"Do-it-yourself" calorimetry for critical life-support systems

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INTRODUCTION

Closed-circuit rebreathers offer significant advantages over open-circuit SCUBA equipment for underwater cave exploration due to their increased duration and potential to reduce the decompression requirements for deep diving [1]. Additionally, such devices produce no bubbles which can affect visibility by dislodging sediments and also supply warm, humidified breathing gas which can increase operator comfort. Although war surplus equipment was employed by civilians for this purpose in 1946 [2], mixed-gas closed-circuit rebreathers have been only been commercially available outside of military circles since 1997 [3]. These mass-produced devices have been widely adopted by amateur divers; however they are unsuitable for cave diving at many sites in the UK owing to their size and configuration (worn on the diver's back). Chest- or side-mounted rebreathers are preferred for use in domestic conditions and, as such units are not readily available, these must be specially constructed for this purpose [4]. Whereas mass-produced rebreathers are subject to stringent testing and certification [5], the enterprising homebuilder must either rely on luck or devise his own methods of establishing the performance of bespoke life-support systems.

A schematic diagram of a rebreather is shown in figure 1. The apparatus consists of a closed-loop system whereby the carbon dioxide present diver's expired breath is removed by a scrubber canister filled with soda lime before being retained in a flexible bag (or counterlung) so that it may be inspired by the diver once more. In order to maintain life, a small flow of pure oxygen is added to the system to match that metabolised by the wearer. Additional ballast gas of air or some other diluent is used to prevent hyperoxia and means of monitoring the partial pressure of oxygen in the system (using one or more electrochemical sensors) is essential to avoid the mixture becoming hypoxic.

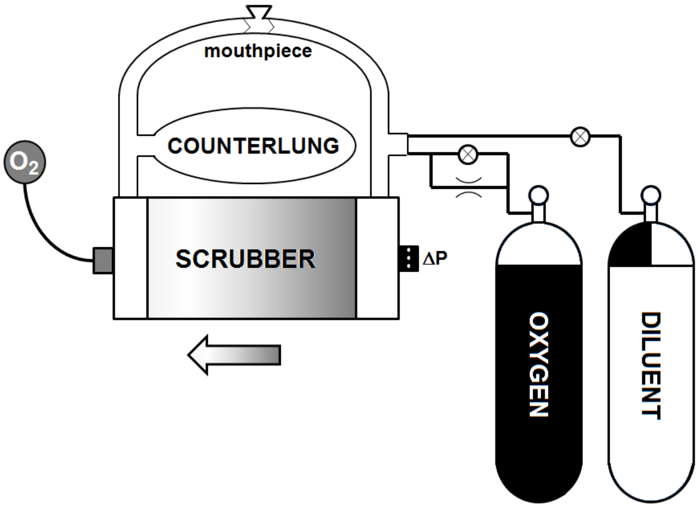

Fig. 1. Closed-circuit mixed gas rebreather schematic.

A critical principle of a rebreather is the use of soda lime to remove carbon dioxide. Any build-up of this gas in the breathing loop can have serious physiological consequences leading ultimately to death [6]. Early symptoms of hypercapnia are often overlooked until it is too late; therefore it is imperative to militate against "breakthrough" of CO_2 from the scrubber by a conservative approach. Ideally, a means of measuring the partial pressure of CO_2 could be incorporated into the breathing loop (as is done for oxygen), however the most reliable methods of gas monitoring that can deliver the necessary accuracy and resolution (e.g. infra-red spectrometry) are difficult to operate in hyperbaric conditions and 100% humidity. Although CO_2 monitors have been incorporated into rebreathers [7], such a device can only tell the user when the breathing loop is in a dangerous condition rather than providing a prediction of remaining duration.

MATERIALS AND METHODS

Tests were done on a variety of scrubber designs of the axial or co-axial type filled with either Intersorb 812 or Spherasorb 408. The former comprises 2 mm diameter cylindrical granules with a typical CO_2 capacity of 150 l/kg whereas the latter takes the form of 3 mm diameter spheres (containing 5% zeolite) and has a CO_2 capacity of 128 l/kg [8]. An array of K-type thermocouples were arranged at equidistant intervals along the soda lime bed radiating in a spiral pattern from a central support. A mixture of carbon dioxide in humidified nitrogen was passed through the scrubber supplied from a pair of mass flow controllers. Carbon dioxide was supplied at a constant rate (typically 1 SLM – corresponding to the metabolic production rate of a diver undergoing moderate exertion [9]) via a 5 SLM mass flow controller (model) using a gas factor of 0.70 [10] to accommodate the use of CO_2 rather than N_2 in the device. A surface air consumption rate of 20 SLM was assumed for all experiments and an appropriate nitrogen flow supplied via a second gas flow controller (0-200 SLM) though a bubbler containing water at room temperature. Both devices were checked for flow rate by reference to precision mass flow controllers reserved for such purpose that are regularly calibrated by their manufacturer to traceable standards. The gas exiting the scrubber was analysed for CO_2 and water content by passing a portion of the flow through a spectrometer (MKS MultiGas™ 2030) with heated transfer lines and a 5 m path length flow cell. The transfer lines and gas cell were heated to 150 °C to prevent condensation of moisture. The relevant gas concentration calibrations supplied by the manufacturer were used for the analysis: these were checked for accuracy against known flows of CO_2 and humidified nitrogen provided by the gas delivery system. The scrubber and bubbler were placed in a large water bath in order to maintain the apparatus at a stable temperature.

RESULTS AND DISCUSSION

A plot of the data obtained from a typical experiment is shown in figure 2. Carbon dioxide breakthrough occurs after approximately 2.5 hours under the conditions of the test which were aimed at approximating operating the scrubber at a depth of 30 m in fresh water (4 bar absolute). This was achieved by flowing 1 SLM of CO_2 diluted with 80 SLM of N_2 in order to achieve the desired residence time in the soda lime bed. These data contain a wealth of information about the progress of the reaction zone through the scrubber. For example, the length of bed required to absorb CO_2 can be estimated as about 80 mm from the temperature distribution recorded by the thermocouples at the time at which breakthrough occurs. The effect of residence time (equating to depth), CO_2 flow rate (relating to diver work load), scrubber geometry and sorbent particle size can be investigated, allowing operational limits to be placed on the device. By deriving differential temperature measurements between pairs of adjacent thermocouples, it is possible to obtain pseudo-calorimetric information about the rate of reaction of soda lime with CO_2 in different parts of the scrubber (figure 3). In principle, it is relatively straightforward to incorporate the necessary electronics to record and display this whilst diving.

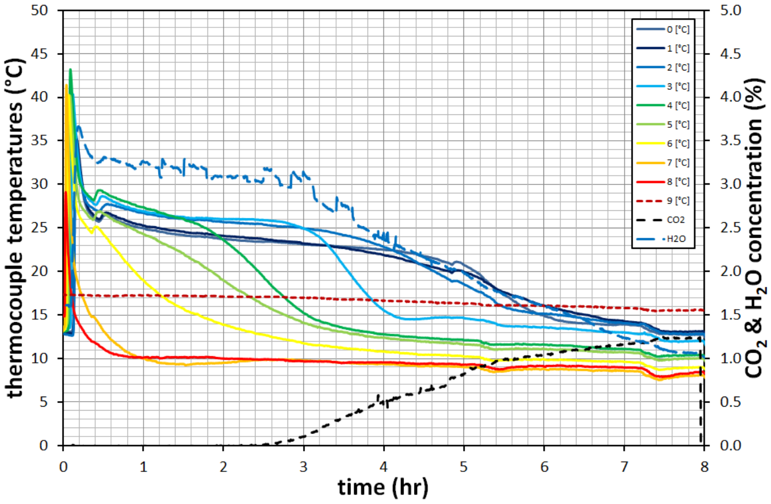

Fig. 2. Raw data from test of a 200 mm long × 145 mm diameter scrubber bed at a simulated operating depth of 30 m of fresh water.

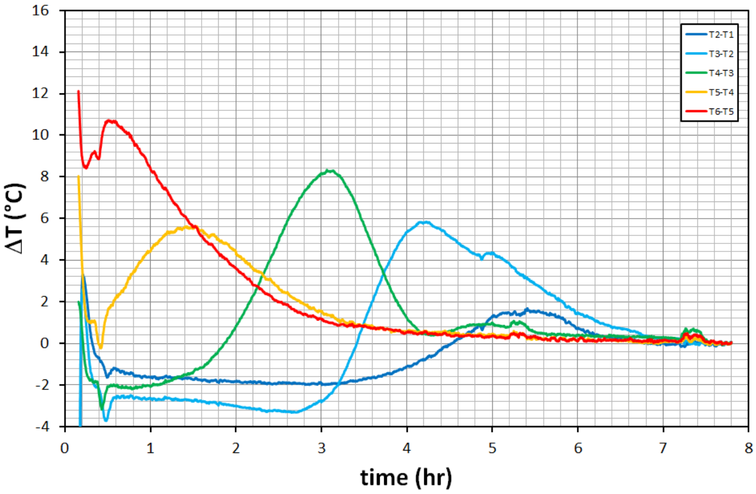

Fig. 3. Differential temperature curves derived from the raw data shown in Fig. 2.

CONCLUSIONS

Laboratory tests on carbon dioxide scrubbers have been used to estimate their endurance under field conditions. By distributing an array of temperature sensors throughout the packing, the location of the active part of the sorbent can be determined. Such an approach could be developed into a submersible monitor for real-time performance measurement.

ACKNOWLEDGMENTS

The author is grateful to DIVELIME for the provision of materials for this work.

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