_{50}$ is hypothesized to be the point at which capture efficiency will be 50%. The computer model was used to search iteratively for the CS, thus generating Z/D values for the CS corresponding to any combination of hood diameter, flow and cross-draught. A ln–ln regression of these values vs the dimensionless predictor variable V_f/V_c yields:

$$\left[\frac{Z}{D}\right]_{50} = 0.372\left[\frac{V_f}{V_c}\right]^{0.595} \tag{3}$$

with an $R^2 = 99.9\%$. The consideration of the deterministic fields leads to three dimensionless parameters and a computer model which will predict capture efficiency for the situation described. Although quantitative information on the turbulent velocity fields is lacking, there are some general principles which are valuable in interpreting experimental results.

Turbulence is a random motion of fluid, defined (HINZE, 1959) as 'an irregular motion which makes its appearance in fluids, gases or liquids, when they flow past solid surfaces, or even when neighbouring streams of the same fluid flow past or over one another.' Inclusive in this definition is a sense of variation in space and time. A

Downloaded from https://academic.oup.com/annweh/article-abstract/30/4/497/165659 by Centers For Disease Control user on 21 July 2020

turbulent velocity V can be apportioned into mean ($\bar{V}$) and fluctuating (v) parts:

$$V = \bar{V} + v. \tag{4}$$

The intensity of turbulence is measured as:

$$v' = \sqrt{\overline{v^2}} \tag{5}$$

and may be expressed as a percentage of the mean velocity, or the relative turbulence intensity. The intensity is of prime importance in the transport of matter in a turbulent field due to turbulent diffusion. Intensity, when considered together with the time the fluid element is subjected to the turbulence, gives some qualitative idea of the amount of mass transfer possible. In simple terms, turbulent transport is greater for greater values of turbulence intensity and longer times.

Another useful concept is the homogeneity of turbulence. A turbulent field is considered homogenous if the turbulence has the same quantitative structure in all parts. It is further classified as isotropic if the statistical features of turbulence have no preference for a given direction, i.e. perfect disorder, and is otherwise anisotropic. In addition, shear flow turbulence refers to the turbulence generated in free space by interacting streams of the fluid; this is the case for a good part of the flow field of the hood and cross-draught. Wall turbulence refers to that generated by fluid interaction with solid surfaces and is characterized by boundary layers. A shear flow turbulence is associated with mean velocity gradients and is anisotropic in nature; this may have significant implications for LEV applications.

The theoretical treatment of turbulent transport is a complex phenomenon usually approached with several simplifying assumptions. The premise of homogeneity (HINZE, 1959) results in the following expression for the displacement of a fluid element:

$$\overline{y^2} = 2v'^2 \int_0^t (t-\tau) R_L(\tau)\, d\tau, \tag{6}$$

where τ is an interval of time, $\overline{y^2}$ the mean square displacement in the Lagrangian co-ordinate direction y, and v'^2 the square of the turbulence intensity of the velocity component in the y direction. The function R_L is the Lagrangian correlation function and is introduced owing to the fact that in a small interval of time τ, the velocities at t_1 and t_2 are correlated, ($\tau = t_2 - t_1$). The function R_L is defined as:

$$R_L(\tau) = \frac{\overline{v(t)v(t+\tau)}}{v'^2}, \tag{7}$$

where the over-bar denotes the ensemble average over a large number of fluid elements.

The limiting values of R_L determine the general forms of the transport equations. If the correlation coefficient is approximately one, then the displacement equation becomes:

$$\overline{y^2} = v'^2 t^2 \tag{8}$$

and the spread of contaminant proceeds proportionally in time. This occurs when the diffusion times are very small. For longer diffusion times $R_L \to 0$ and spread of contaminant is described by the familiar Fickian solution where diffusion is proportional to the square root of time. In addition, as GIFFORD (1982) has observed,

Downloaded from https://academic.oup.com/annweh/article-abstract/30/4/497/165659 by Centers For Disease Control user on 21 July 2020

the intensity of turbulence at the source relative to the turbulence intensity of the entire flow is also important in the short time limit. In all cases the displacement of the fluid element depends upon the product of a turbulent velocity intensity and the time since release or the last point of concern. By using the computer model it is possible to estimate the time of flight along a given streamline as:

$$\Delta t = \frac{\Delta s}{u}, \tag{9}$$

where u is the velocity, assumed constant over a small interval of time Δt, and Δs the change in arc length along a streamline. By summing these intervals along the streamline the total time of flight is obtained. The time of flight along an ICS that enters the hood is termed the capture time, t_c.

In order to incorporate the concept of capture time into the dimensionless variable approach another time quantity is needed. GIFFORD's (1982) treatment indicates that the Lagrangian time scale, t_L, is the variable of interest; therefore, the ratio of the capture time to the Lagragian time scale should be the predictive parameter. The Lagrangian time scale may be thought of as the average time a fluid element persists in motion in a given direction, somewhat analogous to the concept of relaxation time in aerosols. GIFFORD (1982) goes on to show that, as diffusion times decrease ($R_L \rightarrow 1$), the dispersion undergoes a transition of dependency on time determined by the ratio of the turbulence intensity at the source to that of the entire flow. The difficulty in applying any such approach to capture efficiency is that empirical measurements are needed to evaluate turbulence intensities and time scales. Since these quantities are likely to be functions of position in the field, a complete analysis would be quite complex. If it is assumed that the characteristics of turbulence are primarily determined by the interaction of the hood flow and cross-draught flow, then V_f/V_c should serve as a suitable predictor for the effects of turbulent diffusion on contaminant dispersion around the critical streamline.

The fact that the velocity field around the hood shows considerable gradients both in the direction of mean flow and perpendicular to the streamlines negates the assumption of a homogeneous turbulent field and the assumptions which formed the basis of the preceding discussion. However, evidence (HINZE, 1959) exists that the turbulence intensity in shear flows is generally large and that a significant portion of the transport occurs quickly and in the vicinity of the source. The assumption that diffusion times are small seems good, since calculations indicate that capture times are of the order of 0.2 s for the experiments conducted here; within the vicinity of the source the field may be quasi-homogeneous. This suggests that the effects of turbulent diffusion may be largely determined by the conditions at the source.

Several other items regarding the turbulence are pertinent:

(1) Relative turbulence intensity is generally reduced as a flow accelerates. Thus, as a streamline approaches the hood, the relative turbulence intensity should decrease. However, as the hood flange is approached, the boundary layer may exert a strong influence on the turbulent and deterministic fields.

(2) A velocity field with a gradient of the mean velocity normal to the streamlines generates anisotropic turbulence and transfer of mass by turbulent diffusion is skewed to the side with the greater mean velocity. This is particularly significant

Downloaded from https://academic.oup.com/annweh/article-abstract/30/4/497/165659 by Centers For Disease Control user on 21 July 2020

for the situation described, as transfer of contaminant towards the hood would be favoured. it is interesting to note that the assumption of a constant value for a diffusion coefficient in such a field leads to skewing in the reverse direction (HINZE, 1959).

(3) Transfer is from high to low concentrations, i.e. down the concentration gradient.

EXPERIMENTAL WORK

The principal objectives of the experimental work were to confirm the theoretical treatment by examining the measured vs the predicted critical distances (given by eq. 3) and also to assess the impact of turbulent diffusion on the theoretical model. Flanged circular hoods of 5.25, 10.23 and 15.41 cm (2.07, 4.03 and 6.07 in.) in dia. with 12.7 cm (5 in.) wide flanges were operated at flows of from 0.017–0.066 $m^3 s^{-1}$ (35–140 cfm). Cross-draughts of 0.579, 0.986 or 1.524 m s^{-1} (114, 194 or 300 fpm) were induced perpendicular to the hoods by placing them through the side wall of a 1.22 m (4 ft) square wind tunnel. Hoods were positioned far enough into the tunnel to be free from the boundary layer.

A point source of contaminant was modelled using a small needle capped with a fritted ceramic sphere 0.64 cm (0.25 in.) in dia. This served to disperse the contaminant in all directions. With this source only relatively low contaminant flows were possible without significantly changing the symmetry of the contaminant flow field; in addition, pressure drop necessarily restricted the flow. A lathe bed, located outside the wind tunnel wall opposite the hoods, was used to position the source accurately.

Sulphur hexafluoride (SF_6) was used as the tracer gas. The capture efficiency was measured as the ratio of the concentration of gas, in the duct downstream from the hood, when the source was at a given Z/D position (C_z), to the concentration when the source was held at the hood face (C_f):

$$\eta_e = \frac{C_z}{C_f}. \tag{10}$$

The concentration of SF_6 was measured using an ITI portable gas chromatograph (GC). An electron capture detector, sensitive in the part per billion range, was used. The GC was calibrated using an exponential dilution flask, before and after each series of measurements. The source gas was calibration grade 900 ppm SF_6. Contaminant flows varied between 0.833 and 5 $cm^3 s^{-1}$, depending on Q.

RESULTS AND DISCUSSION

Initially eight different ratios of V_f/V_c were obtained experimentally by different combinations of hood diameter, flow and cross-draught. The theoretical values for the critical distance $[Z/D]_{50}$ were calculated using eq. 3. Measurements of capture efficiency were made for each case over a range of Z co-ordinates to give a full range of values for capture efficiency. The data are presented in Table 1 as the average capture efficiency for six repetitions at a specified Z/D value. The results were analysed by using the logistic transform:

$$y = \ln\left[\frac{\eta_e}{1-\eta_e}\right] \tag{11}$$

Downloaded from https://academic.oup.com/annweh/article-abstract/30/4/497/165659 by Centers For Disease Control user on 21 July 2020

TABLE 1. MEASURED CAPTURE EFFICIENCIES

Hood diameter (cm)	Flow (m^3s^{-1})	Cross-draught velocity (ms^{-1})	Axial co-ordinate (cm)	Dimensionless axial distance	Mean capture efficiency
15.405	0.017	0.986	3.18	0.21	0.92
15.405	0.017	0.986	3.81	0.25	0.69
15.405	0.017	0.986	4.45	0.29	0.48
15.405	0.017	0.986	5.41	0.35	0.36
15.405	0.017	0.986	5.72	0.37	0.11
15.405	0.017	0.986	6.35	0.41	0.03
15.405	0.017	0.986	6.99	0.45	0.00
15.405	0.017	0.986	0.00	0.00	1.00
15.405	0.026	0.579	7.62	0.49	0.88
15.405	0.026	0.579	8.26	0.54	0.88
15.405	0.026	0.579	8.89	0.58	0.72
15.405	0 026	0.579	9.53	0.62	0.52
15 405	0.026	0.579	9.86	0.64	0.51
15.405	0.026	0.579	10.80	0.70	0.38
15.405	0.026	0.579	11.43	0.74	0.22
15.405	0.026	0.579	0.00	0.00	1.00
15.405	0.055	0.986	8.89	0.58	0.86
15.405	0.055	0.986	9.53	0.62	0.83
15.405	0.055	0.986	10.16	0.66	0.56
15.405	0.055	0.986	10.80	0.70	0.36
15.405	0.055	0.986	12.07	0.78	0.12
15.405	0.055	0.986	12.70	0.82	0.16
15.405	0.055	0.986	13.97	0.91	0.03
15.405	0.055	0.986	0.00	0.00	1.00
15.405	0.049	0.579	7.62	0.49	0.99
15.405	0.049	0.579	10.80	0.70	0.93
15.405	0.049	0.579	12.07	0.78	0.71
15.405	0.049	0.579	15.24	0.99	0.40
15.405	0.049	0.579	15.88	1.03	0.35
15.405	0.049	0.579	16.51	1.07	0.16
15.405	0.049	0.579	0.00	0.00	1.00
10.226	0.026	0.579	5.08	0.50	1.00
10.226	0.26	0.579	7.62	0.75	0.99
10.226	0.026	0.579	9.53	0.93	0.72
10.226	0.026	0.579	10.16	0.99	0.53
10.226	0.026	0.579	11.43	1.12	0.40
10.226	0.026	0.579	12.70	1.24	0.17
10.226	0.026	0.579	13.34	1.30	0.04
10.226	0.026	0.579	0.00	0.00	1.00
10.226	0.026	0.986	6.35	0.62	0.88
10.226	0.26	0.986	6.99	0.68	0.79
10.226	0.026	0.986	7.62	0.75	0.75
10.226	0.026	0.986	8.26	0.81	0.61
10.226	0.026	0.986	8.89	0.87	0.42
10.226	0.026	0.986	9.53	0.93	0.29
10.226	0.026	0.986	10.16	0.99	0.16
10.226	0.026	0.986	0.00	0.00	1.00
10.226	0.066	0.986	10.16	0.99	1.00
10.226	0.066	0.986	11.43	1.12	0.89
10.226	0.066	0.986	12.07	1.18	0.91
10.226	0.066	0.986	13.34	1.30	0.56
10.226	0.066	0.986	13.97	1.37	0.62

Downloaded from https://academic.oup.com/annweh/article-abstract/30/4/497/165659 by Centers For Disease Control user on 21 July 2020

TABLE 1—*continued.*

Hood diameter (cm)	Flow (m^3s^{-1})	Cross-draught velocity (ms^{-1})	Axial co-ordinate (cm)	Dimensionless axial distance	Mean capture efficiency
10.226	0.066	0.986	15.88	1.55	0.20
10.226	0.066	0.986	17.15	1.68	0.10
10.226	0.066	0.986	0.00	0.00	1.00
5.250	0.026	0.986	7.62	1.45	0.84
5.250	0.026	0.986	8.26	1.57	0.70
5.250	0.026	0.986	8.89	1.69	0.48
5.250	0.026	0.986	9.53	1.81	0.25
5.250	0.026	0.986	10.16	1.94	0.19
5.250	0.026	0.986	0.00	0.00	1.00
5.250	0.026	1.524	1.27	0.24	1.01
5.250	0.026	1.524	2.54	0.48	1.00
5.250	0.026	1.524	3.81	0.73	0.95
5.250	0.026	1.524	5.08	0.97	0.86
5.250	0.026	1.524	6.35	1.21	0.75
5.250	0.026	1.524	6.99	1.33	0.53
5.250	0.026	1.524	7.62	1.45	0.48
5.250	0.026	1.524	8.26	1.57	0.20
5.250	0.026	1.524	8.89	1.69	0.10
5.250	0.026	1.524	0.00	0.00	1.00

and

$$x=\frac{Z}{D}, \tag{12}$$

where y is the natural logarithm of the odds that the contaminant is captured, and x is the dimensionless centreline distance. Regressions of the form:

$$y=\alpha x+\beta \tag{13}$$

yielded significant slopes and R^2 values in excess of 94% for each experimental combination. The results suggest that capture efficiency is described by a cumulative logistic function of the form:

$$\eta_e=\left[\frac{1}{1+e^{(x-\mu)/w}}\right], \tag{14}$$

where: $\omega=-1/\alpha$ and $\mu=\omega\beta$; α and β are the slope and intercept, respectively, of the regressions of y on x. A regression of μ, the experimentally estimated $[Z/D]_{50}$, on the theoretical $[Z/D]_{50}$ yields:

$$\mu=1.13\left[\frac{Z}{D}\right]_{50}-0.082 \tag{15}$$

with an accompanying R^2 of 99%. The 95% confidence interval for the slope does not quite contain 1. This is consistent wth the concept of shear turbulence with velocity gradients favouring transport to the hood, thus making the critical distance a bit larger. The effect is rather small, however, and is consistent with the literature (HINZE, 1959).

The parameter ω is expected to depend on the effects of turbulence. Specifically, it is the spread parameter for the distribution of contaminant about the ICS. It is analogous

Downloaded from https://academic.oup.com/annweh/article-abstract/30/4/497/165659 by Centers For Disease Control user on 21 July 2020

to a standard deviation in a normal distribution, except that in logistic model 46.2% of the distribution lies between the mean and $\pm\omega$. Thus, the logistic distribution is more peaked, or can be considered leptokurtic relative to a normal distribution of the same mean and variance. The probability distribution function for the logistic model is readily obtainable from the cumulative distribution. Figure 2 presents these distributions for three of the experimental conditions examined. They are, in effect, the theoretical predictions of contaminant dispersion about the critical streamline. The spread of contaminant is seen to be greater for greater values of the critical distance, consistent with the intuitive notion that the greater the source–hood separation, the longer the turbulence will have to act on the contaminant and disperse it about the streamline. Attempts to develop a predictive relationship for ω yielded:

$$\omega = 0.04\left[\frac{V_f}{V_c}\right]^{0.6} \tag{16}$$

with an R^2 of 76%.

Substituting eq. (3) into eq. (15), and rounding off constants, yields:

$$\mu = 0.42\left[\frac{V_f}{V_c}\right]^{0.595} - 0.082. \tag{17}$$

If this is approximated as:

$$\mu = 0.4\left[\frac{V_f}{V_c}\right]^{0.6} \tag{18}$$

then dividing eq. (16) by eq. (18) gives: $\omega = 0.1\mu$. This suggests that the spread parameter is proportional to the critical distance and enables a simplification of the model to:

$$\eta_e = \left[\frac{1}{1+e^{10(x/\mu - 1)}}\right], \tag{19}$$

where μ is given by eq. (17).

Equation (19) is a predictive model of capture efficiency as a function of hood diameter, flow, cross-draught velocity and source position. Figures 3–5 display the theoretical curves for capture efficiency overlaid on the experimentally measured values. A validation was conducted to strain the model and examine the fit. A 5.25 cm (2.07 in.) flanged circular hood was operated at 0.026 m^3 s^{-1} (55.7 cfm) and a cross-draught of 0.986 m s^{-1} (194 fpm) was generated perpendicular to the hood centreline. The critical distance was 1.79 duct diameters, well outside the range of previous values. The results, depicted in Fig. 5(a), indicate that the theory slightly overestimates the critical distance. At this hood size, however, a value of 0.1 on the abscissa represents a distance of only 0.53 cm, or approximately the diameter of the 'point' source. The results of all the experimental vs theoretical capture efficiency measurements and predictions are displayed in Fig. 6. The increasing variability in the region of 50% capture is due to the steepness of the theoretical curves in this region and also due to turbulence which randomly affects the position of the critical streamline. Spatial variations in the cross-draught magnitude, of the order of 10%, also contribute to this variation, which is not an uncertainty due to measurement variability but an actual variation in capture efficiency. This fluctuation in capture efficiency is an

Downloaded from https://academic.oup.com/annweh/article-abstract/30/4/497/165659 by Centers For Disease Control user on 21 July 2020

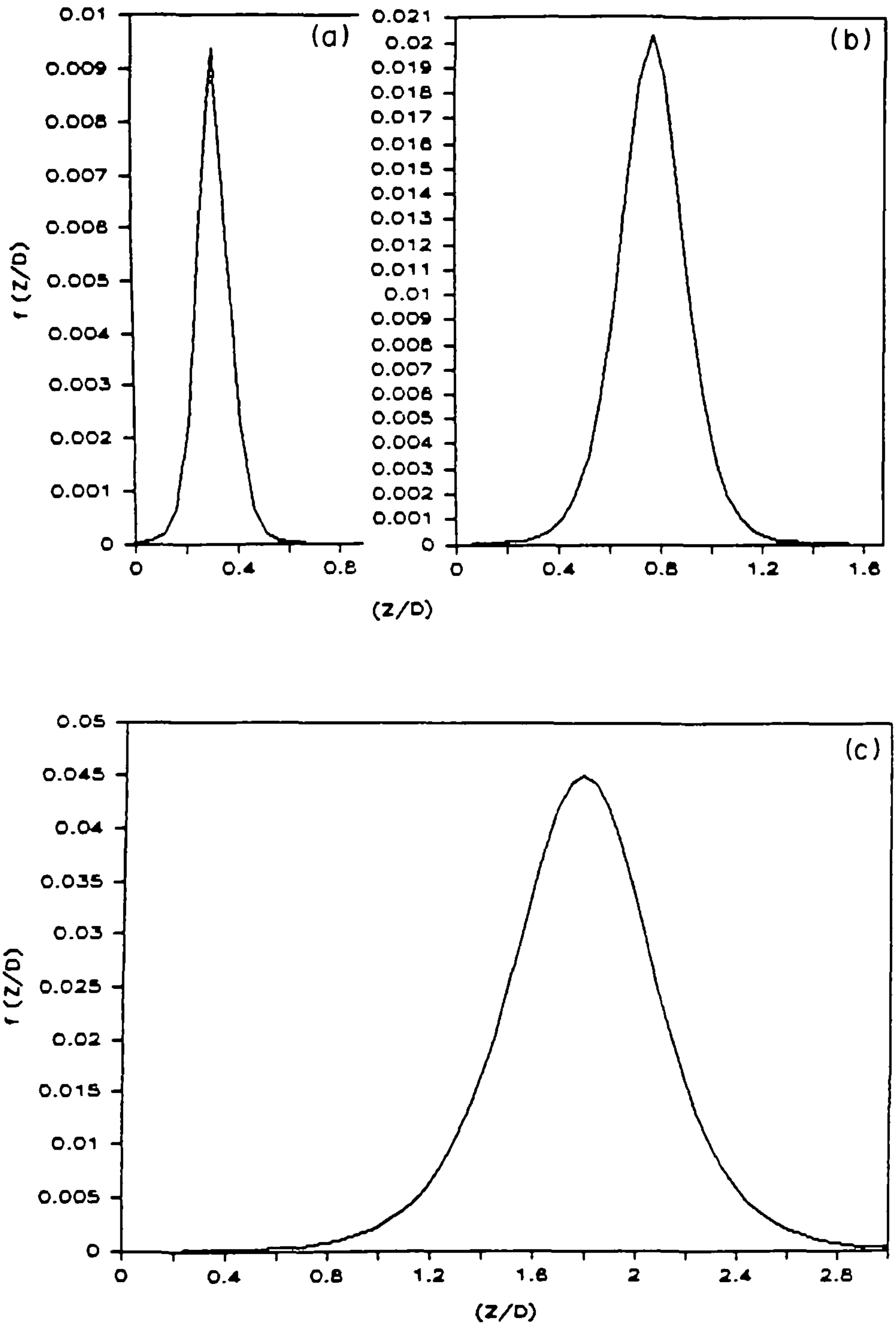


FIG. 2. Theoretical distribution of contaminant about the critical streamline for (a) a 15.41 cm FCH at 0.017 $m^3 s^{-1}$ and a cross-draught of 0.986 $m s^{-1}$, (b) a 10.23 cm FCH at 0.026 $m^3 s^{-1}$ and a cross-draught of 0.986 $m s^{-1}$, and (c) a 5.25 cm FCH at 0.026 $m^3 s^{-1}$ and a cross-draught of 0.986 $m s^{-1}$.

Downloaded from https://academic.oup.com/annweh/article-abstract/30/4/497/165659 by Centers For Disease Control user on 21 July 2020

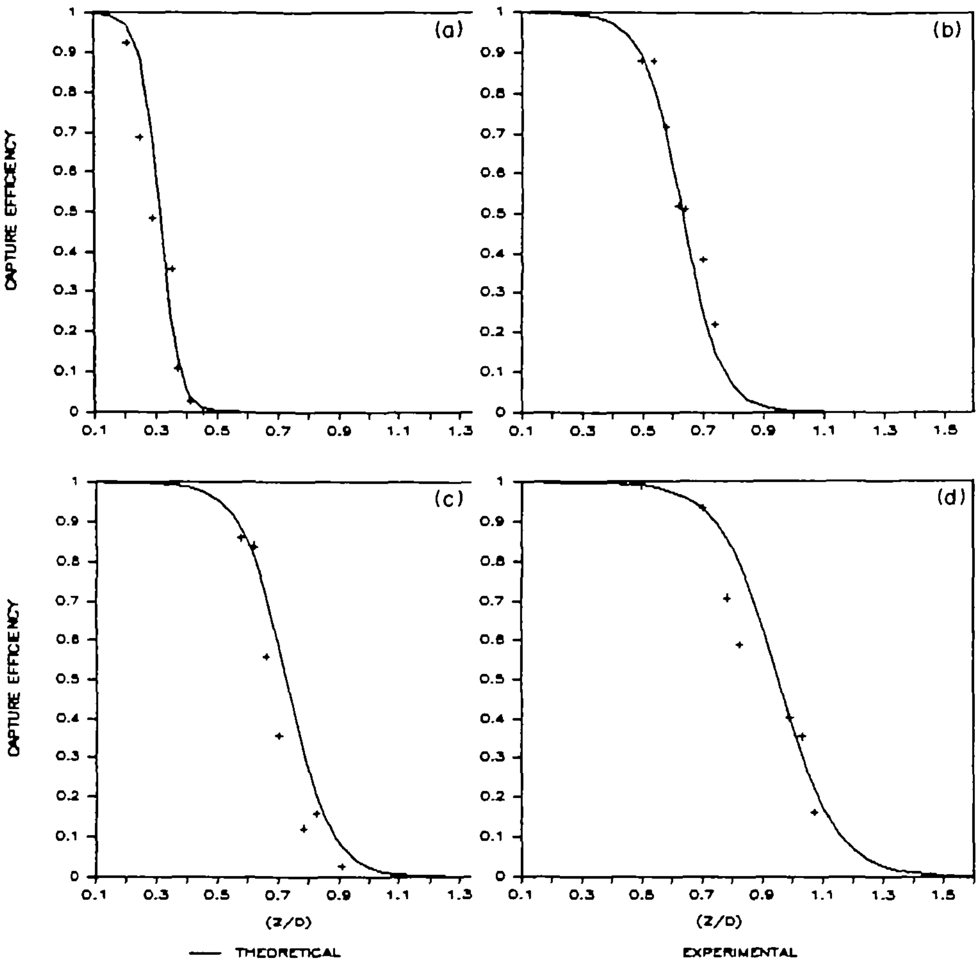


FIG. 3. Theoretical and experimental capture efficiencies for a 15.41 cm FCH at (a) 0.017 $m^3 s^{-1}$ and a cross-draught of 0.986 m s^{-1}, (b) 0.026 $m^3 s^{-1}$ and a cross-draught of 0.579 m s^{-1}, (c) 0.055 $m^3 s^{-1}$ and a cross-draught of 0.986 m s^{-1}, and (d) 0.049 $m^3 s^{-1}$ and a cross-draught of 0.579 m s^{-1}.

important area for further research, particularly in regard to determining acceptable bounds for a given prediction.

Some interesting results for the application of capture efficiency to practical industrial problems can be derived by rewriting eq. (19) as:

$$\frac{x}{\mu} = (0.1)\ln\left[\frac{1-\eta_e}{\eta_e}\right] + 1. \tag{20}$$

For a specified capture efficiency a value, $k_1 = x/\mu$, may be determined, where k_1 is the ratio of the source distance from the hood face to the critical distance. If the distance of the source from the hood (Z) is fixed, then:

$$\left[\frac{Z}{D}\right]_{50} = \frac{Z}{k_1 D} - = 0.42\left[\frac{V_f}{V_c}\right]^{0.595} - 0.082. \tag{21}$$

Downloaded from https://academic.oup.com/annweh/article-abstract/30/4/497/165659 by Centers For Disease Control user on 21 July 2020

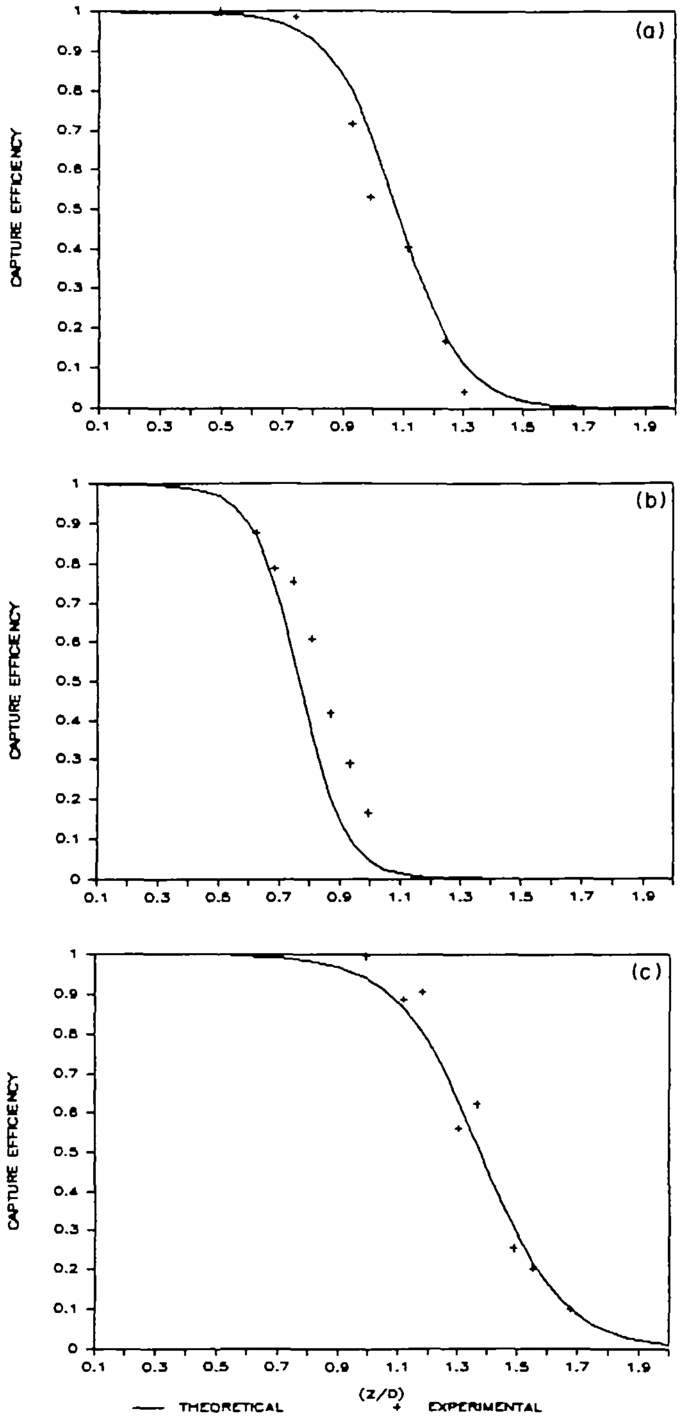
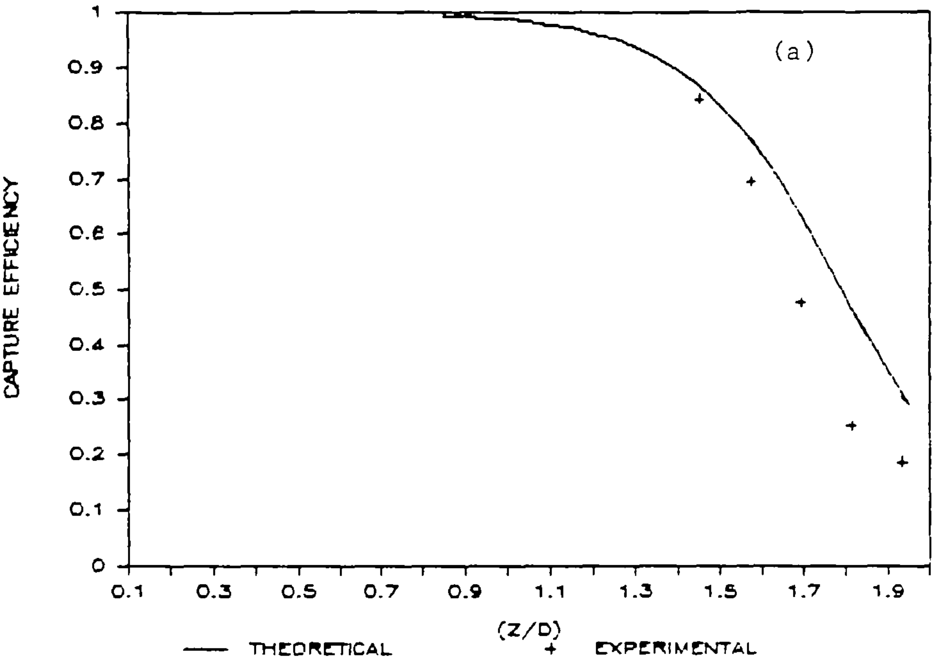


FIG. 4. Theoretical and experimental capture efficiencies for a 10.23 cm FCH at (a) 0.026 $m^3 s^{-1}$ and a cross-draught of 0.579 $m s^{-1}$, (b) 0.026 $m^3 s^{-1}$ and a cross-draught of 0.986 $m s^{-1}$, and (c) 0.066 $m^3 s^{-1}$ and a cross-draught of 0.986 $m s^{-1}$.

Downloaded from https://academic.oup.com/annweh/article-abstract/30/4/497/165659 by Centers For Disease Control user on 21 July 2020



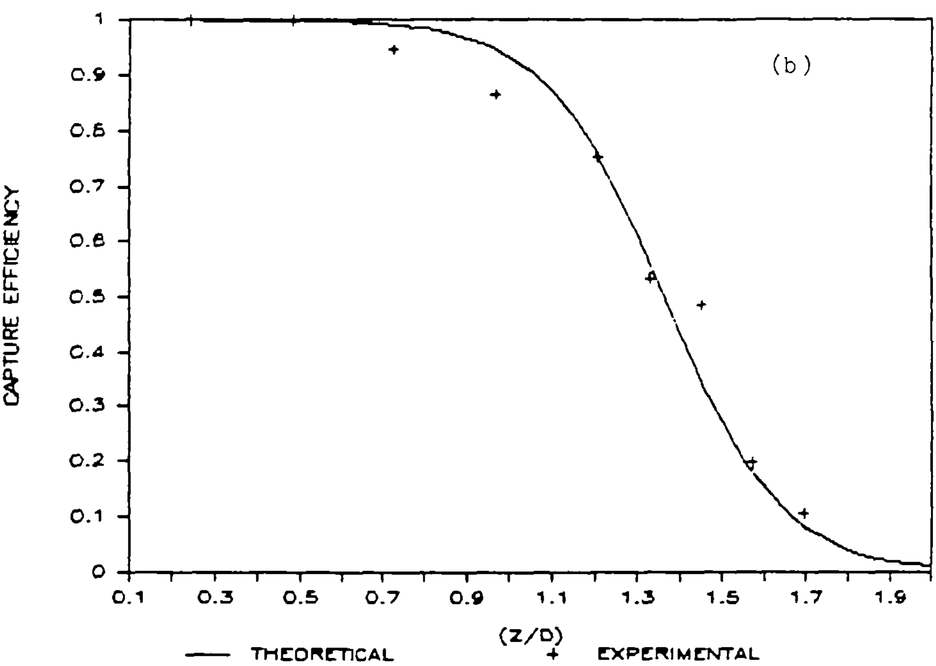


FIG. 5. Theoretical and experimental capture efficiencies for a 5.25 cm FCH at (a) 0.026 $m^3 s^{-1}$ and a cross-draught of 0.986 m s^{-1}, and (b) 0.026 $m^3 s^{-1}$ and a cross-draught of 1.524 m s^{-1}.

Downloaded from https://academic.oup.com/annweh/article-abstract/30/4/497/165659 by Centers For Disease Control user on 21 July 2020

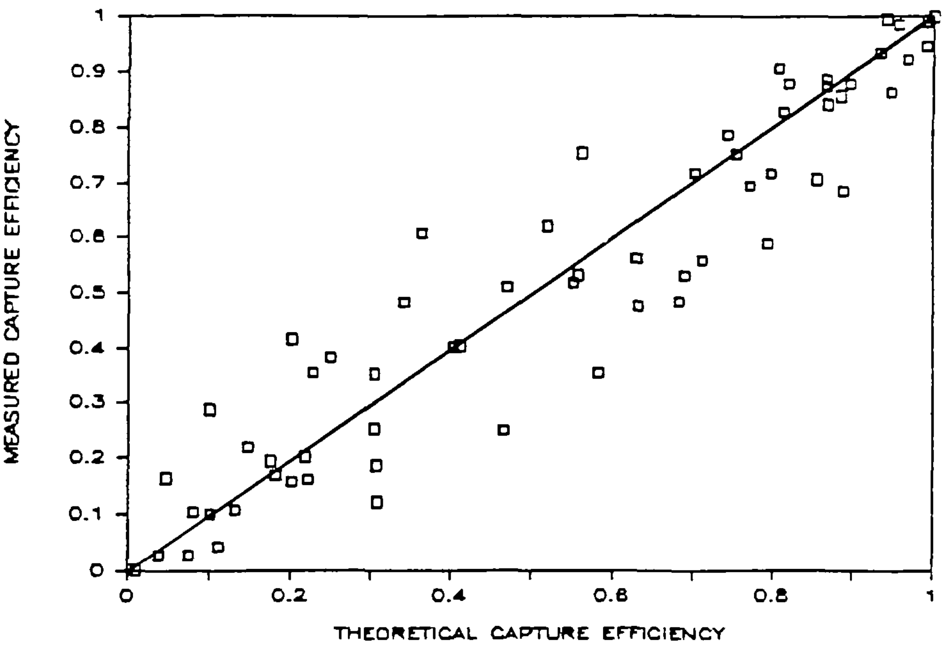


FIG. 6. Measured vs theoretical capture efficiencies.

By substituting for V_f, it follows that:

$$\frac{Z}{k_1} = \frac{0.48}{V_c^{0.595}} \left[\frac{Q^{0.595}}{D^{0.19}} \right] - 0.082D, \tag{22}$$

where D is the hood diameter.

The use of eq. (20) and (22) is best illustrated by example. Assume that a point source of contaminant, conforming to the restriction of negligible source flow, can be positioned no closer than 12.7 cm (5 in.) to an FCH and a capture efficiency of 80% is desired. A question which might be asked is: what flow will maintain the target capture efficiency for a 20.32 cm (8 in.) dia. hood required to operate in cross-draughts of no more than 0.762 m s^{-1} (150 fpm)? In this case k_1 is 0.86, and solving eq. (22) for Q yields an air flow of 0.076 m^3 s^{-1} (160 cfm).

Another application involves the determination of a new flow required to reduce the employee's exposure from one concentration C_1 to a target concentration C_2. This calculation requires the assumption that the worker's breathing zone concentration is proportional to the effective contaminant generation rate:

$$\frac{C_1}{C_2} = \frac{G_1''}{G_2''}. \tag{23}$$

Assuming a constant contaminant generation rate and substituting eq. (2):

$$\eta_{e2} = 1 - C_2 \frac{1 - \eta_{e1}}{C_1}, \tag{24}$$

Downloaded from https://academic.oup.com/annweh/article-abstract/30/4/497/165659 by Centers For Disease Control user on 21 July 2020

where η_{e1} is the capture efficiency giving the exposure C_1, and η_{e2} is the capture efficiency required to obtain the new exposure C_2.

Thus, by knowing the present operating conditions and calculating η_{e1}, the target capture efficiency required to reduce the worker's exposure to the desired level can be estimated using eq. (20). The required flow increase, other parameters held constant, can be calculated using eq. (22). As an example, assume that a 15.24 cm (6 in.) FCH operating at 0.047 $m^3\ s^{-1}$ (100 cfm) in a cross-draught of 0.508 m s^{-1} (100 fpm) exhausts a point source of methyl chloroform 15.24 cm (6 in.) from the hood face on the centreline. The worker's 8 hr time weighted average exposure is measured at 200 ppm and a reduction to 10 ppm is desired. What flow is needed to achieve this target concentration? In this case $x = Z/D = 1.0$, from eq. (17) $\mu = 1.024$, and the use of eq. (19) gives $\eta_{e1} = 0.559$. Application of eq. (24) indicates that the required efficiency, η_{e2}, is 0.978, and by application of eq. (20) $k_1 = 0.6206$. Using eq. (22) the required air flow Q_2 is 0.098 $m^3\ s^{-1}$ (208 cfm).

Although the above examples sound promising, a great deal of empirical work is needed before the application of these or similar equations is possible. The assumption that the breathing zone concentration is proportional to the effective generation rate needs validation. In addition, models of capture efficiency that can account for the variety of source configurations and work place differences are needed. The use of the model presented here is restricted to cases where $[Z/D]_{50} \leq 1.5$, since the empirical validations of the velocity fields did not extend much beyond this range. Extrapolation of the results outside this range must be viewed with caution.

Another limitation arises as $V_c \rightarrow 0$, since the theoretically predicted critical distance becomes infinite (eq. 3). In reality some type of random air movement will always exist independent of the hood, and any real source will have some specified velocity of generation. These forces will become important in the limiting cases, i.e. as V_c approaches the level of the ambient air velocity and as the source velocity approaches the magnitude of the velocities generated by the other fields. The equations and examples given are not meant for field application, but to illustrate that the concept of capture efficiency may be a useful design tool and warrants further research.

CONCLUSIONS

The modified potential flow solution presented previously has enabled the development of a useful model of capture efficiency for the flanged circular hood operating in the presence of a cross-draught perpendicular to the hood centreline and acting on a point source of gaseous contaminant of low strength. The model predicted capture efficiency with a maximal error of approximately plus or minus an absolute 25% at the critical distance. It is capable of specifying the critical distance with accuracy and is useful in examining the effects of shear-generated turbulence on the dispersion of contaminants. The model, in its final form, is given by eq. (19) where $x = Z/D$ and μ is given by eq. (17).

Capture efficiency is a useful tool in the design of LEV systems. More research is needed to determine the applicability and accuracy of the methods described here for estimating adjustments to LEV systems in order to obtain desired levels of control. The most important research concerns the application of the theory to actual LEV installations and in incorporating sources with different generation characteristics into

Downloaded from https://academic.oup.com/annweh/article-abstract/30/4/497/165659 by Centers For Disease Control user on 21 July 2020

the computer model. If accurate models of capture efficiency can be established, economic optimization of control strategies will be possible and the assessment of changing system parameters enhanced. Ultimately, models of breathing zone concentration may be derivable from capture efficiency.

The question of further specifying and defining ω, the spread parameter for the distribution of contaminant about the idealized streamline, is an interesting fluid mechanics question but may not be of critical importance in industrial hygiene applications. It is probably more important to evaluate the model's ability to incorporate flows around objects and people and to determine what effect this type of turbulence may have on the predictions of capture efficiency.

Acknowledgements—The authors thank Mr William A. Burgess, Dr Michael L. Feldstein, and Dr John S. Evans of the Harvard School of Public Health for their valuable contributions to this work. This project was supported by grant RO3 OHO2101-01 from the National Institute for Occupational Safety and Health of the Centers for Disease Control and by the Occupational Safety and Health Education Resource Center NIOSH grant award 5T1 5OH07096 at the Harvard School of Public Health.

REFERENCES

ACGIH, American Conference of Governmental Industrial Hygienists Committee on Industrial Ventilation (1984) *Industrial Ventilation—A Manual of Recommended Practice* (18th edn). Lansing, Michigan.

Burgess, W. A. and Murrow, J. (1976) *Am. ind. Hyg. Ass. J.* **37**, 546–549.

Dallavalle, J. M. (1930) Studies in the Design of Local Exhaust Hoods. Doctoral Thesis, Harvard School of Public Health, Boston, Massachusetts.

Ellenbecker, M. J., Gempel, R. J. and Burgess, W. A. (1983) *Am. ind. Hyg. Ass. J.* **44**, 752–755.

Fletcher, B. (1977) Centreline velocity characteristics of rectangular unflanged hoods and slots under suction. *Ann. occup. Hyg.* **20**, 141–146.

Fletcher, B. and Johnson, A. E. (1986) The capture efficiency of local exhaust ventilation hoods and the role of capture velocity. *Proc. Ventilation* '85 *1st Int. Symp. Ventilation for Contaminant Control*, Toronto, Canada. 1–3 October, 1985. Elsevier Science Publishers, Amsterdam.

Flynn, M. R. and Ellenbecker, M. J. (1985) *Am. ind. Hyg. Ass. J.* **46**, 318–322.

Flynn, M. R. and Ellenbecker, M. J. (1986) Empirical validation of theoretical velocity fields into flanged circular hoods. Submitted to the *Am. ind. Hyg. Ass. J.* March 1986.

Gifford, F. A. (1982) *Atmos. Environ.* **16**, 505–512.

Hinze, J. O. (1959) *Turbulence. An Introduction to its Mechanism and Theory.* McGraw-Hill, New York.

Jansson, A. (1980) *Staub-Reinhalt. Luft.* **40**, 111–113.

Roach, S. A. (1981) *Ann. occup. Hyg.* **24**, 105–132.

Silverman, L. (1943) Fundamental Factors in the Design of Exhaust Hoods. Doctoral Thesis, Harvard School of Public Health, Boston, Massachusetts.

White, F. (1982) *Fluid Mechanics.* McGraw-Hill, New York.

Downloaded from https://academic.oup.com/annweh/article-abstract/30/4/497/165659 by Centers For Disease Control user on 21 July 2020