THE DESIGN OF AXIAL FLOW CANISTERS FOR CARBON DIOXIDE ABSORPTION

M. L. Nickols
A. Purer
G. A. Deason
Naval Coastal Systems Center
Panama City, Florida 32407

Summary

Design data and guidelines are presented to help predict and maximize the performance of axial-flow carbon dioxide canister designs using alkali metal hydroxide absorbers. The data are derived from a series of laboratory tests conducted at the Naval Coastal Systems Center to isolate the effects of environmental and geometric parameters on canister absorption efficiency. A sample canister design is considered to demonstrate the use of the derived data to predict effective canister life.

Introduction

The Navy has a vital interest in identifying improved techniques, or more efficient methods, for removing metabolically produced carbon dioxide from divers' life support equipment. The inability of the CO₂ absorbent to maintain an acceptably low level of carbon dioxide, within the severe environmental conditions seen by divers, has been one of the major obstacles in the development of improved breathing apparatus.

Efficient removal of carbon dioxide is an absolute requirement for any acceptable closed-circuit breathing system. Generally, this is accomplished by passing the diver's expired gas through a fixed bed of granular material which has a strong affinity for CO₂. Although all one-man, closed-circuit systems rely on this general method for CO₂ removal, important differences exist in system geometry and flow behavior between the various systems. Unfortunately, these differences make it extremely difficult to predict the performance of a new system given only information about related existing systems. Our prediction capability is further complicated when new operational performance requirements (i.e., depth, temperature, etc.) are introduced for existing systems or systems being developed. Through necessity, a "cut and try" approach has been utilized when developing a new absorber system. Since diving technology is continually moving into previously inaccessible conditions of service, it is imperative that reliable techniques be developed to simulate and predict the performance of CO₂ absorbers.

It is not always an easy task to predict how a canister will function in a particular environment. Since World War I, when chemical absorbing agents were being investigated for gas masks, engineers have been asking how the absorption efficiency of their CO₂ "scrubbers" can be optimized. What are the most favorable environmental conditions for efficient operation of the absorption canister? How does the geometry of the canister affect this efficiency? Can we predict the performance of a CO₂ scrubber under one flow condition based on our observations of its performance under different flow conditions?

The data in this paper have been developed in an effort to help answer these questions, as well as, help engineers to predict the performance of prototype canister designs. Most design information in this paper is related to the absorption characteristics of High Performance Sodaasorb, manufactured by W. R. Grace Co. This information is derived from a series of laboratory tests conducted between FY 86 and FY 82 to isolate the effects of various environmental parameters on absorption efficiency.

Design Considerations for CO₂ Scrubbers

Many factors which affect the performance of carbon dioxide scrubbers are beyond the control of the designer. For instance, the operational pressure and temperature are usually fixed by the diver's surroundings. Any efforts to operate the scrubber in conditions other than those of the surroundings must be made at the expense of large expenditures of energy and involve complex designs. However, maximum efficiency of the carbon dioxide absorbent can be obtained by following several general design guidelines as summarized in Figure 1.6 They include the following:

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**FIGURE 1. THE ABSORPTION PROCESS**

1. **MAXIMIZE THE GAS RESIDENCE TIME WITHIN THE CANISTER:** In so doing the carbon dioxide in the gas stream has the greatest opportunity to be absorbed by the chemical absorbent. In constant flow systems the residence time can be maximized either by increasing the canister length (a trade-off with canister flow resistance) or by reducing the gas velocity within the canister. The flow velocity can be reduced either by providing a large cross-sectional area within the canister, or by controlling the volumetric flow rate actually going through the canister. For example, bypassing a portion of the gas stream around the canister can effectively reduce this flow rate within the canister while still maintaining an acceptable CO₂ level after mixing downstream of the canister.

In intermittent flow systems, such as those using the pumping action of the breathing cycle, the dead volume within the canister should be made as large as the human tidal volume to maximize absorption efficiency. In so doing the gas from the previous exhalation can reside in the canister during the entire inhalation phase. An intergranular space of approximately 0.5 litres is adequate for resting conditions with up to 3.5 litres required for maximum work rates.

2. **MATCH THE SCRUBBER DURATION WITH THE OXYGEN STORAGE CAPACITY:** The scrubber duration should be adequate to match the expected oxygen consumption by the diver, as dictated by the diver's respiratory quotient (RQ). For a typical RQ of 0.85 the diver would be required to absorb 0.85 litres of CO₂ for each litre of oxygen consumed. A breathing apparatus designed with a system RQ greater than 0.8 to 1.0 (has an excess scrubber capacity) would give a breathing apparatus which would deplete its oxygen source prior to canister breakthrough. An apparatus with
too low a system RQ would cause the diver to carry an unnecessarily large oxygen source.

3. MINIMIZE CANISTER FLOW RESISTANCE: Flow resistance of a breathing apparatus will become subjectively discomfiting during inhalation at magnitudes exceeding 7.0 to 7.5 cm H2O/liter/second. The exhalation resistance should not normally exceed 2.9 cm H2O/liter/second, and should never exceed the inhalation resistance.

4. MAINTAIN ADEQUATE MOISTURE LEVEL IN THE CANISTER: This factor is more important with calcium hydroxide based absorbents than with lithium hydroxide (high absorption efficiencies have been observed with LiOH with gas stream relative humidities as low as 5 percent); however, all hydroxide absorbers require water to initiate their absorption process.

The typical 3-step reaction involved in the absorption of carbon dioxide by Sodasorb, calcium hydroxide based, is:

\[ a. \quad \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{CO}_3 \]
\[ b. \quad 2\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow 2\text{CaCO}_3 + 2\text{H}_2\text{O} \]
\[ c. \quad 2\text{NaOH} + \text{CO}_2 \rightarrow \text{Na}_2\text{CO}_3 + \text{H}_2\text{O} \]

Note that in this process water is necessary to initiate the CO2 absorption (equation a). Note also that water is a by-product of the absorption process (equation b). If the incoming gas stream is saturated with water vapor, the water produced in the absorber bed may not be picked up. This water will then tend to coat the outer surfaces and pores of the absorbent particles, causing a decrease in absorption efficiency. If the incoming gas stream is too dry, the initiation of the reaction may be inhibited or the absorbent bed may be desiccated once the reaction is initiated, thereby limiting further absorption.

As a general rule, moisture levels of the incoming gas stream should be maintained above 70 percent RH when using Sodasorb or Baralyme.

5. MAINTAIN THE CANISTER TEMPERATURE LEVEL WHERE POSSIBLE: The absorption rate of chemical absorbers is related directly to the bed temperature. Experiences from past scrubber development programs have demonstrated consistently the reduced absorption capacities in cold environments. The exothermic reaction typical with most chemical absorbers can provide a substantial quantity of heat to the canister bed (13,500 calories are released per mole of CO2 absorbed by Sodasorb), which when properly insulated from the cold surroundings, can contribute to improved absorption efficiency. This factor is somewhat complicated due to the interrelation of bed temperature and moisture level. Too high a bed temperature will tend to dry out the absorbent, and inhibit the completion of the reactions as discussed above.

**Design Data**

The absorption process within a canister involves at least three processes from the time the CO2 in a gas stream enters until it is chemically absorbed. These may be categorized as the mass transfer of CO2 from the gas stream to the absorbent surface, adsorption at the surface, and, finally, chemical absorption. Satisfactory conditions must exist in each of these phases for the canister to perform as desired.

In the first process, a continual race is underway between the axial flow of the gas stream and the radial flow (due to convective mass transfer) of the CO2 molecules toward the absorbent surface. If the axial flow velocity, V, is excessive, or if the flow path, L, is too short the CO2 molecules will be carried through the canister without having the opportunity to contact the absorbent surfaces. The radial movement will be influenced by the mass diffusivity of CO2 in the carrier gas, Dv, the CO2 concentration of the carrier gas, C, and the path length between the gas midstream and the absorbent surface (related to the absorbent particle size, e, and the canister diameter, D). This radial movement will likewise be influenced by the level of turbulence that exists in the gas stream; a measure of which has been found to be a function of the gas stream density, \( \rho \), and viscosity, \( \mu \).

Once the CO2 molecule has made contact with the surface of the absorbent it must be noted that water is necessary to initiate the absorption process. This water may be furnished by the vapor present in the carrier gas stream, H, or the water mixed into the absorbent, HA.

Following this initial surface reaction, (usually thought of as occurring instantaneously) the CO2 can be chemically absorbed by the active absorbent. This reaction rate, R, must be sufficient to keep up with the rate at which the CO2 is being supplied to the chemical surface to minimize absorption. As with most chemical processes, this rate will be influenced by the ambient temperature.

Assuming the previous conditions, as described above, have been satisfactory and a sufficient mass of active absorbent, W, is available with adequate absorption capacity, A, the carrier gas stream will be cleansed of the CO2. When one or several of the above processes are limited, the exit CO2 level from the canister will rise until it exceeds the physiological limit for safe recirculation, an event commonly referred to as canister breakthrough. The time at which breakthrough occurs is similarly referred to as the breakthrough time, \( t_B \), or canister duration.

From the above discussion we can write a functional expression for the canister breakthrough time as

\[ t_B = \frac{t_B}{(V, T, \rho, \mu, C, H, HA, W, e, L, D, A, D', R)} \]

\[ D_x, T, R \]

\[ \eta = \frac{t_B}{t_{TH}} \]

\[ V \]

\[ T \]

\[ \rho \]

\[ \mu \]

\[ C \]

\[ H, HA \]

\[ W \]

\[ e, L, D, A, D', R \]

\[ D_x, T, R \]

\[ \eta = \frac{t_B}{t_{TH}} \]
where \( t_{TH} \) is the theoretical time to consume all active absorbent in the canister, resulted in the following functional representation of canister performance:

\[
\eta = f(\text{Re}, T, \text{H}, \text{L}, \text{D})
\]

(2)

where

\[
\text{Re} = \frac{\rho \text{Ve}}{\mu}
\]

Note that we have been able to reduce the 15 original functional parameters into six dimensionless groups.

### TABLE 1

PARAMETERS INVOLVED IN CANISTER \( \text{CO}_2 \) ABSORPTION

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Identification</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_B )</td>
<td>Breakthrough Time</td>
<td>( t )</td>
</tr>
<tr>
<td>( V )</td>
<td>Gas Stream Velocity</td>
<td>( L/t )</td>
</tr>
<tr>
<td>( T )</td>
<td>Gas Temperature</td>
<td>( T )</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Gas Density</td>
<td>( m/L^3 )</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Gas Viscosity</td>
<td>( m/Lt )</td>
</tr>
<tr>
<td>( C )</td>
<td>( \text{CO}_2 )  Concentration</td>
<td>( L^3/L^3 )</td>
</tr>
<tr>
<td>( H )</td>
<td>Gas Stream Water Vapor</td>
<td>( L^3/L^3 )</td>
</tr>
<tr>
<td>( \text{HA} )</td>
<td>Absorbent Water Content</td>
<td>( L^3/L^3 )</td>
</tr>
<tr>
<td>( W )</td>
<td>Absorbent Mass</td>
<td>( m )</td>
</tr>
<tr>
<td>( e )</td>
<td>Particle Size</td>
<td>( L )</td>
</tr>
<tr>
<td>( L )</td>
<td>Canister Length</td>
<td>( L )</td>
</tr>
<tr>
<td>( D )</td>
<td>Canister Diameter</td>
<td>( L )</td>
</tr>
<tr>
<td>( D_v )</td>
<td>Mass Diffusivity</td>
<td>( L^2/t )</td>
</tr>
<tr>
<td>( A )</td>
<td>Absorption Capacity</td>
<td>( m/n )</td>
</tr>
<tr>
<td>( R )</td>
<td>Reaction Rate</td>
<td>( m/t )</td>
</tr>
</tbody>
</table>

Basic Units:

- \( t \) = Time
- \( L \) = Length
- \( m \) = Mass
- \( T \) = Temperature

In so doing we have been able to reduce the imponderable mathematics of Equation 1 to a more manageable characterization of six dimensionless groups.

Data from a large series of carefully controlled laboratory tests \(^2\) \^3\(^4\) \^5\(^6\) were handled in the manner described above and plotted in Figure 2. These data show the effects of particle Reynolds number, and canister geometry on the efficiency of a canister to absorb carbon dioxide. All data are based on steady flow through axial canisters.

![FIGURE 2. CALCULATED EFFICIENCY OF STANDARD TEST CANISTER AT VARYING PRESSURES](image)

To use this data to design new canisters or to predict the life of present canisters in varying environmental conditions, we can enter Figure 2 on the abscissa or ordinate depending on the constraining conditions being put on the design. If the system flow rate is known at the depth of interest, the Reynolds number (based on absorbent particle diameter) can be calculated. This Reynolds number can then be used to obtain a canister efficiency, \( \eta \), corresponding to the appropriate operating pressure. The theoretical bed life can then be read from Figure 3, for a specific weight of absorbent, to allow us to calculate a predicted canister life as

\[
\text{Bedlife based on } 0.01 \text{ ata (1% SLE)} \quad \text{CO}_2 \text{ in system flow}
\]

For \( \text{CO}_2 \) concentrations diff from 1% Divide theoretical bedlife from chart by % \( \text{CO}_2 \) (SLE)

![FIGURE 3. THEORETICAL BEDLIFE FOR SODASORB CANISTERS](image)

On the other hand, if a specific canister life is desired, the previously obtained value of \( \eta \) can be used to calculate the necessary theoretical bed life as

\[
\text{Bedlife based on } 0.01 \text{ ata (1% SLE)} \quad \text{CO}_2 \text{ in system flow}
\]

Figure 3 can then be used to determine the mass of absorbent required for this canister life requirement.

The empirical relationship for the efficiency of a standard canister

\[
\eta = \frac{t_B}{t_{TH}} \eta .
\]

(3)

\[
\text{On the other hand, if a specific canister life is desired, the previously obtained value of } \eta \text{ can be used to calculate the necessary theoretical bed life as}
\]

\[
\text{Bedlife based on } 0.01 \text{ ata (1% SLE)} \quad \text{CO}_2 \text{ in system flow}
\]

(4)
\[ \eta_{\text{STD}} = 1 - 0.94e^{\frac{P + 1}{(\frac{Re}{P})^{1.34}}} \]  

(5)

where

\[ P = \text{environmental pressure (atmospheres absolute)} \]

\[ Re = \text{Reynolds number based on absorbent particle diameter} \]

has been found to closely represent the data in Figure 2. This equation can be used to derive a canister efficiency once the Reynolds number of the system flow and the ambient pressure is known.

Note that this derived efficiency is for a saturated gas stream at 21.1°C (70°F) with a canister length-to-diameter ratio and diameter-to-mesh ratio of 7 and 2.75, respectively. For conditions and/or canister geometries other than these, modifying coefficients, as shown in Figures 4 through 8, must be considered to calculate the canister efficiency under actual flow conditions.

The predicted life of this canister can be arrived at by multiplying the theoretical canister life, \( t_{\text{TH}} \), by the canister efficiency, \( \eta \), as

\[ t_{\text{E}} = t_{\text{TH}} \cdot \eta. \]

From Figure 3, we can find the theoretical life of a canister with 12 pounds of HP Sodasorb which sees 5.4 ACFM of 1 percent CO\textsubscript{2} laden gas to be approximately 790 minutes (13.2 hours). As directed in this figure we divide this bed life by the actual percent concentration of CO\textsubscript{2} for levels other than 1 percent. Thus, the actual theoretical bed life will be

\[ t_{\text{TH}} = \frac{790 \text{ minutes}}{0.58} = 1,362 \text{ minutes} (22.7 \text{ hours}). \]

We next arrive at the expected canister efficiency through the use of Figures 2 and 4-8. To enter these charts we must first determine the mean particle Reynolds number, \( Re \), for the canister absorbent material, where

\[ Re = \frac{d \overline{Ve}}{\mu} \]
\[ \bar{V} \] superficial gas stream velocity in the canister, ft/sec

\[ e \] mean absorbent particle diameter, feet

\( \rho, \mu \) the gas stream density and viscosity, respectively.

From the US Navy Diving-Gas Manual\(^1\) an acceptable breathing mixture at 119 metres of seawater (12.8 ATM) would be 84 percent helium/16 percent oxygen with the following gas properties

\[ \rho = 4.16 \text{ kg/m}^3 \quad (0.26 \text{ lbs/ft}^3) \]

\[ \nu = 2.13 \times 10^{-5} \text{ Pa} \cdot \text{s} \quad (1.43 \times 10^{-5} \text{ lbs/ft-sec}) \]

The superficial gas stream velocity is determined by dividing the gas flow rate by the canister cross-sectional area.

\[ \bar{V} = \frac{\frac{5.4 \text{ ft}^3/\text{min}}{\pi (6.25 \text{ ft})^2}}{\frac{1}{60 \text{ sec}}} = \frac{1 \text{ min}}{60 \text{ sec}} = 0.46 \text{ ft/sec} \]

The mean particle diameter of 4 by 8 mesh Soda-sorb (see Table 2) is 0.14 inch. We can now calculate the particle Reynolds number according to the above definition to get

\[ Re = \frac{\frac{.26 \text{ lbs/ft}^2 \times \frac{46 \text{ ft/sec}}{1.43 \times 10^{-5} \text{ lbs/ft-sec}}}{14/12 \text{ ft}}}{1.43 \times 10^{-5} \text{ lbs/ft-sec}} \]

**TABLE 2**

**PARTICLE MESH SIZES**

<table>
<thead>
<tr>
<th>TYLER MESH RANGE</th>
<th>MESH OPENING</th>
<th>MEAN PARTICLE DIAMETER, INCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-8</td>
<td>.187 - .093</td>
<td>0.140</td>
</tr>
<tr>
<td>8-20</td>
<td>.093 - .033</td>
<td>0.063</td>
</tr>
<tr>
<td>10-20</td>
<td>.067 - .033</td>
<td>0.050</td>
</tr>
<tr>
<td>20-60</td>
<td>.033 - .010</td>
<td>0.022</td>
</tr>
<tr>
<td>32-60</td>
<td>.020 - .010</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Re = 97.6

and

\[ Re \cdot \frac{L}{D} = 97.6 \times \frac{14.75}{6.0} = 240. \]

We can now enter the bottom of Figure 2 with a value of Re \( \cdot \frac{L}{D} \) of 240 to arrive at a value for the canister efficiency at 12.8 ATM under the standard conditions shown in the legend, i.e.,

100% RH incoming gas humidity

70°F incoming gas temperature

1% \( CO_2 \) level in incoming gas

6.5-7.0 length-to-diameter ratio of canister

2.75 canister-to-particle diameter ratio.

For this value of Re \( \cdot \frac{L}{D} \) we get approximately

\[ \eta = 0.23 \]

For this example we will assume that the incoming gas stream is 60°F and saturated with water vapor. The canister L/D ratio is 2.5; the canister-to-particle diameter ratio, \( D/e \), is 43; and as stated previously, \( CO_2 \) concentration is 0.58 percent SLE.

The canister efficiency under these conditions is found by multiplying the standard canister efficiency, \( \eta \), by the correction factors from Figures 4 through 8 for conditions which vary from the standard, i.e.,

\[ \eta_{\text{ACTUAL}} = \eta_{\text{STD}} \cdot A_T \cdot A_H \cdot A_C \cdot A_D \cdot A_F \]

where

\[ A_T = \text{Temperature Effect Factor} \]

\[ A_H = \text{Humidity Effect Factor} \]

\[ A_C = \text{CO}_2 \text{ Injection Rate Factor} \]

\[ A_D = \text{Length-to-Diameter Effect Factor} \]

\[ A_F = \text{Wall Effect Factor}. \]

\( A_T \) for 60°F and Re \( \cdot \frac{L}{D} = 240 \) is 1.0 (Figure 4). \( A_H \) is also 1.0 since it is identical to the standard canister (also see Figure 5). \( A_C \) is approximately 1.9 for a \( CO_2 \) level of 0.58 percent SLE (Figure 6). \( A_D \) and \( A_F \) are seen to be 1.0 in Figures 7 and 8 for Re \( \cdot \frac{L}{D} = 240 \). Therefore,

\[ \eta_{\text{ACTUAL}} = 0.23 (1.0)(1.0)(1.9)(1.0)(1.0) \]

\[ \eta_{\text{ACTUAL}} = 0.437 \]

and the predicted canister life will be

\[ t_B = t_{\text{TH}} \cdot \frac{\eta_{\text{ACTUAL}}}{\eta_{\text{STD}}} \]

\[ = 1,362 \text{ min} \times 0.437 = 595 \text{ min (9.9 hrs)} \]

The canister and flow conditions described in the previous example are similar to those seen by the Navy’s MK 12 Surface Supported Diving System. This system is designed to operate at a maximum depth of 390 FSW while supplying 6 ACFM to the diver’s helmet (5.4 ACFM are recirculated through the \( CO_2 \) canister while 0.6 ACFM is exhausted from the helmet). In excess of 10 hours system duration was reported for the MK 12 \( CO_2 \) scrubber at 390 FSW when the inlet gas temperature was maintained above 60°F.\(^1\) During these unmanned tests a simulated diver work cycle was given by 6 minutes injection of \( CO_2 \) into the canister at 0.75 percent SLE (moderate work rate) followed by 4 minutes injection of \( CO_2 \) at 0.33 percent SLE (rest). This gave a mean injection rate over a 10-minute period of

\[ \% \text{ CO}_2 \text{ mean} = \frac{6 \times 0.75 + 4 	imes 0.33}{10} \]

\[ = 0.582\% \]

**Discussion**

The close agreement between the predicted canister life and the experimentally recorded duration of
the MK 12 canister under similar operational conditions is encouraging. A shortcoming of this predictive method, however, is seen when we attempt to look at how the canister life will drop off as the gas stream temperature is decreased (a phenomenon recorded experimentally for the MK 12 canister). Figure 4 shows a decreasing temperature effect factor, $A_T$, as temperature is decreased when values of $Re \cdot \frac{L}{D}$ are less than approximately 56. This would suggest that the effect of temperature is minimal when $Re \cdot \frac{L}{D}$ is greater than a value of 240. The shortcoming of this design data is not understood. It could potentially result from the use of data derived from small, isothermal canisters to predict the performance of relatively large canisters with known bed temperature variations. Further experience with the use of these charts will be necessary before it can be determined whether this shortcoming is universal or only peculiar to the MK 12 design.

References


