Applied Industrial Hygiene

ISSN: 0882-8032 (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/uaph20

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To cite this article: Richard P. Garrison & Muzaffer Erig (1989) Ventilation to Eliminate Oxygen Deficiency in a Confined Space—Part II: Noncubical Models, Applied Industrial Hygiene, 4:10, 260-268, DOI: 10.1080/08828032.1989.10388588

To link to this article: https://doi.org/10.1080/08828032.1989.10388588

Ventilation to Eliminate Oxygen Deficiency in a Confined Space—Part II: Noncubical Models

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This study investigated characteristics of ventilation to eliminate oxygen deficiency for confined space (CS) models having several noncubical shapes. Variations from a basic cubical shape (studied previously) included sideways expansion (normal to the vertical ventilation axis), depthwise expansion (parallel to the ventilation axis), and expansions in more than one direction. Variable design parameters, in addition to shape, included ventilation mode (exhaust and supply), volume flow rate, inlet/outlet elevation, and location inside the CS model. Regressions of the experimental data supplement a database from previous studies of a cubical model. The oxygen recovery data can be used to calculate ventilation times, subject to consideration of limitations which apply to the results. The findings also suggest general guidelines for CS ventilation design. Progressive sideways and depthwise expansions produced progressive increases in ventilation time for oxygen recovery. This variation was consistent for changes in flow rate and inlet/outlet elevation. Depthwise expansion experienced more rapid oxygen recovery than did sideways expansion. Supply ventilation was generally more effective than exhaust ventilation. Orientation of the ventilation axis parallel to the long sides of noncubical CS models caused faster oxygen recovery than when the ventilation axis was parallel to the short sides. Oxygen recovery for CS locations in direct alignment with the supply ventilation outlet was considerably faster than for other, nonaligned locations. Findings suggest that empirical approximations may be determined for development of a multiparameter predictive design model for CS ventilation. Garrison, R.P.; Erig, M.: Ventilation to Eliminate Oxygen Deficiency in a Confined Space—Part II: Noncubical Models. Appl. Ind. Hyg. 4:260-268; 1989.

Introduction

Confined workplaces have many shapes and sizes. Oxygen deficiency is one type of atmospheric hazard which can exist inside a confined space (CS). A previous study has investigated ventilation characteristics for eliminating oxygen deficiency in a closed-top cubical CS model having a single top opening.(1) This previous study has shown that parameters such as ventilation mode (exhaust vs. supply), ventilation volume flowrate, ventilation inlet/outlet (I/O) elevation, and location inside the CS model had significant effects upon the rate of oxygen recovery to ambient level (nominally 21.0 %O_2).

The subsequent study presented here has investigated CS models having noncubical shapes. The shapes studied constitute progressive variations (expansions) from the basic cubical model studied previously. These shape variations involved, in effect, the addition of cubical volumes to the basic cubical model to create several simple noncubical configurations. As in the previous study, ventilation characteristics were tested as they affected oxygen recovery from an initial deficiency.

The objectives of this study were to 1) observe and evaluate ventilation (oxygen recovery) characteristics of noncubical CS models and 2) add to the data base established by the previous study. It is planned that this data base can be used subsequently to develop an empirical design model capable of predicting CS ventilation performance.

This research was part of a project funded by the National Institute for Occupational Safety and Health (NIOSH) to test, evaluate, and develop information on ventilation for work in confined spaces.

Experimental Facilities and Methods

With the exception of the CS models, the experimental facilities for this study were the same as the previous study. This consisted of the CS models and attendant systems for releasing nitrogen into the models to create oxygen deficiency, ventilating the CS models, sampling air and monitoring oxygen concentrations at specific locations, and collecting data (%O_2 vs. time) using analog/digital conversion and a personal computer. The oxygen monitoring system utilized four electrochemical sensors for simultaneous continuous measurements from four locations inside each CS model. A more detailed discussion is provided in the first study.(1)

Figure 1 illustrates the CS model shapes which were studied. Shapes A and B are cubical. Shape A, measuring 0.61 m (2.0 ft) on each edge, was the basic shape studied previously and is "contained" within all of the other models. The overall dimensions of Shape B are twice those of A, with a volume eight times greater. Shape B represents an expansion from the basic CS Model A in three directions. Five noncubical shapes (C, D1, D2, E1, and E2) were investigated in this study.

Shape C had the same height, 0.61 m (2.0 ft), as the basic cube (Shape A), with twice the width and length, 1.22 m (4.0 ft). Shape C

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was, in effect, the top half of Shape B and represented two-directional sideways (perpendicular to the ventilation axis) expansion from the basic CS Model A.

Shapes D1 and D2 were the same model but with different ventilation configurations. The D shapes each had twice the volume of CS Model A. Shape D1 involved sideways (horizontal) expansion from CS Model A, with the vertical ventilation axis parallel to the short sides of the model, measuring 0.61 m (2.0 ft). Shape D2 was configured vertically, representing depthwise expansion from CS Model A, with the ventilation axis parallel to the long sides of the model, measuring 1.22 m (4.0 ft).

Shapes E1 and E2 also were the same model, except for the orientation of the ventilation axis. The E shapes had three times the volume of the basic cubical model. Shape E1 involved sideways expansion from CS Model A and was configured with the vertical axis of the ventilation inlet/outlet parallel to the short sides, measuring 0.61 m (2.0 ft). Shape E2 involved depthwise expansion from CS Model A and was configured with the ventilation axis parallel to the long sides, measuring 1.83 m (6.0 ft).

Figure 2 shows the experimental facility with the CS models, C, D (D1/D2), and E (E1/E2). The models were constructed of plywood on their top, bottom, and two sides, with clear plexiglas on the other two sides. The interior wooden surfaces were painted black. The size and position of the top opening was the same for all of the CS model shapes in Figure 1, i.e., 15.2 cm (6.0 inches) in diameter and centered in a corner, 15.2 cm (6.0 in.) from each of the two closest walls of the model. The inside diameter of the ventilation pipe, 5.1 cm (2.0 in.), was the same for all of the models.

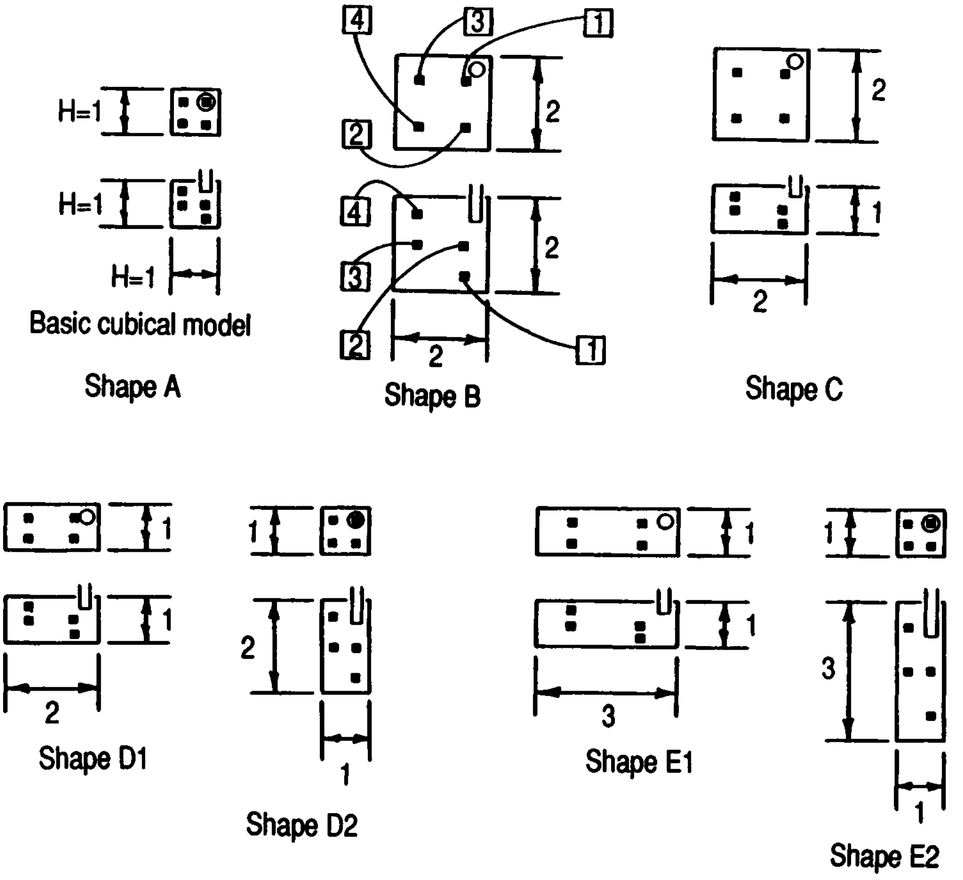
The four sampling locations were set at the same nondimensional positions for all models. This was done to accommodate development of a predictive model and involved different actual positions for each model. These locations may be described as follows:

- Location 1 was the lowest, at 15 percent of the total model height from the bottom, centered in the vertical quadrant containing the ventilation pipe.
- Locations 2 and 3 were diagonally opposed to each other, at the midplane (50% model height) and centered in quadrants adjacent to that of Location 1.
- Location 4 was diagonally opposed to Location 1, at an elevation 85 percent of model height.

A total of 108 (2 × 3 × 3 × 6) cases were tested, consisting of two ventilation modes, three volume flow rates, and three inlet/outlet elevations for each of the six new CS models. These cases can be specified as follows:

- Exhaust and supply ventilation modes.
- Volume flow rates of 20, 40, and 60 ACH (air changes per hour obtained by dividing the actual ventilation volume flow rate by the volume of the CS model).
- Inlet/outlet (I/O) elevations of 25, 50, and 75 %H (percentage of model height measured from the bottom).
- CS Models B, C, D1, D2, E1, and E2 (CS Model A was studied previously).

The test procedure for measuring oxygen deficiency was the same as in the previous study.[1] An oxygen deficient atmosphere



Note: O denotes ventilation opening, ■ denotes sampling point

FIGURE 1. Top and front views of the CS model shape and size variations, ventilation opening positions, and air sampling locations.

TABLE I. Regression Values of Oxygen Recovery Time Constants (C) for Exhaust Ventilation with Different CS Model Configurations

CS Parameters			Oxygen Recovery Time Constant (C)						
			CS model configuration						
Inlet/ Outlet Elevation	Volume Flow Rate	Location	Basic Cubical Model	Sideways Expansion		Depthwise Expansion		Multi-directional	
				(×2)	(×3)	(×2)	(×3)	(2D)	(3D)
(%H)	(ACH)	(1–4)	A	D1	E1	D2	E2	C	B
25	20	1	0.33*	0.35	0.31	0.34*	0.35*	0.29	0.30
		2	0.34	0.34	0.31	0.32	0.32	0.30	0.29
		3	0.36	0.33	0.30	0.33	0.33	0.32	0.28
		4	0.27	0.35	0.24	0.29	0.30	0.25	0.29
	40	1	0.70*	0.58	0.49	0.70*	0.70*	0.48	0.50
		2	0.61	0.53	0.49	0.60	0.69	0.47	0.48
		3	0.61	0.54	0.44	0.60	0.60	0.51	0.48
		4	0.67	0.53	0.42	0.59	0.58	0.48	0.49
	60	1	1.03*	0.75	0.56	0.88*	0.88*	0.61	0.68
		2	0.88	0.73	0.58	0.86	0.86	0.57	0.58
		3	0.81	0.70	0.55	0.80	0.86	0.68	0.60
		4	0.92	0.73	0.54	0.86	0.82	0.62	0.62
50	20	1	0.35*	0.31	0.34	0.37*	0.35*	0.32	0.30
		2	0.36	0.31	0.33	0.34	0.33	0.31	0.30
		3	0.36	0.31	0.27	0.34	0.32	0.34	0.27
		4	0.30	0.30	0.23	0.30	0.30	0.26	0.29
	40	1	0.72*	0.57	0.45	0.67*	0.64*	0.48	0.51
		2	0.66	0.55	0.48	0.60	0.60	0.47	0.50
		3	0.65	0.55	0.40	0.60	0.60	0.49	0.46
		4	0.69	0.56	0.35	0.58	0.55	0.45	0.45
	60	1	0.92*	0.81	0.62	0.90*	0.91*	0.53	0.62
		2	0.81	0.71	0.65	0.83	0.84	0.52	0.59
		3	0.81	0.76	0.55	0.82	0.83	0.58	0.58
		4	0.84	0.76	0.56	0.80	0.80	0.54	0.64
75	20	1	0.18*	0.30	0.31	0.36*	0.37*	0.24	0.26
		2	0.20	0.29	0.30	0.33	0.34	0.24	0.25
		3	0.20	0.29	0.27	0.33	0.34	0.23	0.26
		4	0.17	0.24	0.25	0.32	0.33	0.20	0.25
	40	1	0.30*	0.49	0.42	0.64*	0.67*	0.28	0.32
		2	0.28	0.48	0.41	0.56	0.61	0.29	0.32
		3	0.27	0.47	0.42	0.56	0.61	0.29	0.33
		4	0.24	0.49	0.38	0.50	0.58	0.27	0.34
	60	1	0.51*	0.72	0.52	0.89*	0.91*	0.30	0.44
		2	0.48	0.63	0.54	0.76	0.83	0.32	0.41
		3	0.48	0.64	0.48	0.80	0.80	0.31	0.45
		4	0.48	0.65	0.50	0.79	0.79	0.30	0.45

Note: All locations are in centers of vertical quadrants of CS models: 1) near bottom (15 %H) in same quadrant as ventilation inlet/outlet (I/O), "*" indicates location is in alignment with (directly below) I/O; 2) and 3) at midplane (50 %H) in quadrants adjacent to I/O; and 4) near top (85 %H) in quadrant opposite (most distant from) I/O.

TABLE II. Regression Values of Oxygen Recovery Time Constants (C) for Supply Ventilation with Different CS Model Configurations

CS Parameters			Oxygen Recovery Time Constant (C)						
			CS model configuration						
Inlet/ Outlet Elevation	Volume Flow Rate	Location	Basic Cubical Model	Sideways Expansion		Depthwise Expansion		Multi-directional	
				(×2)	(×3)	(×2)	(×3)	(2D)	(3D)
(%H)	(ACH)	(1–4)	A	D1	E1	D2	E2	C	B
25	20	1	10.60*	0.38	0.30	8.50*	7.30*	0.30	0.28
		2	0.76	0.42	0.30	0.62	0.51	0.32	0.29
		3	0.75	0.40	0.31	0.62	0.49	0.30	0.28
		4	0.44	0.32	0.28	0.42	0.43	0.27	0.27
	40	1	8.10*	0.54	0.48	7.00*	6.00*	0.52	0.51
		2	0.82	0.49	0.45	0.70	0.57	0.48	0.50
		3	0.87	0.48	0.48	0.78	0.70	0.54	0.51
		4	0.81	0.46	0.45	0.68	0.56	0.51	0.52
	60	1	5.60*	0.72	0.71	5.30*	5.00*	0.77	0.72
		2	0.98	0.71	0.68	0.90	0.83	0.73	0.76
		3	1.06	0.68	0.71	1.00	0.95	0.78	0.77
		4	1.01	0.67	0.71	0.90	0.85	0.74	0.82
50	20	1	1.14*	0.36	0.30	0.83*	0.51*	0.30	0.29
		2	0.65	0.41	0.27	0.51	0.42	0.31	0.30
		3	0.63	0.36	0.29	0.56	0.50	0.29	0.29
		4	0.42	0.30	0.25	0.40	0.43	0.27	0.26
	40	1	1.22*	0.54	0.51	1.10*	0.83*	0.53	0.51
		2	0.70	0.55	0.44	0.66	0.64	0.47	0.53
		3	0.71	0.51	0.46	0.70	0.70	0.50	0.53
		4	0.70	0.50	0.43	0.60	0.71	0.48	0.53
	60	1	1.88*	0.77	0.72	1.50*	1.16*	0.75	0.77
		2	0.92	0.79	0.68	0.92	0.90	0.70	0.79
		3	1.01	0.77	0.70	0.99	1.00	0.71	0.80
		4	0.98	0.76	0.65	0.90	1.00	0.72	0.80
75	20	1	0.62*	0.32	0.26	0.53*	0.41*	0.29	0.34
		2	0.49	0.34	0.24	0.42	0.38	0.30	0.34
		3	0.52	0.32	0.24	0.45	0.38	0.29	0.34
		4	0.42	0.28	0.22	0.40	0.37	0.28	0.34
	40	1	0.64*	0.55	0.49	0.90*	0.72*	0.51	0.61
		2	0.71	0.52	0.41	0.70	0.68	0.48	0.61
		3	0.72	0.50	0.44	0.69	0.68	0.50	0.62
		4	0.73	0.48	0.41	0.69	0.68	0.48	0.63
	60	1	0.87*	0.71	0.72	0.92*	1.12*	0.75	0.90
		2	0.92	0.78	0.65	1.00	1.00	0.71	0.93
		3	0.86	0.76	0.67	1.00	1.10	0.72	0.90
		4	0.95	0.79	0.63	1.00	1.10	0.73	0.90

Note: All locations are in centers of vertical quadrants of CS models: 1) near bottom (15 %H) in same quadrant as ventilation inlet/outlet (I/O), "*" indicates location is in alignment with (directly below) I/O; 2) and 3) at midplane (50 %H) in quadrants adjacent to I/O; and 4) near top (85 %H) in quadrant opposite (most distant from) I/O.

FIGURE 2. Experimental facility showing CS Models C, D, and E (bottom, right, and left, respectively) and the ventilation, nitrogen release, air sampling, and oxygen monitoring systems.

was created by releasing nitrogen into a CS model. Samples of air from the four locations inside the model were drawn past the oxygen sensors and O_2 (%) vs. time (minutes) was recorded by the computer. Data for each test were collected continuously until all locations had recovered to the ambient oxygen level, with one measurement approximately every second for each location in sequence.

Regression of Experimental Data

Tables I and II present the results of nonlinear regressions of the experimental data (%O_2 vs. time). This was done using the same exponential model, Model 1, used in the previous study.(1)

$$\%O_2 = 21 - (21-B)e^{-Ct}$$

In this model, the coefficients (21–B) and C represent the initial oxygen concentration and a recovery time constant, respectively. The value of C describes the rate of oxygen recovery from an initial deficiency. Model 1 was selected over Model 2 of the previous study because it is simpler and yielded strong enough correlation with the experimental data to satisfy design purposes.

The regressions were performed in the same manner as the previous study, on a personal computer using commercial statistical software (SYSTAT). The regression data describe the experimental data quite well. For the 108 test cases, the coefficients of determination (R^2) averaged 99.6 percent, ranging from 94.8 percent to 99.9 percent. The regression data were determined to represent the experimental data with a confidence of greater than 99 percent. The standard errors of the model estimates were less than 1 percent of the experimental data.

Tables I and II, for exhaust and supply ventilation, respectively, provide the regression data for the CS model shapes tested in this study, i.e., Shapes D1, D2, E1, E2, C, and B, and for Shape A from the previous study.(1) Values of C are given for each of the four sampling locations. Regression values for (21–B) were not included because they do not enter into calculations for ventilation time using the exponential model. These tables supplement the database for the cubical CS Model A provided in the previous study.(1) The complete database, for cubical and noncubical models and other subsequent studies, may be utilized in subsequent development and evaluation of multiparameter predictive computer models for CS ventilation design.

It should be noted that oxygen recovery was much (five or more times) faster for Location 1 under supply ventilation for CS Models A, D2, and E2, for which this location was aligned with (directly below) the ventilation outlet. The C values for Location 1 in Table II are significantly greater than 1.0 for low (25 %H) I/O elevations at all flowrates (ACH) for these models. This effect was less pronounced as the models expanded in a depthwise direction. This characteristic emphasizes the general importance of directing supply airflow towards a specific location whenever possible to maximize contaminant dilution at that location.

It should also be noted that oxygen recovery was generally faster for supply ventilation than for exhaust. This can be characterized by the average C values for Tables I and II, which are C = 0.5 (exhaust) and C = 0.63 (supply), respectively. The "average" for supply is conservative because C values for Location 1 which exceeded 1.0 were averaged as being 1.0 in order to avoid biasing the overall average.

Ventilation Time and Limitations

The most useful direct application of the recovery time constant (C) regression database is for calculating approximate ventilation time for oxygen recovery. Ventilation time can be derived from the regression model. It is a function of the initial and final oxygen levels and the recovery time constant.

$$\begin{array}{l}\text{Ventilation time (minutes)} \\ \text{for oxygen recovery}\end{array} = \frac{\ln\left[(21-\%O_2\ \text{initial})/(21-\%O_2\ \text{final})\right]}{C}$$

Table III is a condensation of the data in Tables I and II. Data for different locations have been eliminated. The C values in Table III are regression data for application throughout the CS model. These data are the minimum values of C for the four sampling locations for each test case. These approximations do not account for situations in which a specific location is directly aligned with a supply ventilation outlet, for which oxygen recovery is much faster and C may be significantly greater than 1.0. However, for practical applications, C = 1.0 represents very rapid recovery, and there is no benefit for design in specifying C values greater than 1.0.

It is useful to consider some example situations. The C values in Table III range roughly from C = 0.2 (low flow rates, 20 ACH, and high, 75 %H, I/O elevations) to C = 1.0 (high flow rates, 60 ACH). Two possible recovery situations would be 1) 90 percent recovery (e.g., from 10 %O_2 to 20 %O_2) and 2) 99 percent recovery (e.g., from 10 %O_2 to 20.9 %O_2). Ventilation times would be calculated to be 1) 2.4 minutes for 90 percent recovery with C = 1.0, 2) 12.0 minutes for 90 percent recovery with C = 0.2, 3) 4.7 minutes for 99 percent recovery with C = 1.0, and 4) 23.5 minutes for 99 percent recovery with C = 0.2. These data, subject to their limitations, suggest that mechanical ventilation can eliminate oxygen deficiency within a relatively brief period of time.

It is important to keep in mind some of the major limitations of these data which will affect ventilation time to eliminate oxygen deficiency in a confined space. These limitations include the range of CS model configurations studied, different contaminant characteristics causing oxygen deficiency, and the application of

TABLE III. Minimum Recovery Time Constants (C) for Calculating Ventilation Time for Different Confined Space Configurations with a Single Top Opening when Oxygen Deficiency is Caused by a Neutrally Bouyant Gas or Vapor

CS Ventilation Design Parameters		Oxygen Recovery Time Constant (C)						
		CS configurations						
Inlet/ Outlet Elevation	Volume Flow Rate	Basic Cubical Shape	Sideways Expansion		Depthwise Expansion		Multi-directional	
			(×2)	(×3)	(×2)	(×3)	(2D)	(3D)
(%H)	(ACH)	A	D1	E1	D2	E2	C	B
Exhaust								
25	20	0.27	0.33	0.24	0.29	0.30	0.25	0.28
	40	0.61	0.53	0.42	0.59	0.58	0.47	0.48
	60	0.81	0.70	0.54	0.80	0.82	0.57	0.58
50	20	0.30	0.30	0.23	0.30	0.30	0.26	0.27
	40	0.65	0.55	0.35	0.58	0.55	0.45	0.45
	60	0.81	0.71	0.55	0.80	0.80	0.52	0.58
75	20	0.17	0.24	0.25	0.32	0.33	0.20	0.25
	40	0.24	0.47	0.38	0.50	0.58	0.27	0.32
	60	0.48	0.63	0.48	0.76	0.79	0.30	0.41
Supply								
25	20	0.44	0.32	0.28	0.42	0.43	0.27	0.27
	40	0.81	0.46	0.45	0.68	0.56	0.48	0.50
	60	0.98	0.67	0.68	0.90	0.83	0.73	0.72
50	20	0.42	0.30	0.25	0.40	0.42	0.27	0.26
	40	0.70	0.50	0.43	0.60	0.64	0.47	0.51
	60	0.92	0.76	0.65	0.90	0.90	0.70	0.77
75	20	0.49	0.28	0.22	0.40	0.37	0.28	0.34
	40	0.64	0.48	0.41	0.69	0.68	0.48	0.61
	60	0.86	0.71	0.63	0.92	1.00	0.71	0.90

$$\text{Ventilation time (min)} = \frac{\ln[(21 - \%O_2 \text{ initial})/(21 - \%O_2 \text{ final*})]}{C}$$

*Final $\%O_2$ must be less than 21.0 to avoid division by zero.

findings for small laboratory models to larger actual confined spaces.

Extension of the data from this study to significantly different CS configurations will have uncertain effects. If other CS configurations have a larger opening or more than one opening, the ventilation time probably would be less (higher C values). A fully open top, for example, was found to be unable to sustain an oxygen deficiency caused by nitrogen, even without mechanical ventilation.(1) Different locations of the top opening could change the ventilation effectiveness. For example, moving the CS opening closer to the center of the space would be expected to improve ventilation effectiveness, increasing C values and decreasing ventilation times. The less effective "corner" location was selected for these studies as a means of providing more conservative results.

If other CS configurations involve expansions beyond those of the CS models of this study, it is likely that ventilation times would increase (lower C values). The presence of internal surfaces and structures could also greatly affect airflow patterns, ventilation effectiveness, and necessary ventilation times inside confined spaces.

The previous study of the cubical CS Model A has indicated C values as low as about C = 0.1 for very low volume flowrates, e.g., 6 ACH.(1) In fact, the previous study has shown that measured recovery times for the cubical model increased substantially for low flowrates (less than 20 ACH) and high inlet I/O elevations (above 75 %H).

It is also important to note that oxygen deficiency in these studies was caused by nitrogen which is effectively a neutrally buoyant "contaminant." Preliminary testing conducted as part of this project has indicated much slower oxygen recovery (lower C values) in the lower regions of CS models when oxygen deficiency is caused by heavier-than-air substances.

Questions will always be raised concerning how well small laboratory models can predict characteristics inside actual confined spaces. Testing was conducted to evaluate ventilation effectiveness for CS models of significantly different size. This involved modifications to CS Model A to make it geometrically similar to CS Model B—specifically, using a one-half smaller top opening and ventilation I/O pipe diameter and moving the top opening one-half the distance closer to the nearest corner of the model. Geometric similarity and equivalent nondimensional flow rate (ACH) were found to be necessary and sufficient for the smaller model to perform in the same manner as the larger model. Field studies with actual confined spaces will be another important means for validating findings from laboratory studies.

One customary method for dealing with uncertainties in design is to apply a safety factor. This is done in conventional dilution ventilation design for health and fire protection. The greater the uncertainties and the potential hazards, the greater the safety factor. There is very little information available at this time for recommending appropriate safety factors for the data in Table III. For very low flow rates, findings from the previous study(1) suggest that safety factors of 2–3 should be applied to increase ventilation time calculated using 20 ACH data in Table III. Recommendations for safety factors for other variable conditions, such as heavier-than-air contaminants, highly toxic contaminants, and substantially different CS configurations, cannot be made until more data is available. Combinations of these variable factors could lead to very large overall safety factors and long ventilation times, measured in hours rather than minutes, to assure recovery from an oxygen deficiency.

Experimental Findings

The CS models from this study involved three types of progressive shape variation (expansions) from the basic cubical CS Model A. These were 1) sideways expansion by adding one (for CS Model D1) and two (for CS Model E1) cubic units the same size as CS Model A, 2) depthwise expansion by adding one (for CS Model D2) and two (for CS Model E2) cubic units, and 3) multidirectional expansion in two sideways directions by adding three cubic units (for CS Model C) and in three directions by adding seven cubic units (for CS Model B). These variations allowed evaluation of characteristic effects of different CS model shapes in a systematic manner.

Figure 3 presents the minimum oxygen recovery time constants (C) of Table III and illustrates the effect of flow rate (ACH) variation on this important parameter. It is evident that C increases with ACH and that it does so in a roughly linear manner for all CS model configurations over the range from 20 ACH to 60 ACH. It is believed that this characteristic will facilitate development of a multiparameter predictive design model, for which ACH will be a major parameter, to approximate ventilation performance for confined spaces.

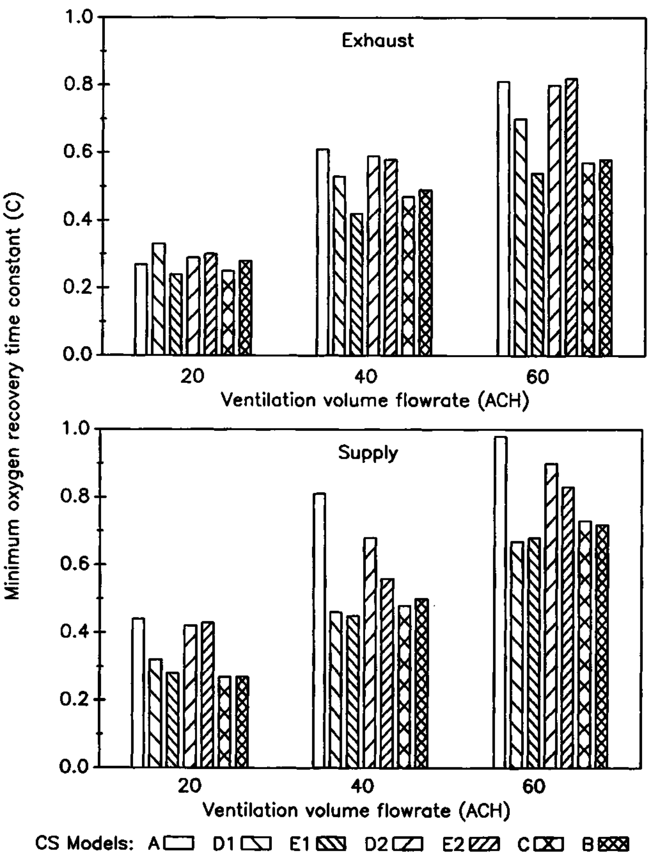


FIGURE 3. Minimum oxygen recovery time constants (C) for exhaust and supply ventilation for CS Models A, D1, E1, D2, E2, C, and B at an inlet/outlet (I/O) elevation of 25 %H.

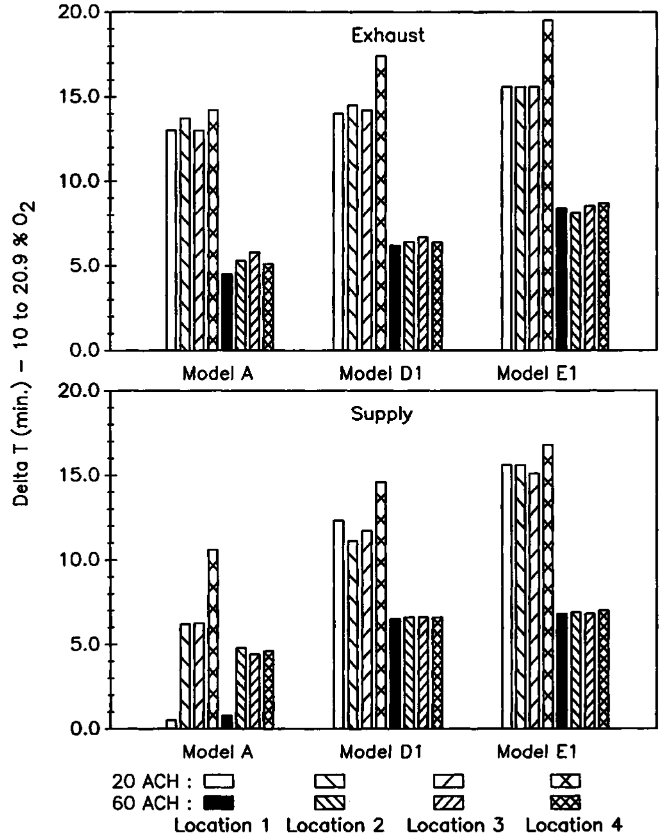


FIGURE 4. Oxygen recovery times, delta T (10–20.9 %O_2), for sideways expansion from CS Model A to CS Models D1 and E1 at I/O elevation 25 %H.

Figures 4 through 8 present selected comparisons of some of the CS models to show characteristics of different shape variations. Delta T, the time for essentially complete (99%) recovery from 10 %O_2 to 20.9 %O_2, was calculated from the C values in Tables I and II. Delta T is used for these comparisons because it is a more tangible or intuitive parameter than the oxygen recovery time constant (C). Comparisons are made at both low and high flow rates (20 ACH and 60 ACH) and at a low I/O evaluation (25 %H). The low I/O elevation was selected because it is more representative of actual CS situations. The characteristics shown in these figures (25 %H) are generally more pronounced for higher I/O elevations (50 and 75 %H), with one exception being the very rapid oxygen recovery for Location 1 under supply ventilation for some CS configurations (Models A, D2, and E2).

Figure 4 shows the changes in oxygen recovery time for sideways model expansion (CS Models A, D1, and E1). It is clear that delta T increased progressively in the A–D1–E1 sideways expansion. This characteristic is apparent for both exhaust and supply ventilation, with recovery times for supply being less than for exhaust. Location 4, most distant from the I/O opening, was generally slowest to recover for low flow rates (20 ACH) with less variation for the different locations at high flow rates (60 ACH). Location 1, closest to the I/O opening, is shown to be significantly different from the other locations only for CS Model A, for which it is in direct alignment with and close to the supply ventilation outlet.

Figure 5 provides a comparison of oxygen recovery times for depthwise expansion in the progression A–D2–E2. These re-

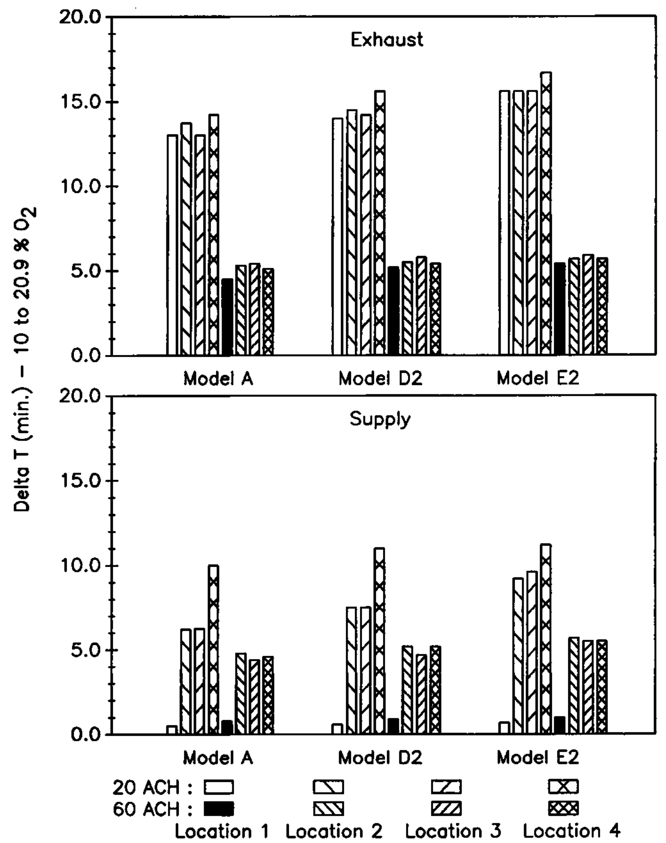


FIGURE 5. Oxygen recovery times, delta T (10–20.9 %O_2), for depthwise expansion from CS Model A to CS Models D2 and E2 at I/O elevation 5 %H.

covery times are generally less than for sideways expansion (Figure 4). Depthwise expansion indicates progressive increases in recovery time, but the effect is less pronounced than for sideways expansion. Location 4 shows slower recovery for 20 ACH but not for 60 ACH, suggesting that the higher flow rate caused more complete mixing. Location 1 shows consistent rapid recovery for supply ventilation for all three of these models, for which it is close to and in alignment with the ventilation outlet.

Figure 6 illustrates characteristics of multidirectional expansion from CS Model A to CS Model C (two directions) and to CS Model B (three directions). Multidirectional expansion caused increases in recovery time for both CS Models C and B. These increases were generally more pronounced for supply ventilation than for exhaust. There was little significant difference between CS Models C and B, nor was supply ventilation significantly different than exhaust for these two models. Multidirectional expansion tended to reduce ventilation effectiveness, but it did not appear to make much difference whether the expansion was in two or three directions.

Figures 7 and 8 provide comparisons of effects for changing the orientation of the ventilation axis, parallel to either the short sides (sideways expansion) or long sides (depthwise expansion) of the noncubical CS models (Shapes D and E). These are the same data as in portions of Figures 4 and 5, providing different comparisons.

Figure 7 shows that oxygen recovery was slightly faster for CS Model D2, having the ventilation axis parallel to the long sides (depthwise), than for CS Model D1 having the ventilation axis parallel to the short sides (sideways). Recovery time decreased with increasing flowrate (ACH) and was shorter for supply than for exhaust ventilation. The variations in delta T were generally consistent with very little difference between locations, except for Location 1 for CS Model D2 under supply ventilation.

Figure 8 indicates similar but more pronounced results for larger (Shape E) models. Ventilation in the direction of the longer sides for CS Model E2 (depthwise) experienced faster oxygen recovery than did ventilation parallel to the shorter sides for CS Model E1 (sideways). Supply ventilation recovered somewhat more rapidly than exhaust, and delta T decreased with increasing ACH.

Conclusions and Ventilation Guidelines

The study of CS models has provided information which can be useful in designing ventilation for work in confined spaces. It can be argued that some findings simply confirm what would be intuitive to industrial hygienists and others with experience in ventilation control. However, it is sometimes reassuring to know that these principles can be supported by experimental measurement.

Conclusions and guidelines for CS ventilation resulting from this study may be summarized as follows:

- Oxygen recovery time is a function of the initial deficiency, the desired level of recovery, the CS shape, the ventilation configuration (exhaust/supply, I/O elevation) and volume flow rate (ACH), and location inside the space. It can be represented reasonably well by an exponential model, for which a recovery time constant (C) describes the rate of recovery. Table III provides conservative (minimum values from this study) estimates of C values for different CS configurations,

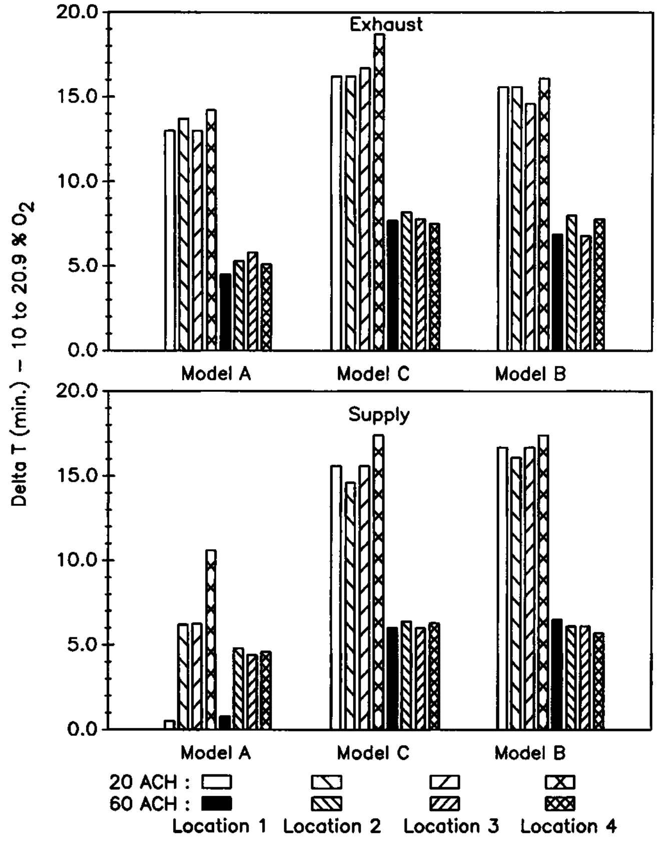


FIGURE 6. Oxygen recovery times, delta T (10–20.9 %O_2) for multi-dimensional expansion from CS Model A to CS Models C and B at I/O elevation 25 %H.

which can be used to calculate ventilation time for specific CS configurations. Ventilation time varies inversely with C.

- Mechanical ventilation can cause relatively rapid oxygen recovery from a deficiency caused by a neutrally bouyant contaminant (e.g., nitrogen). For the range of CS model shapes studied, the minimum ventilation time for complete (99%, e.g., 10 %O_2 to 20.9 %O_2) recovery ranged between about 5 minutes (for $C = 1.0$) and 25 minutes (for $C = 0.2$) for volume flow rates not less than 20 ACH.
- Ventilation time decreases (and C increases) in a roughly linear manner with increasing flow rate for a given CS configuration. The specific characteristic (slope) of this variation is different for different CS configurations. This characteristic, based upon regression data for C, may tend to underestimate actual ventilation time for very low flowrates (less than 20 ACH). It is recommended that a minimum flow rate of 20 ACH be used for CS ventilation design.
- Low ventilation inlet/outlet elevations (25 %H) generally cause more effective ventilation (faster oxygen recovery) than higher elevations for both exhaust and supply ventilation. This indicates that dilution is improved throughout the space by increasing the distance between the points at which air enters and leaves the confined space.
- Supply ventilation generally causes more rapid oxygen recovery than does exhaust. Supply ventilation at low elevations and at locations in alignment with the outlet caused very rapid oxygen recovery (five or more times faster) than for locations not aligned with the outlet. This indicates that optimum supply ventilation design would be to locate the outlet close to and directed towards where work is being conducted. This, however, must also involve consideration for moving work locations, possible adverse "wake" effects with airflow directed past a worker's body, and possible dispersion of contaminants enhanced by the supply airflow "jet."

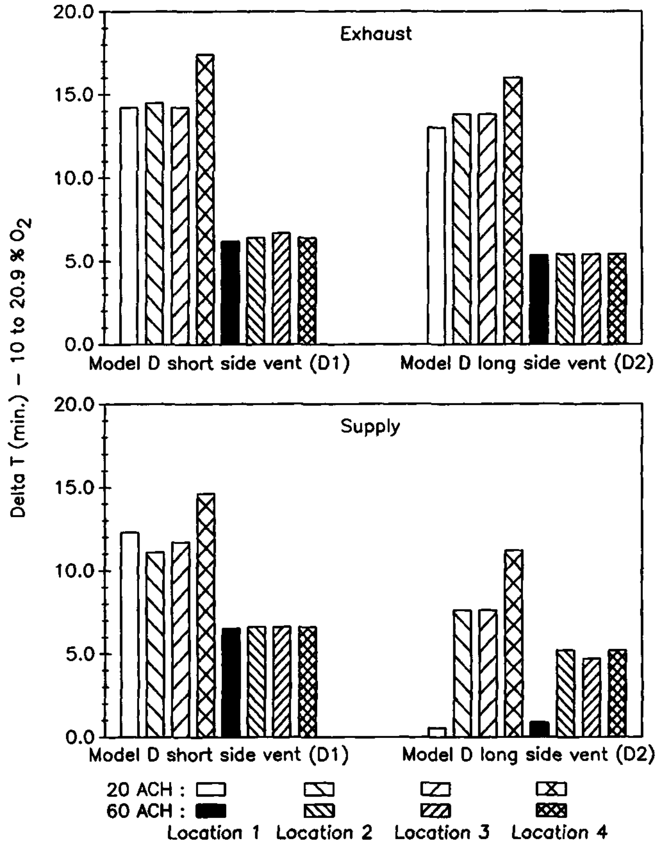


FIGURE 7. Oxygen recovery times, delta T (10–20.9 %O_2), for the ventilation axis parallel to the short *vs.* long sides of CS Models D1 and D2 at I/O elevation 25 %H.

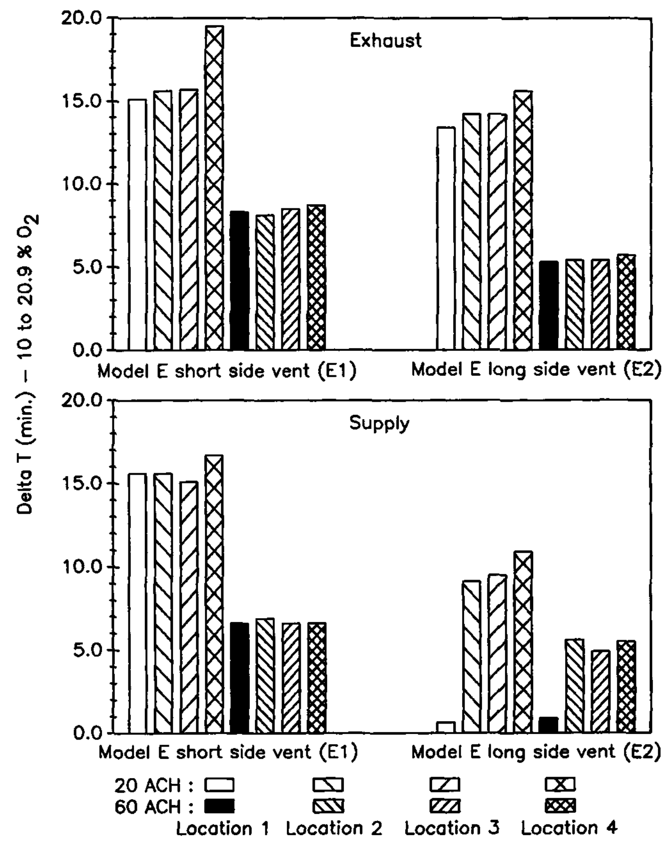


FIGURE 8. Oxygen recovery times, delta T (10–20.9 %O_2), for the ventilation axis parallel to the short *vs.* the long sides of CS Models E1 and E2 at I/O elevation 25 %H.

- Sideways expansion of a CS (from a basic cubical shape) will increase ventilation time for oxygen recovery. This applies for situations where the ventilation inlet/outlet axis is perpendicular to the direction of the expansion (i.e., parallel to the short sides of the CS configuration).
- Depthwise expansion also increases oxygen recovery time. However, the increases are generally less than for sideways expansion. This applies for situations in which the ventilation inlet/outlet axis is parallel to the direction (long sides) of the expansion.
- For a given noncubical CS shape, oxygen recovery time is less when the ventilation axis is parallel to the longer sides than it is when the ventilation axis is parallel to the shorter sides.
- Expansion of a CS configuration in two or three directions also increases oxygen recovery time. However, relatively little difference was observed between two-directional and three-directional expansions for equal expansion factors (i.e., two times in this study).
- Findings from these studies should be considered to have significant limitations. It would be appropriate to apply rough "safety factors" for calculations of ventilation time. Major limitations include oxygen deficiency having been caused by a neutrally buoyant material (nitrogen), limited CS configu-

rations (e.g., a single top opening, specific opening size and location, and limited CS shapes), and uncertainties in extending model data to actual confined spaces.

Recommendations

Mechanical dilution ventilation is effective and should be used to eliminate oxygen deficiency for work in confined spaces. This and the previous studies have shown that oxygen recovery time can be approximated for specific situations using a simple mathematical model.

It is recommended that Table III be used to approximate ventilation time for oxygen recovery, subject to limitations discussed previously. It is also recommended that general guidelines, discussed in the previous section, be considered and applied in designing ventilation for confined spaces.

Individuals responsible for CS ventilation should be mindful of the significant limitations of current knowledge. These limitations are best dealt with by application of safety factors, causing ventilation times to increase by multiples of the safety factors.

Further studies are planned to help provide data for quantifying some of the limitations. These include characteristics of heavier-than-air contaminants causing oxygen deficiency and for characteristics of trace level (e.g., "toxic") contaminants. Work is planned to develop a multiparameter interactive microcomputer model for aiding in CS ventilation design and to conduct field studies which could help to validate or revise findings based on laboratory testing.

It is strongly recommended that greater emphasis be placed upon mechanical ventilation as a primary means of control for potentially hazardous atmospheres inside confined spaces. Administrative controls are and always will be important. Ventilation design models, no matter how well they predict ventilation effectiveness, will not preclude the need for safe procedures. However, administrative controls do not diminish a hazardous condition—engineering controls, such as ventilation, do cause conditions to be less hazardous.

It is hoped that the publication of findings from studies such as these will help to stimulate discussion on ventilation for confined spaces. There exists much practical experience which is unknown and unavailable to the vast majority of individuals responsible for safety in CS activities. There is much need for improved and expanded guidelines and regulatory standards to reduce the needless incidents of injury and death resulting from work in confined spaces.

Reference

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Received 7/29/88; review decision 12/21/88; revision 6/27/89; accepted 7/7/89