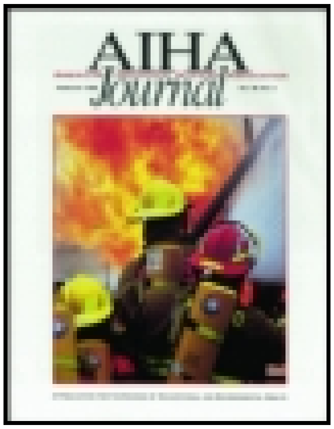

American Industrial Hygiene Association Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/aiha20

MODELING A WORKER'S EXPOSURE FROM A HAND-HELD SOURCE IN A UNIFORM FREESTREAM

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Published online: 04 Jun 2010.

AM. IND. HYG. ASSOC. J. 52(11):458–463 (1991)

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The phenomenon of boundary layer separation can be an important factor in determining a worker's exposure to toxic airborne pollutants. A conceptual model was developed to understand this phenomenon and to predict the average concentration in the reverse flow region downstream of a worker in a uniform freestream. Subsequently, the assumptions of this model were tested experimentally in wind tunnel studies. On the basis of these results, a revised model is presented and validated by using a tracer gas method. The revised model provides a reasonable estimate of the average concentration in the reverse flow region of the mannequin. Empirical models are presented that relate both the average concentration in the reverse flow region and the breathing zone concentration to the body dimensions and the freestream air velocity. Applications and limitations of the results are discussed.

Local exhaust ventilation (LEV) protects workers from exposure to toxic airborne materials produced by various industrial processes. A successful LEV system achieves an acceptable breathing zone concentration with an appropriate margin of safety in a reliable, economic fashion.[1] Unfortunately, current design equations for predicting capture velocity are established on the basis of an unobstructed flow field into the exhaust hood.[2] The presence of a worker in the flow field calls into question the validity of this approach. As air flows around the worker toward the hood, boundary layer separation may occur and result in the formation of counterrotating eddies on the downstream side of the worker. These eddies may transport the contaminant into the breathing zone, particularly when employees position the work between themselves and the source of local exhaust (i.e., the typical orientation).

The adverse effect of reverse flow on breathing zone concentration was demonstrated by several authors.[3–7] George et al.[6] developed a simple mass balance model to estimate the concentration in the reverse flow region of an employee working in a uniform freestream with the typical orientation. This model included several assumptions that were subsequently tested by flow visualization techniques and hot-film anemometry.[8] The purpose of this research is to revise the mass balance model based on the previous experimental results and then to validate the revised model with a tracer gas method.

REFORMULATION OF VORTEX SHEDDING MODEL

The simple mass balance model,[6] developed to predict concentrations in the reverse flow region of a worker, assumes the following.

1. The worker can be represented by a circular cylinder of finite height H and diameter D.
2. The whole body is subject to the vortex shedding process, which occurs over the entire height of the worker.
3. Vortex shedding is the principal contaminant removal mechanism.
4. The area of a vortex covers one-half the formation region.

The formation region is defined[9] as the zone immediately downstream of the cylinder that extends until fluid from outside the wake crosses the wake axis. Studies[9,10] suggest that this region is approximately a cylinder diameter wide. On the basis of these assumptions, the spatially and temporally averaged concentration (C_{st}) within the zone is

$$C_{st} = \frac{Q_s}{Q_v} \tag{1}$$

where Q_s is the flow of contaminant into the zone and Q_v is the air-contaminant-mixture flow out of the zone. In the exact sense, C_{st} is a long-term average in time and a volume average in space. The formation region is assumed to be a cylinder as tall (H) and as wide (D) as the worker. Here, D is the width at the chest of the worker, perpendicular to freestream, which will be used throughout this paper. Because the volume cleared with every vortex shedding event is assumed to be one-half the formation region, the vortex volume (V) is

$$V = \frac{\pi}{8} D^2 H \tag{2}$$

*Support for this research was provided by the Shell Oil Company Foundation and the National Institute for Occupational Safety and Health, Grant 5 R01 OH02392-02.

By Assumption 1 in the previous list, the frequency with which a vortex is shed from one side of the worker is

$$f = \frac{SU}{D} \quad (3)$$

where U is the freestream velocity and S is the Strouhal number. The Strouhal number, for flow around a circular cylinder, remains constant at 0.21 for Reynolds numbers from 400 to about 200 000. This represents a range in which Reynolds numbers around workers will almost always fall.

Because the frequency f in Equation 3 is from one side of the cylinder only, the total frequency with which a vortex is shed from either side of the cylinder is twice the frequency from a single side, or 2f; thus, $Q_v = 2fV$. A simple approximation for the average concentration is

$$C_{st} = \frac{Q_s}{Q_v} = \frac{19Q_s}{\pi UHD} \quad (4)$$

In a previous study,[8] some of the assumptions used in this model were tested.

Assumptions 1 and 2 were examined by hot-film anemometry and flow visualization techniques. Experimental results suggested that airflow around a person immersed in a uniform freestream has a three-dimensional nature. Above the chest level, a downwash effect (i.e., air flowing down over the head and the shoulders) is important; from the chest to the elbows, a combination of downwash and vortex shedding exists; and from the waist to the hip vortex shedding appears dominant. In the region subject to vortex shedding, each vortex is shed downstream at a dimensionless frequency (Strouhal number) of 0.19, which is lower than 0.21 for the two-dimensional circular cylinder. This Strouhal number is the average value from the chest level to the hip level, and a statistical analysis showed no difference among the levels.[8] In addition, a coherent vertical flow is present in the proximity of the body; in the upper section (above the hip level) the mean flow is directed upward; and in the lower section, the mean flow is directed downward.

Assumption 4 was not easy to test because of the vague definition of the formation region. Instead, the area of a vortex was estimated by measuring the vortex size directly from the videos obtained from flow visualization. The average area of a vortex from the waist to the thigh was approximately 70% of the area of a circle with a diameter equal to the mannequin width at the given level.[8]

Assumption 3, contaminant removal by vortex shedding, was studied by several researchers[11–15] for the transport of contaminant in the wake downstream of bluff bodies. One of their conclusions[15] is that although transport of material into and out of the near-wake region of a disk (axisymmetric body) is dominated by turbulent diffusion, the mass transport for a long, flat plate (two-dimensional body) is dominated by the periodic shedding of vortices, and to a lesser extent by turbulent diffusion. If a worker is regarded more as a flat plate than a disk, it is reasonable to assume that the periodic shedding of vortices is the main transport mechanism downstream of the worker. This is supported by the fact that vortex shedding was observed from the chest to the hip in the previous study.[8]

To revise the original mass balance model based on the above results, the air-contaminant-mixture flow out of the reverse flow region is computed by integrating the vortex size and Strouhal number at each level over the entire height of the mannequin. However, based on flow visualization results, smoke below the hip level moved downward and escaped from the lower reverse flow region rather than being transported into the upper region. Thus, it is assumed that from the chest down to the hip level, approximately 0.3H (where H is the height of the mannequin) vortex shedding occurs with a frequency represented by an average Strouhal number of 0.19. The same diameter D is used as in the original model. If the average area of each vortex is 0.7 times the area of a circle with the same diameter as that of the mannequin at the chest level, then the vortex volume (V) is

$$V = 0.7\left(\frac{\pi}{4}D^2\right)(0.3H) \quad (5)$$

Because:

$$f = \frac{0.19U}{D} \quad (6)$$

a modified approximation for the spatially and temporally averaged concentration is

$$C_{st} = \frac{50Q_s}{\pi UHD} \quad (7)$$

EXPERIMENTAL MATERIALS AND METHODS

The experiments were carried out in a low-speed, open-circuit wind tunnel 5 ft square and 8 ft deep. The fan was equipped with a variable torque to control the air velocity in the tunnel within the range of 25–275 fpm. The longitudinal component of freestream turbulence intensity was approximately 7%.

As shown in Figure 1, a commercial anthropometric mannequin, 41 in. tall and 8 in. wide at the chest, was placed on the centerline of the tunnel, about 1.5 ft from the tunnel face, and in a typical work orientation with respect to exhaust, facing

FIGURE 1. Experimental setup

downstream. To sample the breathing zone concentration, one end of a 0.25-in. diameter tube was inserted through the back of the mannequin's head and mounted in the mouth. The other end of the tube was connected to an infrared spectrophotometer located outside the tunnel.

Neutrally buoyant 10% sulfur hexafluoride (SF_6) was used as a tracer gas (an air-helium-SF_6 mixture with the same molecular weight as that of air). The tracer was released through a 1/4-in. diameter ceramic sphere at a flow of 0.005 cfm. Pores in the sphere allowed the gas to diffuse in all directions. The sphere was mounted in the hands of the mannequin, and a constant differential pressure regulator was used to reduce fluctuations in the flow rate.

A moving mechanism controlled from outside the wind tunnel was used to position the receptor at the sampling point without interfering with the airflow. By using the smoke-wire technique, the interference of the device itself with airflow patterns was qualitatively checked. No significant difference between the airflow field with and without the device in the tunnel was observed. A sampling network with 4-in. × 4-in. uniform square grids was developed consisting of 45 sampling points: 7, 10, 12, and 16 points in four planes at the chest, elbow, waist, and hip levels, respectively. The breathing zone concentration was assumed to represent the concentration at the neck and nose level.

All experiments were run at freestream velocities of 100, 150, and 250 fpm. The Reynolds numbers associated with these velocities are 6837, 10 256, and 17 094, respectively, based on an 8-in. mannequin chest width. The system was allowed to equilibrate for 15 min, then the concentration was measured for 15 min at 0.2 Hz by the spectrophotometer connected to a microcomputer in which an analog/digital converter was installed. Preliminary results indicated that a 15-min average concentration taken after the initial equilibration period was representative of the average concentration for the first hour. After a sampling period, the receptor was repositioned and the process repeated. After sampling each plane, the breathing zone concentration was measured. This entire procedure was repeated once. The total number of concentration measurements was 294 (49 sampling points × 3 velocities × 2 repetitions).

RESULTS AND ANALYSIS

Results of the tracer gas measurements are shown in Table I. The average concentrations at each level show much difference, particularly between the level of the chest and the elbow because the source of tracer gas was positioned between these two levels. The breathing zone concentrations (BZC) were slightly less than the average concentration in the reverse flow region. The temporal coefficient of variance averaged for the sampling points at each level is given in the parentheses to compare how the concentrations vary with time. In general, temporal variation in the breathing zone concentrations is greater than the temporal variation in the reverse flow zone

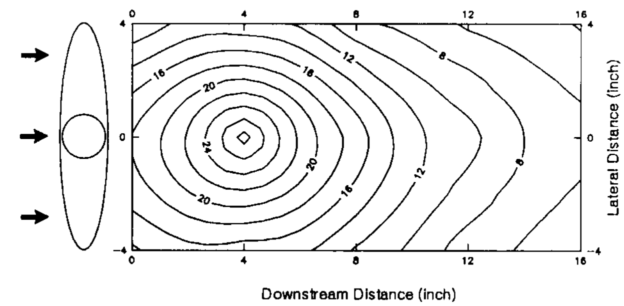

FIGURE 2. Concentration contour map with freestream velocity of 150 fpm at elbow level (unit of concentration: ppm)

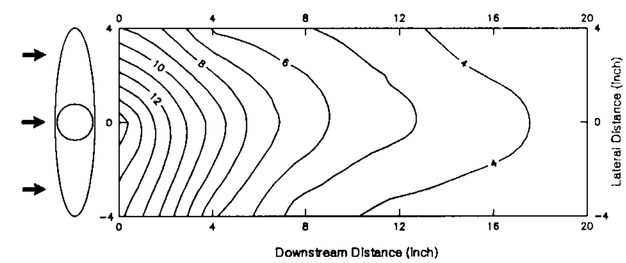

FIGURE 3. Concentration contour map with freestream velocity of 150 fpm at hip level (unit of concentration: ppm)

TABLE I. Results of the Tracer Gas Measurements[A]

Level	100 fpm First Run	100 fpm Second Run	150 fpm First Run	150 fpm Second Run	250 fpm First Run	250 fpm Second Run
Chest	61.2 (12.9)[B]	72.2 (6.9)	36.7 (9.4)	47.2 (11.9)	21.1 (6.8)	18.2 (10.4)
Elbow	22.3 (17.9)	26.2 (9.8)	12.6 (11.2)	15.2 (13.6)	10.1 (11.2)	9.0 (9.2)
Waist	17.4 (12.9)	20.0 (10.6)	10.1 (10.0)	11.2 (8.8)	6.9 (8.5)	6.4 (7.3)
Hip	12.1 (13.0)	14.4 (15.1)	6.1 (14.8)	6.9 (16.3)	5.7 (6.1)	4.2 (5.8)
BZC	18.7 (26.8)	20.2 (42.4)	11.3 (33.7)	12.6 (25.5)	7.3 (27.1)	7.1 (32.9)
Average	23.3	27.3	13.4	16.1	9.3	8.0

[A]All units in ppm (%).
[B]( ): Average temporal coefficient of variance.

concentrations, probably because the head region is more sensitive to the direction of freestream air because of the relatively narrow dimension.

Concentration contour maps presented in Figures 2 and 3 illustrate the pattern of contaminant dispersion at the level of elbow and hip, respectively, at the freestream velocity of 150 fpm. The spot with the highest concentration in Figure 2 is around the position of tracer gas source.

The data of each run fit a lognormal distribution well. To check whether there is some difference in the pattern of contaminant dispersion among the different freestream velocities, the spatial variances of the logarithms of the measured concentration at each level of the mannequin are calculated and presented in Table II. The data show that not much difference in the variances exists among freestream velocities at each level of the mannequin, except at the waist level for the velocity of 250 fpm, relatively low spatial variance. This is supported by an F test, which evaluates the significance of the difference between two variances. The difference between variances at 150 fpm and 250 fpm at waist level is significant, $p < 0.05$; no significant difference exists among other combinations.

The results are summarized and compared with theoretical predictions in Table III. The revised model overestimates the concentration in the reverse flow region by 38% at the low velocity and up to 61% at the high velocity; i.e., the magnitude of overestimation is proportional to freestream velocity. Breathing zone concentrations are about 80% of the average concentration in the reverse flow region.

The comparison of experimental concentrations with the predicted values from the models at different freestream velocities is illustrated in Figure 4. The top curve with the shaded region represents the predicted concentration by the revised model, Equation 7, with one standard deviation.[16] The reason the revised model has this range is that the reformulation is based on experimental results for vortex shedding frequency and vortex size from the study.[8] The bottom curve plots the concentration predicted by the original model: Equation 4. Because the original model is purely a conceptual one, there is no error band. The measured average concentrations in the reverse flow region and the breathing zone concentrations fall between the two models. The error bars represent one standard deviation about the measured concentrations.

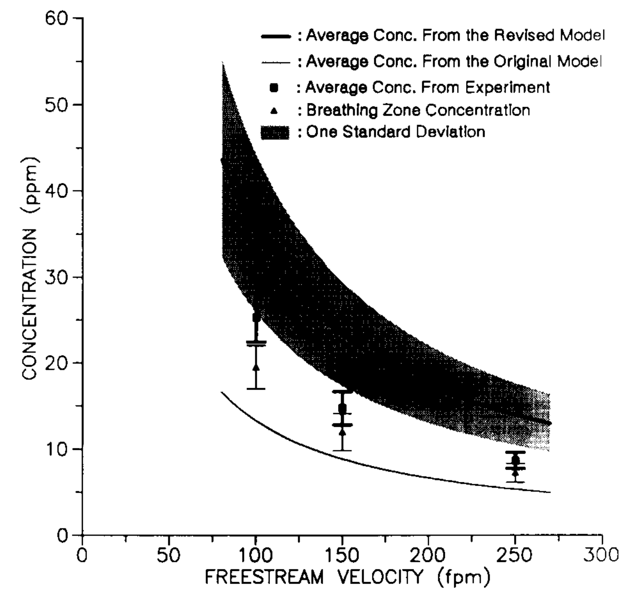

FIGURE 4. Comparison of experimental concentrations with predicted values

Least squares regression analyses were conducted to relate the average concentration in the reverse flow region (C_{st}) and the breathing zone concentration (C_{bz}) to a dimensionless variable. The variable is $Q_s/(UHD)$ where Q_s is the contaminant flow rate, U the freestream velocity, D the chest breadth of a worker, and H the height of the worker. In fact, this dimensionless variable is a combination of three different pieces of information:

- The contaminant source: Q_s
- The flow condition: UH (proportional to Reynolds number)
- The shape of the worker: H and D

Statistical analysis gives the following empirical formulas:

$$C_{st} = \frac{10.96Q_s}{UHD} \quad (8)$$

$$C_{bz} = \frac{8.62Q_s}{UHD} \quad (9)$$

with $r^2 = 0.97$ and 0.99, respectively. Knowing the source flow (Q_s: cfm); the freestream velocity (U: fpm); the height (H: ft);

TABLE II. Variance of the Logarithms of the Measured Concentration by Freestream Velocity and Level

Level	*DF*[A]	*100 fpm*	*150 fpm*	*250 fpm*
Chest	14	0.521401	0.733219	0.503611
Elbows	20	0.265944	0.192958	0.220455
Waist	24	0.182895	0.230691	0.098377
Hip	32	0.303081	0.236869	0.210883

[A]Degrees of freedom.

TABLE III. Comparison of the Measured Concentrations with Predictions

Air Velocity (fpm)	*Measured Average Concentration (C_{avg}) (ppm)*	*Breathing Zone Concentration (BZC) (ppm)*	*Predicted Concentration from Eq. 7 (C_{pred}) (ppm)*	$\frac{BZC}{C_{avg}}$	$\frac{C_{pred}}{C_{avg}}$
100	25.3	19.5	34.9	0.77	1.38
150	14.7	12.0	23.3	0.81	1.58
250	8.7	7.2	14.0	0.83	1.61

and the chest breadth (D: ft); the average concentration (C_{st}: ppm) in the reverse flow region and the breathing zone concentration (C_{bz}: ppm) can be predicted with good accuracy.

DISCUSSION

The empirically revised model (Equation 7) overestimates the average concentration in the reverse flow region. There are several factors not included in the model that may significantly affect its predictive capability.

First, mass transport into and out of the reverse flow zone by turbulent diffusion was not considered. This mechanism may lead to more exchange at the boundary of the zone; hence, lower measured concentrations than predicted. A previous study[6] suggested the growing importance of turbulent diffusion and enhanced transport with increasing Reynolds number. As shown in Table III, the ratio of the breathing zone concentration to the average concentration in the reverse flow zone increases from 0.77 to 0.83 with increasing freestream velocity. This may reflect enhanced transport by turbulent diffusion. In addition, the ratio of the model prediction to the average measured concentration in the zone increases with freestream velocity from 1.38 to 1.61, increasing loss of mass from the reverse flow zone as velocity increases.

Second, it was assumed that there is no vertical mass transport between the lower region, below the hip level, and the upper region. If there is vertical transport, it may reduce the concentration in the upper region. In other words, if there is upward flow from the lower region with relatively low concentration to the upper region, it may reduce the concentration in the region of interest. If downward flow exists, the air with high concentration will escape from the region of interest and also reduce the concentration.

Third, only the region from the chest to the hip was considered subject to the vortex shedding process, and thus responsible for contaminant removal from the region of interest. Some contaminant may, however, go up to the neck and the head and escape from the region of interest, thus reducing the concentration. In addition, there is uncertainty in estimating the area of a vortex because of the dispersion of the smoke used in the flow visualization studies and the difficulty in isolating a vortex from the video screen.

Equations 7, 8, and 9 suggest that the average concentration in the reverse flow region and the breathing zone concentration are inversely proportional to UHD. To extend the experimental results to actual conditions geometric similarity is required, i.e., a scale model must be used; and the Reynolds number of the model must equal that of the actual situation, i.e., dynamic similarity. To maintain geometric similarity, experimental dimensions would have to be multiplied by a factor of about 1.6, based on the height (65.6 in.) of the average U.S. person.[17] To maintain Reynolds number equality, UD = constant, velocities would need to decrease by the same factor. The velocity range used in this study is approximately equivalent to 63–156 fpm when scaled to a real situation. If the freestream velocity (U) is constant, the concentration will be inversely proportional to HD, which implies that the exposure for a bigger person may be lower than that for a smaller one. In addition, increasing the freestream velocity will not always be a cost-effective measure to control a worker's exposure. The marginal cost will gradually increase because of the inverse proportionality of the breathing zone concentration to the freestream velocity.

The models and the experimental results presented here are for a simple situation. Several important factors have not been considered, including accelerating flows into hoods, workplace activity, significant contaminant source momentum, workpieces in front of the worker, and crossdrafts. A complex problem is introduced whenever one of the above factors is included in this simple case. There may be two other approaches to attack this complex problem economically. One is computer simulation[18] and another is the scale modeling used in this study. Both approaches should be used together and vigorously tested in the field.

CONCLUSIONS

The objective of local exhaust ventilation is to control the concentration of toxic airborne contaminants in a worker's breathing zone. Current design practices do not consider the effect of an object in front of the exhaust hood. The reverse flow zone formed downstream of the worker can pull the contaminant back into the breathing zone. To understand this phenomenon, a simple conceptual model was developed and the assumptions tested.

In this study, the original model is revised based on experimental results and the revised model is validated by using a tracer gas method in a wind tunnel. Experimental results are in reasonable agreement with those predicted from either the original or the revised model. Additionally, results suggest the growing importance of turbulent diffusion and enhanced mass transport with increasing Reynolds number. The inverse proportionality of the breathing zone concentration to the freestream velocity and the dimensions (height and width) of a worker suggest that the exposure for a bigger person may be lower than that for a smaller person.

Furthermore, increasing the freestream velocity will not always be a cost-effective measure to control worker exposure. Caution is necessary when extrapolating the results to real-life situations, however, because the stationary mannequin, the passive contaminant source, and the uniform freestream used in this study are not representative of many industrial situations. Although these factors may limit the applicability of the results, this type of study can improve understanding of contaminant control in the workplace. Further research into this complex problem is presently underway.

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