Carbon Dioxide Absorption and Channelling in Closed Circuit Rebreather Scrubbers

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Introduction:

Closed Circuit Rebreather (CCR) technology - a type of Self Contained Underwater Breathing Apparatus (SCUBA) technology - has in recent years become the predominant professional technology of choice in the commercial, military and technical diving communities [1]. CCR technology achieves the recycling of breathing gas by passing the gas through a carbon dioxide (CO_2) chemical scrubber combined with the introduction of pure oxygen into the resultant scrubbed gas to maintain oxygen content at a life supporting level. One of the main dangers currently faced by divers using this equipment is the risk of CO_2 poisoning if the scrubber fails [2]. This life threatening failure occurs due to CO_2 breakthrough - breakthrough being defined as the passing of unscrubbed canister effluent through the chemical absorbent. A variety of reasons exist for CO_2 breakthrough - not all of the reasons are understood, can be identified or indeed compensated for by the operator [3]. The investigation of CO_2 absorption within CCR technology is essential to identify breakthrough causes and design for failure reduction. An extensive review of CCR design, applications and current modelling techniques identifies the need to enhance CCR simulation through mixture model theory to simulate the chemical reactions occurring within the rebreather scrubber system.

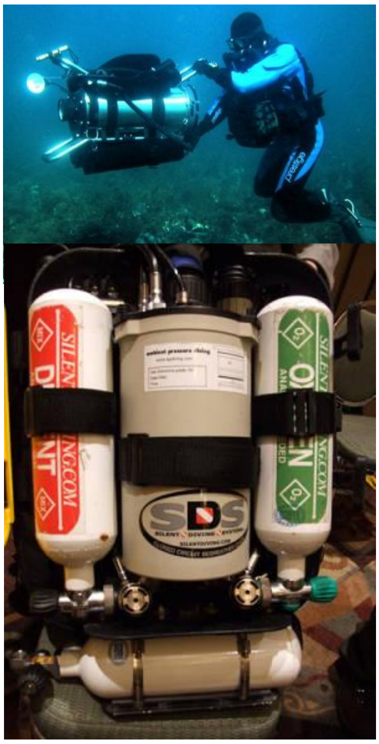


Figure 1
Closed Circuit Rebreather (Centre Canister)

Methodology:

Transient computational fluid dynamic (CFD) models are developed to investigate the kinetics of flow and CO_2 absorption focusing on the chemical reaction between the absorbent soda lime and CO_2. The developed analytical models represent the first reported mixture model CFD theory simulation of CCR scrubber technology (achieved via Ansys CFX 13.0 platform). The simulation studies undertaken present a transient model with the ability to investigate seven key parameters affecting scrubber performance - geometry, wall temperature, inlet velocity, pressure, CO_2 absorption, granule size and material selection. Key parameter sensitivity on CO_2 breakthrough is investigated, analysed and demonstrated. The requirement of strong coupling between CO_2 and soda lime phases dictates the mixture model as best suited for the investigated liquid-particle mixture. Analyses of mesh size, mesh type and inflation are undertaken to independently characterise the accuracy of the developed model and convergence prior to further comparisons with developed experimental data. The importance of mesh refinement is demonstrated and the contribution of inflation and grid independence to the accuracy of the model is quantified.

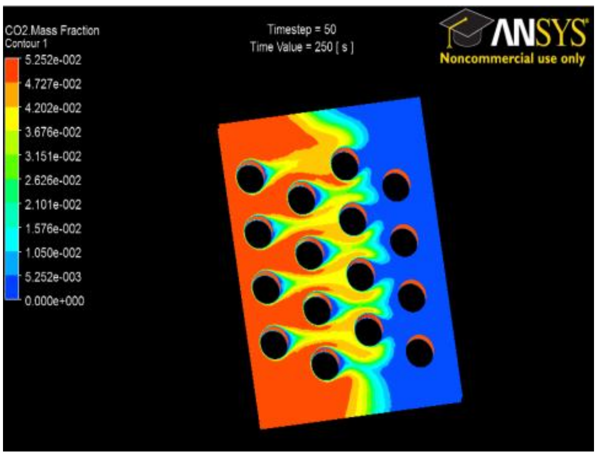


Figure 2
Transient Modelling of Granular CO_2 Absorption (Author 2012)

Experimental testing technology for key parameter investigation is designed, developed, manufactured and commissioned. An experimental program to study the impact of CO_2 breakthrough parameters is devised and undertaken. The incorporation of CO_2, O_2, humidity and temperature sensors into the developed test rig enables the comprehensive experimental investigation of scrubber capacity to absorb CO_2 in a controlled environment, thereby facilitating the benchmarking of initial designs against existing literature.

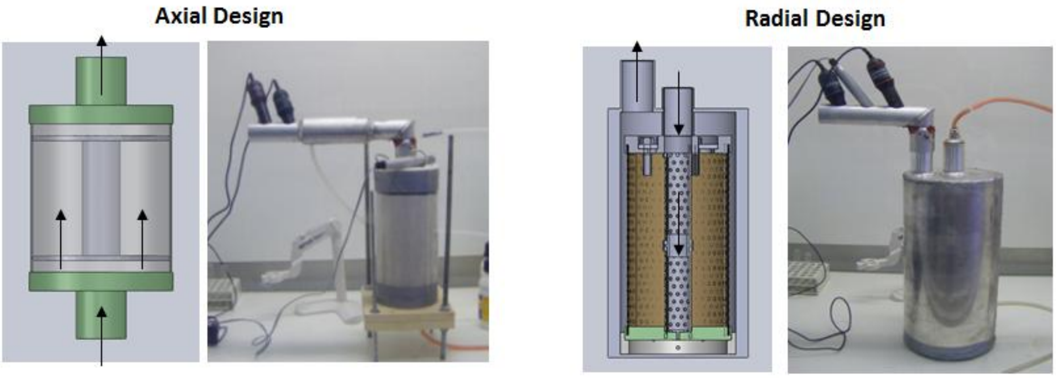


Figure 3 Axial and Radial Scrubber Performance Experimental Investigation Set-Up Phase 1 (Author 2012)

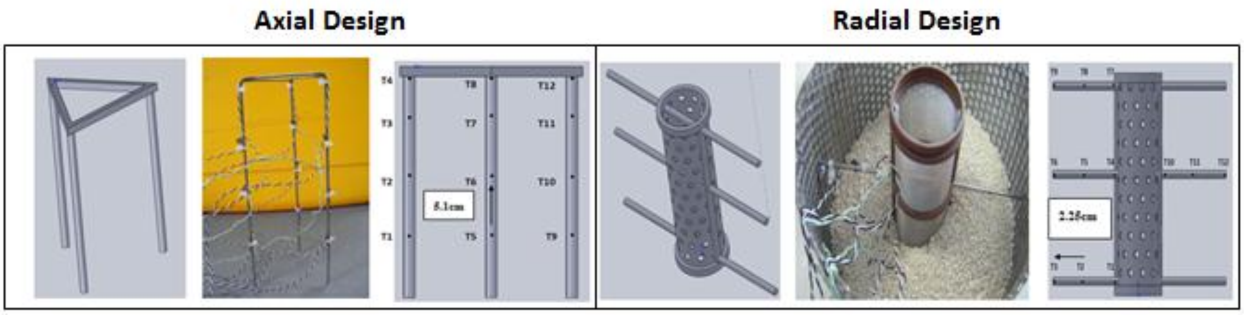
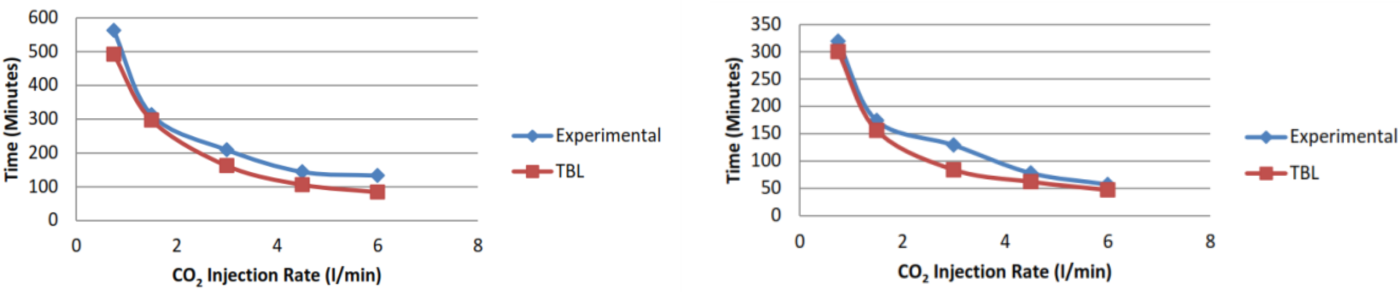


Figure 4 Axial and Radial Scrubber Performance Experimental Investigation Set-Up Phase 2 (Author 2013)

Results:

Validation of the developed experimental approach and methodology is undertaken and achieved as illustrated in Figure 5.



Axial Scrubber

Radial Scrubber

Figure 5 Comparison of Experimentally Determined CO_2 Injection Rates with Theoretical Bed-Life (TBL) Calculations from Nuckols et al. (1996) [4] (Author 2013)

CO_2 absorption is further inferred by thermocouple placement and experimental measurement application at various locations within the canister. Relationship between reaction and temperature is utilized to give an indication of absorption within the scrubber. As the chemical reaction occurs, the temperature rises and water vapour is produced. Temperature measurement is determined to yield the most consistent indication of CO_2 absorption. Humidity correlation becomes more erratic at higher humidity levels. A comprehensive body of experimental data is produced and benchmarked against current literature.

The body of experimental data is employed to validate the author developed transient CFD models to further the knowledge of CO_2 absorption. Static artificial neural network models are also developed and employed to assess parameter efficiency boundary conditions. The developed analyses also achieve good correlation with simulation work carried out by Clarke (2001) [5] where a direct link between the efficiency of CO_2 absorption and cold temperatures was characterised. The analysis of this parameter in the current work is illustrated in Figure 6.

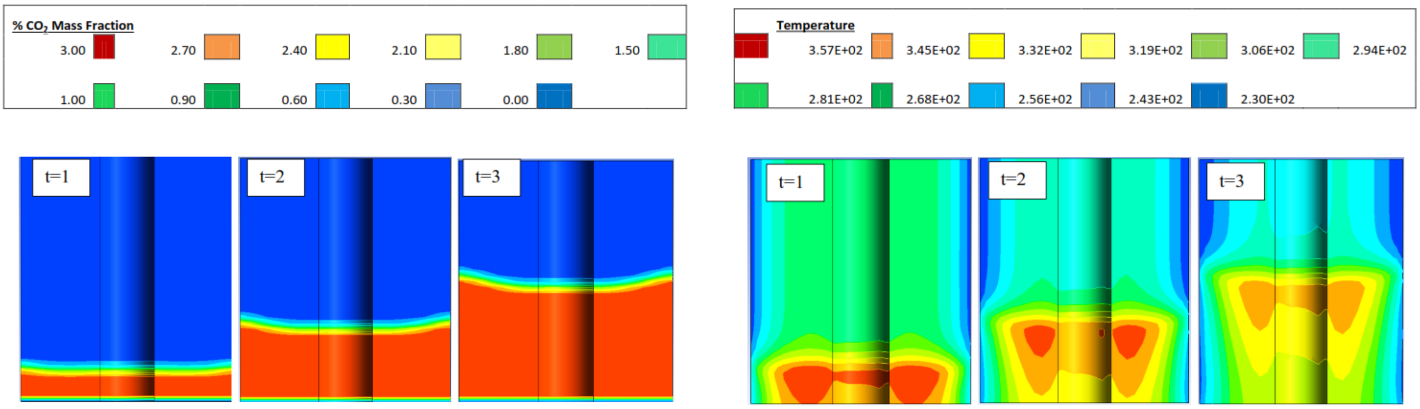


Figure 6 Transient Computational Fluid Dynamic Model Prediction of CO_2 Absorption and Temperature (K) Profiles for Axial Scrubber (Author 2013)

Discussion:

The capability and reliability of the developed mixture model theory CFD simulation to simulate the reaction between CO_2 and soda lime in closed circuit rebreather scrubbers is demonstrated. The development of validated transient computational fluid dynamic models for closed circuit rebreather scrubber analysis allows the simulation to assist in future designs of CCR systems. The developed models enable the simulation of alternative scrubber geometries, which may be subjected to external parameters to assess performance. The simulation, analysis, assessment and optimisation of alternative CCR scrubber designs prior to invoking prototype / manufacturing cost confers a significant advantage, reducing cost, time and can assist the decision to manufacture a given CCR scrubber system. The developed models advance the technology of monitoring scrubber performance in real time for a user. Data collected from a user may be fed into the developed system to allow a visual analysis of the scrubber.

Conclusion:

A versatile model simulating chemical reactions within a closed circuit rebreather canister for different geometrical scrubber designs is developed and shown to be capable of analysing the design parameters of interest. The developed closed circuit rebreather scrubber model brings new learning into the study of kinetics of CO_2 absorption. Recommended future work includes the advancement of the model analysis to incorporate further physiological parameters such as fluctuation of inlet flow rate to represent the variable breathing rate of divers. The completion of the computational fluid dynamics and static artificial neural network models in this way points to the development of a comprehensive and real time validated predictive model for closed circuit rebreather users.

References:

[1] United States Navy. U.S. Navy Diving Manual. Diving Medicine and Recompression Chamber Operations. Revision 6. Volume 2. U.S. Government Printing Office, Washington, D.C. 20402. Naval Sea Systems Command 2008.

[2] Deep Life Open Revolution Family of Rebreathers, Failure Mode, Effect and Criticality Analysis. Mechanical Failure Mode Analysis. Report 4. 2010

[3] Navy Experimental Diving Unit.U.S. Navy Unmanned Test Methods and Performance Goals for Underwater Breathing Apparatus. Technical Manual No.01-94. 1994.

[4] M.L. Nuckols, A.S., W. Tucker, Life Support Systems Design: Diving and Hyperbaric Applications. 1996.

[5] Clarke, J.R., Computer Modelling of the Kinetics of CO_2 Absorption in Rebreather Scrubber Canisters. Proceedings of OCEANS, 3: p. 1738-1744. 2001