Modelling of the Nnormobaric and Hyperbaric Facilities Ventilation

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Abstract: This paper is the result of many work and research programs. During the execution of the projects, it was proposed a new mathematical model of the process of ventilation of a semi-closed rebreather. Its validation required making a special simulator of gas exchange in the breathing process. Use of the device made experimental validation of the proposed model possible. This model has been adjusted to the process of ventilation in hyperbaric chambers. The validation process required developing a new type of carbon dioxide emission simulator. The generalization of the adopted method for the submarine ventilation process was only an obvious consequence of earlier considerations. However, the validation process required to undertake extensive research on a real object, which confirmed the validity of the modelling method adopted. The research on ventilation of the mining excavation constituted the validation of the adopted research approach. In typical residential and public buildings, similar methods have been used relatively recently. In general, they involve air-conditioning of the sealed buildings. This entails the need to regenerate the respiratory atmosphere inside, making them similar to military facilities. Methods of protection against contamination can be used with regard to atmospheric pollution, especially in the work environment. As in the case of military facilities, the methods of modelling ventilation in standard and hyperbaric objects described here would allow developing more accurate methods to design and use ventilation and air-conditioning systems in buildings.

Keywords: Ventilation, Semi-closed Circuit Rebreather (SCR), Hyperbaric Chamber, Submarine, Mining Excavation

1. Introduction

The aim of the work was to develop and verify some mathematical ventilation models for the semi-closed circuit rebreather *SCR* [1] and generalise the presented calculation models to other hyperbaric objects, for example: hyperbaric chambers, submarines and those used in mining excavation. In most situations in a submarine or a mining excavation there exists a slightly higher pressure as compared to the atmospheric pressure, but further, for the simplification purpose, these facilities will be classified as normobaric. The mathematical modelling enables combining the micro and macro objects of the hyperbaric and normobaric technique [2]. The developed models have an analytical character. Therefore, they are subject to physical interpretations. For this reason the semi-analytical and analytic models were not searched for. For the sake of the analysed phenomena character the statistic models of phenomena were not searched for either.

2. Experiments with the Rebreathers

The experiments concerning the mathematical ventilation models were performed during manned and unmanned experimental diving aimed at verification of the decompression procedure proposed. The experiments were carried out for semi-closed rebreathers *SCRs*. The tested *SCRs* should feature the same parameters as the parameters assumed to derive the mathematical model. It is the main condition necessary to perform the experiments by means of a metabolic simulator. A series of experimental dives were carried out with such a simulator.

The adequacy of the assumed mathematical model at limits of oxygen partial pressures was tested during pressure tests with the use of diving apparatuses. The experiments were carried out in parallel with verification experiments of the decompression procedure based on the experiments carried out in the hyperbaric swimming simulator [3-6] – Figure 1.

Figure 1. The hyperbaric swimming simulator.

There were more similar trials carried out but the system was modified. That is why the results obtained are not sufficient to draw conclusions concerning the adequacy of the mathematical ventilation model. The probability of the proposed mathematical model acceptance was not further maximised because of the high experimental costs.

It seems that the best method for experimentation is to apply a breathing machine simulating a breathing action with simultaneous oxygen sampling from the breathing space and carbon dioxide emission for unmanned tests. As in this case the carbon dioxide emission is maintained at the proper level there is no necessity to carry out manned experiments, and the experimental results are repeatable with known accuracy of reproduction. Within the framework of the financially supported project the special laboratory set was built. It can be used to carry out less expensive experiments and get the results without the necessity to carry out manned experiments. The mathematical model was verified during the unmanned tests with the use of *SCRs* – Figure 2.

Figure 2. Stand of combined simulators: respiratory, metabolic and hyperbaric.

In order to simulate the breathing process it is necessary to solve two some technical problems, i.e. the mechanical representation of pulmonary ventilation and simulation of gas exchange in the course of breathing. The processes should be simulated with sufficient accuracy and repeatability. There is no need for representation of each detail of the processes. It is not necessary to simulate the real ventilation process. Usually it is assumed that the respiration shape should be approximated to sinusoidal character. As a matter of fact each of the hyperbaric research centres has their own evaluation standards.

A series of standards concerning the respiration volume, and the respiration rate have been established, however, they are similar regarding most of the parameters.

During a simulation of the breathing action and gas exchange, the exact representation of the inhalation and exhalation shape is not essential. Attention should be focused on the oxygen consumption and carbon dioxide emission to that place.

A reactor with a catalyst for burning chemical compounds can be used as a metabolic simulator. The combusted chemical substance is added to the volume drawn from the breathing loop of *SCR* through the inhale hose using a breathing simulator. After the mixture thus formed has passed through the reactor, it is returned together with the combustion products to the breathing loop of the diving apparatus through the exhale hose [7]. A tested attachment that enables oxygen uptake and carbon dioxide emission was connected to the breathing machine.

That simulator was developed and used to verify the mathematical model of ventilation developed for *SCRs*. Owing to the experiments carried out, the exactness of the theoretical ventilation model in *SCRs* [4-6] could be tested.

The developed experimental laboratory stand enables continuing research on ventilation in various diving apparatuses. Further research focused on developing reactors that could be used for other research purposes such as regeneration of an ecologically confined space, e.g. during saturation [8] dives or in submarines [9], is recommended.

3. Unmanned Experiments with the Hyperbaric Chambers

Mathematical models for hyperbaric chamber ventilation and regeneration can be derived with the use of a similar procedure as in the case of *SCR* ventilation. The investigations were performed to check whether the mathematical models of ventilation derived for *SCR* can be also applied to hyperbaric chambers. The experimental results confirmed such a possibility.

The procedures proposed to employ to obtain mathematical models of ventilation can be used in both a micro scale and macro scale. The macro scale is concerned with the diving technique. It is important that the presented analytical models, compared to the empirical and semi-empirical models, be related to the physical phenomena occurring in the hyperbaric environment.

The consistence of the assumed theoretical model can be tested using the carbon dioxide simulator [10] – Figure 3. The comparison of the experimental and theoretical results is satisfied.
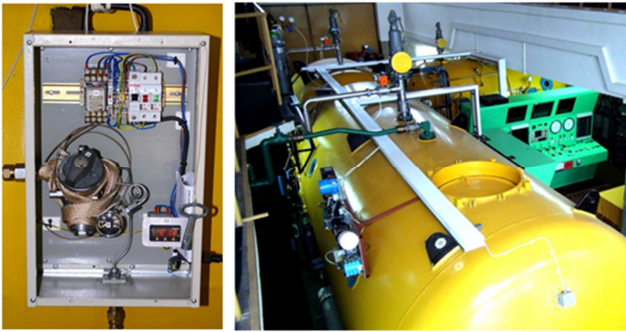
Figure 3. *The carbon dioxide simulator on the left; the Diving Gear & Underwater Work Technology Department's hyperbaric complex DGKN-120 on the right.*

The results of the preliminary experiments confirmed the usability of the applied mathematical models for the interrupted and continuous ventilation parameters. The earlier assumptions concerning the necessity to use an undetermined ventilating medium excess were confirmed as well. As it follows from the above, in order to find the mathematical model that can be used to calculate the maximum excess of ventilating medium it is necessary to carry out further experiments [4, 9-11].

The aim of the presented experiments was to find out whether the ventilation the mathematical models applied to the *SCRs* can be applied also to hyperbaric chambers.

The procedures proposed to develop mathematical models of ventilation can be applied on a micro scale and macro scale as well. The macro scale is concerned with the diving methodology. It is important that the empirical and semi-empirical models when compared to the presented analytical models be related to the physical phenomena occurring in the hyperbaric environment.
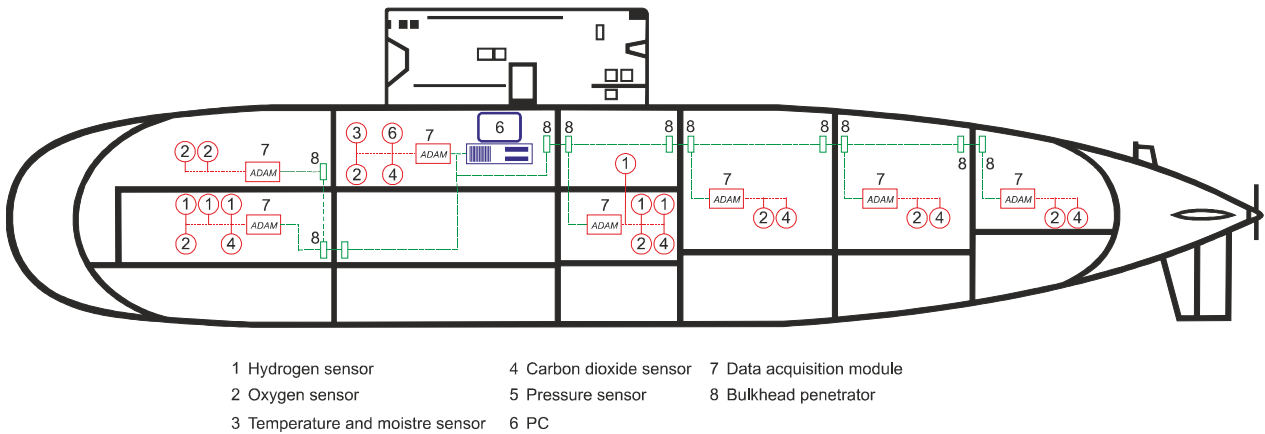

1 Hydrogen sensor	4 Carbon dioxide sensor	7 Data acquisition module
2 Oxygen sensor	5 Pressure sensor	8 Bulkhead penetrator
3 Temperature and moistre sensor	6 PC	

Figure 4. *Submarine atmospheric monitoring system.*

4. Experiments on a Submarine

In 2000, a Polish KILO class submarine was equipped with an experimental submarine atmospheric monitoring system – Figure 4. This system had been developed the Naval Academy. The monitoring system consisted of oxygen, hydrogen, carbon dioxide gas analysers, and temperature, moisture, and pressure sensors. The sensors and analysers were connected to a central industrial computer by data acquisition modules into *RS 485* industrial standard net. Readouts could be recorded every second or longer period of time.

The submarine measuring net was connected by a deck-mounted telephone connector and a water-proof electric cable comprising a twisted pair of wires connected to the portable laboratory. And via an RS 485/RS 232 converter to a typical PC situated in laboratory container, capable of monitoring atmosphere in the submarine with a special computer program – Figure 5.

The test involved simulation of submarine atmosphere carbon dioxide CO_2 contamination, stabilisation of CO_2 content, and ventilation with fresh air.
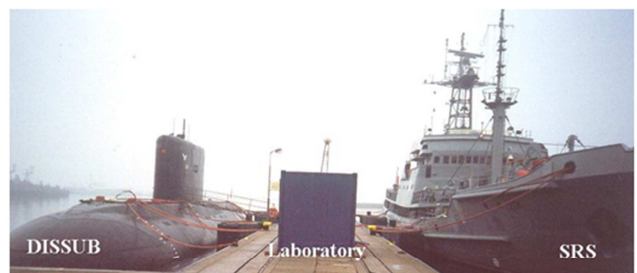

Figure 5. *Above: arrangement of the main elements for the experiment; below: a containerized, portable laboratory.*

The submarine rescue compartment consisted of two decks which divide the compartment into three sub-compartments of equal volume – Figure 4. There were stairs between decks, and a cargo hatchway between the lower sub-compartments.

Preliminary CO_2 concentration was created by releasing CO_2 from four bottles – two on the first and two on the second deck. There were additional two analysers used for measuring CO_2 concentration by the submarine atmosphere monitoring system, on top of the upper and lower bilges of the lowermost compartment.

5. Sealed Mining Excavation

In mining plants, there exists a hazard of occurrence of unhealthy atmosphere [12]. Harmful pollutants can come from various sources. In coal mining, they come from fires of coal and flammable hydrocarbons. In other mines, for example in copper mines, they can form during fires of machinery or when gases accumulated in a rock mass fall through cracks. During fires or flarebacks, large amounts of toxic gases can be released, which, if spread quickly, can surprise the crew, even in locations far from the fire or flareback. The smokiness of excavations occurring during a fire makes it difficult for the endangered crew to withdraw along the specific escape routes. In extreme cases, the crew will not be able to withdraw from the excavation face.

A plan for various rescue action scenarios is developed in advance to respond to cases of occurrence of hazards in a mine. The plan specifies, among other things, escape routes, which the crew may use to withdraw from the endangered zone to a safe place. In the case of long escape routes, the respiratory protection equipment used by the crew may not be sufficient to ensure safe exit from the danger zone. The solution may be construction of refuge chambers, which in the event of a fire will secure a safe haven for the crew. The possibility for the crew to survive the period of danger in such chambers gives the management of the rescue operation time necessary to take action to help them.

Due to the installation of an air-tight breathing system in the refuge chamber, when an atmosphere hazardous for safe breathing forms, a group of miners can survive for a period assumed in the chamber design. The basic elements of the life-saving system are sets of inhalers equipped with half-masks using air contained in high-pressure bottles. The chamber should be fitted with the necessary control and measurement equipment, communication means, etc., in accordance with the design assumptions and applicable regulations.

The chamber was placed in the excavation connecting two gates having a length of min.10 m, width at the thrill of about 5 m and height of about 2 m. The chamber was isolated from the gates with walled dams, in which the entrance door to the chamber was built in sluice-box arrangement. The main dimensions of the chamber were adopted as guidelines for the construction of the life-saving system – Figure 6.

The dams were made of concrete blocks, the walls were plastered on both sides, the ground was levelled and hardened. The tightness of the rock mass and walls sealing off the chamber from excavations was provided with generally available means.
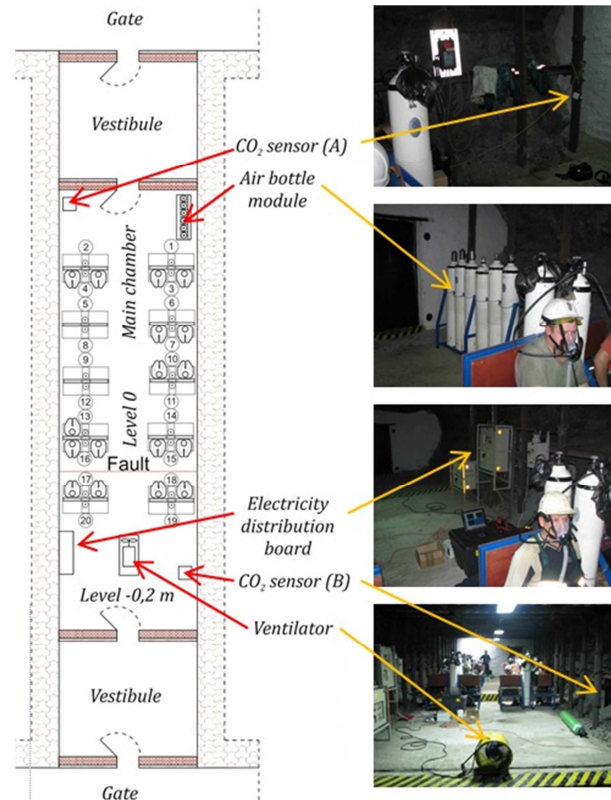

Figure 6. *Arrangement of equipment items during tests.*

The ventilation of the chamber prior to its evacuation was to be provided by one or two racks with six air cylinders designed for ventilation of the atmosphere in the chamber just prior to the planned end of human stay inside it – Figure 6. The release of air was to be achieved through the total opening of the tank.

The ventilation tests were carried out without the participation of people. Carbon dioxide CO_2 was released into the empty and ventilated chamber, stored in two cylinders. The cylinders were located near the sensors of the CO_2 monitoring system.

The complete research results into the chamber ventilation were published earlier and will not be referred here [13].

The results of the final test will be discussed here. After 8 kg CO_2 were released into the chamber space, the ventilation tests were carried out sequentially, based on two schemes:

Simulation of laminar flow through slow and even release of 90 m^3 of air into the chamber space for about 25 min

simulation of turbulent flow of even air release of 31 m^3 to the space of the chamber for about 1 min

In the initial period, the stratification of the carbon dioxide content in the atmosphere of the chamber after its release from the cylinders was clearly visible. However, after about 10 min rapid homogenization and disappearance of the initial stratification took place. Such rapid homogenization could be caused by mechanical movements of the atmosphere of the chamber caused by a stream of released carbon dioxide. Initially carried out ventilation was at a lower intensity of the air stream. Then, after the disappearance period of the effect of the first ventilation process, determined for approx. 20 min,

a more intensive ventilation process was carried out using a tenfold higher air stream [13].

The measurement results for both ventilation processes demonstrated extraordinary compliance with the theoretical model. Previously, several times obtained were the results which did not show less compatibility of the theoretical model with the results of measurements [13].

It can be stated that the results of the research on such a large and complex object as a mining excavation were surprisingly consistent with the proposed mathematical model. This suggests that the approach used to model the ventilation process for a mining excavation is sufficiently accurate to predict its course at the assumed level of credibility, thus enabling its practical use for designing mine refuge chambers.

The scientific measures described here were aimed at finding out whether the mathematical ventilation models applied for the *SCRs*, hyperbaric chambers, sealed mining excavation, submarines ventilation mathematical model.

There is good conformity between the mathematical model and the real measurements from experiments. Only at the end of the ventilation process, a slight deviation was observed, probably caused by weak homogenisation into all compartment volumes.

6. Discussion

The basic issue in designing objects intended for people to stay inside them is to provide these objects with the right amount and quality of breathing gas. The ventilation process of systems with closed or semi-closed circulation of breathing gas, in particular hyperbaric facilities, causes many additional medical and technical problems, which do not occur in typical objects with normobaric pressure.

In an atmosphere that fills an ecologically closed or semi-enclosed system, there is always some accumulation of pollutants and a need to replenish the used oxygen. In hyperbaric conditions, acceptable concentrations of many pollutants are usually smaller by an order of magnitude [12]. Also, the oxygen content must be kept within narrower limits, because this essential component of the breathing gas reveals its carcinogenic and toxic properties [14-16]. Such action of oxygen and pollution in hyperbaric conditions constitutes a physiological problem that is difficult to solve [17].

To control concentration of pollutants and oxygen in conditions of increased pressure greater measurement accuracy than in normobaric conditions must be ensured. This makes it necessary to use laboratory-class devices in the conditions typical for these systems to operate [18]. In practice, it is difficult to use, for example, mass spectrometry methods in a diving bell, because there is a lack of analysers of this type which could be both cheap and resistant to severe operating conditions [4]. It is for this reason that research investigations which allow increasing accuracy of measurement methods are important in ensuring safety for people who stay in this environment for a long time. They include chemometric studies using data mining methods.

As already mentioned, the parameters of respiratory environment are the most difficult to provide inside objects that are ecologically closed or semi-closed systems. These include hyperbaric complexes, submarines, bunkers, survival chambers, etc. The results of the research aimed at improving safety conditions became apparent after the tragedy of the Kursk submarine. Rescuing the crew of a submarine or divers is currently a global problem, and the results of research on the safety of such operations are publicly available, unlike research on ventilation processes in other military objects, such as shelters. NATO specialists are required to disseminate knowledge in the field of safety, which includes problems related to ventilation processes. The results obtained are general solutions and can be applied to typical buildings.

Search for mathematical models is a commonly used procedure. When dealing with complex issues, methods used to search for empirical or semi-empirical models are used. With regard to less complicated problems, attempts are made to develop analytical models that have physical interpretation. Validating the latter is often unnecessary because they are based on the verified laws of nature.

It was conducted research aimed at development and verification of a general analytical mathematical model of ventilation process, both for objects with semi-closed and closed circulation of breathing gas, for hyperbaric and normobaric conditions to verify the general mathematical model developed of the hyper- and normobaric ventilation process by conducting research on selected, possibly diversified real objects. In the research a diving apparatus with closed circulation *SCRs* was selected as a model of a small hyperbaric object, and a hyperbaric chamber was selected as a model of a large object. A submarine was selected as a model of a large normobaric object with closed circulation of breathing gas and a mining excavation was selected as a model of a semi-closed object.

The research was carried out over a period of about 30 years and initially it was not aimed at finding and verifying the general, analytical mathematical model of ventilation process. The cycles of research resulted from the needs of the Armed Forces of the Republic of Poland, and above all the Polish Navy. In the course of the research, however, a concept to generalize the applied approach was developed, which was used to develop an adequate, with regard to practical applications, analytical mathematical model of the ventilation process in such objects [2, 4].

The presented approach can be extended to other military objects and can be used in civilian applications especially when faced with terrorist threat. This approach can be directly employed to design of ventilation systems for chemical industry factories or air-conditioned buildings. Due to the specific properties of such buildings, efforts are made to seal them completely.

The account of the research relates to the types of object and the tests are described in a chronological order. At the beginning, the modelling of the ventilation process in diving apparatuses with closed and semi-closed circulation and its

validation tests are discussed [4-6, 19]. Here, to maintain the order in which the types of object are described, included are most recent studies, also being conducted now which have not been published yet. Next, it was generalized the presented approach to hyperbaric chambers and submarines [2, 4, 8-11]. Designing and modelling regenerative breathing apparatuses and assessment of their operating safety with regard to the assumed diving technology is based primarily on learning and predicting the changes occurring during the ventilation process in their breathing space. The verified mathematical model of the ventilation process in diving apparatuses facilitates computer-supported simulation analyses. In the 1990s, a research project was carried out at the Naval Academy to develop a national diving method with use of *SCRs* with constant dosing of the previously prepared breathing gas (pre-mix). As a result of the work done and the analysis of diving accidents, it was assumed that the mathematical models used at that time were not sufficiently accurate to develop optimal diving procedures [4].

The macroscopic models of ventilation in a *SCR* with constant dosing of pre-mix required precise verification. Such a procedure is necessary to secure survival of people in extremely unfavourable conditions. Conduct of this kind of work for the needs of aviation, as well as in the space industry and underwater activities is governed by many strict regulations. The final trial always embraces experiments with participation of people. To carry out these experiments permission by the Ethics Committee for Scientific Research should be obtained. The studies based on simple statistical inference from the results of the experiments with people confirmed the sufficient accuracy of the analytical mathematical model used for decades [1]. A critical analysis of this approach, however, showed some deficiencies in elaborating research results with this method. Therefore, it was proposed a research method based on the use of a simulator. The original position of the metabolic simulator of gas exchange guaranteed reproducible measurement conditions [7]. The results of research showed that the modeling method used so far was not a sufficiently accurate approximation of the processes taking place. As use of the previous model might lead to deviations from the assumed working conditions, which are potentially dangerous for the diver, and difficult to detect when the existing research procedures were applied and it was proposed to modify.

7. Conclusion

The article summarizes 30 years of research. The result of the research carried out and described in this article is the development and verification of the approach to modelling of ventilation processes. The presented approach is a return to deterministic modelling, abandoned due to the lack of good methods to assess the volume of ventilated space. Finding a way to measure this value was the key element in the research carried out. The presented approach can change the current approach to ventilation processes by replacing semi-empirical models with more accurate analytical models.

The research on the process of ventilation of a hyperbaric complex, in a submarine and a mining survival chamber, confirmed the effectiveness of the proposed approach to modelling ventilation process. Initially used to model ventilation of a diving apparatus this approach has now become generally applicable as a methodology.

Search for mathematical models is a commonly used procedure. When dealing with complex issues, methods to search for empirical or semi-empirical models are used. With regard to less complicated problems, attempts are made to develop analytical models that have physical interpretation. Validating the latter is often unnecessary because they are based on the verified laws of nature. The research carried out was aimed at developing and verifying a general analytical mathematical model of the ventilation process, both for objects with semi-closed and closed circulation of breathing gas, for hyperbaric and normobaric conditions.

A new mathematical model of the process of ventilation of a *SCR* with constant dosing of the previously prepared breathing gas has been proposed. To validate it a special simulator of gas exchange in the breathing process had to be built. The unique in the world device was designed, tested and implemented. Use of the device made experimental verification of the proposed model possible.

The proposed model has been adapted to the process of ventilation in hyperbaric chambers. The validation process required developing a new type of carbon dioxide emission simulator. A prototype of such a simulator was designed and built. It was used for experiments, thus confirming the assumptions which had been originally made. Generalization of the adopted method for the submarine ventilation process was only an obvious consequence of the earlier considerations. However, the validation process required carrying out extensive research on a real object. It confirmed the validity of the modelling method adopted. The research on ventilation of a mining excavation constituted the validation of the adopted research approach.

Efforts to seal industrial objects in order to protect people working there against external pollution have been taken for a long time. In typical residential and public buildings, similar methods have been used relatively recently. In general, they involve air-conditioning of the sealed buildings. This entails the need to regenerate the respiratory atmosphere inside, making them similar to military facilities. Also, implementing civil defence recommendations typical buildings have to meet the requirements concerning protection of people. Methods of protection against contamination can be used with regard to atmospheric pollution, especially in the work environment. As in the case of military facilities, the methods of modelling ventilation in standard and hyperbaric objects described here would allow developing more accurate methods to design and use ventilation and air-conditioning systems in buildings. Using them in some buildings is justified in the period of the increased terrorist threat.

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