Compact Recreational Rebreather With Innovative Gas Sensing Concept and Low Work of Breathing Loop Design

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ABSTRACT

Recreational rebreathers are increasingly popular, and recreational diver training organizations now routinely offer training for rebreather diving. Few rebreathers on the market, however, fulfill the criteria of a dedicated recreational rebreather. These remain based on traditional sensor technology, which may be linked to rebreather use having an estimated 10 times the risk of mortality while diving compared with open circuit breathing systems. In the present work, a new recreational rebreather based on two innovative approaches is described. Firstly, the rebreather uses a novel sensor system including voltammetric and spectroscopic validation of galvanic pO_2 sensor cells, a redundant optical pO_2 sensor, and a two-wavelength infrared pCO_2 sensor. Secondly, a new breathing loop design is introduced, which reduces failure points, improves work of breathing, and can be mass fabricated at a comparatively low cost. Two prototypes were assembled and tested in the laboratory at a notified body for personal protective equipment before both pool and sea water diving trials. Work of breathing was well below the maximum allowed by the European Normative. These trials also demonstrated that optical pO_2 sensors can be successfully employed in rebreathers. The pCO_2 sensor detected pCO_2 from 0.0004 to 0.0024 bar. These new approaches, which include a new concept for simplified mechanical design as well as improved electronic control, may prove useful in future recreational diving apparatus.

Keywords: rebreather, pO_2 control system, O_2 sensor, CO_2 sensor, counterlung

Introduction

In recreational diving, autonomous open circuit (OC) breathing systems are dominant. Breathing gas is most often carried in a single high-pressure cylinder on the back of the diver. The diver inhales through an on-demand regulator, which delivers gas at ambient pressure. The exhaled gas is expelled into the surrounding water. Breathing gases in recreational diving are mainly compressed air but also oxygen (O_2)-enriched air, usually referred to as NITROX. For deeper diving, a proportion of the nitrogen (N_2) in the breathing gas is substituted with helium (He) and the resultant blend known as TRIMIX.

Compared with alternative breathing systems, OC diving faces several disadvantages. The breathing gas is dry and cold and produces expelled bubbles that disturb the environment. The main disadvantage though is the relatively poor gas efficiency, which only worsens with increasing depth. Just a fraction of O_2 from the breathing gas is used in any system before it is exhaled by the diver, and in the case of OC, it is then expelled into the environment. Therefore, a typical recreational dive with one 12-L cylinder filled with air compressed to 200 bar and thus containing 500 L of oxygen may not last more than 40–45 min at 20-m depth; although with, for example, an O_2 metabolism of 0.8 L/min, the O_2 content in the cylinder should suffice for more than 10 h of diving.

In contrast to OC diving apparatus, diving with a closed circuit rebreather (CCR) more efficiently uses the available breathing gas and is less disruptive to the environment (Shreeves & Richardson, 2006). The exhaled gas

is not expelled into the surrounding water but is returned back into a breathing bag—the so-called *counterlung*. Carbon dioxide (CO_2) is chemically turned into insoluble carbonate and removed from the gas while passing through a scrubber. Metabolized O_2 is replaced by oxygen from a small high-pressure supply cylinder. The simplest form of a CCR uses pure oxygen as the breathing gas. However, oxygen becomes increasingly toxic at partial pressures exceeding approximately 1.6 bar, so the operational depth limit of such devices at sea level is 6 msw.

For deeper diving with CCR, the partial pressure of oxygen (pO_2) must be maintained at less than 1.6 bar to minimize the risk of oxygen toxicity and yet also as high as can be safely tolerated to reduce both the uptake of inert gas into the diver's tissues and the concomitant risk of decompression sickness. This is achieved by diluting the gas in the breathing bag with a mixture containing inert gas such as air, NITORX, TRIMIX, or HELIOX (a blend of O_2 and He). This mixture is known as the diluent. While O_2 CCRs are relatively uncomplicated mechanical devices, CCRs using blends of gas containing only a proportion of oxygen use oxygen sensors for monitoring pO_2 in the breathing gas and an electronic system for maintenance of the pO_2 within acceptable limits.

The earliest recreational rebreathers date back to 1996 when Dräger launched the Atlantis and later the Ray and Dolphin. The Dräger Ray came with a price tag that offered a realistic alternative to OC equipment. However, those units were semiclosed rebreather (SCR) systems where gas was still expelled into the environment and the systems were not as silent as CCRs. Their gas efficiency was much greater compared with OC systems, even though a significant portion of the breathing gas was still wasted.

More advanced CCRs for deep "technical" divers have been available since approximately 1995. A common attribute among currently available models is that they are relatively more complex to operate than either OC or SCR, they require practice and regular training, and they take longer to prepare (including manual checklists) before any dive and longer maintenance after diving. Such systems are not well suited to recreational divers who perform a relatively low number of dives per year—for example, during holidays only—since only a high level of training and more regular diving assures an acceptably low level of risk.

The first electronically controlled CCR specifically intended for sport divers was introduced in 2009 (Shreeves, 2009). For the first time, predive tests and operation under water were automated. For rebreather novices with an OC diving certification, this reduced the initial learning demand. When CCRs became available specifically for recreational divers, then large recreational diver training agencies launched rebreather training programs, also specifically for recreational divers.

Meanwhile, the mere availability of rebreathers and training is not enough for a market success, as Mark Caney, Head of the Professional Association of Diving Instructors TecRec Division, explained in his 3T (Training/Technology/Travel) concept (Caney, 2010). Many recreational divers devote themselves to diving on vacation only, and many also do this at a place far from home. To become a market success, the rebreather not only has to be transportable but also usable at the diving site. Therefore, diving locations that accept rebreather divers are required to provide O_2 filling equipment and should be able to supply CO_2 filters used to "scrub" the exhaled gas of CO_2.

We believe that there are other important factors conditioning the commercial success of recreational rebreathers:

- Safety: The risk of mortality while diving a CCR is estimated to be approximately 4–10 times greater than OC diving (Fock, 2013). Rebreather features that may help reduce rebreather accidents include the following:
  - full automation to avoid user errors,
  - reliable O_2 sensor system to avoid a hypoxic or hyperoxic breathing gas composition,
  - O_2 sensor system that can detect sensor failures: current O_2 sensor technology is known to be failure prone and O_2 sensor failures happen frequently,
  - CO_2 sensor to detect a scrubber failure, and
  - low work of breathing
- Price: To be successful in the recreational rebreather market, the price of a recreational rebreather should be comparable to a price of an upper-end OC technical diving configuration. The CCRs currently available on the market are complex systems with more relatively expensive parts and higher production costs than OC system components. Thus, it is unlikely that the current systems will become available at prices comparable to OC systems. Therefore, new approaches in mechanical design as well as electronic and sensor technology are required.
- Shorter pre- and postdive preparation of the rebreather: While OC diving systems can be assembled

in short order and require only a minimum of maintenance (rinsing in fresh water after a dive is usually enough), CCRs require that the breathing loop is disassembled, cleaned, disinfected, and dried.

The current paper addresses these three factors with two fresh approaches. Firstly, a novel gas control system is introduced that uses, for the first time in CCR technology, voltammetric galvanic pO_2 sensor validation and optical pO_2 sensors as backup systems in combination with a highly automated user interface. Secondly, lower manufacturing costs, short pre- and postdive preparation/maintenance of the unit as well as low work of breathing are addressed with a simplified breathing loop concept.

State of the Art of Rebreather Design: Breathing Loop

There are two dominant counterlung positions found in today's recreational and technical rebreathers (Kellon, 1998). Over-the-shoulder counterlungs provide acceptably low work of breathing, are accessible by the diver during the dive, and can be easily equipped with manual O_2 and diluent injection buttons. However, a proportion of divers report that they prefer a free chest and avoid such front-mounted counterlungs. In contrast, back-mounted counterlungs have a greater work of breathing and/or a hydrostatic imbalance that may even fall outside of limits set by the European standard for rebreathers (EN14143:2003), and yet they provide a higher degree of convenience for certain types of sport diving (e.g., cave exploration).

The breathing loop mouthpiece, counterlungs, and scrubber are usually connected with corrugated hoses and appropriate connectors. For example, in rebreathers detailed by Shreeves in 2009, a total of four corrugated hoses were used to connect the components. Breathing hoses typically have a connector at each end with one o-ring in each connector. Every additional part increases the risk of system failure, especially when they are connected in series (Fock, 2013). Additionally, the overall work of breathing also depends on the amount of connectors, gas resistance in the loop, length of hoses, etc. Therefore, many rebreathers hardly meet the limits for the work of breathing defined in the European Normative EN14143:2003, especially at high respiratory minute volumes.

State-of-the-art mouthpieces for recreational rebreather diving can be switched between two modes: In the closed circuit mode, the diver breathes from the breathing loop of the rebreather. If the rebreather fails, then the diver can switch the mouthpiece to OC mode using gas from either the diluent cylinder or a separate cylinder carried specifically for such an emergency. Such mouthpieces are known as "bail out valve mouthpieces."

Some manufacturers also integrate an automatic loop diluent valve into the mouthpiece by using the valve of the OC mode. To function correctly, this requires that the cracking pressure (to initiate gas injection) is adjusted accordingly to the mode. While in OC mode, the cracking pressure should be adjusted to a value between 1 and 3 mbar; in closed circuit mode, the cracking pressure should be set to 25–35 mbar, otherwise the hydrostatic pressure equivalent to the difference in depth between the mouthpiece and the counterlung may lead to a free flow of diluent into the counterlung. This is a particular problem when a diver uses a CCR with back-mounted counterlungs, as in the horizontal diving position there is a constant negative inspiratory pressure, primarily caused by the rebreather's hydrostatic imbalance (Kellon, 1998).

O_2 Sensor System

CCR systems that use a gas other than 100% O_2 cannot be purely mechanical since they require pO_2 monitoring and control. Galvanic pO_2 sensors are uniformly used in CCRs to measure pO_2. The pO_2 in the breathing loop is held within a tolerable range by replacing metabolized O_2 either manually or automatically with fresh O_2 from a supply cylinder. In an electronic CCR, a solenoid gas injector for adding O_2 is incorporated (Shreeves & Richardson, 2006).

It is imperative that oxygen sensors measure pO_2 correctly because the safe range for breathing is fairly narrow. Incorrect pO_2 readings from faulty pO_2 sensors can lead to too little O_2 (hypoxia) or too much O_2 (hyperoxia or "oxygen toxicity"). Either condition is life threatening. Indeed, unsustainable breathing gas composition in the rebreather loop is believed to be the primary cause of many fatalities (Vann et al., 2007; Buzzacott et al., 2009).

Galvanic oxygen sensors in rebreathers essentially operate in similar fashion to a metal/air battery (Chang et al., 1993; Sieber, 2012). Oxygen is dissociated and reduced at the cathode to hydroxyl ions. These pass through the electrolyte and oxidize the metal anode (Pb). When the cathode and anode are electrically loaded with a resistor (typically between 50 and 300 Ω), a current proportional to the rate of oxygen consumption is generated.

A diffusion barrier (sensor membrane) is mounted in front of the cathode. This limits the volume of molecules able to reach the cathode during any particular period. All O_2 molecules at the cathode get reduced. The amount of molecules reaching the cathode follows Fick's First Law of Diffusion and is proportional to the pO_2 in front of the sensor membrane. Thus, the current of the (ideal) sensor is dependent only on the pO_2 in front of the sensor membrane.

Each sensor changes its output over time due to consumption of the cathode. While new sensors may typically achieve an output of up to 14 or 15 mV in air, after 1 year of usage the output may have decreased to below 8 mV. Therefore, sensors in rebreathers are usually calibrated before each dive by exposing them to air or 100% O_2.

The current produced by a sensor increases with temperature (about 2–3% per 1 K) as the diffusion is temperature dependent. Galvanic cells used in rebreathers are typically equipped with a small electronic board on their underside. These include a load resistor; thus, on the terminals of the sensor, one terminal does not relate to current but voltage. Additionally, a small resistor network with a negative temperature coefficient is used for temperature compensation.

Failure modes of galvanic sensors include the following:
- Nonlinearity: Functional pO_2 sensors usually have a linear output and a constant slope of about 40–60 mV/ bar. In a nonlinear sensor, this slope is not constant but dependent on environmental factors such as, for example, ambient pressure, temperature (defective temperature compensation) or pO_2.
- Current limitation is a special case of nonlinearity, where the sensor fails to provide a linear output above a certain pO_2.
- Slow sensor signal response: While a typical sensor response time is about 6–10 s, water condensation on the sensor membrane or low temperature can result in response times of 30 s to several minutes.
- Other mechanical failures (electrical connections broken, cell housing damaged, etc.).

In all failure modes, the sensor no longer produces an electronic signal corresponding to the pO_2 in front of the sensor membrane. As a consequence, the control loop may inject too little or too much O_2, and either case may quickly lead to an unsustainable breathing gas mixture.

Whereas electronic O_2 injectors are robust and failures are unlikely during a dive, sensor failures happen relatively more frequently. Rebreather manufacturers commonly address this problem by using three pO_2 sensors instead of merely one, together with a voting algorithm. Here the sensor signals are continuously compared with each other. If one sensor signal differs from the others, then that sensor signal is "voted out." Such voting algorithms will fail, however, if two or more sensors concurrently malfunction.

The basis for such an approach is the assumption that sensors fail independently. This is, however, not always the case. O_2 sensors in a CCR are subjected to a common environment. If sensors are installed together in a rebreather, then they will also have the same "diving history." Therefore, having three or possibly even more O_2 sensors may not provide triple or higher redundancy in the event of every type of sensor failure (Jones, 2012).

An alternative to the voting algorithm is true sensor signal validation (Sieber et al., 2008), commonly used in medical analyzers. In the case of a CCR galvanic sensor cell readings are validated by flushing them with gas of a known O_2 fraction at regular intervals, for example, every 2 min. This differs to the voting algorithm because true sensor validation gives real-time feedback on sensor operation as the sensor is checked for linearity, current limitation, and response time.

A current, limiting disadvantage of true sensor validation is the additional hardware effort, which includes two additional solenoid gas injectors. This results in both additional manufacturing costs and also additional failure points. A slightly leaking solenoid gas injector may continuously flush the sensors with gas. In such an eventuality, the sensor signal may not only correspond to the pO_2 in the loop but might also be influenced by the leaking gas stream.

An alternate approach to galvanic pO_2 sensor validation has been described (Sieber et al., 2012), where the analog electronic board of pO_2 sensors was substituted with low-cost microprocessor-based multifunctional sensor electronics. This allowed on-board signal processing including digital temperature compensation. In addition, by using the internal digital-to-analog converter of the microcontroller, it was possible to perform voltammetry and impedance spectroscopy of the sensor. These measurements indicated the electrochemical constitution of a sensor (including the cathode, anode and the electrolyte). If the characteristics of any sensor differ significantly from its baseline values, then this indicates sensor malfunction and/or changed electrochemistry, which may soon lead to a sensor failure. An advantage of this technology is that additional hardware costs were

very low in comparison with the true sensor validation approach.

One alternative to galvanic pO_2 sensors are solid state ceramic sensors. Solid state pO_2 sensors are based mainly on the ionic conductivity of ceramic materials (Park et al., 2009). For many years, this technology has been deployed in cars for combustion control (i.e., lambda probes). At present, only yttria-doped zirconium dioxide (Zirconia, YDZ) is applied in commercial transducers as a conducting solid state electrolyte. Conductivity in YDZ requires high temperatures. Therefore, the transducer is heated by an electrical resistance to reach an operating temperature of about 650°C, which demands considerable energy. Micromanufacturing allows miniaturization of such sensors, which results in reduced power consumption for heating. An overview of micro-solid state gas sensors can be found elsewhere (Dubbe, 2003; Bogha et al., 2007). Solid state electrolyte sensors can also be designed for other gases, for example, NASICON is a suitable ionic conductor for a solid state CO_2 transducer. A rebreather sensor module has been developed consisting of one solid state sensor for pO_2 and one for pCO_2 (Sieber et al., 2011a, 2011b). Preliminary results are promising, but no serial production process has commenced; therefore, existing results are purely academic. It may be expected to take several years before such sensors could be used in commercially available CCRs.

Another possible alternative for galvanic pO_2 sensors are optodes, which are optical pO_2 sensors. To our knowledge, such sensors have not previously been tested in CCRs. These optical pO_2 sensors consist of a chemical layer with illuminated color pigments. The color pigments start to fluoresce at a corresponding wavelength. Optical filters are used to separate the illumination light and the fluorescence signal. In the presence of O_2, the fluorescence is quenched; thus, the output signal is reduced. Such sensors are most sensitive when no or only traces of O_2 are present. The sensitivity decreases with increasing pO_2. Recently, new fluorescence pigments have been developed (Borisov et al., 2008), which may also allow reliable measurements of pO_2 above 1 bar. Alternatively to measuring the absolute sensor signal, one can also measure the decay time. As the time constant is only a few microseconds for measurements at 0.21 bar pO_2 and even shorter at higher pO_2, time measurement is difficult. However, decay time offers a unique advantage in that factory calibration becomes possible, as decay time does not change over the lifetime of the sensor.

CO_2 Sensors and Scrubber Monitoring

A malfunction of the scrubber or even the absence of a scrubber leads to a rapid increase of pCO_2 in the breathing loop. This is known to account for numerous CCR fatalities. Today, two methods of scrubber function monitoring are available. The first approach examines the heat generated in the scrubber to give a prognosis on the remaining scrubber lifetime (Warkander, 2003). Secondly, direct gaseous pCO_2 measurement can be done with optical absorption spectroscopy, as CO_2 absorbs infrared light at 4.3 μm. One sensor used in rebreathers is the OEM CO_2 sensor module from Gas Sensing solution (Glasgow, UK). It is a one wavelength optical sensor measuring the absorption of infrared light at 4.3 μm. The advantages include a relatively small size, low power consumption, and commercial availability. However, as this sensor is based on a single wavelength measurement, contamination of the sensor or condensation of water on the internal components may lead to a falsely increased output signal.

Two academic research results, both of which are still far from commercial availability, may in the future provide alternative pCO_2 measurement technology; pCO_2 sensors based on ionic solid state sensor technology described above (Sieber et al., 2011b) and optical films that change color in the presence of CO_2 (Shashidhar & Kane, 2012).

New Recreational CCR Prototype

The purpose of the current project was to develop a rebreather prototype with safer gas management, low manufacturing cost, and simplified loop design to provide a realistic alternative to OC diving systems. In summary, the important key features of it were as follows:

- simplicity and ease of use, assembling, and diving;
- high level of automation to enable simplified training and operation of the rebreather;
- low work of breathing comparable to a high-quality OC regulator;
- compact, low weight, if possible suitable for transport in cabin luggage;
- integrated O_2 sensor validation to detect pO_2 sensor failures;
- CO_2 monitoring;
- bail out valve mouthpiece, with integrated overpressure valve, if possible; and
- price-wise alternative to OC equipment, i.e., designed in a way that allows simple molds and cost-efficient production.

Electronic System Design

Currently, there are two common electronic solutions used in rebreathers. One is based on having two independent electronics where if one of the electronics fails, then the second can be used. The other approach uses a network of microcontrollers that is designed in such a way that the microcontrollers are able to check each other and detect a failure (Sieber et al., 2011a). In a recreational CCR redundant electronics are not necessary. It is only important that a failure is reliably detected as, by definition, recreational dives do not include decompression obligations and, therefore, bailout and abortion of the dive is the response to any serious system failure. Therefore, a distributed system design with a network of microcontrollers was chosen. Figure 1 details the layout of the electronic system of the rebreather prototype.

Controller Electronics

The core component of the controller board is an 8-bit microcontroller. Even though galvanic sensor cells are failure prone, especially when used in rebreathers, they still provide the most accurate reading. Therefore, two galvanic sensor cells (Figure 2) were incorporated in the design. Instead of using temperature-compensated cells, a galvanic cell with a single load resistor (82 kΩ) and a coaxial gold-plated connector was chosen. Two analog high-pressure sensors (0–300 bar) measured the O_2 and diluent cylinder pressures. One temperature sensor was included in the electronic design for digital temperature compensation of the galvanic pO_2 sensors. Ambient pressure was measured with a 14-bar digital absolute pressure sensor. Two

FIGURE 1

Electronic layout of the rebreather.
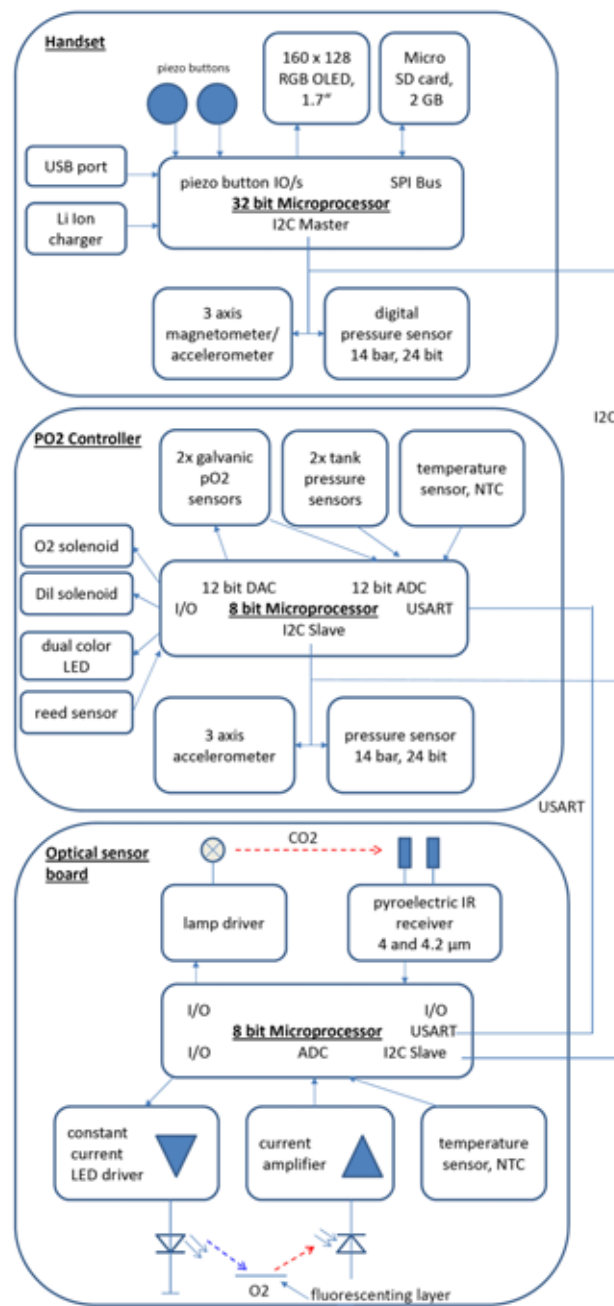
solenoid controllers drove two electromagnetic solenoid injectors for O_2 and diluent. The injectors were rated for a maximum differential pressure of 8 bar but were successfully tested up to 15 bar.

The digital to analog converter of the microcontroller was used to apply voltages across the sensor cell and perform voltammetry and impedance spectroscopy. The concept of using voltammetry with galvanic sensors has been previously detailed (Sieber et al., 2012). By using voltammetry, it is possible to measure the internal impedance of the galvanic pO_2 sensor

Sensor compartment of the prototype CCR.

and to create a characteristic plot, which reflects sensor chemistry and state of the electrodes. Changes of this plot indicate that a sensor is at or close to the end of its useful life.

Optical Gas Management Unit

As mentioned earlier, galvanic pO_2 sensors may possibly all fail at the same time, for example, if they hail from the same production lot and share the same history of operation in a CCR. Even though with voltammetry it is possibly to detect many types of galvanic sensor failures, alternative pO_2 sensor technology may provide useful additional safety.

Based on promising preliminary laboratory results with optical pO_2 sensors, a new sensor element was designed. The electronic part consisted of a blue LED and a photodiode with a low noise current amplifier. A red gelatin filter separated the blue excitation light from the red fluorescence light. The components were encapsulated in optically clear epoxy resin of 5-mm thickness. The optical layer with color

pigments was glued onto the top of the resin. This layer was prefabricated in the form of self-adhesive stickers; thus, it could easily be replaced by the diver.

Gaseous CO_2 sensing is an important safety feature in a rebreather. To avoid problems associated with single wavelength pCO_2 monitors, a dual wavelength pCO_2 sensor was designed. It consisted of two pyroelectric elements, each equipped with an optical band-pass filter (one at 4.0 µm, the other at 4.25 µm). An incandescent light illuminates the sensor through a path of 50 mm. The optimal measurement rate was found to be 1 Hz to achieve the most suitable balance between sensitivity, update rate, and power consumption. A second 8-bit microcontroller was used to read the optical pO_2 sensor as well as the pCO_2 sensor.

Handset

A console diving computer-like handset was developed as the user input device (Figure 3). It featured a 160×128 pixel color OLED screen

and two piezo input buttons. The core component is a powerful 32-bit microcontroller operated at 12 MHz and optionally at 60 MHz. A 32-bit processor was chosen in order to be able to provide sufficient processing power to calculate advanced decompression algorithms such as the Variable Permeability Model (Yount & Hoffman, 1986; Yount & Strauss, 1976; Kuch et al., 2011) or the Reduced Gradient Bubble Model (Wienke, 1990) in real time and while also driving the OLED display with an update rate of at least 2 Hz. The handset also includes a 2-GB flash memory, a 14-bit digital pressure sensor, a three-axis magnetometer, and a three-axis accelerometer.

Communication Protocol

Connecting devices underwater usually requires expensive cables and connectors so a wireless solution was desirable. Unfortunately, wireless links traditionally used in diving computers are only capable of transmitting a few bytes per second. Faster transmitters such as those used in consumer electronics do not work well underwater (Lloret et al., 2012). Therefore, with current technology, the electronic components of this rebreather prototype were connected with cables. Several interfaces exist that can be used for communication between the microcontrollers. Controller Area Network (CAN) Bus, for example, is fast, well proven in safety critical systems and is insensitive to electrical interferences. From this point of view, it would be suitable for rebreathers. Unfortunately, CAN requires additional electronic components and hardware CAN interfaces are only available on automotive microcontrollers. As the diver and all cables are surrounded by water,

FIGURE 3

Handset of the rebreather.

FIGURE 4

Rebreather design with novel counterlung concept.

Lid with electronic and
sensor compartment

Counterlung

Harness

Wing/BC

O2 and Diluent Tank
3l, 300 bar

external electrical interferences are reduced. Therefore, it was convenient to use an interface based on ground referenced single-ended voltage inputs, rather than a differential pair of CAN.
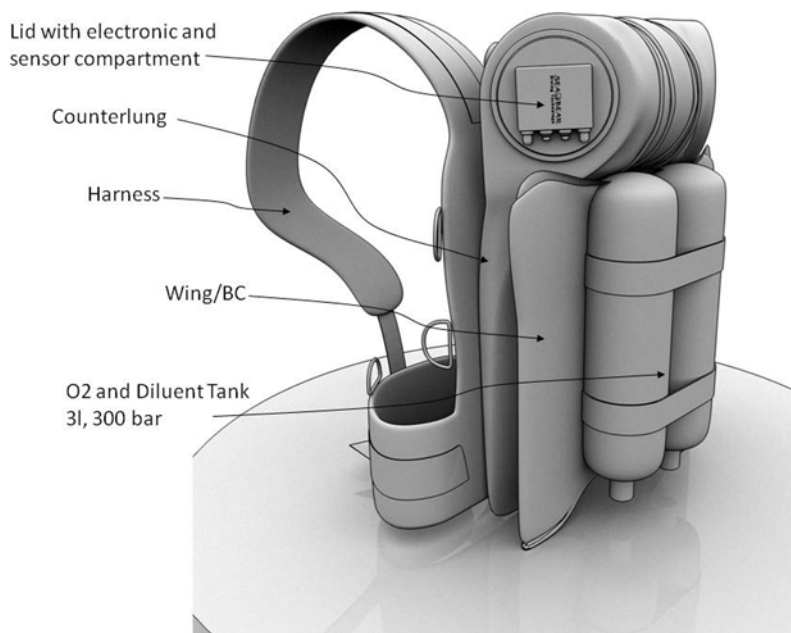
Serial peripheral interface is an interface implemented in nearly all microcontrollers on the market. This interface uses three communication lines plus one chip select line for each slave connected to the master. It allows high data transmission rates. I2C is an interface that requires only two communication lines but operates at lower speed. Previous research demonstrated that the operation speed of I2C is sufficient for rebreathers (Sieber et at., 2011a). For these two reasons, I2C was implemented in the current project with only a single master system utilized to increase the stability of the communication. Additionally, the controller electronics communicated with the microcontroller of the optical sensors via a separate Universal Synchronous/Asynchronous Receiver/Transmitter (USART) interface.

Novel Loop Design

The main idea for the loop design of the rebreather prototype detailed in this paper was to use a single piece counterlung into which a CO_2 filter cartridge could be inserted (Figure 4).

In this way, a separate filter housing and otherwise necessary hose connections could be omitted. The counterlung was equipped with a large opening of diameter of 160 mm through which a filter cartridge was inserted. This diameter was selected so that already commercially available filter cartridges (Poseidon, Sweden or Micropore, USA) could be used. The opening was then closed with a lid, which also housed the electronic components. Figure 5 illustrates how the CO_2 filter was placed between the inhale and exhale section of the counterlung. This novel design allowed a simple manufacturing process where the counterlung could be fabricated from a single piece of high-frequency weldable fabric.

Mouthpiece Design

In addition to the open and closed circuit modes, the specifications of the mouthpiece of the prototype also included an automatic diluent valve and a loop overpressure valve. The design focused on a simple and cost-efficient production using a low-cost injection molding process. Figure 6 shows the design of the mouthpiece. A barrel could be rotated to switch between open and closed circuit positions. A second stage downstream valve (Scubapro R190) was integrated. A second "dummy" valve was situated in front of the downstream valve for the purpose of applying a force onto the diaphragm to increase the cracking pressure to 30 mbar in the closed circuit position. The loop overpressure valve consisted of a one directional valve and a plate that was held by a spring against a seat. The cracking pressure of the over pressure valve was configured to be about 25 mbar. By rotating the barrel from the closed circuit position to the OC position, the lever of the "dummy" valve was

FIGURE 5

The scrubber cartridge is inserted into the counterlung, where it sits in between inhale and exhale section.
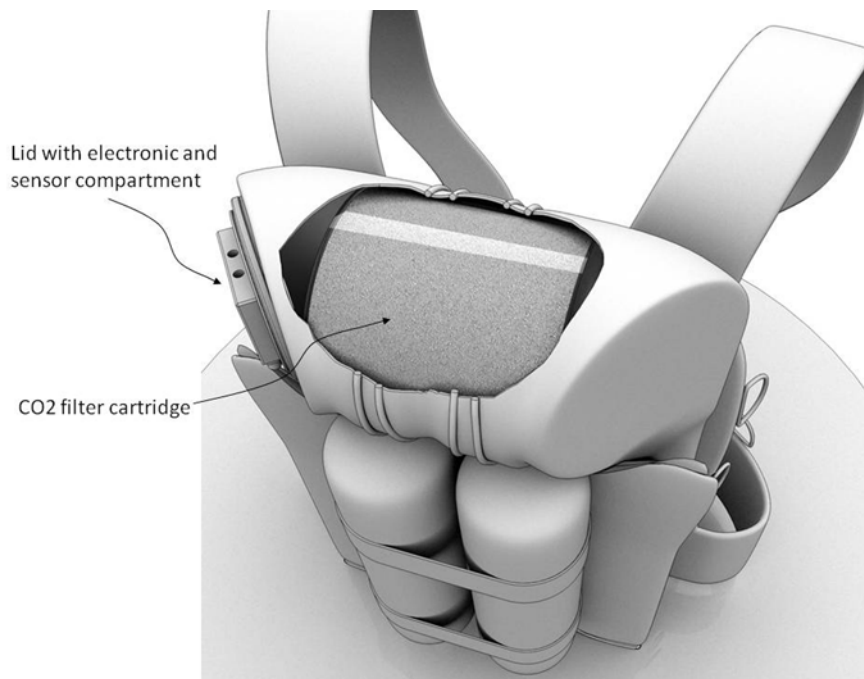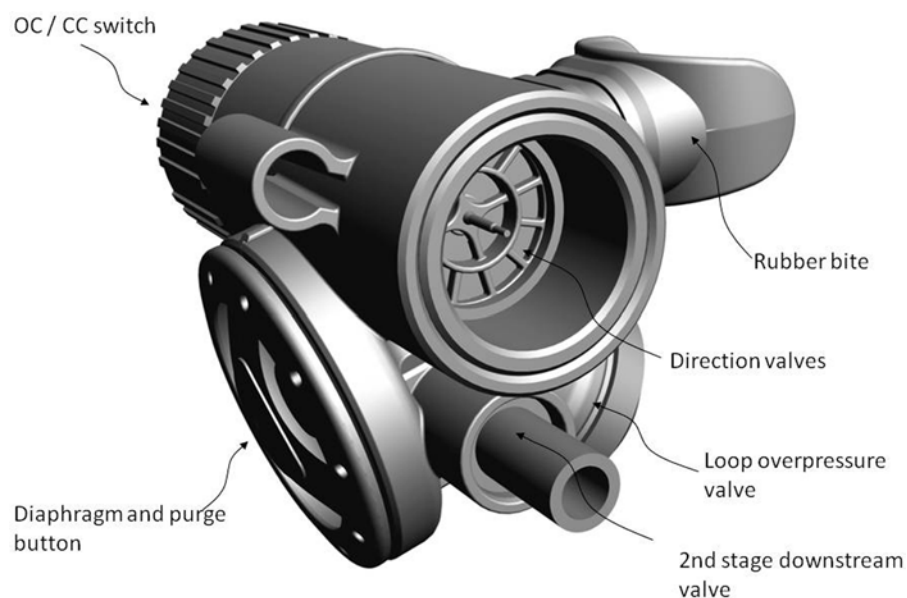

FIGURE 6

Mechanical design of the mouthpiece.

pulled away from the diaphragm and the additional force released. By the same action, the spring of the overpressure valve was also released. This way the diver could exhale with minimum resistance.

Results
Specifications of the CCR Prototype

Two prototypes of the proposed recreational rebreather were manufactured. The specifications are as follows:
- integrated counterlung, maximum capacity 2 times 4 L (restricted to a total volume of 5 L when built into the harness);
- sensor system with two galvanic pO_2 sensors, one optical O_2 sensor, and one optical dual wavelength pCO_2 sensor;
- distributed microcontroller network with three microcontrollers;
- integrated scrubber, 1.8 kg, estimated duration of 120 min;
- two steel cylinders, 3 L, and 300 bar each;
- streamlined design, compact size, low weight (can be carried onto commercial aircraft as hand luggage; the weight of the rebreather excluding cylinders was 4.8 kg);
- counterlungs serve as water traps —in each a sponge is inserted that can absorb up to 0.3 l;
- Li ion rechargeable battery supply, consisting of two pieces Trustfire 16340 type cells, with a capacity of approximately 600 mAh each; and
- average current consumption of 120 mA.

Five counterlung prototypes were manufactured from single sheets of polyurethane-coated fabric. All welding was performed with a 1.5-kW high-frequency welding machine. Ten mouthpieces were produced with

a rapid prototyping silicon mold. The handset (Figure 3) showed all dive-relevant information and was used to initiate the automatic predive tests. Its features were:

- 160 × 128 pixel color OLED display,
- 32-bit microprocessor,
- ZH-L16C decompression algorithm with gradient factors,
- tilt compensated compass,
- 2-GB internal flash memory, and
- USB port.

Operation of the Prototype

Operation of the rebreather was simpler than for currently available CCRs. Predive tests were simplified by an automatic procedure. First, critical components such as pressure sensors, solenoid valve, and microprocessor were electronically tested. After that the loop was checked (negative and positive overpressure test), and the sensors were calibrated.

All dive and rebreather data were stored in the internal SD card every 5 s. This was done in .csv files, which subsequently allowed simple processing of the data in spreadsheet software such as Microsoft Excel. When the handset was connected to a USB port of a personal computer, it was recognized as mass storage device (like a USB thumbdrive), and the internal flash memory was mounted as a logical drive. All dive data could be downloaded without additional software.

Laboratory Testing of the Prototype

Before in-water trials were carried out, the rebreather was tested at a notified body (DEKRA, Essen, Germany). Figure 6 presents the work of breathing test results. In either horizontal or +90° positions, the work of breathing results was far below limits defined in EN14143:2003 (Figure 7). The main reasons for this were as follows:

- All components were designed to have minimum flow resistance.
- The number of pneumatic parts such as hose connectors, couplers, etc., was reduced by nearly a factor of 2.
- The overall flow resistance and work of breathing were reduced significantly.

FIGURE 7

Results of work of breathing laboratory testing according to EN14143:2003.
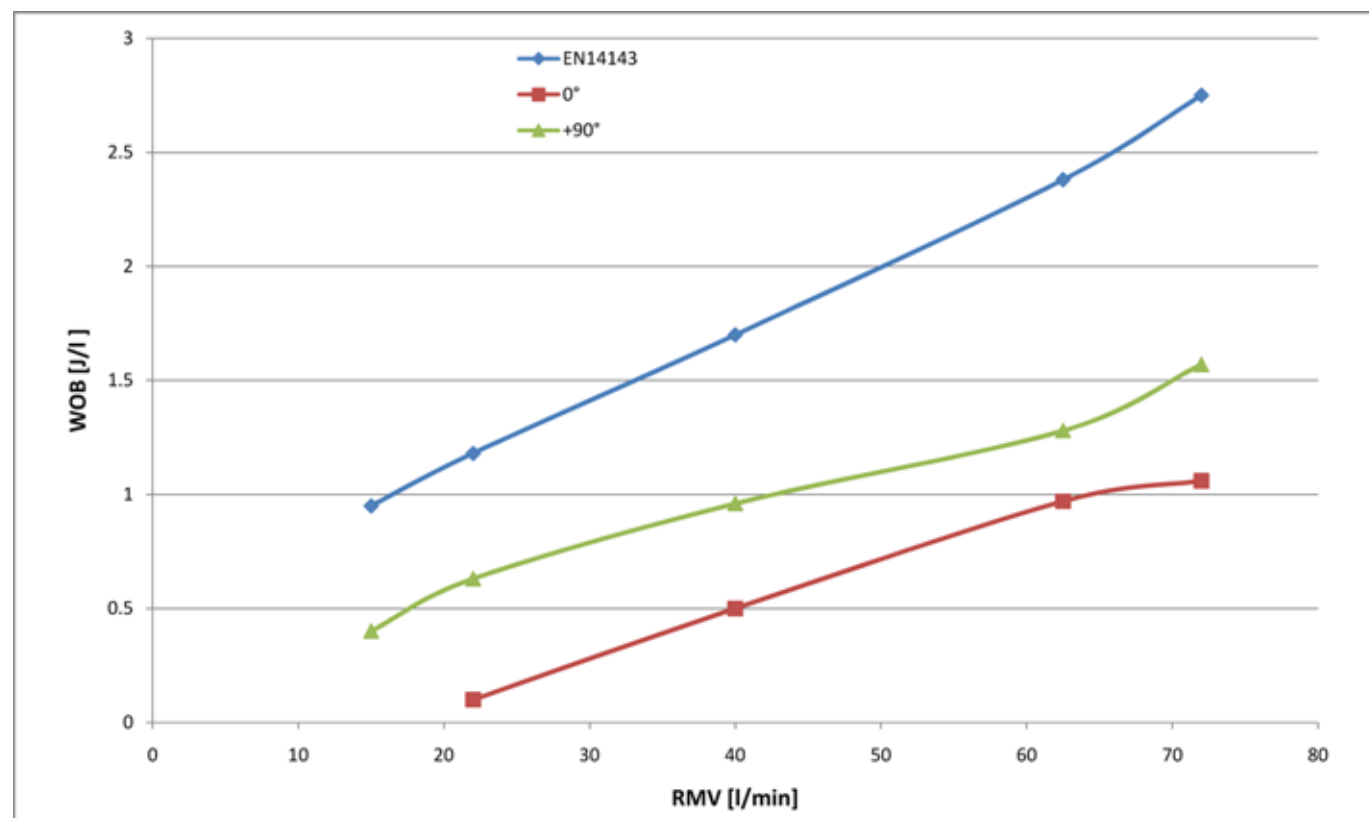
Moreover, DEKRA tested and certified the tank pressure sensors for compliance to EN250 and the ambient pressure/depth sensor, real-time clock, and the pressure tolerance of the handset for compliance with EN13319.

The implementation of the decompression algorithm was validated with 70,000 simulated dive profiles.

The optical sensors were characterized in a pressure chamber up to 2 bar pO_2. Unlike galvanic pO_2 sensors, pO_2 optodes do not produce an output linear to the pO_2; therefore, a single calibration point with O_2 or air is not sufficient (Figure 8). Instead, a 3-point calibration was implemented based on the Stern-Volmer equation. Three parameters are calculated during the calibration:

- K (Stern Volmer quenching constant)/sensitivity,
- S0 (signal at 0 pO_2), and
- X correction factor for nonideal color separation filters and stray light.

The quenching constant as well as S0 decrease with increasing temperature; therefore, temperature compensation had to be performed. With the first prototype, we were able to achieve an accuracy of 2–5% from 0.2 to 1 bar and 10% above 1 bar pO_2.

Figure 9 shows a characteristic plot of a galvanic pO_2 sensor obtained with the voltammetry circuit. The second plot is from a faulty cell. Even though this particular sensor could be calibrated on the surface with a normal signal output, it failed during diving. In this case, the reason for the sensor failure was a passivated cathode where, similar to a current limited cell, the output became static above a certain pO_2. The plot of the faulty cell differs significantly from the working cell in terms of the shape of the rise and fall time of the sig-

nal. In this case, the plot could be used to identify the faulty sensor.

The pCO_2 sensor was characterized in a computer-controlled pressure chamber with a calibration gas containing 5% CO_2. Figure 10 shows the signal response of the CO_2 channel (4.25 μm wavelength) as well as the reference channel (4 μm wavelength) from air at a pressure of 1–6 bar, corresponding to a pCO_2 of 0.0004–0.0024 bar. The signal intensity of the reference channels was not affected by an increase in pCO_2. Changes of the supply voltage or condensation inside the measurement chamber affected both measurement and reference signals in the same way; thus, the measurement signal could be corrected.

In-Water Trials

Following the laboratory testing of the rebreather, in-water tests were

FIGURE 8

Raw signals from the optical pO_2 sensor in a hyperbaric chamber. Note: the slope decreases with increasing pO_2. The sensor signal decreases with increasing temperature; thus, temperature compensation is also required.
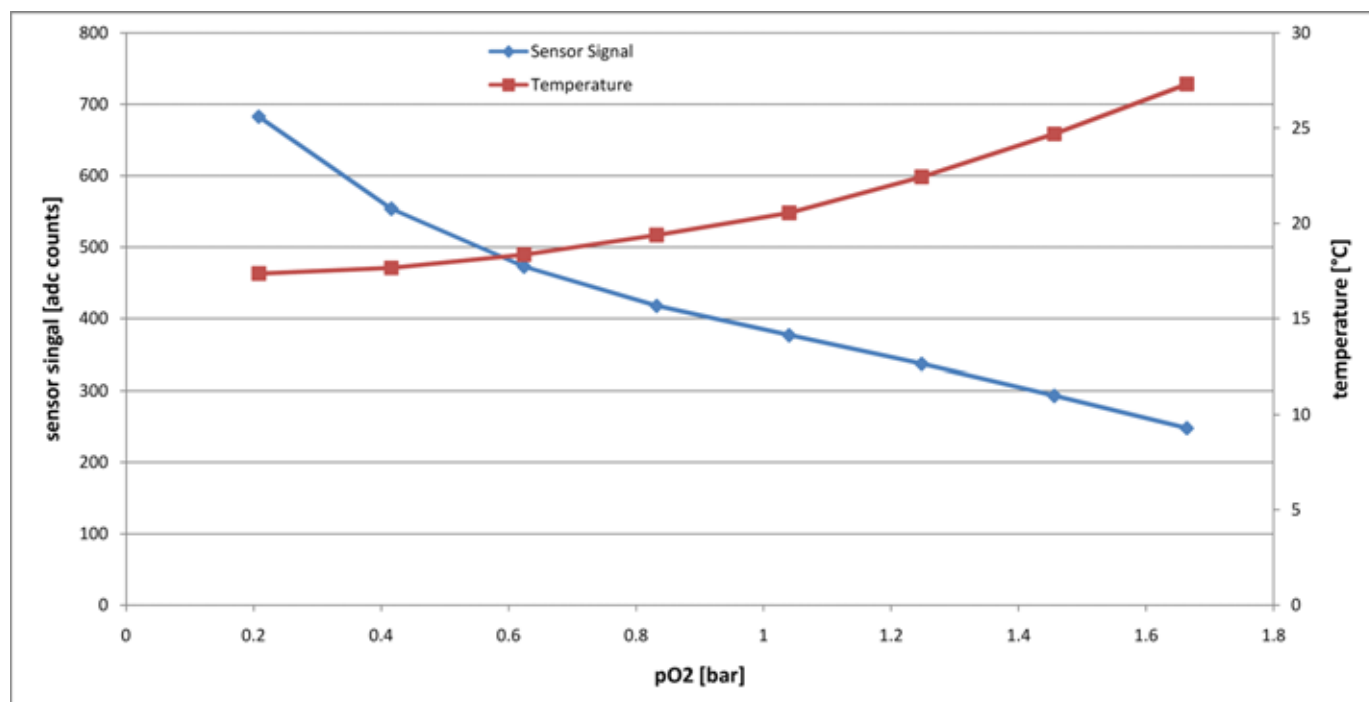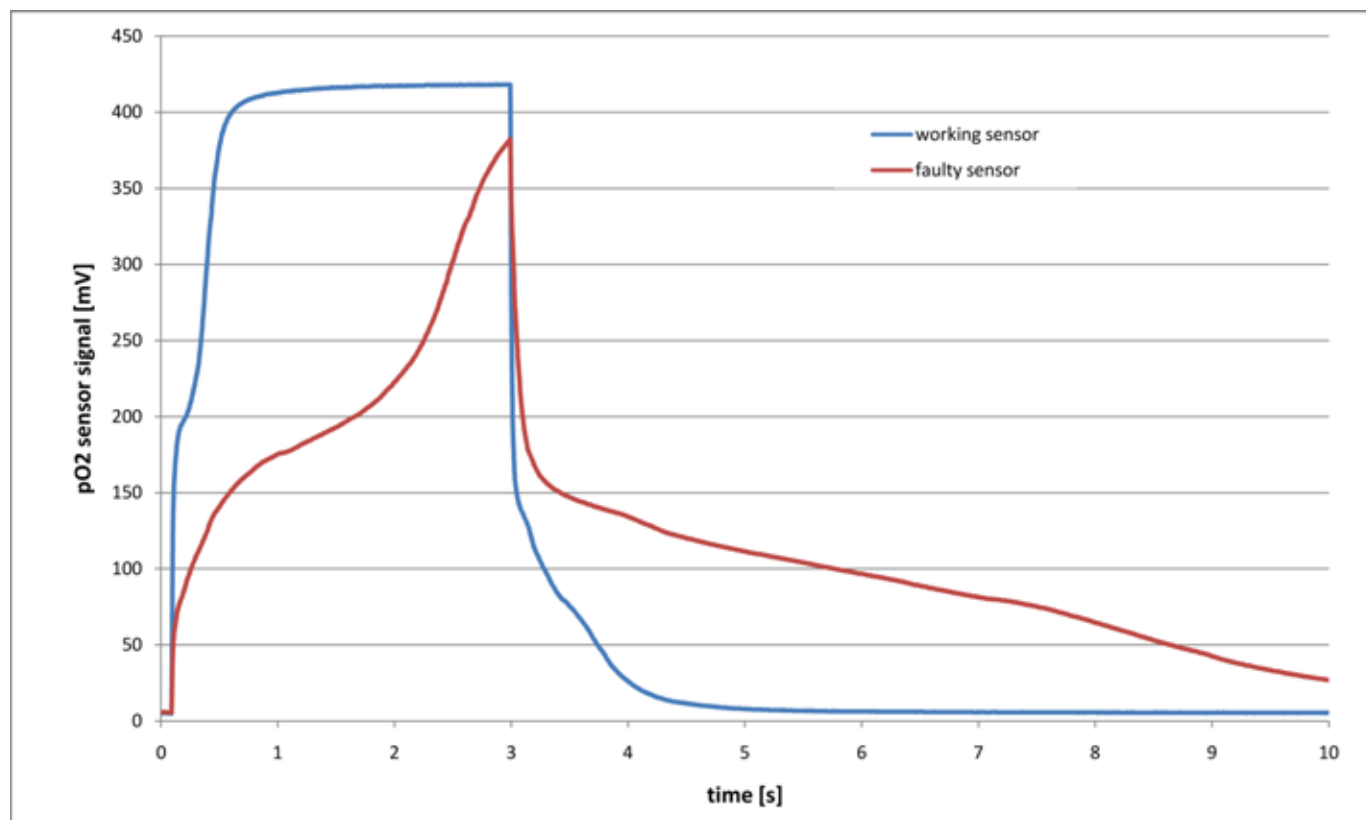
Example plots of galvanic pO_2 sensors voltammetry. The plot from the faulty sensor differs significantly from the characteristic plot from a correctly working sensor.

carried out in a 10-m-deep freshwater pool. Initially, the cylinders were mounted with their valves facing downwards. In this position, the rebreather was not well balanced; therefore, the position was reversed and the cylinders were mounted with their valves facing upwards. The immediately apparent disadvantage with this configuration was that the diver was not able to operate the cylinder valves while diving but, since this is not a requirement for a recreational rebreather, it was considered acceptable.

Successful pool dives were then followed by tests in the Mediterranean Sea. Maximum depth was 40 msw, maximum dive time was 70 min, and the water temperature was 12 °C. The pO_2 setpoint of the controller was programmed to be 0.5 times the ambient pressure till a depth of 10 msw (essentially a constant fraction mix with 50% O_2) and at depth of >10 m constant 1 bar pO_2. All dives were successfully performed without incident. Figure 11 shows depth and pO_2 during a 40-msw test dive in the Mediterranean Sea.

Discussion and Conclusion

An innovative CCR prototype was manufactured (Figure 12). This prototype combined a novel sensor concept and an innovative loop design. The voltammetric validation of the galvanic pO_2 sensor cells allowed recognition of many sensor failures including aging effects such as cathode passivation or current limitation. For the first time, an optical O_2 sensor has been used in a rebreather. Even though optodes are usually employed to measure traces of O_2, the circuit performed well for pO_2 measurements up to 1.6 bar. These optical pO_2 sensors are extremely robust, insensitive to humidity and may, therefore, be an alternative to traditional galvanic pO_2 sensors used in rebreathers. However, while readout of galvanic pO_2 sensors is rather simple, optode signal processing is more challenging: A 3-point calibration together with complex temperature compensation is necessary. Nonetheless, this research demonstrated that optical

FIGURE 10

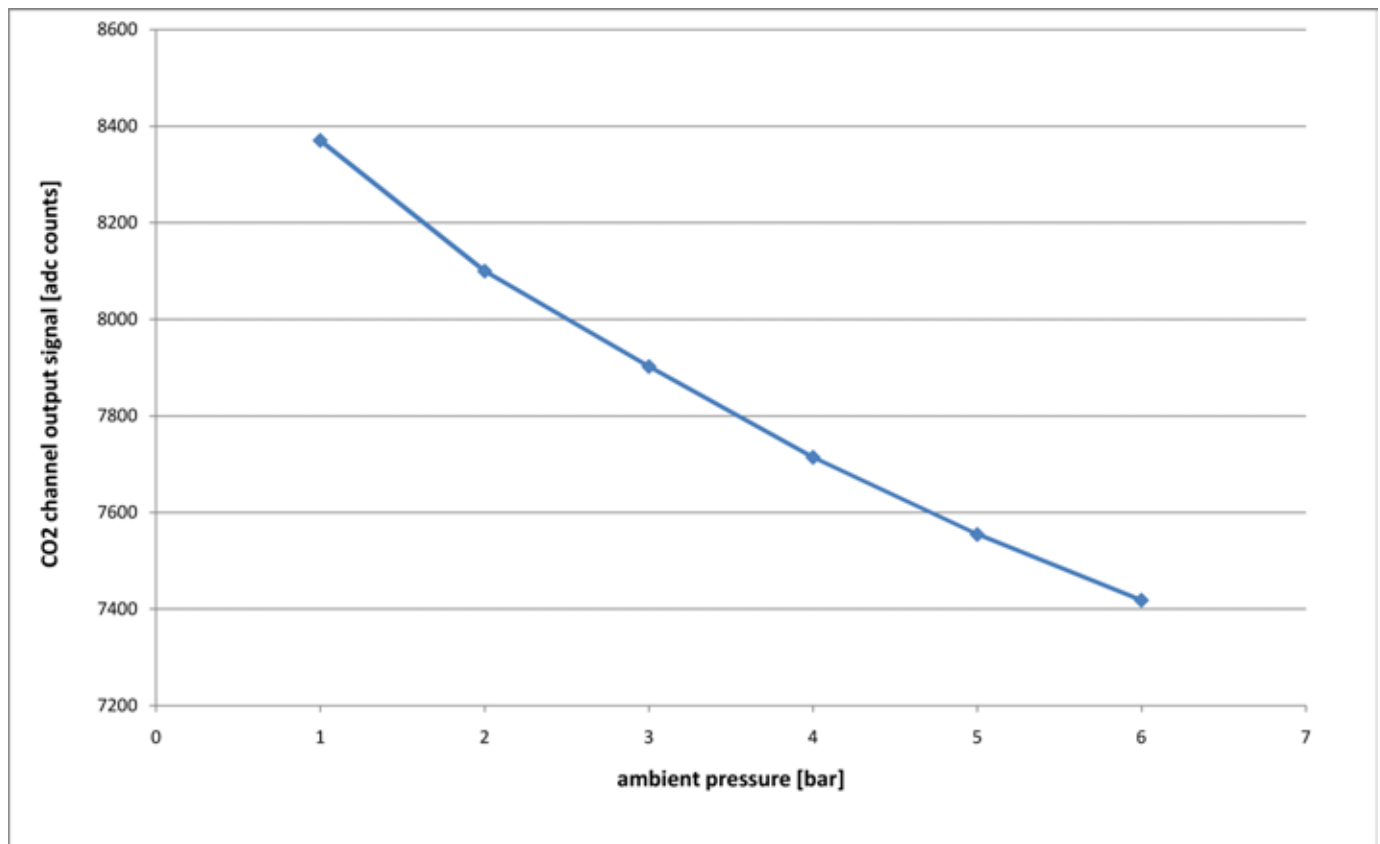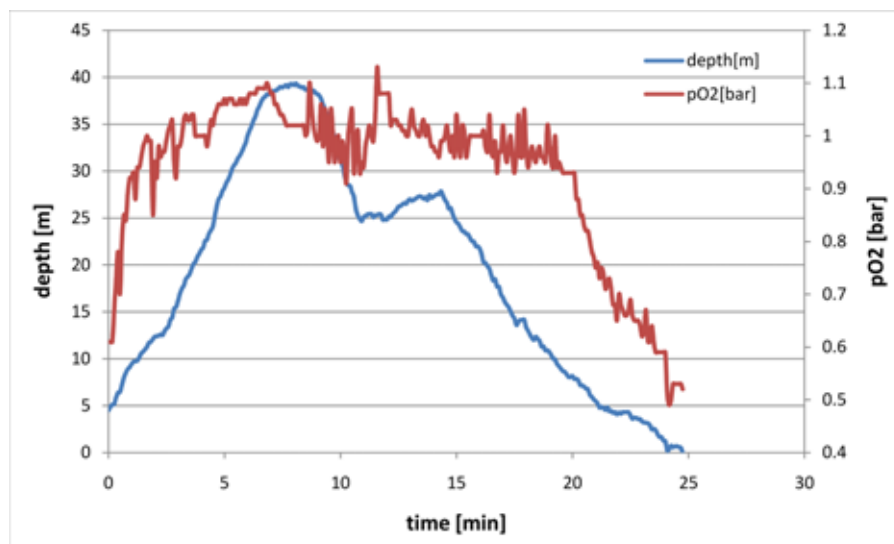CO_2 sensor output in a hyperbaric chamber with air containing 400 ppm CO_2.

FIGURE 11

Test dive in the Mediterranean Sea to a maximum depth of 40 m. Between surface and 10 m depth, the pO_2 controller was set to maintain a constant fraction of 50% O_2. The pO_2 setpoint was 1 bar for depths deeper than 10 m.
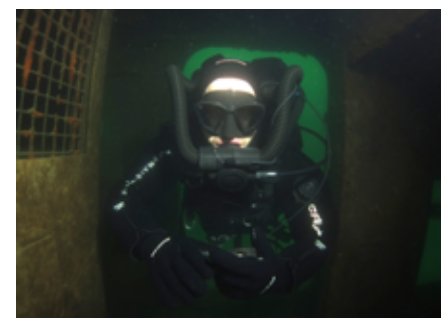

pO_2 sensors can be successfully employed in rebreathers.

Further possibilities to integrate optodes into CCRs exist. For example, fitting them between the mushroom direction valves inside the mouthpiece

FIGURE 12

Diver with the rebreather prototype in a wreck in an Austrian lake.

would allow assessment of inhaled as well as exhaled pO_2. Optodes can be produced as single use parts with a production cost of only cents. The sensor film (the chemical layer) might be mounted on an adhesive and replaced for each dive; thus, any diver could use a new sensor on each dive and the aging of sensors would no longer be of concern. Alternatively, the sensor film might be sprayed or printed onto CO_2 filter cartridges (Fischer et al., 2010). In that way, each time a filter is changed, the O_2 sensor would be concurrently replaced by a new one.

Scrubber monitoring is an important task in rebreather diving. While existing single wavelength infrared CO_2 monitoring is failure prone, dual wavelength measurement has a reference channel, and therefore, erratic readings, caused for example by condensation, can be detected and may even be automatically corrected for.

The second approach of the current paper addressed simplification of the breathing loop. By integration of the scrubber into the counterlung, it was possible to reduce the amount of connectors, bill of materials, and pre- and postdive preparation time. A new mouthpiece with optimized cross sections together with the simplified counterlung scrubber concept has the potential to significantly reduce work of breathing, as demonstrated by the laboratory measurements recorded by a notified body.

The authors are convinced that rebreathers will continue to increase in popularity among recreational divers. However, a rebreather must likely be especially developed according to the needs of recreational divers if it is to become a market success. The current paper has presented several new approaches including a new concept for simplified mechanical design as well as improved electronic control, which may prove useful in future recreational diving apparatus.

Acknowledgments

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