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Development of a Normobaric Hypoxia Chamber for Studies in Human Physiology

Desarrollo de una Cámara de Hipoxia Normobárica para Estudios en Fisiología Humana

Desenvolvimento de uma Câmara de Hipóxia Normobárica para Estudos em Fisiologia Humana

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ABSTRACT

One of the great challenges faced by aviators is to realize the individual physiological effects caused by hypoxia. Hypoxia is the condition that the human body faces when it does not receive an adequate supplement of oxygen in the body tissues and cells. Deprivation of appropriate oxygenation leads to reduced cognitive and visual capacity, thereby leading to unconsciousness and even death in extreme cases. It is therefore required that aviators receive training to recognize such symptoms to ensure flight safety. This paper describes the development of a portable and low cost Normobaric Hypoxia Chamber (NHC). The NHC provides training in situations of hypoxia for aviators. To be portable and cost-effective, the NHC was constructed using a PVC pipe structure, coated with transparent vinyl canvas and fitted with latches to access and seal the internal atmosphere of the chamber from the rest of the environment. The NHC control system was designed to acquire signals from O^2 and CO^2 sensors, to process and control the hardware of the gas mixture actuators, which allow the oxygen concentration within the NHC to be changed, and to homogenize the air within the NHC and carry out the exhaustion of the interior of the chamber. The results show that the development of the CHN has fulfilled the prerequisites established in the project. The NHC can be used to train aviators under controlled conditions and to carry out research on human physiology related to hypoxia.

Keywords: Normobaric hypoxia chamber. Physiological changes. Training in hypoxia. Flight safety.

RESUMEN

Uno de los grandes desafíos enfrentados por los aviadores es percibir los efectos fisiológicos individuales causados por la hipoxia. La hipoxia es la condición que el cuerpo humano se enfrenta cuando no recibe un adecuado suplemento de oxígeno en los tejidos y las células del cuerpo. La privación de oxigenación adecuada ocasiona la reducción de la capacidad cognitiva y visual, pudiendo, en casos extremos,

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llevar a la inconsciencia y al óbito. Por lo tanto es necesario que los aviadores reciban entrenamiento con el objetivo de reconocer tales síntomas, a fin de garantizar la seguridad de vuelo. En este artículo se describe el desarrollo de una Cámara de Hipóxia Normobárica (CHN) portátil y de bajo costo. La CHN posibilita entrenamiento en situaciones de hipoxia para aviadores. Para ser portátil y de bajo costo, la CHN fue construida a través de una estructura en tubos de PVC, revestida con lona vinílica transparente y dotada de cierres para acceder y aislar la atmósfera interna de la cámara del resto del ambiente. El sistema de control de CHN está diseñado para adquirir señales de los sensores de O_2 y CO_2, procesar y controlar el hardware de los actuadores responsables de la mezcla gaseosa, que permiten variaciones en la concentración de oxígeno dentro de la CHN y mezclar el aire dentro de la CHN y realizar el agotamiento del interior de la cámara. Los resultados obtenidos muestran que el desarrollo de CHN cumplió los requisitos previos establecidos en el proyecto. La CHN puede ser utilizada en la capacitación de aviadores en condiciones controladas y en la realización de investigaciones en fisiología humana, relacionadas a la hipoxia.

Palabras clave: *Cámara hipoxia normobárica. Alteraciones fisiológicas. Entrenamiento en hipoxia. Seguridad de vuelo.*

RESUMO

Um dos grandes desafios enfrentados por aviadores é perceber os efeitos fisiológicos individuais causados pela hipóxia. A hipóxia é a condição que o corpo humano enfrenta quando não recebe um adequado suplemento de oxigênio nos tecidos e células do corpo. A privação de oxigenação adequada ocasiona, a redução da capacidade cognitiva e visual, podendo, em casos extremos, levar à inconsciência e ao óbito. Portanto é necessário que os aviadores recebam treinamento com o objetivo de reconhecerem tais sintomas, a fim de garantirem a segurança de voo. Este artigo descreve o desenvolvimento de uma Câmara de Hipóxia Normobárica (CHN) portátil e de baixo custo. A CHN possibilita treinamento em situações de hipóxia para aviadores. Para ser portátil e de baixo custo, a CHN foi construída por meio de uma estrutura em tubos de PVC, revestida com lona vinílica transparente e dotada de fechos para acessar e isolar a atmosfera interna da câmara do restante do ambiente. O sistema de controle da CHN foi projetado para adquirir sinais dos sensores de O_2 e CO_2, processar e controlar o hardware dos atuadores responsáveis pela mistura gasosa, que permitem alterar a concentração de oxigênio no interior da CHN, e homogeneizar o ar dentro da CHN e realizar a exaustão do interior da câmara. Os resultados obtidos mostram que o desenvolvimento da CHN cumpriu os pré-requisitos estabelecidos no projeto. A CHN pode ser utilizada na capacitação de aviadores em condições controladas e na realização de pesquisas em fisiologia humana, relacionadas à hipóxia.

Palavras-chave: *Câmara hipóxia normobárica. Alterações fisiológicas. Treinamento em hipóxia. Segurança de voo.*

1 INTRODUCTION

Hypoxia, characterized by inadequate supply of oxygen (O_2) to the body tissues and cells, is a condition that aviators may face due to failures in an aircraft. As the symptoms of hypoxia vary among individuals, it is necessary for the crew to know their own signs and symptoms, in order to allow a possible anticipation of corrective actions, in case of an emergency in the flight.

In aviation, statistically, the type of hypoxia with the highest number of occurrences is hypoxic hypoxia, also known as altitude hypoxia. This situation is caused by the decrease of the atmospheric pressure, mainly due to the increase in altitude, since there is an inherently decrease in the partial pressure of oxygen. Altitude hypoxia has as its main signs and symptoms the gradual decrease in vision, hyperventilation, increased heart rate, decreased psychomotor functions, loss of discernment, semiconsciousness or even unconsciousness and, in more severe situations, can lead to death (RUSSOMANO, 2012).

Although aircraft accidents due to altitude hypoxia are rare (SELF et al., 2010), some cases of decompression of the aircraft that resulted in hypoxia, as in the case of the accident that occurred with the famous North American golfer Payne Stewart, on October 25th, 1999, in South Dakota can be mentioned (CABLE, 2003). Another case, with similar characteristics, occurred on August 2nd, 2005, during a flight of an aircraft of the company Cypriot Helios Airways, in which 110 passengers and 8 crew members died.

According to the Federal Aviation Administration (FAA) and the National Civil Aviation Agency of Brazil (ANAC), US and Brazilian government agencies, respectively, it is required that pilot training courses have subjects related to aerospace medicine, but only theoretical knowledge is required according to the **MCA 58 - Manual of the Commercial Pilot Course - Airplane** developed by the then Ministry of Aeronautics (BRASIL, 2013a).

This article addresses the development of a Normobaric Hypoxia Chamber (NHC) capable of simulating hypoxia under normal pressure conditions, through the supply of an atmosphere with low concentration of oxygen for those inside the NHC; such concentration can be adjusted according to the altitude intended for simulation. The use of this Chamber allows pilots and their crew to carry out a practical training to test and know their own limits and to identify the symptoms in hypoxia condition, so as to act correctly in real situations of emergency during a flight. The NHC also allows the training of athletes (high performance) for better physical conditioning and adaptation to altitude (a very common situation, for example, with soccer players), as well as research related to human physiology and the aging process.

The NHC has interesting characteristics, such as the possibility of simultaneous training of more than one individual, besides an automatic control system that allows the simulation of different altitudes with the decrease of the oxygen concentration. Seeking to develop a NHC with different characteristics compared to those commercially available, the chamber structure was designed to be lightweight, easy to mount, disassemble and transport, whereby it can be installed in several places (without the requirement for special installation), as well such as being low cost.

The purpose for constructing the NHC was to make the simulation of hypoxia currently performed in the Microgravity Center of the Pontifical Catholic University of Rio Grande do Sul (PUCRS), which uses a Hypoxia Mask (to reduce oxygen supply) more real , since in an actual in-flight emergency situation, the mask, on the other hand, will be the adequate source of oxygen for crew members to eliminate the effects of altitude hypoxia. Therefore, in order to improve the training regarding the actions that must be performed by the crew, the ideal is to use a real environment, simulated by a closed chamber, where the atmosphere has low concentration of oxygen and in which flight simulators and other experiments can be adapted to evaluate the concentration and changes in the cognitive process of the crew.

In the scientific literature, it is possible to find several studies on altitude hypoxia, in which the signs and symptoms occurring in humans submitted to an atmosphere with low concentration of oxygen are described. In these works, it is always emphasized the fact that everyone has a different reaction when subjected to hypoxic hypoxia (THE AVIATORS ..., 2012), which justifies the need for a practical physiological training to recognize the individual effects and the dangers that they can cause to flight safety.

2 PURPOSE

The purpose of the present work is to develop a Normobaric Hypoxia Chamber at the Microgravity Center - MicroG, at PUCRS. This paper discusses the concept, design, mechanical and structural components, including how the air mixture with low concentration of oxygen is generated for users, instruments used and the software adapted for their control and safety mechanisms.

3 MATERIALS AND METHODS

For the development of the NHC, a review of literature was carried out, addressing the most relevant aspects related to aviation hypoxia, as well as the different hypoxia simulation methods and existing equipment.

3.1 Hypoxia

Oxygen is the main source of life for humans, responsible for providing energy to cells and tissues. The decrease in an adequate supply of oxygen to cells and tissues, caused by different factors, is called hypoxia. The human being exposed to this situation can have a severe deterioration of the body systems, in particular the central nervous system (especially cells of the brain), causing symptoms like reduction of the visual functions, psychomotor and cognitive alterations and, in extreme cases, loss of consciousness and death (DAVIS et al., 2008; ERNSTING; GRADWELL, 2006; HARDING, 2012; RUSSOMANO, 2012).

The type of hypoxia that most affects aeronauts is known as hypobaric or hypoxic hypoxia, which is the result from any and all environmental occurrences. Under this condition, there is a reduction in the partial blood pressure of O_2 (PA_{O2}), causing a reduction in oxygen diffusion through the alveoli-pulmonary membrane, which results in a decrease in the amount of gas available for the oxygenation of tissues and cells. This type of hypoxia may occur acutely when there is immediate exposure to a minor pressure environment where there is no time for the body to compensate the hypoxia effects (e.g., decompression in flight), or in a chronic way, where there is a progressive exposure, in which there is a period of compensation by the organism. (e.g., mountain climbing) (COSTA, PROTÁSIO, BRASILEIRO, 2009, ERNSTING, GRADWELL, 2006, HARDING, 2012).

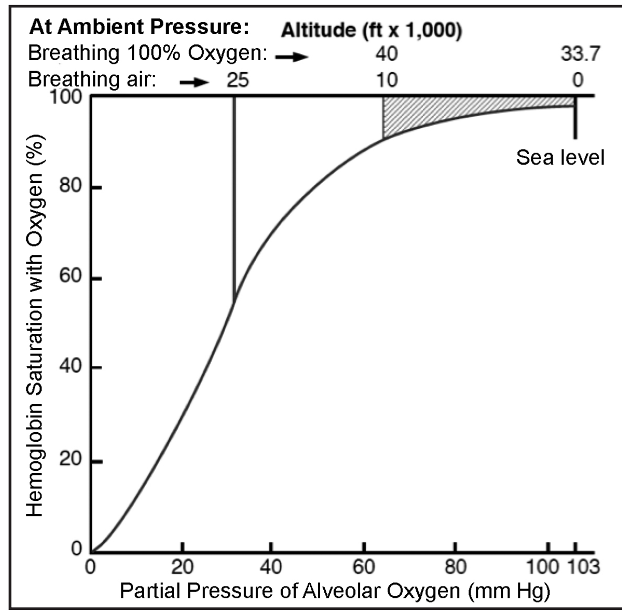
As the altitude increases, there is a decrease in the barometric pressure (Pb) and, consequently, in the partial pressure of the atmospheric gases. The decrease in the partial pressure of the inspired oxygen (PI_{O2}) causes a reduction in the partial pressure of the alveolar oxygen (PA_{O2}). The difference between PI_{O2} and PA_{O2} is shown in Equation 1 (ERNSTING; GRADWELL, 2006; HARDING, 2012; RUSSOMANO, 2012).

$$PI_{O2} - PA_{O2} = PaCO_2 (FI_{O2} + \frac{1 - FI_{O2}}{R}) \qquad (1)$$

Where FI_{O2} represents the fraction of inspired oxygen and R the breathing rate. PaC_{O2} is produced by the rate of CO_2 production in alveolar ventilation. This rate will remain constant up to 10,000 ft. Above that altitude, PA_{O2} drops to levels that trigger respiratory stimulation via arterial chemoreceptors (hyperventilation). This is a protective measure to minimize the effects of hypoxia on the decrease of PA_{O2} and, consequently, on hemoglobin saturation, as can be seen in Table 1 (ERNSTING; GRADWELL, 2006; HARDING, 2012).

The hemoglobin dissociation curve (Figure 1) (relationship between the oxygen saturation curve for Sp_{O2} and PI_{O2}) shows that up to 10,000 ft a large elevation in altitude leads to a small variation of Sp_{O2} and, above 10,000 ft, a small increase in altitude causes a large Sp_{O2} drop and the worsening of hypoxia symptoms (ERNSTING; GRADWELL, 2006; HARDING, 2012; RUSSOMANO, 2012).

Figure 1 – Hemoglobin dissociation curve.



Source: Adapted from Harding (2012).

The symptoms of hypobaric hypoxia are divided into four stages. The **indifferent stage** occurs from the ground up to 10,000 ft (or from the ground up to 39,000 ft with 100% O_2 supplementation), in which the individual is still able to adapt without the need for oxygen supplementation. However, the vision is affected, especially at night. On a night flight at 5,000 ft, 5%

Table 1 – Typical values for hemoglobin pressure and saturation of a healthy subject exposed to hypoxia.

Altitude (ft)	C_2 Concentration (%)	Barometric pressure (Pb) (mm Hg)	Inspired O_2 partial pressure (PI_{O2}) (mm Hg)	Partial pressure of O_2 in arterial blood (PA_{O2}) (mm Hb)	Saturation of hemoglobin (SpO_2) (%)
0,000	20,95	760	148	95	96
8,000	15,54	565	108	56	92
15,000	11,81	429	80	37	79
18,000	10,45	380	69	32	63
20,000	9,61	349	63	29	44

Source: Ernsting and Gradwell (2006).

to 10% of vision is lost, at 10,000 ft, 15% to 25% and above 12,000 ft, from 25% to 30%. There is also an increase in metabolism with greater caloric burning (COSTA, PROTASIO, BRASILEIRO, 2009, RUSSOMANO, 2012).

The **compensatory stage** occurs from 10,000 ft to 15,000 ft (or from 39,000 ft to 42,500 ft with 100% O2). The body tends to compensate for the effects of hypoxia through respiratory and cardiovascular responses, such as hyperventilation and increased heart rate. The main symptoms are drowsiness, alterations in judgment, motor incoordination, slower reasoning, feeling of **well-being** (a certain euphoria), which is the most dangerous sign, since it prevents the individual to take emergency measures (COSTA; PROTÁSIO; BRASILEIRO, 2009; RUSSOMANO, 2012).

The **disturbed stage** is verified from 15,000 ft to 20,000 ft (or from 42,500 ft to 45,000 ft with 100% O2). During this stage, the compensation made by the body is no longer satisfactory. The main symptoms are strong hyperventilation, tachycardia and severe headache. There are alterations in the psychomotor functions, such as a significant increase in reaction time, muscular incoordination and motor incoordination, changes in cognitive functions, such as impairment of performance to new tasks, short and long term memory and logical reasoning impairment, difficulty in solving simple math tasks, loss of judgment, and alteration in visual function as a reduction of perception to light intensity. Visual acuity is decreased with low light and loss of peripheral vision (tunnel vision) (COSTA; PROTÁSIO; BRASILEIRO, 2009; RUSSOMANO, 2012).

At **critical stage** (above 20,000 ft or 45,000 ft with 100% O_2), there is a weakening of the cardiopulmonary and nervous systems, accentuation of the symptoms that occur at the disturbed stage. There is a rapid decrease in mental performance and unconsciousness may occur with little or no symptom, seizures characterized by muscle contractions that produce opisthotonus (head, arm, neck, and spine form a concave backward position), preceded or followed by one or more muscle spasms, semiconsciousness, unconsciousness and death (ERNSTING; GRADWELL, 2006; HARDING, 2012; RUSSOMANO, 2012).

The interval between decreasing oxygen demand to the moment the individual loses the ability to make (protective and corrective) decisions is called Effective Performance Time (EPT). In practice, the most accepted concept is the period that the affected individual retains the ability to correctively act on difficult situations (ERNSTING; GRADWELL, 2006; HARDING, 2012; RUSSOMANO, 2012).

A pilot who flights at 15,000 ft will have 30 minutes or more to recognize symptoms and (or) signs of hypoxia and take action to save passengers and crew from an accident, but that pilot will have a maximum of 20 seconds if flying at 40,000 ft. The effective performance time is shown in Table 2 (ERNSTING; GRADWELL, 2006; HARDING, 2012; RUSSOMANO, 2012).

3.2 Hypoxic Hypoxia Simulation Methods

Hypoxic hypoxia can be generated in two ways. The first is the change in environmental pressure, which will lead to a decrease in the partial pressure (PI_{O2}) that oxygen will exert in the gas diffusion from the lungs to the blood. This type of environment can be simulated in hypobaric chambers. The second form, which will be used in the chamber developed in this work, is obtained by the change in the oxygen volume fraction in the environment. The oxygen volume fraction is directly proportional to the partial pressure exerted by it, so a decrease in the volume of oxygen will consequently decrease the partial pressure exerted on the gas diffusion of the alveoli into the blood. This environmental change can be simulated in normobaric chambers.

Table 2 – Relationship between TDE, altitude and O_2 concentration.

Altitude (ft)	O_2 Concentration (%)	Effective performance time EPT (s)
15,000	11,81	1800 or more
18,000	10,45	1200 to 1800
22,000	8,83	300 to 600
25,000	7,76	180 to 360
28,000	6,80	150 to 180
30,000	6,21	60 to 180
35,000	4,92	30 to 60
40,000	3,87	15 to 20
50,000	-	6 to 9

Source: Russomano (2012).

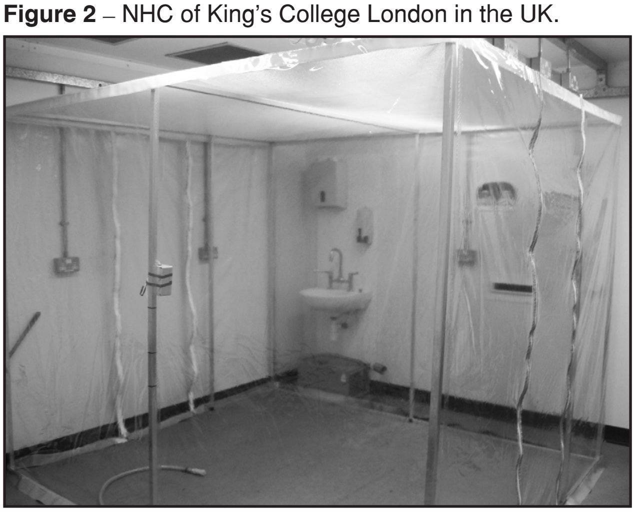
According to the International Standard Atmosphere (ISA), the standard values for barometric pressure and oxygen concentration at sea level are 760 mmHg and 21%, respectively. In a healthy person, hemoglobin saturation (Sp_{O2}) at sea level is approximately 98% to 99% (RUSSOMANO, 2012).

3.2.1 Normobaric hypoxia chamber (NHC)

The NHC or hypoxic tent consists of a room in which there is an insertion of a gaseous mixture, usually nitrogen, with pressure equal to the atmospheric pressure. As there is no variation in pressure, its structure can be constructed as a fully enclosed tent, which may have a plastic or aluminum structure and nylon casing (COLORADO ALTITUDE TRAINING, 2010; HYPOXICO ALTITUDE TRAINING SYSTEMS, 2010).

For this work, hypoxic chambers developed in universities in England and in the United States were investigated. King's College London has a chamber for research on human physiology in extreme environments. This chamber has approximately 9m^2, it is constructed of transparent PVC plastic with aluminum structure, it has openings sealed with zippers (Figure 2), and capacity to host 10 people. The generation of depleted air in oxygen is done through the Training With Altitude Air Generator (TWAAG) equipment. Air monitoring inside the NHC is performed by gas sensors.

Figure 2 – NHC of King's College London in the UK.



Source: The authors.

Embry-Riddle Aeronautical University in the United States also has a normobaric hypoxia chamber manufactured by CAT Altitude Training company. It is constructed of polypropylene plates and aluminum structure, being mounted on a wooden structure elevated above the ground, to allow electrical wiring underneath. It measures approximately 9.6 m^2 and it also has an antechamber. The structure can be used by 9 individuals, besides the possibility of use as a flight simulator. The generation of gas mixture is done with CAT Air Unit equipment. The monitoring is performed by two oxygen sensors, a carbon dioxide sensor, a pressure sensor and a temperature sensor (COLORADO ALTITUDE TRAINING, 2010).

3.2.2 Hypobaric hypoxia chamber

The Hypobaric Hypoxia Chamber (HHC) consists of a room, in which there is an ambient pressure drop. Its operation consists of using vacuum valves to reduce the pressure inside the chamber, simulating the ambient pressure corresponding to the desired altitude. Its construction, operation and maintenance involve more complexity and costs compared to hypoxic normobaric chambers, without the possibility of mobility. Figure 3 illustrates the Hypobaric Chamber of the Brazilian Air Force (FAB).

Figure 3 – HHC of the Brazilian Air Force.

Source: Brasil (2013b).

Comparing HHC and NHC regarding structure, HHC has an extremely complex, robust and heavy structure, unlike NHC, which is lighter and can be modulated and easily transportable.

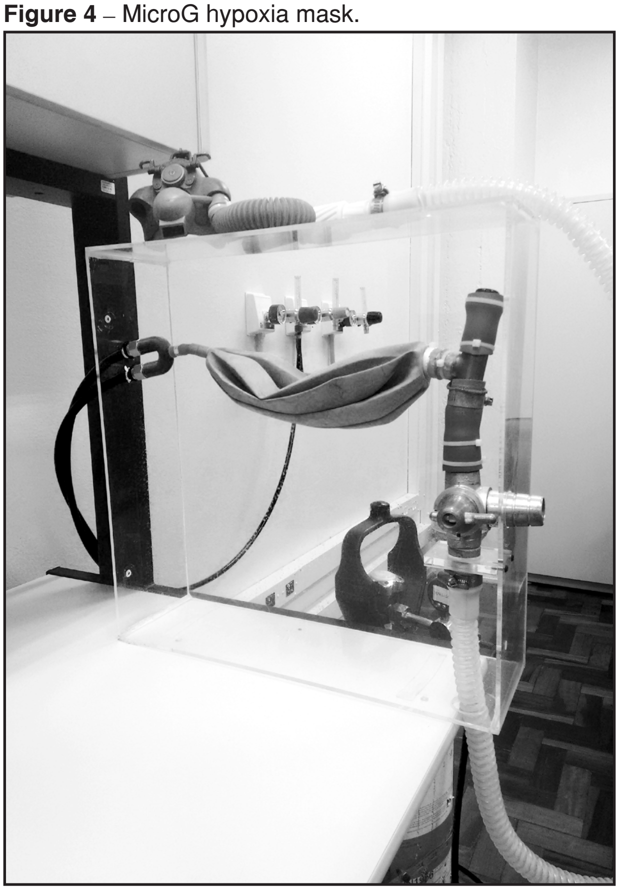
According to Self (2010), after several physiological tests and measured parameters, it has been concluded that NHC is as efficient as HHC for physiological training in hypoxia, with the advantage of having much lower cost and being safe because it decreases the chance of barotrauma and decompression sickness.

3.2.3 Hypoxia mask

Hypoxia masks receive the preselected gaseous mixture through a **simulated** altitude cylinder or generator. Unlike other training modes, the mask does not require infrastructure for its use, which makes the construction, installation and maintenance less costly.

For the training of students of the Aeronautical School of Sciences of PUCRS, the Microgravity Center (MicroG) has developed this system, which is composed of an oxygen mask, silicone trachea, manual selector valve, latex balloon, a medical O_2 cylinder to 100% for use in emergencies, and gas mixture cylinders (O_2 and N2 balancing) (Figure 4).

Figure 4 – MicroG hypoxia mask.



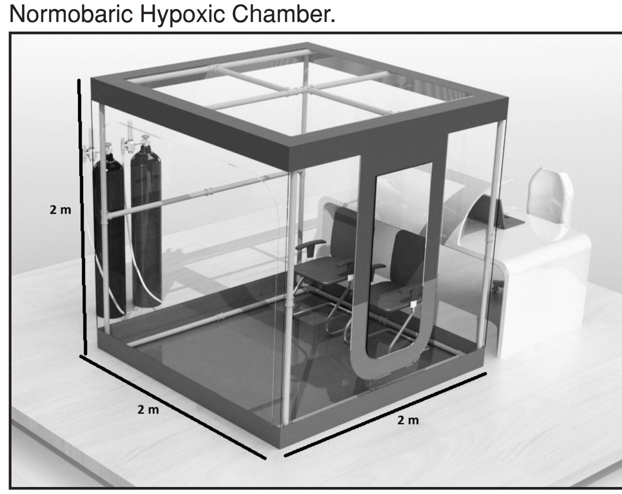
Source: The authors.

3.3 Development of the Normobaric Hypoxia Chamber

The NHC developed at the Microgravity Center has as its final objective the physiological training of pilots and crew in hypoxia and studies of the behavior of the body at high altitudes, through research protocols. Based on this objective, it was found that the NHC should have the following characteristics: material that allows it to be dismountable, easy to transport and as light as possible, whereby its mass should not exceed150 kg. The NHC should still have enough dimensions to allow its use by two volunteers and also include treadmill, exercise bike or cycle ergometer with maximum dimensions of 1.12 m x 0.53 m x 1.13 m. The material of the structure should be impermeable.

From these prerequisites, it was defined that the NHC would have minimum dimensions of height, width and depth of 2 m, as well as light and transparent structure. A design was developed using CAD software (Figure 5). The development of NHC and its control required the creation of dedicated hardware, software and firmware platforms. In the end, each part was integrated into the control system.

Figure 5 – Computer-generated design of the MicroG Normobaric Hypoxic Chamber.



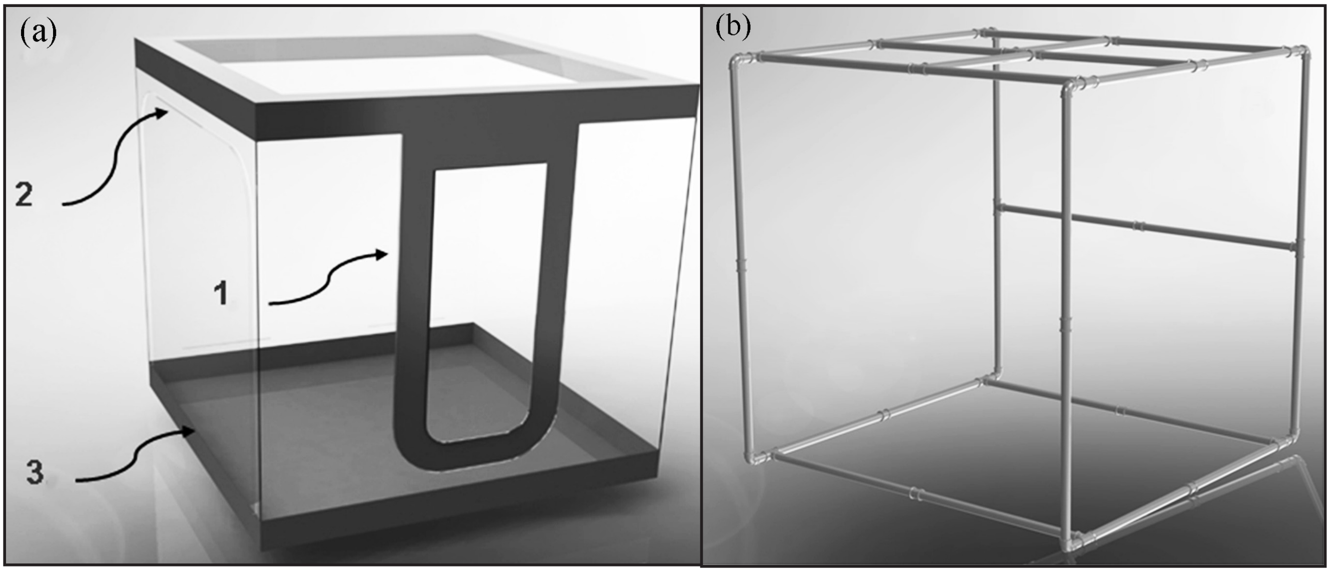
Source: The authors.

3.3.1 Design of the main structure

The NHC was then developed with PVC pipe structure of 40 mm in diameter and coated with vinyl canvas. The biggest advantage of this material is that it can be assembled and disassembled in a few minutes, as well as being lightweight and cost effective. The weight of the structure made of PVC pipes is about 15 kg. Figure 6 (b) shows, the internal structure for NHC support.

A vinyl canvas kp1400 was used in the base coating composition; kp1000 vinyl canvas on the walls; and the **crystal laminate 60** was used for the transparent parts, all containing 0.6 mm thickness and density of 0.2 g/ cm^3. The total dimension of the coating is 24 m^2 and its mass is 48 kg, according to Figure 6 (a).

Figure 6 – (a) Frontal schematic view of the NHC coating. 1: Main entrance; 2: Secondary Entrance; and 3: Zipper. (b) Simulated internal support structure in software.



Source: The authors.

The main entrance was developed in **U**-shape, with width of 0.8 m and height of 1.6 m, sealed with zipper, aiming to allow a quick opening in case of emergency. For the insertion of equipment and objects of the NHC, such as stretchers, chairs and medical equipment, a secondary door was developed, with approximate dimensions of 1.87 m of height x 1.62 m of width.

In order to be able to view the individual from the outside of the chamber, the walls were designed with transparent PVC (60-crystal laminate), except in the reinforcement areas that are in contact with the tubes. For these sites the use of opaque PVC (kp1000 vinyl canvas) was projected, since there is greater resistance. With the intention of having better lighting in the interior, the ceiling was also designed with transparent PVC.

The inlet and outlet of the gas tubes and the electrical wiring were designed to be inserted into the chamber by means of two zipper openings at the rear, measuring 0.4 m. To facilitate the assembly of the structure, a zipper was placed in the lower part of the coating, making it possible to separate the floor from the walls.

3.3.2 Sensors

For the control of the gas mixture inside the NHC, an O_2 sensor and a CO_2 sensor were used. The oxygen sensor is a PSR-11-915-2 model from Analytical Industries. The output ranges from 23 µA to 30 µA and it is equivalent to the 0% to 100% O_2 scale. The response is less than 20 seconds to reach 90% of the measured value and its service life is 60 months.

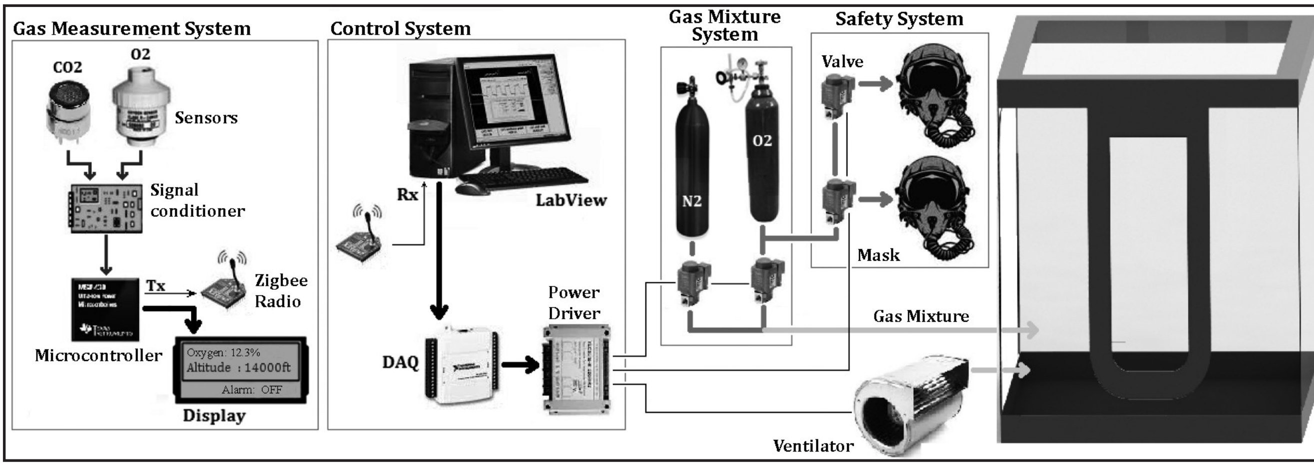
The CO_2 sensor used is a MG811 model from Parallax. The sensor operates by electrolytic principles, where the gas activates the internal heating element, generating a small voltage at the output, in the same proportion as the amount of gas exposed to the air. This sensor requires a voltage that can vary from 6.5 V to 12.0 V.

3.3.3 CHN Hardware

The NHC hardware consists of two parts: one responsible for the reading of the gas sensors and communication, and the other for the control of the valves and the air homogenization fan, and therefore for the O2 concentration, as shown in Figure 7.

For the automatic control of gas opening and closing, a two-way VSMA-1422 solenoid valve was used. The gas measurement system consists of an oxygen sensor PSR-11-915-2, a CO_2 sensor MG811 and a board using 16-bit microcontroller from the MSP430 family of Texas Instruments dedicated to instrumentation and reading of these sensors. This board is also responsible for transmitting the sensor data, via a Zigbee radio, to a computer in which the control software developed on the LabView platform is executed.

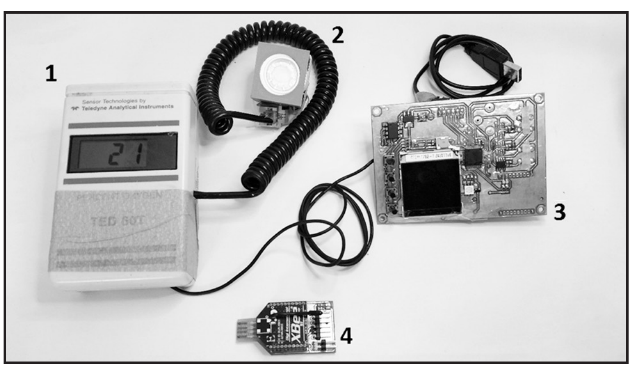
Figure 7 – NHC hardware schema.



Source: The authors.

This electronic board was designed in CAD software (Altium Designer) and machined with a CNC LPKF S63 two-layer milling machine. For the user interface, a keyboard containing four buttons was added, including a graphic display and a buzzer for warning signaling (Figure 8). A portable oximeter model TED 60T was used to check the gas measurement system.

Figure 8 – Hardware. 1: Portable Oximeter; 2: Oxygen Sensor; 3: Developed electronic board; and 4: Zigbee module.



Source: The authors.

The electrical triggering of the gas control valves and the air homogenization fan is done using a DAQ board of the National Instruments model USB-2006, connected to a computer that processes the sensor information to obtain the ratio of O_2 and N_2 desired. The DAQ module is connected to a ULN2003 driver, which allows the driving of nine relays. To accommodate the printed circuit board, a plastic box was used, the front cover being replaced by one designed in the SolidWorks software and printed on the 3D MakerBot 2X printer, in which terminals for the electrical connection were inserted.

To ensure the homogenization of the gas mixture, a fan (009-B40-22", manufacturer SPAL) was used. During and after the use of the NHC, the gas mixture needs to be exhausted to an external environment, so an Elgin MC-11B ventilator has been adapted along with a base (connector support), connector and flexible hoses. To adapt them to the system, it was necessary to print some parts on the 3D Makerbot 2X printer in ABS material. For safety, masks with 100% medical oxygen were made available inside the chamber. The mask used in the oxygenation system is the MBU-12/P type, from GENTEX, provided by FAB for this project.

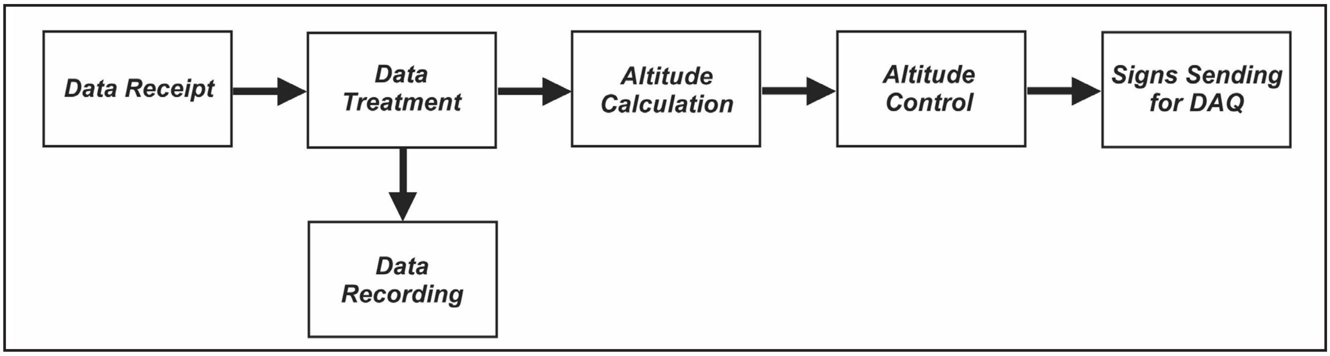
3.3.4 NHC Firmware

The firmware was developed in C programming language, using the Eclipse development environment for programming the MSP430F2619 processor. For a more robust performance of the firmware, i.e., fail-safe when sending packages to the software, the handshake transmission mode has been deployed.

3.3.5 *NHC Software*

Software was developed in the LabView development platform, having as its main function to control all the systems involved in the project and to be the Graphical User Interface (GUI) with the system. It receives data packages sent by the sensing system, processes the data, writes it to a text file, calculates and controls the gases according to the altitude set-point and, finally, sends the signals to the control system. Figure 9 shows the software block diagram.

Figure 9 – Block diagram of the software.

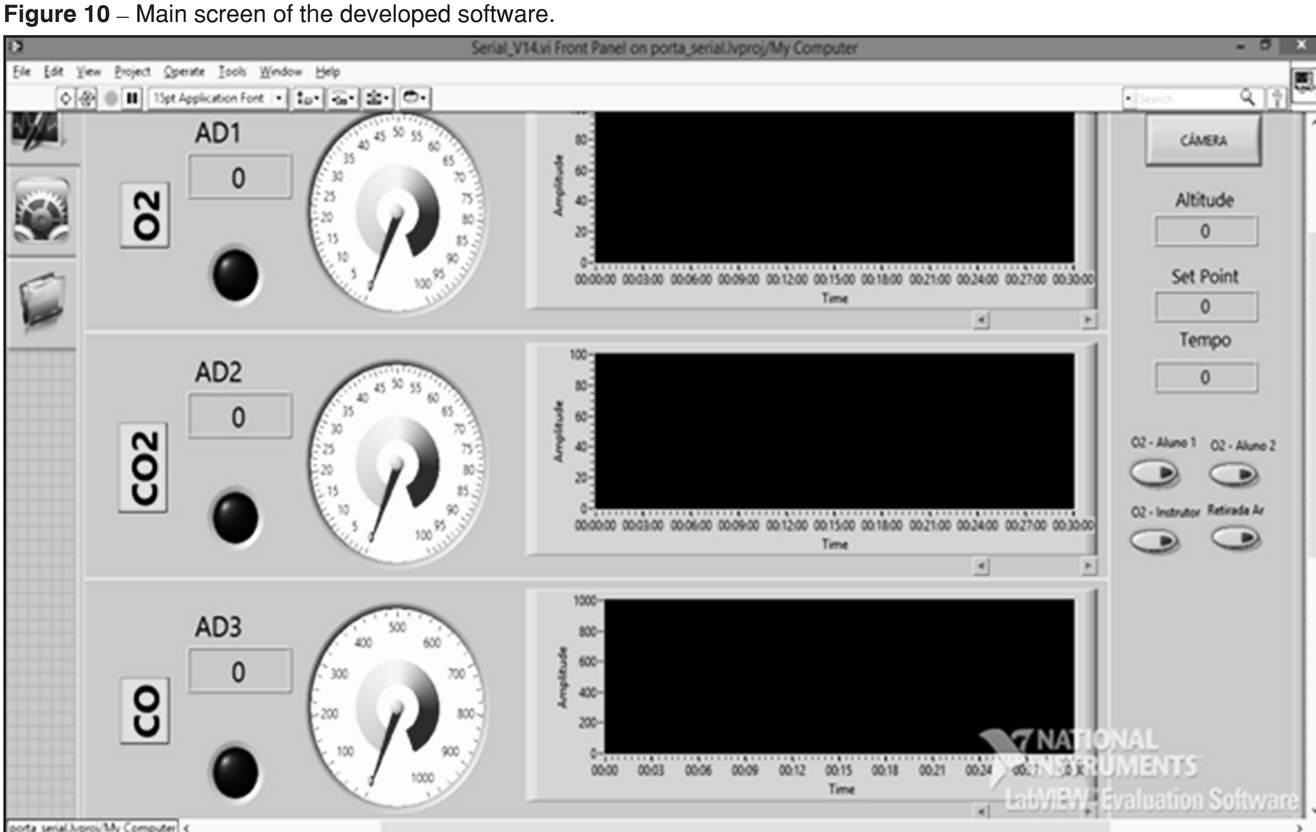


Source: The authors.

The software starts by means of the data reception block, which will then receive the data packages sent by a serial port (COM) of the sensing system. Then, the received data package is checked, and at the end the data package is allocated in the **Value Accepted** variable. The values of **O_2**, **CO_2** and **CO** can be recorded in a text file, according to the user's needs.

The software was designed with three screens. The viewer screen is the main one, where the user visualizes the values of the main parameters of the system, such as O_2, CO_2 and CO, besides activating the Webcam module and solenoid valves of the security system. The system configuration screen is responsible for all software configuration, including alarm limits, serial port, and recording addresses. The input screen is responsible for the insertion of altitude set-points with the possibility of automatic or manual input, in addition to enabling the activation of all equipment managed by the control system. In Figure 10, the main screen is shown.

Figure 10 – Main screen of the developed software.



Source: The authors.

3.3.6 NHC control system

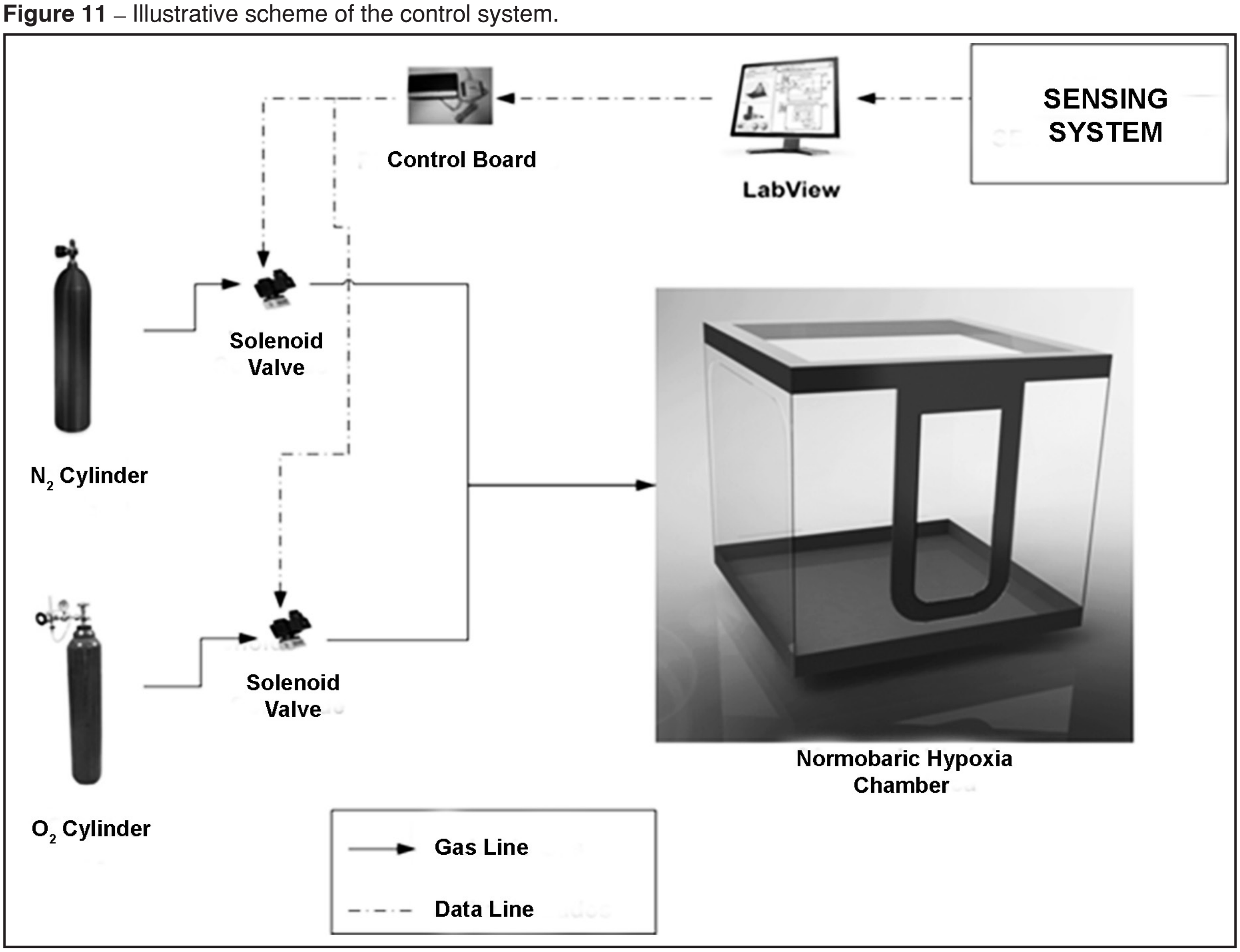
In order to determine the gas mixture inside the NHC, which generates a hypoxic environment, according to pre-established requirements in training or research protocols, a controlled gas delivery system was developed, integrating the software, hardware and firmware. In addition to these components, the system consists of oxygen and nitrogen cylinders, solenoid valves and compressed air hoses. In Figure 11, it is possible to visualize an illustrative scheme of the control system.

4 RESULTS AND DISCUSSION

For the development of this project, the following characteristics were defined for the NHC: to be detachable and easy to transport; have a mass of less than 150 kg; have transparent structure; be made of waterproof material; and contain sufficient dimensions to permit the simultaneous use of two volunteers, and also include a treadmill and (or) an exercise bike and (or) a cycle ergometer.

For the development of the structure, PVC pipes were chosen because they are a light material, low cost compared to other materials analyzed (aluminum and wood) and because they fulfill the prerequisite of being detachable and easy to transport. The chosen coating was vinyl canvas Kp1000, Kp1400 and **crystal** laminate **60** because it is impermeable and allows an internal view of the outside, fulfilling the prerequisite of having a transparent structure and using impermeable material. Regarding the dimensions, there were no changes in relation to the initial design, i.e., the stipulation was maintained, the 2 m x 2 m x 2 m dimension, which is appropriate for the training of pilots and athletes, and may involve the simultaneous use of two volunteers and a piece of equipment for physical exercises. The weight of the complete structure is around 63 kg, thus it is lower than the prerequisite referring to its maximum weight. Therefore, this has proven that the concept and design of the NHC successfully followed the prerequisites established at the beginning of the project.

Figure 11 – Illustrative scheme of the control system.



Source: The authors.

To ensure the safety and correct operation of the hardware control system, a seal test and a hardware control test was developed, as described below. The sealing test (Figure 12) was comprised in the application of white smoke inside the chamber, resulting in the visual verification of leaks, considered minimal, located on the zippers of the openings, concluding that the NHC is safe to use. However, individuals who stay around the chamber during research protocols or training should also take precautions, such as monitoring oxygen saturation in the blood, by means of oximetry to avoid undesired hypoxia. It is recommended that the enclosure where the NHC is installed is well ventilated, avoiding to lead individuals who are near to the equipment to hypoxia.

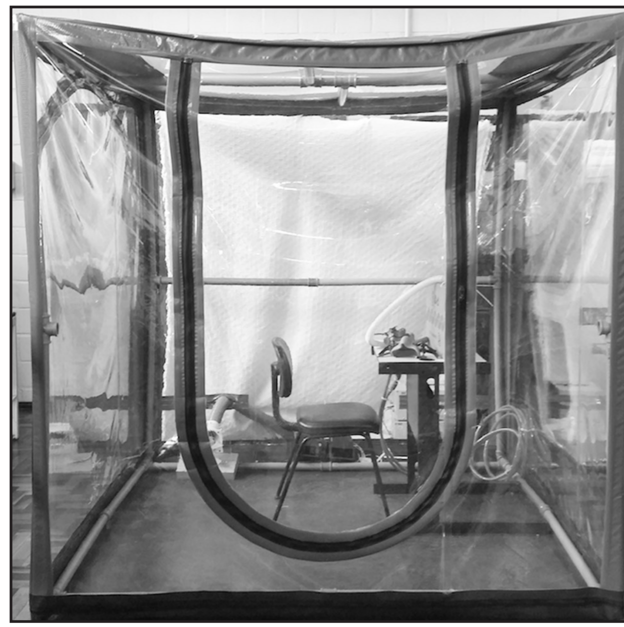
Figure 12 – Sealing test in NHC.

Key: On the right side, one can see the NHC completely filled with white smoke. On the left side, there is minimal visual leakage through the zipper. Such leaks are compensated by the control system.
Source: The authors.

The bench test of the operation of the hardware control system was performed in order to verify the correct operation and eventual overheating of the hardware control module. The first result showed that when turning on or off coils and engines, noise was generated, causing problems in the DAQ module. To solve this problem, filters were added to the output of the hardware control module. No overheating in the hardware control module occurred. An improvement implemented, compared to the chambers surveyed, is in the safety aspect. The NHC performs CO_2 control through its embedded sensors, and once the CO_2 level reaches a pre-programmed critical level, an audible alarm is triggered for safety actions to be taken. Such actions consist of opening the chamber and immediate supplementation of oxygen to the individuals inside it.

The NHC developed presented a low development and design cost in relation to the chambers surveyed. In comparison to the chamber developed in King's College London, the NHC had a total cost of only 4% of it. Compared to the FAB chamber, the cost was around 6%, while in relation to the Embry-Riddle university chamber, it was 14%. The final version of the NHC can be seen in Figure 13.

Figure 13 – Final version of the NHC.



Source: The authors.

5 CONCLUSION

At the end of this project, the physical structure was developed using tubes and vinyl canvas, hardware and firmware, responsible for the gas measurement system and hardware for the control of the valves and of the air homogenization fan. Other developments include software for system control and user **interface** and, finally, the gas delivery system. A test was also carried out to ensure that the structure was sealed and the perfect operation of the hardware control system. It can be concluded, therefore, that the conception and design stages successfully followed all the prerequisites, and that the NHC is safe and secure to use.

The main highlight of this project was in terms of cost, compared to other chambers researched, which allow universities and aeroclubs to acquire the NHC and, consequently, complement pilot training and conduct new aerospace research by opening a field for future studies and positively impact the safety of civil and military aviation.

The NHC can also be used for athlete training and HAST (Hypoxia-Altitude Simulation Test) in patients with respiratory diseases, which increases its applications.

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