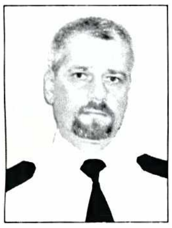

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A mathematical model of ventilation process of a distressed/ /disabled submarine

SUMMARY

In this paper a mathematical model of submarine ventilation which have been experimentally verified, is proposed. Below, the real-object experiment and the mathematical model of the process are presented and their results are compared and discussed.

This study is one of the R&D projects concerning ventilation theory – mathematical modelling of hyperbaric ventilation, conducted by the Naval University of Gdynia for many years.

INTRODUCTION

The investigated mathematical model of submarine ventilation, together with its proof, is presented in Appendix [1].

For experimental verification of the model it was necessary :

- to construct and equip a portable laboratory (Fig.1)
- to angage the Submarine Rescue Ship (SRS) in order to use it as the air bank for precise pressure measuring, as well as
- to prepare a Polish KILO class submarine fitted with an experimental submarine atmospheric monitoring system to serve as the object for distressed/disabled submarine (DISSUB) ventilation measurements.

The so arranged research facility is shown in Fig. 2

Fig.1. The portable laboratory

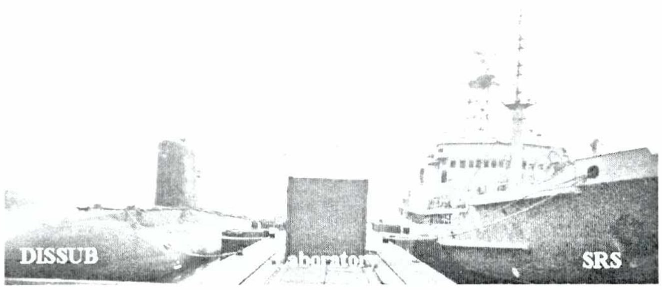


Fig.2. General view of the research facility

INSTRUMENTATION

Submarine atmospheric monitoring system

In the year 2000, a Polish KILO class submarine was equipped with an experimental submarine atmospheric monitoring system. This system was built by the Diving Gear and Underwater Work Technology Dept. of the Naval University of Gdynia. Its implementation was preceded by laboratory tests of gas analysers and other instruments [3]. The monitoring system consisted of gas analyzers of oxygen, hydrogen and carbon dioxide, as well as temperature, moisture, and pressure sensors. The sensors and analyzers were connected to a central Advantech industrial computer. In the system readouts can be recorded every second or for a longer time (usual readout time : 5 s); also, with the use of a typical hard disk it is possible to collect at least 3-year data.

Software and data transmission

The RS 485 submarine measuring net was connected through a deck-fixed telephone connector and a waterproof electric cable to the portable laboratory, and via an RS485/RS232 converter to a typical PC capable to monitor the submarine's atmosphere by the use of a special computer program.

TESTING METHOD

The tests consisted of :

- simulation of carbon dioxide contamination
- stabilization of carbon dioxide contents (homogenisation), and
- ventilation by the fresh air from the SRS air bank.

Simulation test of DISSUB ventilation

For simulating preliminary carbon dioxide concentration in the DISSUB rescue compartment cylinders filled with (3.50±0.01)kg CO_2 and (0.25±0.01)kg N_2 were used. The DISSUB rescue compartment consisted of two decks dividing it into three sub-compartments of equal volume. In the compartment stairs between decks, and a 2 m^2 cargo hatchway between the lower sub-compartments, were installed.

Tab.1. Main metrological data of the used CO_2 analyzer

POLYTRON IR CO_2 analyzer of Drägerwerk AG Lübeck	
principle of work :	spectrophotometer IR
measurement range :	0 ÷ 4.5 $\%_V$
zero repeatability :	≤ ± 0.01 $\%_V$
sensitivity :	≤ ± 5 $\%_V$
pressure effect :	≤ ± 0.16 % measuring value·hPa^{-1}
drift :	≤ ± 0.4 % measuring value·$month^{-1}$
cross sensitivity :	aldehydes, ketones, moisture

Preliminary carbon dioxide concentration was generated by releasing the gas from four cylinders – two on the first and two on the second deck. Two POLYTRON IR CO_2 analyzers (Tab.1) were applied for measuring carbon dioxide concentration (submarine atmosphere monitoring system), installed on the top of the upper and lower bilges of the lowermost compartment.

Homogenisation and ventilation

Homogenisation of the rescue compartment atmosphere was quickly proceeded (it took 1 h on average - Fig. 3). The stable value of carbon dioxide concentration and the average volume of the empty compartment was used to calculate the compartment parking/filling by equipment ratio (factor ζ) (Fig.3). The average fresh-air flow rate was calculated from measurements of the pressure drop in the SRS air bank. The values were necessary to perform calculations of the ventilation model shown in Fig. 3 and Appendix.

Initially, it was assumed that air pressure would have increased before ventilation process. But ventilation process started almost immediately due to leakage. This is evident from Fig.3, where initially a slight internal pressure increment is observed then followed by a fast pressure drop. This was caused by the sea-surface position of the DISSUB in which the submarine seals worked in reverse direction (due to higher pressure outside the hull).

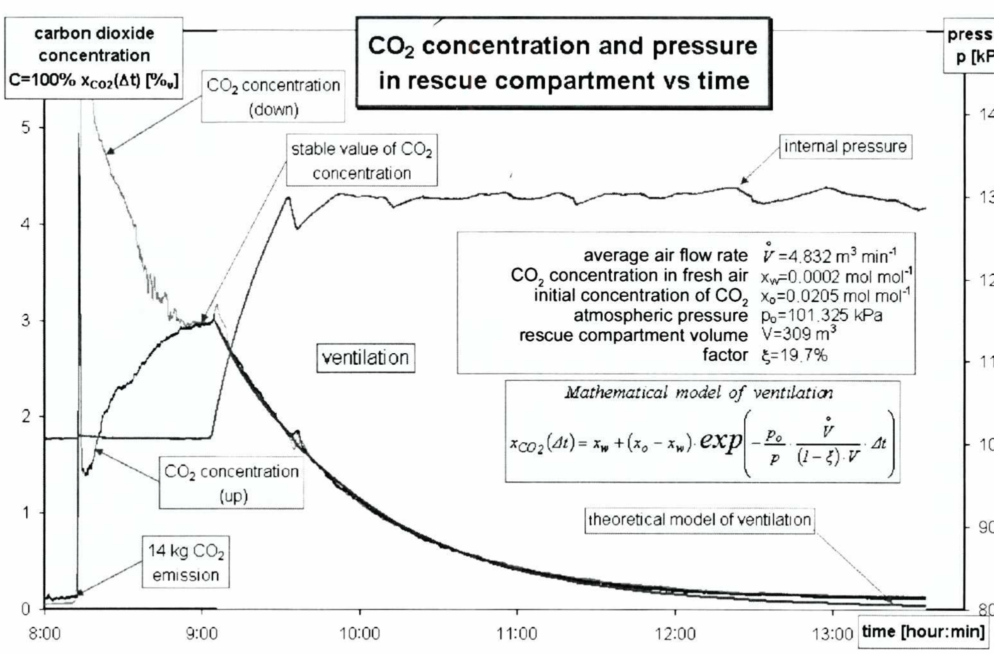
Results and their discussion

On the basis of the results presented in Fig.3 it can be stated that a good conformity between the mathematical model and the measurements of real carbon dioxide content is observed.

Only at the end of the ventilation process a slight difference, probably caused by weak homogenisation of the air in all compartment spaces at low concentration of carbon dioxide, can be observed (as in the mathematical model perfect homogenisation was assumed). This effect emphasizes an influence on the effectiveness of the ventilation process. It suggests that in such case another mathematical model is needed for ventilation process modelling which would take into consideration e.g., resistance against diffusion. Nevertheless the presented model (Fig. 3) can be deemed sufficient for practical applications.

FINAL REMARKS

- Sufficient conformity of the results obtained from the proposed mathematical model of DISSUB ventilation and the results of the performed experimental investigations makes it possible to predict - with a sufficient accuracy - ventilation parameters needed during submarine rescue operations.



$$x_{CO_2}(\Delta t) = x_w + (x_o - x_w)\cdot exp\left(-\frac{p_o}{p}\cdot\frac{\dot{V}}{(1-\xi)\cdot V}\cdot\Delta t\right)$$

Fig.3. Results of measurements and calculations of CO_2 concentration in ventilated DISSUB's compartment

- It seems necessary to perform measurements for the DISSUB in submerged conditions as many air outlet ways could disturb the picture of the modelled DISSUB ventilation process. However, corresponding simulation investigations conducted by means of a Hyperbaric Chamber Simulator suggest that the achieved results are correct [2].
- In this research any simulation of carbon dioxide humidity or that additional due to the crew's metabolism, was not taken into account. It is possible to arrange such experiments by using a carbon dioxide simulator [3,6], however in the author's opinion it seems to be unnecessary.

Acknowledgement

Logistic costs of this submarine ventilation research was high therefore the author would like to take this opportunity to thank Ministry of Defense for their financial support, and the crews of the Polish Navy Ships: ORP "ORZEŁ" and ORP "LECH" for their enthusiasm and help.

Appraised by Zbigniew Korczewski, Assoc.Prof.,D.Sc.

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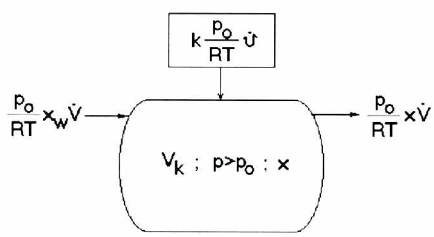
Appendix 1. Derivation of the relationship of CO_2 molar fraction in function of time for the continuous habitat ventilation(integral method)



$\overset{o}{V}$	flow rate of the ventilating medium [$dm^3\cdot min^{-1}$]
$\overset{o}{\upsilon}$	personal CO_2 emission [$dm^3\cdot min^{-1}$]
x_w	CO_2 molar fraction in the ventilating medium [$mol\cdot mol^{-1}$]
p_o	normal pressure [kPa]
R	universal gas constant [$J\cdot K^{-1}\cdot mol^{-1}$]
T	temperature [K]
V_k	habitat volume [m^3]
k	number of people

ASSUMPTION :	$\overset{o}{V}=\overset{o}{V}(p=p_o)\quad \overset{o}{\upsilon}=\overset{o}{\upsilon}(p=p_o)$
THESIS :	$x(O_2)=f(t)$

PROOF :

1°	$\frac{p}{R\cdot T}\cdot V_k\cdot\frac{\partial x}{\partial t}=\frac{p_o}{R\cdot T}\cdot\overset{o}{V}\cdot x_w-k\cdot\frac{p_o}{R\cdot T}\cdot\overset{o}{\upsilon}-\frac{p_o}{R\cdot T}\cdot\overset{o}{V}\cdot x$	from the scheme of oxygen molar balance
2°	$\frac{\partial x}{\partial t}=\frac{p_o}{p}\cdot\frac{\overset{o}{V}\cdot x_w}{V_k}+k\cdot\frac{p_o}{p}\cdot\frac{\overset{o}{\upsilon}}{V_k}-\frac{p_o}{p}\cdot\frac{\overset{o}{V}}{V_k}\cdot x$ marking : $a=\frac{p_o}{p}\cdot\frac{1}{V_k}\left(\overset{o}{V}\cdot x_w+k\cdot\overset{o}{\upsilon}\right)=const$ $b=\frac{p_o}{p}\cdot\frac{1}{V_k}\cdot\overset{o}{V}=const$	as for the stable conditions $\overset{o}{V}=const$ $\overset{o}{\upsilon}=const$
3°	$\frac{\partial x}{b\cdot x-a}+\partial t=0$	from 2° after dividing both sides of equation by (bx-a)
4°	$\int\frac{dx}{b\cdot x-a}+\int dt=C$ where : C - the integration constant	from 3° and the integral definition
5°	$\frac{1}{b}\ln\lvert b\cdot x-a\rvert+t=C\quad\Rightarrow\quad\ln\lvert b\cdot x-a\rvert\equiv b(C-t)=C'-bt$	from 4°
6°	$\exp(C'-b\cdot t)=C''\cdot\exp(-b\cdot t)\equiv bx-a$	from 5° and from natural logarithm definition
7°	If, for the boundary conditions $t\to 0\Rightarrow x\to x_o$, then : $C''=b\cdot x_o-a\Rightarrow(b\cdot x_o-a)\exp(-b\cdot t)=b\cdot x-a$	from 6°
8°	$x(t)=x_w+\frac{k\cdot\overset{o}{\upsilon}}{\overset{o}{V}}+\left(x_o-x_w+\frac{k\cdot\overset{o}{\upsilon}}{\overset{o}{V}}\right)\exp\left(-\frac{p_o}{p}\cdot\frac{\overset{o}{V}}{V_k}t\right)$	from 2° and 7° **q.e.d.**