

Design and development of human metabolic simulator for a deepwater manned submersible

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In order to cater to the scientific demand for deep ocean exploration with human presence, manned submersible capable of operating up to 6000 m depth is being designed and developed at National Institute of Ocean Technology. The submersible can accommodate three personnel inside the confined space volume of 4.8 m³ human capsule (personnel sphere) for total endurance of 108 h (12 h normal mission and 96 h in case of emergency). Human Metabolic Simulator was developed by following Det Norske Veritas guideline to validate the life support system design during initial stages of qualification inside the personnel sphere. By considering human respiratory quotient (RQ), HMS was designed by combusting propane gas (RQ 0.6) to produce carbon dioxide, water and heat.

Keywords: Human metabolic simulator, life support system, manned submersible, personnel sphere, respiratory quotient.

TRIESTE was the first bathyscaphe which reached a recorded depth of 10,911 m in the Mariana Trench near the Pacific Ocean, encouraging researchers to consider that any ocean depth can be safely reached by human beings¹. Following Trieste, many highly skilled and efficient designs of human occupied vehicles (HOVs) have been developed, which have changed the understanding of deep-ocean ecology and its marine deposits.

The National Institute of Ocean Technology (NIOT), Chennai, under the aegis of the Ministry of Earth Sciences (MoES), Government of India, has indigenously developing a manned submersible/HOV for 6000 m operational capability, named MATSYA 6000, intended to serve the scientific community for deep-ocean biological, chemical and geological observations. This will provide direct physical contact at the site of interest.

The submersible is equipped with various subsystems like manipulators to collect samples of organisms and rocks, thrusters to move the vehicle in a particular direction at a set rate, personnel sphere along with life support system (LSS) to accommodate three people, vehicle control system for safety and navigation, ballast systems for ascent and descent of the vehicle, syntactic foam for

buoyancy and lithium polymer battery pack for power supply. The HOV is targeted for deep-sea mineral explorations such as polymetallic manganese nodule, hydrothermal sulphides, gas hydrates, etc. apart from deep-sea biodiversity research and search operations, etc.

The manned submersible can carry three human beings, inside the personnel sphere of 4.8 m³ internal volume at atmospheric condition. The vehicle is aided with LSS to maintain essential physical functions for three people during operational and emergency endurance of 12 and 96 h respectively. Figure 1 shows some of the subsystems of MATSYA 6000, such as personnel sphere (PS), ballast and trim system, energy devices (battery), control and communications system and LSS²⁻⁴. The manned submersible has been designed and developed according to the certification and classification society rules of Det Norske Veritas (DNV).

Design principle of the human metabolic simulator

Different methods such as cryogenic liquefaction, removal of oxygen in the gas by oxidation, removal of oxygen by extracting mixed gas and injecting oxygen-free gas and lastly, complete combustion have been used for developing the metabolic simulator. The first human metabolic



Figure 1. Three-dimensional view of the manned submersible MATSYA 6000.

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system (HMS) was devised in the 1950s in USA, named 'Bird Universal Medical Respirator', for artificial lung ventilation in anaesthesia and intensive care units^{5,6}. Following the same principle, NIOT had developed a HMS to allow exchange of respiratory gases and the possibility to study the effect of ventilation parameters on the composition of gases in the alveolar space model. This will be a replica of humans due to its ability to generate reproducible data without risking direct human exposure during the testing phase (Figure 2). The HMS equipment designed will reproduce the primary metabolic effect of three persons in the confined atmosphere to qualify LSS⁷⁻⁹.

Metabolic demand of humans may vary with weight and physical condition. The same human being performing the repeated test might have different metabolic demands based on exertion and thus, the metabolic unit developed can be employed to quantify testing of the breathing apparatus⁵ used as a reliable device with repeatability^{9,10}. This unit would give high precision and ease of control, which can be useful in verifying and qualifying LSS.

The LSS design follows classification society (DNV) norms to cater to safe living conditions for human beings in an enclosed space (4.8 m³) inside a personnel sphere (PS)^{1,10}. Hence, this article considers theoretical and experimental work based on the following DNV norms¹⁰:

- Typical values applicable for standard atmospheric conditions (at 20°C and 1013 mbar).
- Oxygen (O₂) demand per person: 15 l/h (resting); 40 l/h (working); 26 l/h (average).
- Carbon dioxide (CO₂) production per person: 22 l/h (average).
- Humidity: 50% ± 20%.
- Heat production: 265 kJ/h.
- Total endurance: 108 h (operation: 12 h; emergency: 96 h).

Psychological impact of gases on the human body

According to occupational safety and health administration (OSHA) guidelines¹¹, oxygen levels below 19.5% can cause severe effects like nausea and vomiting, lethargic

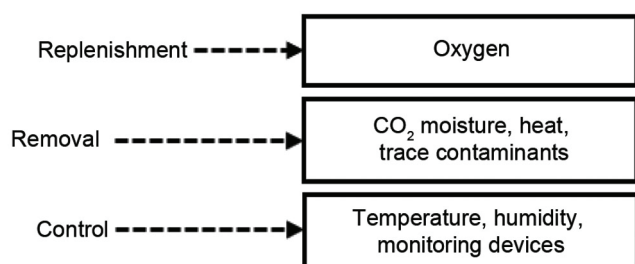


Figure 2. Essential parameters required for the human metabolic simulator (HMS) set-up¹.

movements and perhaps unconsciousness. Breathing air containing less than 6% oxygen produces spasms and apnoea, followed by cardiac arrest in a short duration. Even if a worker survives this hypoxic insult, organs may show evidence of hypoxic damage, which may be permanent¹¹. Furthermore, sustained exposure to above-normal or shorter exposure to very high partial pressure of oxygen can damage cell membranes, alveoli in the lungs, retinal detachment and may also lead to seizures. Therefore, maintaining oxygen for human comfort by following rules and safety standards is paramount^{10,12-14}.

Similarly, the produced CO₂ should be scrubbed-off continuously in the confined space; otherwise it could lead to various health hazards. According to OSHA, the permissible exposure limit (PEL) for CO₂ is 5000 ppm for an 8 h workday. According to the National Institute of Occupational Safety and Health (NIOSH)⁷, continuous CO₂ exposure limit of more than 10,000–20,000 ppm can have adverse effects like electrolytic imbalance and metabolic abnormalities. Higher toxicity can cause excitation followed by depression of the central nervous system⁷. Therefore, it is obvious that the excess CO₂ concentration must be controlled so as to protect the crew/occupant's judgement and physical ability, during normal times and emergency and hence according to the DNV guidelines, CO₂ partial pressure should be maintained within 0.005–0.010 bar (ref. 10).

Carbon monoxide (CO) is naturally produced by human beings by catabolism of heme forming carboxy-haemoglobin. The normal human carboxy-haemoglobin (COHb) level is 0.4%–1%; this can be measured while breathing¹⁵. CO being a colourless, odourless and insipid gas, it can be lethal if the exposure limit is exceeded. Its affinity to haemoglobin is about 250 times higher than O₂. The presence COHb could reduce the capacity to carry O₂ in the blood stream. Also, 2% of COHb can decrease the work capacity of humans, 10% can cause shortness of breath and dilation of cutaneous blood vessel, while 60%–70% can cause unconsciousness, intermittent convulsion, respiratory failure or even death under longer duration¹⁶. Therefore, according to OSHA, the PEL of CO should not exceed more than 50 ppm during the 8 h time period¹⁷. Thus, CO production in any form should be strictly monitored and the necessary scrubber materials should be utilized.

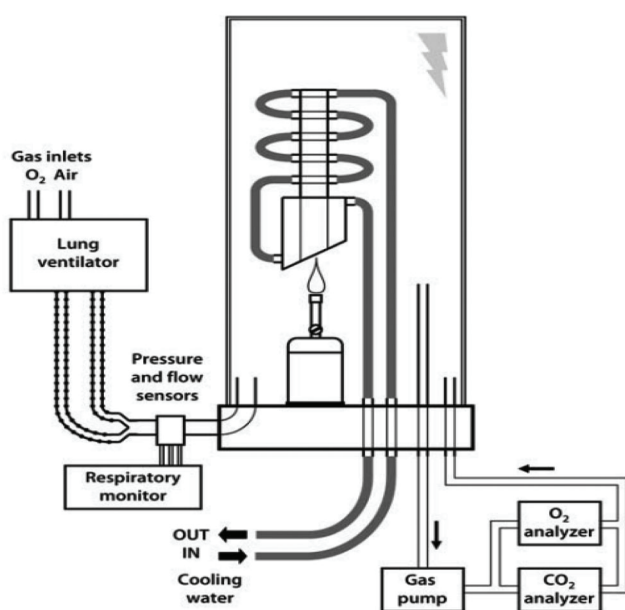
Methodology

Human metabolic simulator design

Survival of the crew in the confined space is called life support, whereas their comfort is termed as habitability^{1,7,8}. In order to survive and function efficiently within the sealed chamber, the occupants must be supplied with oxygen while getting rid of any toxic gases produced during the process (Figure 2).

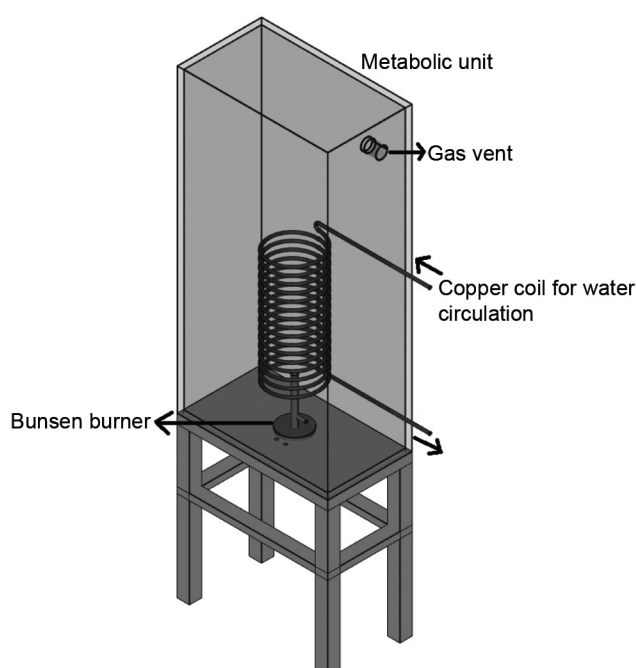
Table 1. Consolidated theoretical calculations required before designing the human metabolic simulator for 140 litre volume

1 atm pressure, at room temperature (20°C)	One personnel	Two personnel	Three personnel	Remarks
Oxygen flowrate (lpm)	0.43	0.87	1.3	Average human inhalation
Propane gas flowrate (lpm)	0.09	0.17	0.26	To effect combustion and produce CO ₂
CO ₂ production (lpm)	0.26	0.52	0.78	CO ₂ produced from combustion is less than that produced by human
Amount of CO ₂ to be refluxed (lpm)	0.10	0.21	0.32	Quantity of CO ₂ to be refluxed to match human exhalation
Heat production from the chemical reaction (kJ/h)	468.9	937.9	1406.8	The heat energy produced is more than the human production
Average human heat production (kJ/h)	265	530	795	Heat produced by an average human being
Excess heat production in comparison to an average human being (kJ/h)	203.9	407.9	611.8	Amount of excess heat to be removed by cold-water circulation

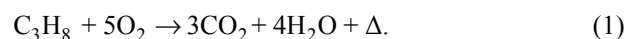
**Figure 3.** Overall idea for the lung model¹².

The oxidative nutritive material in the human body provides energy in accordance with the law of constant composition, i.e. the amount of reactants is proportional to the amount of products¹⁸⁻²¹. Thus, keeping LSS in mind, the HMS was modelled for three people according to the manned submersible criteria, but the experiment was performed for a single person (Figure 3). The HMS can perform the metabolism of three human beings by varying the propane and oxygen flow rates (Table 1). The proposed set-up was based on human respiration, perspiration and metabolism by combustion of propane and producing CO₂, water and heat under atmospheric conditions^{5,9,18}. Metabolic rate measurements are extremely important to determine human heat dissipation into the environment for a time period.

Figure 4 shows the Computer-Aided Design and Drafting (CADD) diagram of HMS setup which consists of acrylic box (metabolic unit (MU)) of volume 140 litres, copper coil to maintain temperature inside MU, micro-

**Figure 4.** CADD drawing of the HMS set-up.

Bunsen burner for effective combustion and a vent (closed at the time of experiment). The whole HMS setup was placed on a steel base containing water bath for leak proofing. Combustion reaction between propane and oxygen is shown in the eq. (1)



Theoretical calculations were done prior to oxygen and propane supply to generate CO₂, moisture and heat from the reaction^{5,9,22}. Propane and oxygen gases were regulated using flow controllers and temperature was controlled by circulating water through the copper coil inside the MU. The O₂, CO₂, pressure, and humidity and temperature sensors were placed inside the MU, and the experiments were constantly monitored and logged.

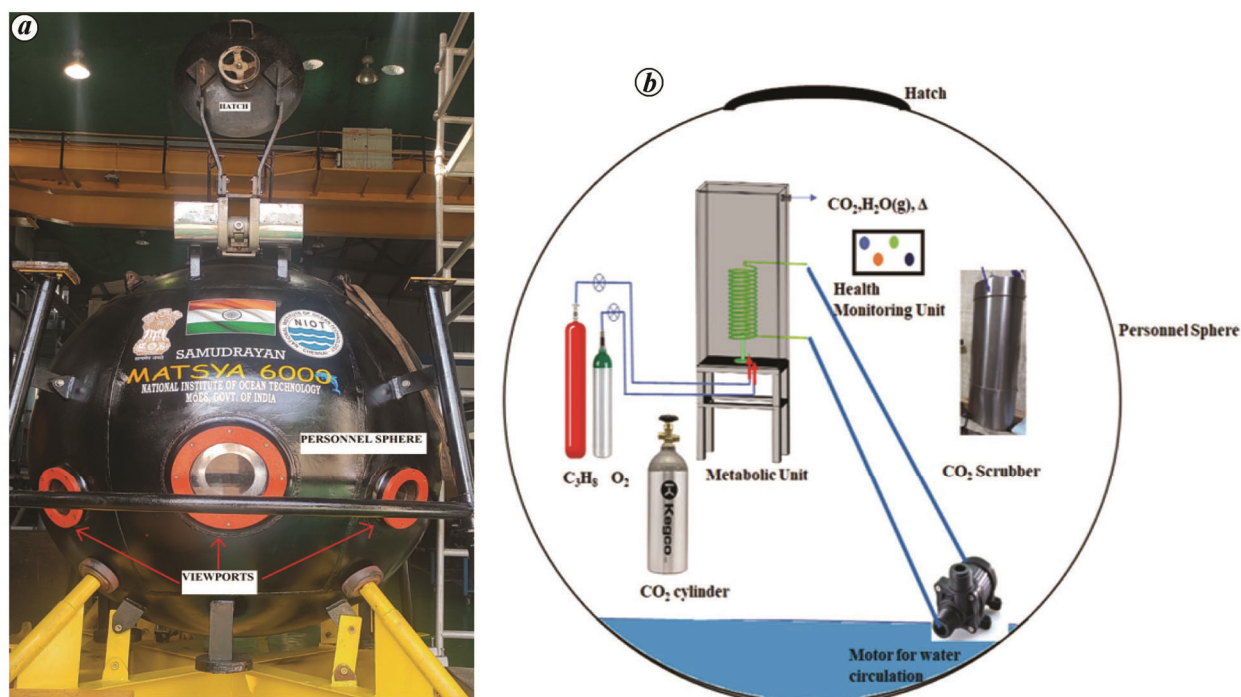


Figure 5. a, Personnel sphere for the manned submersible. b, Experimental set-up inside the personal sphere.

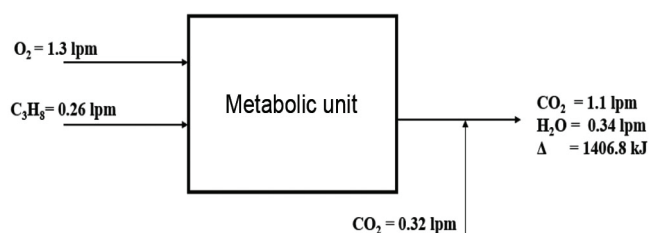


Figure 6. Block diagram of HMS for three people.

Apart from laboratory experiments, the designed HMS set-up was placed inside the PS of the manned submersible of 4.8 m³ to simulate the actual scenario (Figure 5 a and b). The collected water was pumped continuously using a motor to maintain the temperature inside the PS. Extra CO₂ was added along with that produced to match CO₂ production of human beings⁵. CO₂ scrubbers with soda lime were installed to remove the produced CO₂ continuously and maintain DNV standards for human safety.

Experimental procedure

To test the life support equipment, HMS was used by replicating human metabolism^{9,23}. Figure 6 shows an overall view of the process. The block diagram shows oxygen and propane gas required to produce CO₂, heat and moisture for three people based on the calculations shown in Table 1.

Figure 7 shows the laboratory HMS set-up consisting of monitoring sensors like oxygen (Riken Keiki-OX-O₂), CO₂ (Dräger-X-am 8000), temperature, pressure and humidity (Lutron MHB-382SD) and multi-gas sensors (Dräger-X-am 8000). Results from the experimental and theoretical studies show that complete combustion of propane gas with oxygen produces 469 kJ/h, whereas an average human being produces only 265 kJ/h heat energy. The excess heat energy of 204 kJ/h must be removed from the MU, which was achieved by circulating water. The water circulation served two purposes, i.e. it condensed the flue gas condensate which would not affect

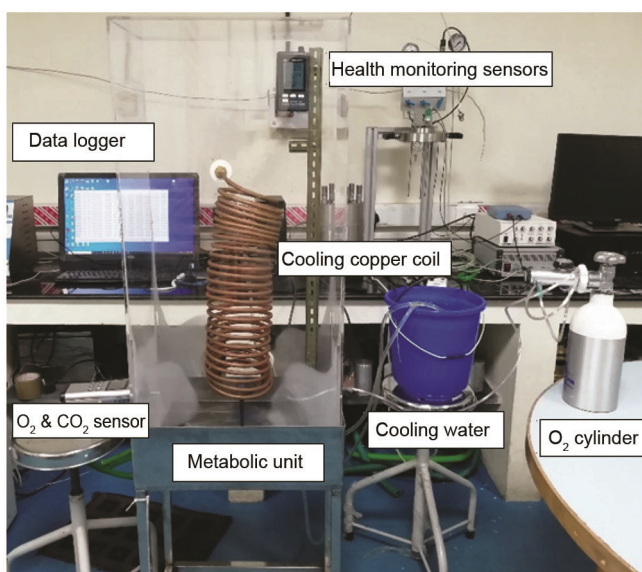


Figure 7. Laboratory set-up of HMS.

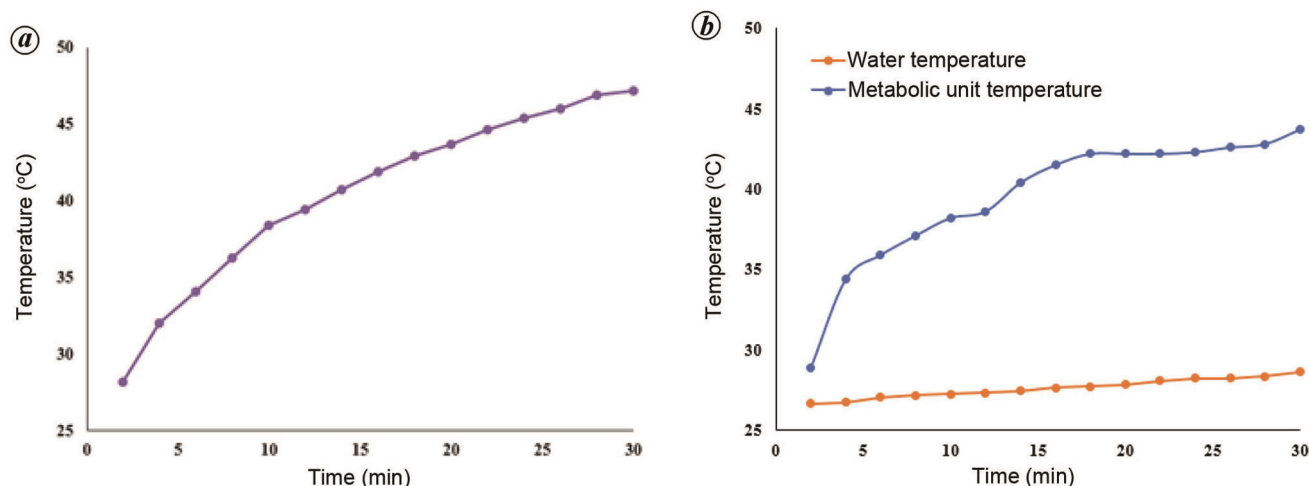


Figure 8. Rise in air temperature inside the metabolic simulator: (a) without water circulation and (b) with water circulation.

the volume of the gas, and it sustained the temperature between 35°C and 40°C (Figure 7)^{5,6}.

Results and discussion

In order for the HMS to work efficiently, the combustion methodology was adopted. The advantage of complete combustion is based on the type of fuel used, and hence propane gas was used for the experimental study as the respiratory quotient was well within the human respiratory range^{1,6,20}.

The experiment was conducted for single person demand by combusting propane at 0.09 lpm flow rate with oxygen supply at 0.43 lpm, in a controlled environment using a flow regulator and producing 0.26 lpm CO₂. Extra CO₂ was added by simply injecting the gas from the supply tank at 0.1 lpm to the produced CO₂ to match the human production along with heat and moisture. Parameters were continuously monitored and logged. Water was circulated to maintain the temperature inside the MU in a more controllable state⁵.

Enthalpy change

The standard enthalpy of reaction is the enthalpy change that occurs in a system when a chemical reaction transforms 1 mol of matter into another at standard conditions, as given in eq. (2).

$$\Delta H_{rxn}^{\circ} = \sum \Delta H_f^{\circ} \{\text{products}\} - \sum \Delta H_f^{\circ} \{\text{reactants}\}. \quad (2)$$

Enthalpy change is an exothermic reaction for complete combustion from eq. (2).

Figure 8a shows that during the experiment the temperature inside the MU increased by ~20°C, i.e. 27°–

47°C, when no water was circulated. Copper coil having high thermal conductivity (386 W/m K) was used for effective heat transfer to control the temperature inside the MU, in order to match the heat produced by humans. Figure 8b shows that water circulated from a tank of 10 litre volume at 0.7 lpm rate removed 83 kJ of energy from the MU. The circulated water temperature increased by 2°C (i.e. 26°–28°C) and the temperature of the MU was reduced from 47.2°C to 43.7°C (Figure 8b). The presence of heat inside the MU was due to convective heat transfer with the air present inside the unit, conductive heat transfer by the heating coil and heat lost.

Oxygen consumption

In order to enter into the confined space, atmospheric oxygen concentration should be maintained within 19.5%–23.5% (ref. 7). We were able to maintain the oxygen level within the above-mentioned range in our experiment, but the build-up of CO₂ hindered oxygen consumption (Figure 9)^{24–26}. It was observed that within half an hour, O₂ depleted from 20.9% to 18.5% and CO₂ production reached 50,000 ppm (i.e. 5% volume) resulting in incomplete combustion, i.e. by producing CO (Figure 9). During this period, change in flame colour was also observed from blue to bright orange, i.e. complete to incomplete combustion transition due to excessive CO₂ build-up. The experiment was continued by venting out the build-up gases at a constant rate, which is similar to the human production inside the PS and O₂ was maintained as 20.9%.

In the actual scenario O₂ should be replenished with continuous removal of CO₂ and controlled humidity for human survival inside the PS (Figure 2). Fifty-four medical-grade oxygen cylinders of 1.2 litre volume with 137 bar pressure that can release around 170 litres of oxygen were placed inside the PS. During any extreme event, the

compressed oxygen cylinders inside the pressure hull must not exceed 1.3 bar absolute pressure and O₂ concentration should not go beyond 25% in case of leak and subsequent emptying of one cylinder. The oxygen sensor measures oxygen percentage (19–23) inside the PS and helps control the solenoid-operated control valve, with a manual override for redundancy. The CO₂ removal system is based on absorbing CO₂ from ambient air inside the PS. Each soda lime (4.5 kg) scrubber was replaced every 6 h during the experiment. In case of failure of the control system, both CO₂ scrubbers will be switched on manually. There are two spare scrubbers in case of failure. The moisture generated inside the PS is due to metabolism of three human beings. Temperature inside the PS ranged from 10°C to 20°C due to equilibrium between heat produced by humans and the equipment inside the PS, and the ocean water temperature outside it. Ambient air inside the PS is continuously displayed and stored for monitoring and controlling the ambient air quality to avoid any breathing, toxicity or potential hazard. A fire surveillance and extinguishing system is placed to prevent any potential hazard due to fire inside the PS. Even

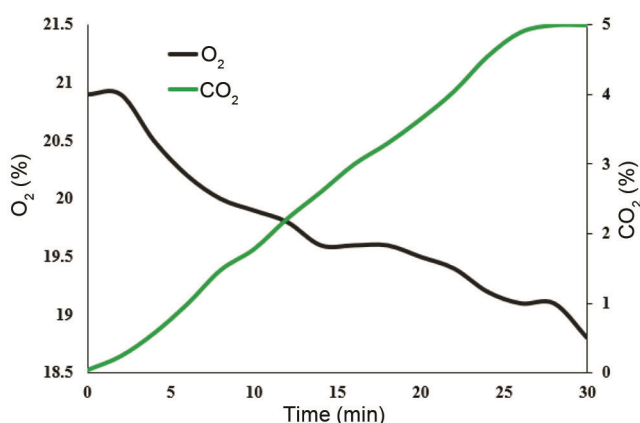


Figure 9. Oxygen depletion with CO₂ build-up.

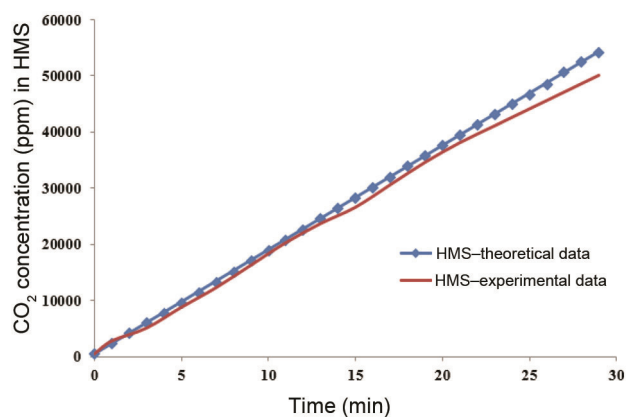


Figure 10. Experimental and theoretical CO₂ production during 140 litre volume of HMS setup.

in the worst-case scenario, if the PS is contaminated due to failure of the CO₂ removal system or oxygen supply system, or toxic gas contamination or leakage or any other failure, the emergency breathing apparatus will ensure survival of the crew until the manned submersible ascends to the ocean surface or normalcy is restored.

Gases from the MU are vented out from the HMS to PS and the produced CO₂ is continuously removed using the soda lime-based radial-flow scrubbing system.

Carbon dioxide production

The major source of CO₂ in the manned submersible is through human respiration. Depending on the dietary considerations, the average consumption of O₂ and release of CO₂ is called respiratory quotient (RQ)^{1,24}

$$RQ = \frac{\text{Volume of CO}_2 \text{ produced}}{\text{Volume of O}_2 \text{ consumed}} \quad (3)$$

RQ for an average human being's metabolism lies between 0.3 and 1.0. It ranges between 0.3 and 0.7 for lipids, 0.8 for protein and 1 for carbohydrates. CO₂/O₂ ratio is attained by combusting propane to produce CO₂ as shown in eq. (1). Propane gas was utilized since its RQ is 0.6.

Figure 10 shows theoretical and the experimental data of combustion of propane and CO₂ production for 30 min durations.

An average human being would release 77,000 ppm (i.e. 7%) of CO₂ in half an hour in a confined space of 140 litre volume, whereas in the HMS combustion reaction CO₂ production was 56,000 ppm. Thus the shortfall of 21,000 ppm CO₂ will be added to match the human exhalation^{5,9} (Figure 11). After placing other units like the CO₂ scrubber, monitoring units, gas cylinders, MU, etc. CO₂ production in 4.8 m³ volume of the PS would be about 2700 ppm. The gases produced from the MU will be vented out to simulate human conditions inside the PS and will be scrubbed using soda lime as the CO₂ scrubber to avoid CO₂ retention and poisoning²⁷.

Carbon monoxide production

Humans produce CO naturally because of the heme-oxygenase enzyme, which is the catabolism of heme, resulting in the human COHb level of 0.4%–1% while breathing^{16,28}.

During the experiment, due to incomplete combustion of propane, oxygen levels had dropped and CO level increased up to 40 ppm in the same time span inside the MU (Figure 12). Incomplete combustion will not arise in the PS because CO₂ is continuously scrubbed during the entire experiment. The produced CO₂ was removed using soda lime scrubber and CO production was controlled using activated charcoal^{29,30}.

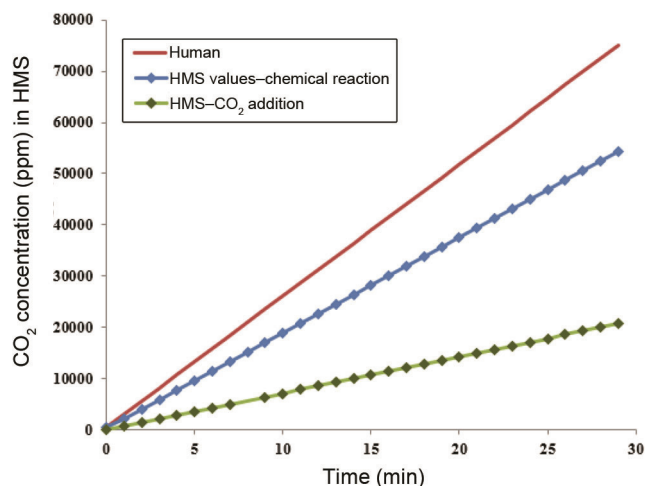


Figure 11. CO₂ addition in comparison to human production.

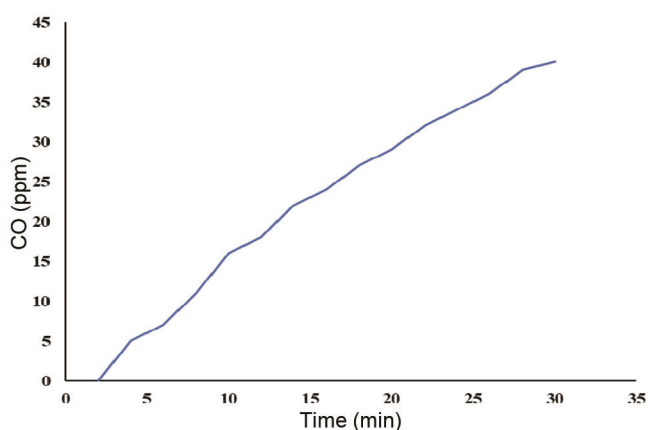


Figure 12. Production of CO with time.

In case of an emergency situation, if oxygen supply inside the PS is cut-off during the testing phase and propane continuously flows inside the PS at 0.09 lpm, combustion would cease to exist inside the unit, but increase in propane concentration will generate an alarm in the lower explosion limit (LEL) sensor. The occupational exposure limit of propane gas is 2100 ppm (i.e. 10% LEL)³¹. Theoretical calculations show that it would take ~82 min to reach 10% LEL inside the PS of 4.8 m³ volume. Feedback control command has been designed to operate the solenoid coil-based shut-off valve with fail-safe mechanism to cut-off the propane supply based on LEL concentration measurement from the sensor³².

The HMS was designed and developed by following lung model to match human beings for validation of LSS in an enclosed space of a manned submersible with PS of 4.8 m³ volume. This will play an important role in simulating human metabolism such as oxygen consumption, CO₂ and heat production using propane combustion technique inside the PS without endangering human beings in the enclosed space.

Conclusion

We have designed and developed the HMS for qualification of LSS in an underwater human-rated vehicle using propane combustion technique by mimicking the lung model with respiratory quotient of 0.6. This will help us understand the critical parameters that are needed to maintain human comfort and habitability in a confined space. Theoretical and experimental works were performed following DNV guidelines. The HMS will facilitate validation of all subsystems, sensors and alarm of LSS. It has been designed to replace three people inside a manned submersible and avoid risking human lives in an enclosed space for longer endurance during the experimental phase of deployment.

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