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Ventilation to Eliminate Oxygen Deficiency in a Confined Space Part I: A Cubical Model

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Oxygen deficiency is a significant potential hazard for work in confined spaces and can be eliminated by providing adequate mechanical ventilation. This study investigated ventilation effectiveness for restoring depleted oxygen levels in a confined space model. Design parameters included space configuration (cubical shape, open-top vs. closed-top); ventilation mode (exhaust vs. supply), volume flow rate, and inlet/outlet elevation; and location inside the space. Preliminary studies indicated that oxygen recovery for the open-top case was very rapid, even without mechanical ventilation, and this case was not studied in further detail. Oxygen recovery in the closed-top case was generally more rapid for supply ventilation than for exhaust. Ventilation effectiveness (oxygen recovery) improved with increasing flow rate, to a cut-off point above which little additional improvement was shown. Ventilation effectiveness was also affected by inlet/outlet elevation and location in the space. Oxygen recovery occurred in an exponential manner as a function of time, which provided a basis for regression of the experimental data. Regression coefficients established a data base which may be useful in the development of computer modeling for ventilation design. This study is a first step in a more comprehensive program to evaluate and understand ventilation for confined spaces. Limitations constitute opportunities for further study, e.g., modeling size variations, noncubical model shapes, and variable contaminant characteristics. Garrison, R.P.; Nabar, R.; Erig, M.: *Ventilation to Eliminate Oxygen Deficiency in a Confined Space. Part I: A Cubical Model. Appl. Ind. Hyg.* 4:1-11; 1989.

Introduction

Atmospheric hazards inside confined spaces (CS) are among the primary potential hazards for work conducted in these locations. These hazards include unsafe levels of toxic contaminants, flammable and explosive mixtures, and oxygen deficiency. Adverse atmospheric conditions are the leading cause or contributing factor for most accidents resulting in serious injury or death in confined spaces.⁽¹⁻³⁾

Mechanical ventilation is a principal means of engineering control for atmospheric hazards in many workplaces. Confined spaces, most definitely, are no exception. There is a relatively wide body

of knowledge to aid in design of ventilation to control air contaminants in conventional (nonconfined) workplaces.^(4,5) However, there is very little information available which can be applied specifically for confined spaces. This lack of information, combined with (and perhaps partially responsible for) very limited regulatory requirements for ventilation, has diminished awareness of the need to take positive action to provide adequate mechanical ventilation for work in confined spaces.

The major problem in development of useful data and guidelines for designing CS ventilation is the complexity of factors affecting ventilation effectiveness. These factors include, but are not limited to, shape and size of the CS, ventilation mode (exhaust and/or supply) and volume flow rate, location of worksite and ventilation equipment, variable contaminant characteristics, and structures/surfaces affecting air movement inside a CS.

The study presented in this article is part of a research project funded by the National Institute for Occupational Safety and Health (NIOSH) to test, evaluate, and develop useful information for ventilation of confined workplaces. In addition to aiding in ventilation design, it is hoped that this and other related studies will highlight the need and emphasize awareness for providing effective ventilation to reduce potential hazards in CS. It is also hoped that studies such as this will support meaningful regulatory standards to help assure adequate ventilation for confined spaces.

The investigation focuses upon ventilation to eliminate oxygen deficiency. Oxygen deficiency can arise as a hazard inside a CS for two principal reasons: 1) displacement (dilution) of oxygen by large amounts of a relatively nontoxic or inert gas used in a process (e.g., nitrogen, CO₂) and 2) consumption of oxygen inside the space by chemical reaction (e.g., combustion, corrosion, respiration).

This study has addressed several key parameters in the design of ventilation for a CS, specifically:

- Space configuration—open-top and closed-top with a single opening.
- Ventilation mode—exhaust or supply from/to the space.
- Ventilation flow rate—volumetric “air changes” per hour (ACH).
- Ventilation inlet/outlet elevation (%H) in the space.

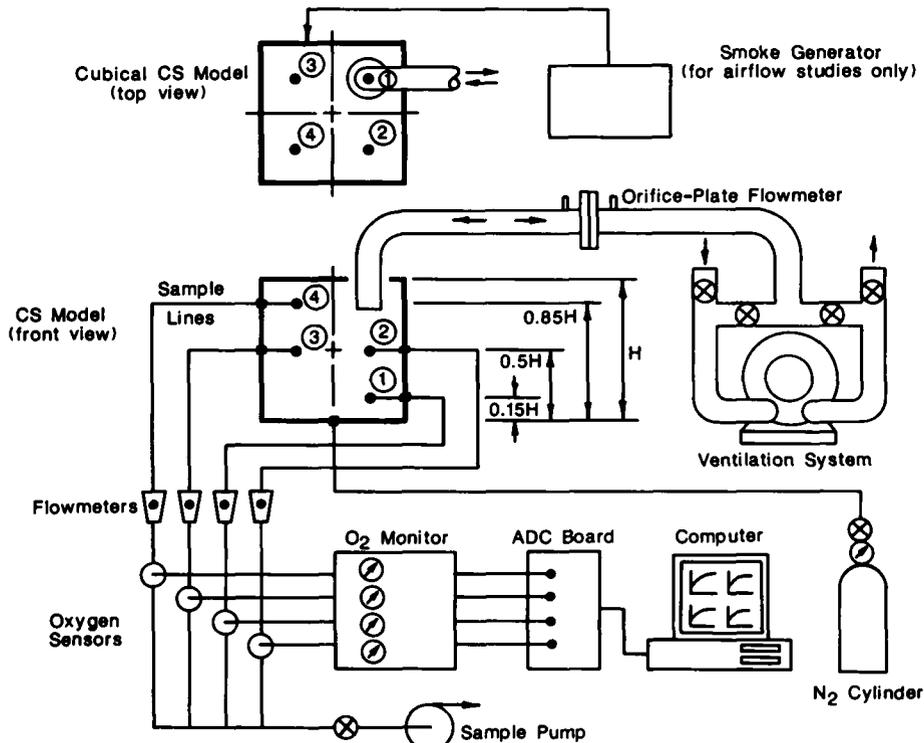


FIGURE 1. Experimental facility diagram.

- Location within the space.

The primary objectives of this study were 1) to conduct laboratory testing of representative situations involving oxygen deficiency inside a CS model, 2) to observe and evaluate the effects of key ventilation design parameters, and 3) to consolidate the experimental findings into a descriptive data base which could be eventually useful in the development of a predictive computer model for ventilation design for confined spaces.

Experimental Facilities

Figures 1 (diagram) and 2 (photograph) illustrate the experimental facilities. The principal components were a cubical CS model; a nitrogen release mechanism; and ventilation, sampling,

and analytical systems. Tracer smoke generation mechanisms were used for preliminary studies.

The CS model for this study was cubical in shape, measuring 0.61 m (2 ft) on each edge. The principal model (Figure 2) consisted of an angle-iron frame with the bottom, three sides, and a removable top made of wood. The front side was made of clear acrylic plastic. The removable top had a single circular opening having a diameter 25 percent of edge length (152 cm, 6 in.) for insertion of a ventilation duct (pipe). A second model of the same size, having three clear plastic sides and black painted wooden top, bottom, and back, was used for air flow pattern (tracer smoke) studies. The cubical shape was selected as the simplest geometric form from which subsequent systematic variations could be made and which is itself representative of some



FIGURE 2. Experimental facility.

actual confined spaces (e.g., vaults, tanks, process equipment).

Nitrogen from a pressurized cylinder was introduced through the bottom of the CS model to create an oxygen-deficient atmosphere. Each experimental test involved establishment of an initial oxygen-deficient concentration (nominally 10 %O₂). Nitrogen flow was terminated prior to each test run, which began with the operation of the ventilation system.

The ventilation system consisted of a small centrifugal blower, inlet/outlet piping and valves, an orifice-plate flowmeter, and plastic pipe (duct) into the CS model with removable end sections of different lengths. The plastic pipe had a nominal inside diameter of 5.1 cm (2 in.) and outside diameter of 6.1 cm (2.4 in.). Valve operation allowed selection of exhaust or supply air flow and control of the volume flow rate to the CS model. Volume flow rates were measured in dimensionless units of volumetric "air changes" per hour (ACH = ventilation flow rate/CS volume).

Samples of air were drawn from inside the CS model at four fixed locations, as specified in Figure 1. Sample locations were based on results of the preliminary studies (discussed subsequently) and to cover the CS volume in a reasonably complete manner. Samples were drawn from a manifold connected to the intake of a small diaphragm pump. Each sampling line consisted of rigid tubing inside the CS model, a bulkhead fitting in the model wall, and flexible tubing to a rotameter (flowmeter), oxygen sensor, and the suction manifold. Equal sampling flow rates (approximately 0.25 L/min) were maintained in each line by using tubing sections of equal length and diameter. Minor adjustments were made in the ventilation volume flow rates to account for the total sampling exhaust flow rate (approximately 0.25 ACH).

The analytical system utilized four electrochemical oxygen sensors, one in each sample line, connected to a four-channel monitor (ENMET Corp.). These sensors responded to the partial pressure of oxygen in the air and provided a linear response over a broad range of oxygen concentration. Analog voltage signals from the sensors were converted to digital data with an analog/digital

conversion (ADC) board (Remote Measurement Systems, Inc.). This digital data was read by a personal computer, displayed on the computer monitor, and stored on diskettes.

Figure 3 is an example of a monitor screen during an experimental test. Data from each channel (O₂ sensor for a specific sampling location) were read sequentially (i.e., channels 1-2-3-4-1, etc.), with each channel reading taking approximately 0.3 seconds. Each reading was an average of ten consecutive measurements, and each complete cycle (one average reading for each channel) required approximately 1.2 seconds. Elapsed time for each reading was recorded using the internal clock of the computer.

Preliminary Studies

Several preliminary studies were conducted to help finalize the experimental design. These studies included observing air flow patterns from tracer smoke and testing open-top vs. closed-top CS model configurations with and without mechanical ventilation.

Tracer smoke was generated in a continuous stream using a commercial smoke generator (ROSCO Laboratories). Smoke tubes (Mine Safety Appliances Co.) provided intermittent, controlled smoke at selected locations inside the model. The principal observations were as follows:

- Supply ventilation air flow patterns were dominated by the discharge jet which caused considerably more turbulent mixing within the model than for exhaust ventilation.
- Open-top exhaust and supply cases indicated better air mixing (less smoke accumulation) than corresponding closed-top cases, with dilution enhanced by the induction of additional air flow from outside the model for open-top supply ventilation.
- Smoke accumulation for the closed-top case was concentrated in the most distant upper corner from the inlet/outlet.

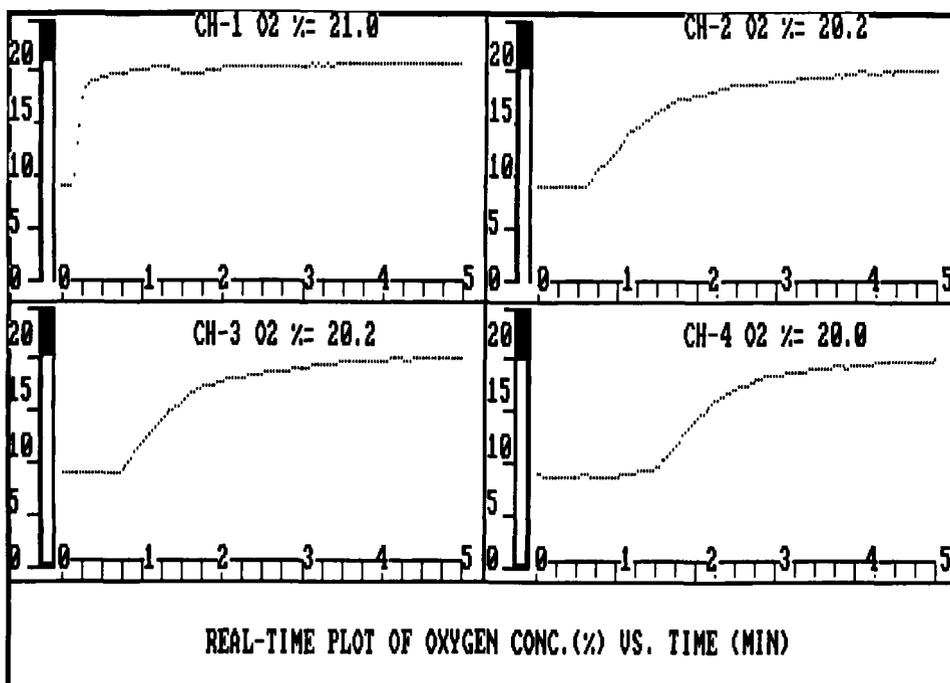


FIGURE 3. Example of computer monitor screen showing real-time data for oxygen concentration in channels (Locations) 1, 2, 3, and 4.

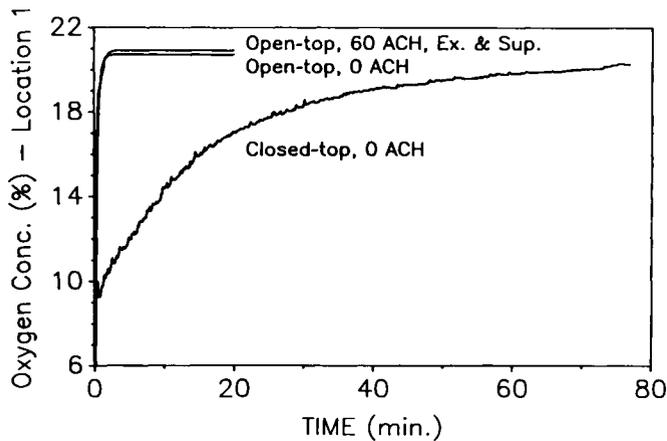


FIGURE 4. Oxygen recovery for an open-top cubical CS model with and without ventilation and for a closed-top model without ventilation.

These smoke studies were useful in selecting the four inlet elevation (%H) sampling locations used for the oxygen deficiency testing. These locations, illustrated in Figure 1, were selected to be 1) directly below (15 %H) the ventilation inlet/outlet, 2) and 3) at the central height (50 %H) and in opposing quadrants, and 4) at a higher elevation (85 %H) diagonally opposed to Location 1. Each sampling location was on the center axis of a vertical quadrant of the CS model, 15 cm (6 in.) from the two nearest walls.

Preliminary testing was conducted to observe oxygen recovery without mechanical ventilation. Figure 4 shows results for the open-top and closed-top cases. It was readily apparent that the open-top case was inherently unstable. Oxygen deficiency was created with a top placed on the model. The top was removed, and oxygen recovery was measured. The open-top case recovered very rapidly (less than 2 min) without any mechanical ventilation (0 ACH). High rates of ventilation (60 ACH, exhaust or supply) had essentially no effect on the rate of oxygen recovery. The closed-top case, however, recovered very slowly (70–80 min) without mechanical ventilation.

It was concluded that the open-top case would not be investigated further in this study because it could not exist for a significant period of time in the cubical confined space model. The inherent instability of oxygen deficiency for the open-top configuration was largely due to the rapid unrestricted diffusion of O₂ throughout the model from the relatively O₂ rich atmosphere above the open top.

Experimental Method

The primary experimental studies involved a systematic progression through two modes of ventilation, at seven volume flow rates and seven inlet/outlet elevations, for a total of 98 test situations ($2 \times 7 \times 7 = 98$) for a closed-top CS model. More specifically, testing was conducted for the following parameters:

- Exhaust and supply ventilation modes.
- Flow rates of 6, 12, 20, 30, 40, 50, and 60 ACH for each mode and inlet/outlet (I/O) elevation.
- I/O elevations of 15, 25, 40, 50, 60, 80, and 100 percent of the CS model height (%H) from the bottom for each mode and flow rate.

Ventilation flow rates were selected to encompass a range likely to be applied for CS ventilation. NIOSH has indicated 20 ACH as a general guideline for CS ventilation in the construction

industry.⁽⁶⁾ A relatively low ventilation rate would be 6 ACH, as sometimes applied for chemical storage areas.⁽⁷⁾ One air change per minute (60 ACH) generally would be regarded as a high rate of ventilation.

A typical experimental test involved the following steps:

- Set up for the desired I/O elevation (%H) and exhaust/supply volume flow rate (ACH).
- Establish an oxygen-deficient atmosphere in the CS model.
- Turn the ventilation system “on” and record oxygen concentration (%O₂) vs. time (min) for each of the four channels (sampling locations).
- Terminate the test after oxygen concentration had recovered to ambient levels (nominally 21 %O₂).

Experimental Findings and Discussion

Oxygen recovery was examined in two different ways: 1) oxygen concentration recovery as a function of ventilation time and 2) delta T, the time to recover from 10 to 20.9 percent O₂. Ambient oxygen level measurements varied marginally from a nominal value of 21 percent O₂. This level established an asymptote for normalization of the experimental data. A nominal value of 20.9 percent O₂ was designated to represent the asymptotic characteristic of oxygen recovery to the ambient level, with a tolerance of 0.1 percent O₂. Oxygen recovery time (delta T) was obtained from experimental data as the time taken from 10 percent O₂ to first reaching a stable (± 0.1 %O₂) value, representative of the nominal 20.9 percent O₂ level.

Figure 5 compares oxygen recovery as a function of ventilation

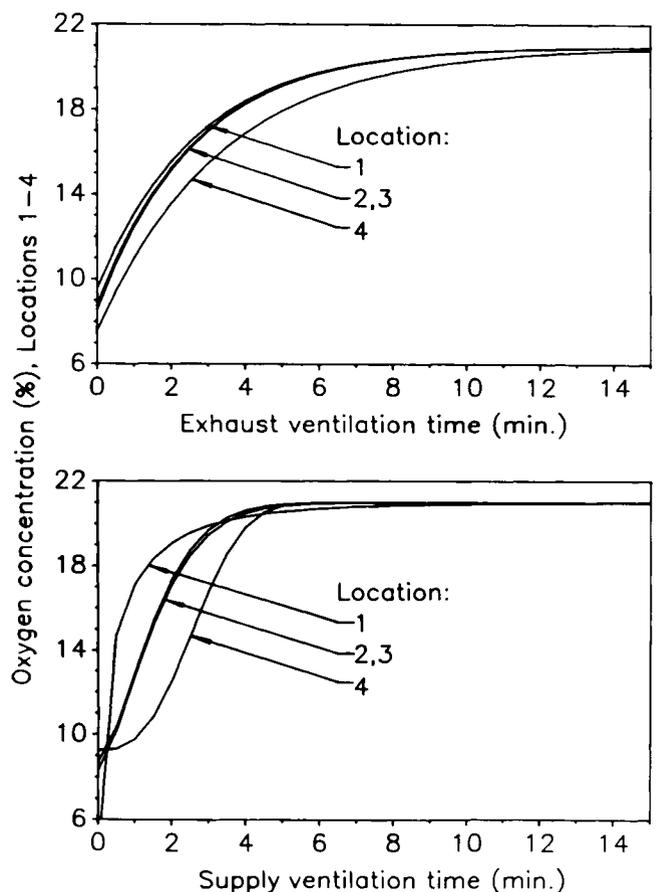


FIGURE 5. Oxygen recovery at different sampling locations for exhaust and supply ventilation of a closed-top cubical CS model (20 ACH, 40 %H).

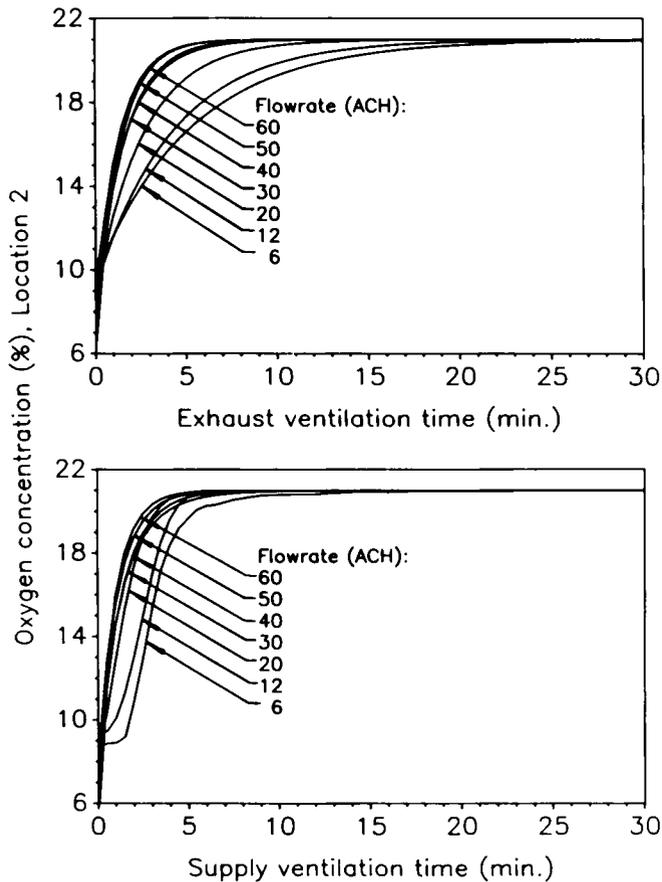


FIGURE 6. Oxygen recovery at different volume flow rates (ACH) for exhaust and supply ventilation of a closed-top cubical CS model (Location 2, 40 %H).

time at the four sampling locations for the exhaust and supply modes. Comparisons were made for the ventilation situation of 20 ACH and 40 %H I/O elevation. These data show that rates of oxygen recovery varied significantly with location in the CS model. Oxygen recovery was nearly complete at some locations several minutes earlier than at other locations.

The exhaust case demonstrated a typically exponential recovery for all sampling locations, initially with oxygen concentration increasing rapidly, followed by a gradual increase to the ambient level. In contrast, the supply case response resembled a sigmoid curve for sampling Locations 2, 3, and 4. Oxygen concentration at Location 1 was significantly different from the other locations, increasing very rapidly from the start-up of supply ventilation. This was due, presumably, to this location being aligned with (directly below) the ventilation outlet.

Location 1 (Figure 5) showed the fastest recovery for both exhaust and supply modes, with the slope of the recovery curve being much steeper in the supply case. Location 4 showed the slowest recovery for both ventilation modes, indicating considerably less effective air mixing (dilution) at this most distant location. Locations 2 and 3 demonstrated practically equivalent oxygen recovery. Oxygen recovery, overall, was faster for supply ventilation compared to exhaust ventilation.

Variations in oxygen recovery with location in the CS model suggest that an additional design parameter (not investigated in this study) may be useful for characterizing location-related effects. A location parameter might be described as the distance between a specific location and some fixed or movable reference point, e.g., the opening in the CS top or a point on the bottom

aligned with the inlet/outlet or the center of the inlet/outlet opening itself. A location parameter could be described in dimensionless units based upon the space configuration. It could be a particularly useful parameter for investigating characteristics of different (non-cubical) CS configurations.

Figure 6 compares the effects of variable ventilation flow rate on oxygen recovery at Location 2 for the exhaust and supply modes. Location 2 (midplane, 50 %H) was selected for purposes of comparison because it was reasonably representative of overall ventilation effectiveness. Oxygen recovery was faster at higher flow rates for both ventilation modes. However, increasing the air flow rate above 30 ACH did not significantly improve recovery in the exhaust mode, compared to a similar "cut-off" at about 20 ACH for the supply mode. This indicated greater ventilation effectiveness for the supply mode compared to the exhaust, until reaching a limiting flow rate above which the differences were relatively small.

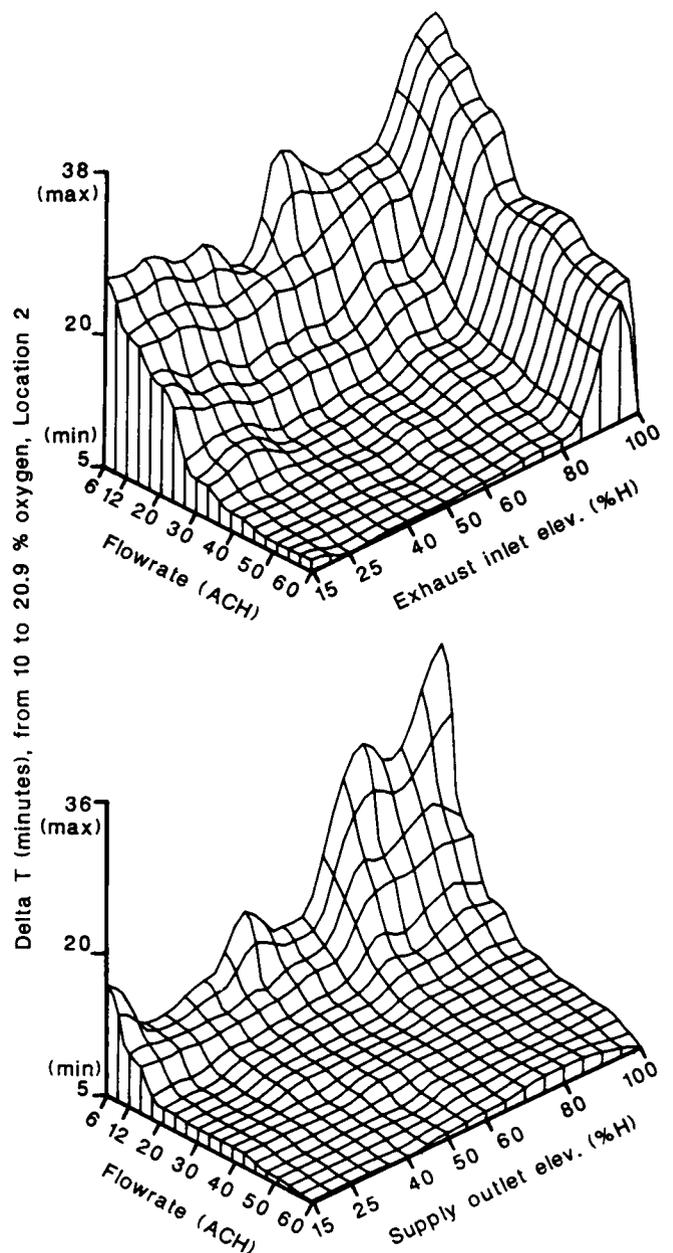


FIGURE 7. Oxygen recovery time, delta T (10–20.9 %O₂), for exhaust and supply ventilation of a closed-top cubical CS model (Location 2).

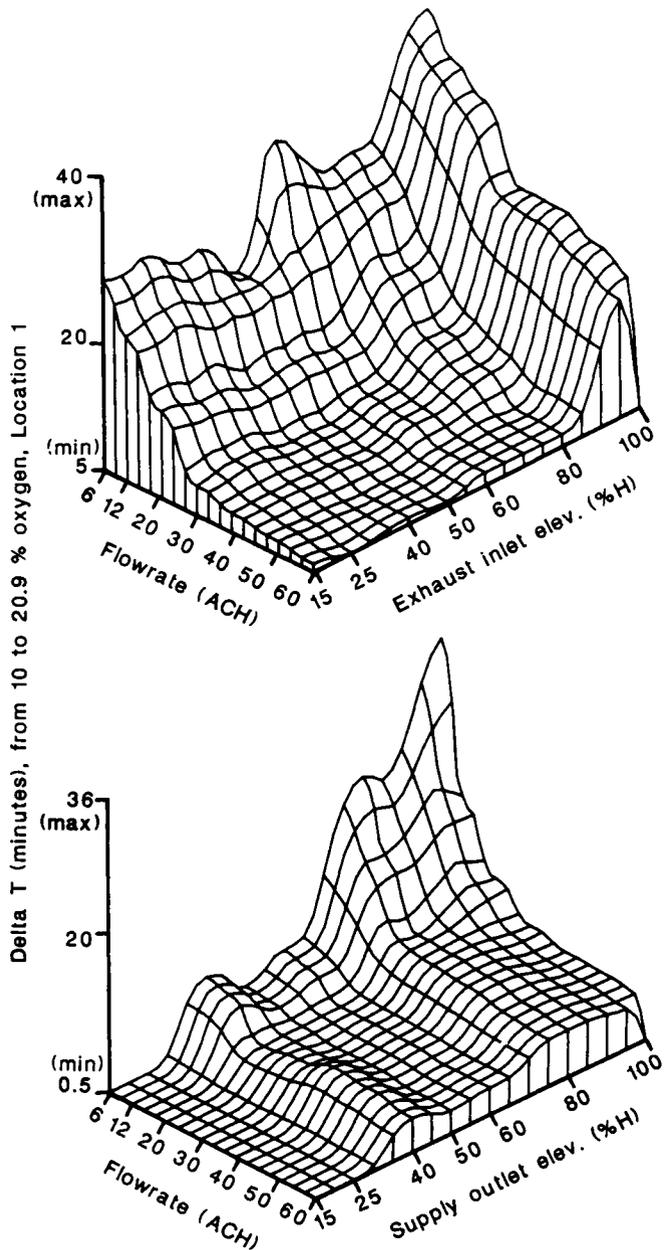


FIGURE 8. Oxygen recovery time, delta T (10–20.9 %O₂), for exhaust and supply ventilation of a closed-top cubical CS model (Location 1).

Figure 7 is a three-dimensional plot of experimental data intended to illustrate the effects of three important design parameters: 1) ventilation flow rate (ACH), 2) I/O elevation (%H), and 3) delta T (min) recovery time (10–20.9 %O₂). The figure shows characteristics for exhaust and supply modes at Location 2 for the 49 I/O combinations studied. Two characteristics of the graphics software (SURFACE II) used to make these three-dimensional plots should be noted: 1) some surface characteristics (e.g., depressions) are generated by spatial interpolation between specified data points, and 2) the vertical axis (delta T) is set at a fixed length and scaled between the minimum and maximum data values.

Figure 7 suggests several design-oriented observations:

- Delta T was significantly higher for exhaust ventilation than for supply at flow rates below 30 ACH and inlet elevations of 80 %H and higher.

- Delta T for supply ventilation was not adversely affected (increased significantly) as a function of outlet elevation, except for low flow rates, especially at 6 ACH.
- Exhaust and supply modes had comparable recovery times (e.g., less than 10 min) in the exhaust “basin” (less than 60 %H and more than 30 ACH) and in the supply “valley” (elevations above 20 ACH).
- Increasing exhaust flow rate beyond 30 ACH (for elevations below 80 %H) and supply flow rates beyond 20 ACH resulted in marginal reductions in delta T.

Figure 8 is a similar plot of oxygen recovery time (delta T) for Location 1 under exhaust and supply ventilation at different flow rates and I/O elevations. Location 1 was discussed previously (Figure 5) as having significantly different characteristics from other locations for the supply case. This was due to its position directly below the ventilation outlet which may be particularly important in connection with work inside confined spaces when the supply outlet is directed towards the working position.

Figure 8 indicates that exhaust ventilation effectiveness, measured as recovery time (delta T) at Location 1, was not significantly different from Location 2, as a function of either flow rate (ACH) or inlet elevation (%H). However, supply ventilation effectiveness for Location 1 was significantly different, suggesting two design-oriented observations:

- Delta T for supply ventilation at a location aligned with the outlet (e.g., Location 1) was significantly shorter than for other locations (e.g., Location 2) even at low flow rates.
- Oxygen recovery for low supply outlet elevations (15 to 25 %H) was very rapid (delta T less than 1.0 min) regardless of flow rate (6 to 60 ACH) at locations aligned with the outlet (e.g., Location 1).

Statistical Findings and Discussion

Statistical analyses were conducted on a personal computer using commercially available software (SYSTAT). The following mathematical model was used to represent experimental observations:

$$\%O_2 = 21 - (21-B)e^{-Ct} \quad (\text{Model 1})$$

where:

%O₂ = poxygen concentration (%)

t = ventilation time (min)

21–B = regression coefficient representing the initial oxygen-deficiency (%)

C = regression coefficient representing a time constant

Model 1 is an attenuated step-function, beginning at level B and approaching a final asymptotic level of 21 percent O₂ exponentially, with attenuation characterized by the time constant, C. A variation of Model 1 was applied for some of the experimental data.

$$\%O_2 = 21 - (21-B)e^{-Ct^D} \quad (\text{Model 2})$$

Model 2 differs from Model 1 by the addition of a “fitting exponent” (D) applied to the time parameter (t). This additional parameter allowed higher coefficients of determination (R²) for some of the experimental data than were possible with Model 1 (for which D = 1).

Nonlinear regression was selected to facilitate analyses of the intrinsically nonlinear characteristics of the experimental data. The regressions were conducted by an iterative Quasi-Newton method, using a least-squares loss function with convergence

TABLE I. Regression Data (Model 1) for Exhaust Ventilation to Eliminate Oxygen Deficiency in a Closed-top Cubical CS Model

CS Parameters		Model 1: %O ₂ = 21 - (21-B)e ^{-Ct}							
		CS Location							
		1		2		3		4	
Outlet Elevation (%H)	Volume Flow Rate (ACH)	(21-B)	C	(21-B)	C	(21-B)	C	(21-B)	C
15	6	11.5	0.17	12.5	0.18	12.4	0.17	13.5	0.15
	12	13.8	0.23	14.9	0.23	14.7	0.23	16.4	0.19
	20	12.3	0.27	10.9	0.30	12.5	0.26	13.5	0.26
	30	11.3	0.54	13.5	0.54	13.2	0.54	16.2	0.44
	40	12.2	0.69	14.0	0.63	14.3	0.63	15.6	0.58
	50	12.1	0.80	13.8	0.67	14.3	0.67	16.0	0.70
60	14.4	0.81	15.8	0.76	15.9	0.72	18.1	0.78	
25	6	11.5	0.17	12.1	0.18	12.1	0.18	13.3	0.15
	12	14.0	0.22	14.9	0.22	14.9	0.23	16.1	0.18
	20	12.2	0.33	13.0	0.34	13.4	0.36	14.4	0.27
	30	11.6	0.44	14.6	0.51	15.2	0.55	17.0	0.43
	40	10.6	0.70	12.8	0.61	12.7	0.61	14.5	0.67
	50	12.1	0.81	13.9	0.71	14.2	0.74	14.8	0.74
60	13.1	1.03	15.0	0.88	14.8	0.81	16.0	0.92	
40	6	10.5	0.18	11.3	0.19	11.3	0.18	11.9	0.15
	12	11.6	0.24	11.9	0.23	12.1	0.25	13.2	0.20
	20	11.5	0.37	12.3	0.38	12.5	0.38	13.5	0.30
	30	10.5	0.60	11.6	0.56	11.7	0.55	13.1	0.52
	40	12.0	0.69	13.3	0.63	13.4	0.62	13.9	0.64
	50	13.3	0.84	14.7	0.77	15.5	0.76	15.1	0.77
60	10.9	0.91	12.7	0.76	12.9	0.84	13.9	0.85	
50	6	10.9	0.22	11.5	0.23	11.4	0.23	12.5	0.19
	12	13.2	0.23	14.0	0.24	14.0	0.24	15.1	0.20
	20	11.4	0.35	12.0	0.36	12.2	0.36	13.6	0.30
	30	12.1	0.60	13.3	0.59	13.2	0.58	15.2	0.56
	40	12.4	0.72	13.8	0.66	13.7	0.65	15.7	0.69
	50	11.9	0.88	12.8	0.74	13.8	0.79	14.4	0.85
60	11.7	0.92	13.0	0.81	13.5	0.81	13.4	0.84	
60	6	11.6	0.14	11.5	0.14	11.7	0.14	12.7	0.12
	12	11.4	0.23	12.3	0.23	12.2	0.24	13.6	0.19
	20	12.0	0.35	12.0	0.40	13.0	0.36	13.0	0.35
	30	11.6	0.55	12.5	0.51	12.5	0.49	13.8	0.52
	40	11.3	0.60	12.7	0.55	13.2	0.60	12.7	0.58
	50	10.4	0.73	12.2	0.66	12.2	0.67	12.0	0.67
60	11.5	0.88	13.0	0.69	13.8	0.83	13.7	0.80	
80	6	10.8	0.17	11.1	0.17	11.2	0.18	12.1	0.16
	12	11.4	0.18	11.8	0.20	12.0	0.20	12.9	0.17
	20	11.6	0.30	12.0	0.28	12.3	0.27	13.4	0.24
	30	12.3	0.45	12.7	0.40	13.1	0.39	14.5	0.35
	40	12.2	0.51	13.0	0.48	13.4	0.48	14.5	0.48
	50	12.9	0.69	13.8	0.69	14.2	0.65	13.8	0.71
60	13.6	0.84	15.2	0.73	15.2	0.81	15.0	0.77	
100	6	12.1	0.12	12.0	0.12	12.1	0.12	12.8	0.11
	12	13.8	0.14	14.4	0.15	14.2	0.14	15.7	0.13
	20	14.2	0.16	13.9	0.16	14.4	0.16	15.6	0.15
	30	15.0	0.21	15.3	0.21	15.4	0.22	17.1	0.18
	40	11.6	0.20	12.3	0.20	12.6	0.20	13.3	0.21
	50	11.6	0.23	12.1	0.22	12.0	0.23	12.4	0.23
60	11.6	0.24	11.7	0.25	12.3	0.24	12.7	0.23	

accuracy specified at 0.1 percent. The method was effective, with convergence occurring within a maximum of 100 iterations in all cases. The possibility of obtaining multiple solutions was investigated by regressing several cases with different initial values of regression coefficients and also by using the Simplex method to compare selected results. No multiple solutions were found, thus validating the effectiveness of the Quasi-Newton method.

Tables I and II present the regression coefficients obtained for Model 1 for the exhaust and supply modes, respectively. A total of 392 nonlinear regressions were conducted on Model 1 for the closed-top cubical CS model, involving 196 regressions for both the exhaust and supply modes (49 tests with 4 locations each). All experimental ventilation schemes in the exhaust mode were found to fit Model 1 extremely well, with R² values averaging

TABLE II. Regression Data (Model 1) for Supply Ventilation to Eliminate Oxygen Deficiency in a Closed-top Cubical CS Model

CS Parameters		Model 1: %O ₂ = 21 - (21-B)e ^{-Ct}							
		CS Location							
		1		2		3		4	
Outlet Elevation (%H)	Volume Flow Rate (ACH)	*(21-B)	C	(21-B)	C	(21-B)	C	*(21-B)	C
15	6	24.5	8.94	16.6	0.29	16.6	0.29	17.1	0.15
	12	27.4	10.45	20.4	0.50	20.6	0.49	21.0	0.28
	20	16.7	6.72	19.5	0.69	19.8	0.69	20.9	0.38
	30	31.0	10.73	19.1	0.96	20.2	0.98	21.8	0.65
	40	18.1	6.34	15.4	0.86	16.0	0.94	17.0	0.89
	50	31.9	9.71	15.0	0.84	15.5	0.90	15.9	0.82
60	30.0	10.01	14.8	0.99	16.0	0.97	16.1	0.95	
25	6	22.7	6.30	16.2	0.27	16.2	0.27	19.5	0.11
	12	18.5	7.44	18.3	0.50	18.3	0.48	19.0	0.28
	20	27.8	10.60	19.5	0.76	19.7	0.75	20.4	0.44
	30	2.7	0.32	16.7	0.91	15.6	0.88	18.3	0.63
	40	30.2	8.12	14.9	0.82	16.4	0.87	16.9	0.81
	50	9.9	4.39	14.0	0.86	13.7	0.89	14.5	0.82
60	12.8	5.56	13.6	0.98	14.0	1.06	15.2	1.01	
40	6	12.4	0.22	11.5	0.10	11.5	0.09	12.4	0.08
	12	12.6	0.77	15.8	0.43	15.7	0.43	16.5	0.23
	20	10.6	0.94	14.8	0.68	15.0	0.66	16.2	0.41
	30	10.0	0.86	13.9	0.76	13.3	0.74	16.7	0.62
	40	10.3	0.84	13.5	0.75	13.8	0.76	14.5	0.73
	50	9.9	0.89	12.7	0.86	13.1	0.86	13.3	0.85
60	12.0	1.07	13.8	1.01	14.4	1.01	14.2	1.01	
50	6	8.9	0.87	14.4	0.29	14.4	0.29	15.4	0.16
	12	9.4	0.82	15.6	0.49	15.8	0.47	17.0	0.31
	20	8.8	1.14	15.0	0.65	15.0	0.63	16.4	0.42
	30	8.5	1.25	13.2	0.60	13.9	0.63	15.4	0.51
	40	8.1	1.22	13.9	0.70	13.9	0.71	15.1	0.70
	50	10.5	1.79	13.8	0.79	14.1	0.80	14.9	0.80
60	10.0	1.88	13.7	0.92	14.6	1.01	14.7	0.98	
60	6	8.9	0.61	14.8	0.34	15.4	0.34	15.6	0.21
	12	9.4	0.59	14.6	0.43	14.9	0.43	16.3	0.28
	20	10.1	1.05	14.2	0.59	14.9	0.60	20.9	0.40
	30	8.4	1.05	16.0	0.65	15.2	0.68	16.8	0.57
	40	8.2	1.04	13.4	0.67	14.4	0.73	14.8	0.70
	50	8.5	1.55	12.7	0.77	14.1	0.85	14.0	0.81
60	9.5	1.71	14.0	0.93	14.6	0.96	15.3	0.97	
80	6	11.2	0.20	12.7	0.16	12.7	0.15	13.7	0.13
	12	14.2	0.30	11.0	0.34	13.0	0.29	15.6	0.23
	20	10.9	0.62	13.5	0.49	14.1	0.52	15.5	0.42
	30	8.8	0.73	15.6	0.59	13.6	0.56	14.0	0.56
	40	9.3	0.64	13.7	0.71	14.9	0.72	14.9	0.73
	50	9.7	0.92	14.2	0.87	14.8	0.80	15.0	0.86
60	12.9	0.87	13.4	0.92	14.0	0.86	14.0	0.95	
100	6	11.8	0.13	12.4	0.13	12.2	0.12	13.1	0.11
	12	11.0	0.27	12.2	0.26	12.4	0.27	13.0	0.22
	20	11.2	0.45	12.9	0.40	13.0	0.43	13.4	0.40
	30	11.0	0.72	13.7	0.58	13.3	0.57	14.0	0.56
	40	11.3	0.89	14.0	0.71	14.5	0.71	14.7	0.71
	50	11.3	1.01	14.0	0.82	14.3	0.76	14.9	0.81
60	11.9	1.19	14.2	0.97	14.4	0.86	15.3	0.98	

*Values of (21-B) greater than 21.0 are the result of regression. See text for further discussion.

99.2 percent for Table I (R² ranging 97.0–99.9%). This indicated that on the average, 99.2 percent of the variation in experimental oxygen levels (exhaust mode) was accounted for by Model 1.

Experimental data obtained in the supply mode also provided high correlation coefficients with Model 1, with an average R² value of 92.0 percent for Table II (R² ranging 56.6–99.0%). The

relatively poor fit of experimental supply data compared to exhaust data using Model 1 was consistent with the relatively “sluggish” initial response of oxygen recovery for relatively low supply flow rates at Locations 2, 3, and 4. This is illustrated in Figure 5. The sigmoid nature of the oxygen recovery curves at low supply flow rates was accommodated in the analysis by using Model 2,

TABLE III. Regression Data (Model 2) for Supply Ventilation to Eliminate Oxygen Deficiency in a Closed-top Cubical CS Model

CS Parameters		Model 2: %O ₂ = 21 - (21-B)e ^{-Ct^D}											
		CS Location											
		1			2			3			4		
Outlet Elevation (%H)	Volume Flow Rate (ACH)	*(21-B)	C	D	(21-B)	C	D	*(21-B)	C	D	(21-B)	C	D
15	6	24.9	8.85	0.99	11.8	0.01	3.32	11.8	0.01	3.30	11.79	0.0002	4.20
	12	27.4	10.45	1.00	11.3	0.03	3.53	14.3	0.03	3.43	14.40	0.001	4.44
	20	13.0	14.63	1.64	14.9	0.27	2.31	14.7	0.23	2.54	14.23	0.007	4.81
	30	31.0	10.73	1.00	19.4	0.98	0.97	21.4	1.05	0.92	17.40	0.360	1.64
25	6	36.4	5.64	0.72	11.4	0.02	2.89	11.4	0.02	2.91	11.88	0.002	3.40
	12	18.5	7.44	1.00	13.3	0.06	2.91	13.3	0.07	2.75	13.50	0.003	3.86
	20	27.8	10.60	1.00	15.1	0.37	2.00	15.3	0.38	1.92	14.75	0.038	3.21
	30	39.3	15.19	1.00	18.3	1.02	0.87	19.6	1.13	0.74	15.88	0.450	1.31
40	6	10.6	0.09	1.43	10.8	0.07	1.13	11.7	0.10	0.97	11.78	0.060	1.10
	12	12.5	0.76	1.00	11.7	0.07	2.48	11.6	0.07	2.42	11.51	0.004	3.45
	20	16.8	1.46	0.57	12.3	0.42	1.53	12.7	0.43	1.44	11.77	0.047	2.81
	30	17.7	1.46	0.51	15.8	0.91	0.83	17.0	1.00	0.73	14.30	0.430	1.35
50	6	65.7	2.93	0.24	11.3	0.08	1.81	11.5	0.09	1.72	10.95	0.009	2.48
	12	23.8	0.19	0.42	13.3	0.28	1.43	13.7	0.29	1.36	12.60	0.030	2.60
	20	92.5	3.52	0.23	14.5	0.61	1.05	15.5	0.66	0.95	13.63	0.220	1.50
	30	107.0	3.90	0.23	14.1	0.69	0.90	10.4	0.84	0.80	13.30	0.330	1.33
60	6	15.8	1.29	0.53	12.0	0.11	1.72	12.5	0.13	1.63	11.80	0.016	2.31
	12	14.1	1.08	0.60	13.0	0.29	1.28	13.6	0.32	1.20	12.50	0.045	2.42
	20	27.3	2.09	0.39	13.9	0.56	1.04	14.2	0.54	1.09	13.33	0.216	1.48
	30	882.0	5.65	0.12	16.1	0.66	0.99	19.1	0.94	0.73	15.50	0.470	1.15
80	6	12.3	0.27	0.86	12.2	0.13	1.10	12.2	0.13	1.10	12.48	0.075	1.21
	12	14.2	0.30	1.00	12.4	0.44	0.85	14.1	0.31	0.95	13.00	0.090	1.54
	20	13.7	0.84	0.69	13.0	0.45	1.06	14.0	0.50	1.03	12.50	0.200	1.67
	30	16.0	1.38	0.51	13.8	0.61	0.98	14.0	0.60	0.94	14.76	0.620	0.92
100	6	12.4	0.16	0.91	12.5	0.13	0.99	13.0	0.17	0.89	12.88	0.100	1.03
	12	11.8	0.33	0.89	12.0	0.26	1.01	12.7	0.28	0.90	12.50	0.150	1.20
	20	12.5	0.55	0.84	12.2	0.34	1.12	13.4	0.45	0.97	13.00	0.380	1.04
	30	14.4	0.99	0.69	12.9	0.52	1.12	12.8	0.52	1.07	14.00	0.560	0.99

*Values of (21-B) greater than 21.0 are the result of regression. See text for further discussion.

with the fitting exponent (D).

Additional regressions were performed using Model 2, for four supply flow rates (6, 12, 20, and 30 ACH), at the seven outlet elevations. The regression coefficients are presented in Table III. Experimental data were found to fit Model 2 extremely well, with an average R² value of 99.5 percent for Table III. This represents an average improvement in R² of 12.7 percent for comparable data in Table II.

The values of coefficients obtained in Tables I, II, and III were between one and two orders of magnitude greater than the values of their standard errors (multiples of 20 to 50). High R² values combined with very low standard errors of estimates indicated high confidence (greater than 99%) levels for the coefficients obtained. Sample sizes were reasonably large compared to the number of parameters estimated (minimum of 80 data points), indicating relatively unbiased estimation.

The regression analyses using Models 1 and 2 yielded some values for the parameter B which were significantly different from the experimental initial oxygen level (nominally 10 %O₂). This variation was greater for supply (Tables II and III) than for exhaust (Table I) ventilation and was most pronounced for Location 1. In some extreme cases, the coefficient (21-B) was greater than 21. This resulted from very high rates of oxygen recovery immediately following start-up of ventilation at outlet elevations at or below 60 %H, causing regression estimates having negative intercept (B) values. This does not constitute a practical limitation

because calculations using the regression data will yield positive oxygen concentrations whenever ventilation time exceeds 0.1 minute.

Figure 9 compares the descriptive values of Models 1 and 2 for example cases having "typical" and "poor" R² values (Location 4, 80 %H, 50 ACH exhaust and Location 2, 15 %H, 6 ACH supply,

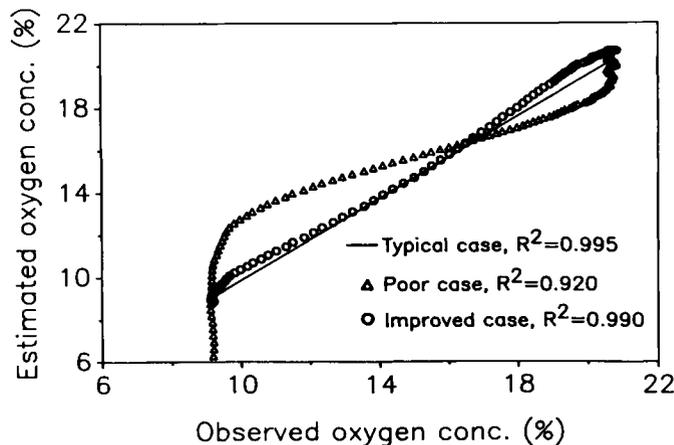


FIGURE 9. Estimated (regression) vs. observed (experimental) oxygen concentration for typical and poor cases using Model 1 and the improved "poor" case using Model 2.

respectively). This figure illustrates the improved fit obtained for the "poor" case by using Model 2. The "typical" case using Model 1 had very high correlation as indicated by the nearly straight line with a slope of about 1.0 for estimated versus observed oxygen levels. The "poor" case, which had a highly systematic residual spread, was improved substantially by using Model 2, with an improvement of 7 percent in the R² value (92–99%).

Calculation of Recovery Time

The highly descriptive capability of the regression models, although strictly applicable to this experimental data, suggests a procedure to estimate oxygen recovery time for ventilation of oxygen-deficient situations in a cubical closed-top CS model. A general method for using the data in Tables I, II, and III may be summarized as follows:

- Select a ventilation flow rate (ACH, exhaust or supply) and I/O elevation (%H) from data in Tables I, II, or III.
- Specify initial and final oxygen concentrations—the initial oxygen level should not be lower than the regression intercept B for the selected situation.
- Use the regression data in Tables I, II, or III to calculate the time (T1) corresponding to the initial oxygen level.
- Use the regression data to calculate the time (T2) corresponding to the final oxygen level.
- Calculate recovery time (min) as T2 minus T1.

The following is an example calculation using exhaust ventilation with a flow rate of 20 ACH, inlet elevation of 50 %H, initial level of 12 percent O₂, and final (e.g., acceptable for working in CS) level of 20 percent O₂. Data from Table I for Location 1 provide the following relationships:

$$12 = 21 - (11.4) \exp(-0.35 T1)$$

$$20 = 21 - (11.4) \exp(-0.35 T2)$$

These may be solved for T1, T2, and recovery time (T2–T1):

$$T1 = \frac{\ln\left[\frac{21-12}{11.4}\right]}{(-0.35)} = 0.67 \text{ min}$$

$$T2 = \frac{\ln\left[\frac{21-20}{11.4}\right]}{(-0.35)} = 6.95 \text{ min}$$

$$\text{Recovery Time} = T2 - T1 = 6.95 - 0.67 = 6.28 \text{ min}$$

This procedure could be performed very easily by a computer program, using the data base of Tables I, II, and III. However, it should be kept in mind that this data base applies strictly to the CS model studied. The extent to which this or modified data can be applied to more general, actual design calculations remains to be determined.

Limitations and Further Study

Variations in confined space situations in the real world are almost limitless. Many situations will be so different from the situations of this study that the findings from this study will be of little use for ventilation design. All actual confined spaces will

be larger than the laboratory model of this study. Some variations will involve different and distinctly non-cubical CS shapes; spaces with more than one opening and/or internal surfaces affecting air movement within the space; variable contaminant characteristics which are significantly different from oxygen deficiency such as toxic contaminants at relatively low levels and contaminants which are substantially "heavier-than-air"; and contaminant emission characteristics which may be continuous and/or time-dependent during the CS work activity.

This study is a first step in an effort to characterize CS ventilation. Other studies are planned, and some are underway, to address limitations including some of those listed above. Certainly, the complexity of the problem leaves room for much more work. Just as certainly, the importance of the overall objective, i.e., to reduce potentially fatal hazards, warrants continued progress.

Further work will be needed to make the results of this study and subsequent studies genuinely useful to individuals, including industrial hygienists who are responsible for designing and evaluating ventilation for confined spaces. This requires development of an empirical design data base, emphasizing 1) general predictive capability from multiple-parameter models, which do not rely upon lengthy data tabulations to represent effects of various design parameters and which have been shown to apply for actual confined spaces; 2) relationships between the conventional air mixing factor (K) and appropriate design parameters for steady-state and time-dependent dilution ventilation; and 3) incorporation of findings into a user-friendly computer design model to facilitate calculations from basic input data.

Conclusions/Recommendations

The following are principal conclusions of this study:

- Space configuration (open-top vs. closed-top) profoundly affected oxygen recovery, with the open-top case being essentially unsustainable for oxygen deficiency in a cubical CS model.
- The cubical shape and small size of the model used for this study not only provide a reasonable modeling starting point, but also represent major limitations which deter general application of the data until further studies establish predictive value.
- Supply ventilation was generally more effective than exhaust ventilation in bringing about oxygen recovery. Effects related to ventilation flow rate, inlet/outlet elevation, and location in the CS also have important implications, as illustrated in Figures 7 and 8.
- Location was particularly important for supply ventilation for which oxygen recovery was generally rapid in alignment with the outlet (Location 1) and was delayed at the most distant location (Location 4).
- Oxygen deficiency is a very specific type of hazardous atmosphere and is quite different from others which may exist in a confined space. Ventilation effectiveness for oxygen recovery may have very different characteristics for other types of contaminated atmospheres.

It is recommended that further studies continue towards the overall objective of developing a useful computer model to assist in ventilation design for work in confined spaces. Subsequent work on oxygen deficiency, currently underway, should emphasize 1) modeling characteristics affecting the application of lab-

oratory test results to actual circumstances and 2) shape and size characteristics associated with noncubical CS models. It is also recommended that relatively complex data bases utilizing simple mathematical models, such as presented here and anticipated from further studies, be utilized to develop more consolidated predictive models.

Until further research is completed, the results of this preliminary study should be understood to suggest, but not confirm, ventilation design guidelines for oxygen deficiency in confined spaces. The general predictive capability of the data is not yet tested. The predictive capability of Tables I, II, and III will be enhanced if further studies demonstrate close agreement (high correlation) between small and substantially larger CS models. It will be enhanced by close geometric similarity to actual confined spaces, and will be reduced by variations.

Perhaps the overall conclusion to be drawn from this study is that mechanical ventilation can be effective in eliminating oxygen deficiency in a closed CS. Oxygen recovery to safe levels may require only a matter of minutes and can be very rapid with effective ventilation design. Individuals who are responsible for worker safety in closed confined spaces should be aware of this and insist upon some form of mechanical ventilation whenever the potential for oxygen deficiency exists. Failure to do so has

resulted in preventable accidents, injuries, and deaths in confined spaces.

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