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THE IMPACT OF PARAMETERS OF AIR HYPERBARIC EXPOSURE ON THE DECOMPRESSION CHAMBER FIRST VENTILATION

ABSTRACT

The material presents an analysis of the impact that the parameters of air hyperbaric exposure have on the time remaining to the beginning of the first ventilation, as calculated with two mathematical models. The research has been conducted in the form of simulations that take into account standard parameters of exposure. Differences between the analysed models have been indicated, and the influence of the changes of particular input values in the analysed models on the output values has been defined.

Key words:
underwater works, decompression chambers, marine engineering.

INTRODUCTION

The research connected with the operation of hyperbaric facilities, especially decompression chambers, has been conducted by the Department of Underwater Works Technology of the Naval Academy in Gdynia (DUWT) for several years now. One of the main areas of such research is related to the methodology of atmosphere ventilation in the decompression chamber. The person who pioneered these works was the first head of the DUWT, Cpt. Medard Przylipiak. The rudiments of the theory of ventilation in hyperbaric facilities were laid out in 1971 in a collective work edited

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by W. Poinc entitled *Underwater works* [7]. He developed this issue in a publication entitled *Equipment and diving works — a handbook*, 1981 [8]. Cpt. Przylipiak laid the foundations of the theory and postulated a series of experimental studies related to its verification and its final development. Sadly, his sudden death interrupted these ambitions. The studies were continued by Cpt. Ryszard Kłos, PhD, Eng. (reserves) and Cdr. Zbigniew Talaśka, PhD, Eng (reserves) who defended their doctoral dissertations in 1990 and 1994 on subjects related to ventilation in hyperbaric facilities, whereas neither of the investigated issues was related to air atmosphere in the decompression chamber [3, 9]. Cpt. Kłos spent a great many years on a coherent theory of ventilation in hyperbaric chambers, which culminated in his successful defence of the postdoctoral dissertation at the Gdańsk University of Technology in 2007 on the subject. He published the results of his research in a number of publications and papers [1, 2]. The last of the doctoral dissertations related to the theory of ventilation that was defended at the department was a dissertation on the methodology of ventilation in the decompression chamber during air hyperbaric exposures, which was defended in 2004 and published as a monograph in 2007 [5, 6]. The three mentioned doctoral dissertations were reviewed by Prof. Adam Charchalis.

The present paper presents the results of the analysis of time value changes before the beginning of the first ventilation during air hyperbaric exposures in a decompression chamber, calculated with an equation developed by Cpt. Przylipiak and Cpt. Kłos. For the purposes of the present paper, the theory developed by Cpt. Przylipiak is referred to as model 1, whereas the theory developed by Cpt. Kłos, model 2.

ISSUE

The methodology of the decompression chamber operation for air exposures provides for the possibility of conducting the process of ventilation of the chamber with the use of two mathematical models [6], where the time remaining to the beginning of ventilation is defined with the following equations (1), (2):

$$\tau_1 = \frac{V_k C_{CO_2 max} p}{C_{CO_2 wyd} \dot{V}_p k p_0}, \qquad (1)$$

where:

τ_1 — time remaining to the beginning of the first ventilation of the decompression chamber compartment [min];

V_k — the volume of the decompression chamber [dm^3];
C_{CO_2max} — permissible content of carbon dioxide in the chamber's atmosphere at a given depth of exposure [%];
p — pressure of the exposure in the chamber [KG/cm^2];
C_{CO_2wyd} — the content of carbon dioxide in the air exhaled by the diver [%];
$\dot{V}_p$ — minute ventilation of the diver's lungs with air [dm^3/min];
k — number of divers staying in the compartment of the ventilated chamber [–];
p_o — atmospheric pressure of [KG/cm^2];

$$\tau_1 = \frac{V_k}{k\dot{V}_{O_2}}\left(\frac{p_{CO_2max} - px_1}{p_0}\right), \tag{2}$$

where:
$\dot{V}_{O_2}$ — oxygen consumption by one diver staying in the ventilated compartment of the decompression chamber [m^3/min];
p_{CO_2max} — maximum permissible partial pressure of carbon dioxide in the atmosphere of the ventilated decompression chamber [kPa],
x_1 — the initial molar ratio of carbon dioxide in the atmosphere of the ventilated decompression chamber [mol/mol],
the remaining determinations as for the equation (1).

At times, some divers use the mnemonic version of the equation to quickly evaluate the time remaining to the beginning of the first ventilation of the chamber (1):

$$\tau_1 = \frac{V_k}{50k}. \tag{3}$$

It is possible only when one bears in mind that this form of equation is used for strictly defined conditions of the exposure that allow only for standard parameters related to the effort of the divers who are staying in the chamber. Equation (3) is derived from equation (1) by substituting for C_{CO_2max} the following relationship:

$$C_{CO_2max} = \frac{100\% p_{CO_2max}}{p}. \tag{4}$$

Then equation (1) becomes:

$$\tau_1 = \frac{V_k 100\% p_{CO_2max}}{C_{CO_2wyd}\dot{V}_p k p_0}. \tag{5}$$

Next, introducing to the relationship (5) standard parameters: the content of carbon dioxide in the air exhaled by the diver (C_{CO_2wyd}) at the level of 5 [%], a minute ventilation of the diver's lungs ($\dot{V}_p$) at the level of 15 [dm3/min], maximum permissible partial pressure of carbon dioxide in the chamber's atmosphere (p_{CO_2max}) at the level of 0.015 [KG/cm2] and atmospheric pressure (p_0) equal to 1 [KG/cm2] (on account of the period of time in which the above methodology of ventilation was developed and the correctness of the future calculations, an old system of units has been applied here). On the completion of calculations the following result has been obtained:

$$\tau_1 = 0{,}02\frac{V_k}{k} = \frac{V_k}{50k}. \tag{6}$$

Therefore, the equation form (1) expressed with the relationship (3) easily absorbed by divers, but correct only in the existence of figures in the parameters used in equation (5). However, for the evaluation of the impact of input parameters in the equations on the change of the time value remaining to the first ventilation, only the equation form expressed by the relationship (1) may be used.

METHODOLOGY

The impact of the parameters in hyperbaric exposure on the time remaining to the first ventilation during air exposure was analysed with the use of basic mathematical theorems derived from Lagrange's theorem [4]:

$$if\ \frac{dy}{dx} > 0 \Rightarrow if\ x \nearrow \Rightarrow y \nearrow; \tag{7}$$

$$if\ \frac{dy}{dx} = 0 \Rightarrow if\ x \nearrow \Rightarrow y = const; \tag{8}$$

$$if\ \frac{dy}{dx} < 0 \Rightarrow if\ x \nearrow \Rightarrow y \searrow. \tag{9}$$

Next, for each analysed equation $y = f(x, x_1, x_2, \ldots . x_{n-1}, x_n)$ its form was determined by reducing it with regard to the analysed parameter (x) and reducing it to the relationship directly defining the function $y = f(x)$. The next step was to examine the sign of the first derivative of such function and use the theorems (7), (8) and (9). Next, standard parameters of the exposure were assumed and the value of function $y = f(x, x_1, x_2, \ldots . x_{n-1}, x_n)$ was calculated for $x \neq const, x_1 = const, x_2 = const, \ldots \ldots x_{n-1} = const, x_n = const$. On that basis differences between analysed models were defined and the impact of the parameters of hyperbaric exposure on the time remaining to the first ventilation was determined, as calculated by model 1 and model 2.

THE ANALYSIS OF MODEL 1

In equation (1) there are seven input values, three of which will be constant regardless of exposure conditions ($C_{CO_2max}, C_{CO_2wyd}, p_o$), two are linked by function ($\dot{V}_p = f(k)$), where this relationship is directly proportional and if $k \nearrow \Rightarrow \dot{V}_p \nearrow$, then the impact of the changes of these values on input value will be similar. The remaining three input values (k, V_k, p) in equation (1) are changeable and dependent on the conditions of the exposure. For these values an analysis of the impact of these changes on the input value from equation (1) will be conducted. Analysing the impact of the changes in the volume of the chamber on the time value remaining to the first ventilation from equation (1), one may assume that:

$$a = \frac{C_{CO_2max} p}{C_{CO_2wyd} k \dot{V}_p p_0}. \tag{10}$$

Then equation (1) becomes:

$$\tau_1 = a V_k. \tag{11}$$

Hence

$$\frac{d\tau_1}{dV_k} = a \Rightarrow if\ V_k \nearrow \Rightarrow \tau_1 \nearrow. \tag{12}$$

Whereas when analysing the impact of the number of divers on the time value remaining to the first ventilation from equation (1), one may assume that:

$$b = \frac{V_k C_{CO_2max} p}{\dot{V}_p C_{CO_2wyd} p_0}. \tag{13}$$

Then equation (1) becomes:

$$\tau_1 = \frac{b}{k}. \tag{14}$$

Hence

$$\frac{d\tau_1}{dk} = \frac{-b}{k^2} \Rightarrow if\ k \nearrow \Rightarrow \tau_1 \searrow. \tag{15}$$

When analysing the impact of changes in exposure pressure on the changes of input values in equation (1) one should note that in this equation this value is in the nominator of the fraction, but it is multiplied by values, of which one is dependent on this parameter:

$$\begin{gathered} x_{CO_2max} = \frac{C_{CO_2max}}{100\%} \rightarrow C_{CO_2max} = 100\% x_{CO_2max}; \\ p_{CO_2max} = x_{CO_2max} p \rightarrow x_{CO2_{max}} = \frac{p_{CO2_{max}}}{p}. \end{gathered} \tag{16}$$

Then

$$C_{CO_2max} = \frac{100\% p_{CO_2max}}{p}. \tag{17}$$

Maximum permissible partial pressure of carbon dioxide (p_{CO_2max}) in the chamber's atmosphere is a constant value independent of the conditions of exposure. It is a changeable value in the function of a molar fraction of carbon dioxide in the chamber's atmosphere (x_{CO_2max}) and the exposure pressure (p), which means that with the pressure increasing it will be achieved with a lower molar fraction of this component in the chamber's atmosphere. However, in equation (1) this phenomenon will not be manifested, for when we substitute the equation (17) we obtain:

$$\tau_1 = \frac{V_k \frac{100\% p_{CO_2max}}{p} p}{\dot{V}_p C_{CO_2wyd} k p_0} \rightarrow \tau_1 = \frac{V_k p_{CO_2max}}{\dot{V}_p C_{CO_2wyd} k p_0}, \tag{18}$$

where:

$$p_{CO_2max} = const. \tag{19}$$

Taking into account the above we obtain

$$\frac{d\tau_1}{dp} = 0. \tag{20}$$

Which means that the change in pressure has no influence on input values of equation (1).

THE ANALYSIS OF MODEL 2

In equation (2) there are also seven input values, two of which are constant (p_0, p_{CO_2max}); two others are linked to the function relationship ($\dot{V}_{O2} = f(k)$) and four values are dependent on the parameters of exposure (V_k, k, p, x_1). For these values an analysis of the impact of these changes on the output value from equation (2) will be conducted.

Analysing the impact of the changes in the volume of the decompression chamber on the time value remaining to the first ventilation from equation (2), one may say that:

$$\tau_1 = \frac{V_k}{k\dot{V}_{O_2}}\left(\frac{p_{CO_2max} - px_1}{p_0}\right) = V_k\left[\frac{1}{k\dot{V}_{O_2}}\left(\frac{p_{CO_2max} - x_1 p}{p_0}\right)\right]; \tag{21}$$

$$if\ a = \frac{1}{k\dot{V}_{O_2}}\left(\frac{p_{CO_2max} - x_1 p}{p_0}\right) \rightarrow \tau_1 = V_k a. \tag{22}$$

Then

$$\tau_1 = V_k a \rightarrow \frac{d\tau_1}{dV_k} = a \Rightarrow if\ V_k \nearrow \Rightarrow \tau_1 \nearrow. \tag{23}$$

Similarly, when analysing the changes in the number of divers one may say that:

$$\tau_1 = \frac{V_k}{k\dot{V}_{O_2}}\left(\frac{p_{CO_2max} - px_1}{p_0}\right) = \frac{1}{k}\left[\frac{V_k}{k\dot{V}_{O_2}}\left(\frac{p_{CO_2max} - x_1 p}{p_0}\right)\right]; \tag{24}$$

$$if\ a = \frac{V_k}{k\dot{V}_{O_2}}\left(\frac{p_{CO_2max} - x_1 p}{p_0}\right) \rightarrow \tau_1 = \frac{a}{k}. \tag{25}$$

Then

$$\tau_1 = \frac{a}{k} \rightarrow \frac{d\tau_1}{dk} = -\frac{a}{k^2} \Rightarrow if\ k \nearrow \Rightarrow \tau_1 \searrow. \tag{26}$$

But when analysing the changes in exposure pressure in the chamber one may say that:

$$\tau_1 = \frac{V_k}{k\dot{V}_{O_2}}\left(\frac{p_{CO_2max} - px_1}{p_0}\right) = \frac{V_k\left(\frac{p_{CO_2max - x_1 p}}{p_0}\right)}{k\dot{V}_{O_2}} = \frac{\frac{V_k p_{CO2_{max}}}{p_0} - \frac{V_k x_1 p}{p_0}}{k\dot{V}_{O_2}}; \tag{27}$$

$$\tau_1 = \frac{\frac{V_k p_{CO2_{max}}}{p_0} - \frac{V_k x_1 p}{p_0}}{k\dot{V}_{O_2}} = \frac{\frac{1}{p_0}\left(V_k p_{CO_2 max} - V_k x_1 p\right)}{k\dot{V}_{O_2}}; \tag{28}$$

$$\tau_1 = \frac{\frac{1}{p_0}\left(V_k p_{CO_2 max} - V_k x_1 p\right)}{k\dot{V}_{O_2}} = \frac{V_k p_{CO_2 max} - V_k x_1 p}{p_0 k\dot{V}_{O_2}}; \tag{29}$$

$$\tau_1 = \frac{V_k p_{CO_2 max} - V_k x_1 p}{p_0 k\dot{V}_{O_2}} = \frac{V_k p_{CO_2 max}}{p_0 k\dot{V}_{O_2}} - \frac{V_k x_1 p}{p_0 k\dot{V}_{O_2}}; \tag{30}$$

$$if\ a = \frac{V_k p_{CO_2 max}}{p_0 k\dot{V}_{O_2}}\, i\ b = \frac{V_k x_1 p}{p_0 k\dot{V}_{O_2}} \rightarrow \tau_1 = a - bp. \tag{31}$$

Then

$$\tau_1 = a - bp \rightarrow \frac{d\tau_1}{dp} = -b \Rightarrow if\ p \nearrow \Rightarrow \tau_1 \searrow. \tag{32}$$

Analysing the influence of changes of the initial content of carbon dioxide in the chamber's atmosphere which is manifested in equation (2) through molar fraction (x_1), the equation (27) may be expressed:

$$\tau_1 = \frac{V_k p_{CO_2 max}}{p_0 k\dot{V}_{O_2}} - \frac{V_k x_1 p}{p_0 k\dot{V}_{O_2}} = \frac{V_k p_{CO_2 max}}{p_0 k\dot{V}_{O_2}} - \frac{V_k p}{p_0 k\dot{V}_{O_2}} x_1; \tag{33}$$

$$if\ a = \frac{V_k p_{CO_2 max}}{p_0 k\dot{V}_{O_2}}\, i\ b = \frac{V_k p}{p_0 k\dot{V}_{O_2}} \rightarrow \tau_1 = a - bx_1. \tag{34}$$

Then

$$\tau_1 = a - bx_1 \rightarrow \frac{d\tau_1}{dx_1} = -b \Rightarrow if\ x_1 \nearrow \Rightarrow \tau_1 \searrow. \tag{35}$$

CONCLUSIONS

The present paper provides an analysis of two mathematical models which enable a determination of time remaining to the beginning of the first ventilation of atmosphere in the decompression chamber during air hyperbaric exposures. A basic observable difference between the analysed models is the lack of model 1 sensitivity to the changes in the pressure of hyperbaric exposure in the compartment of the ventilated decompression chamber (fig. 1). Although in equation (1) this value is present as an input variable, then next to it, in the nominator of the equation, there is a maximum permissible content of carbon dioxide which, as follows from the relationship (4) and (17) is also dependent on the value of exposure pressure, which follows from relationship (16). Such an equation pattern (1) means that theoretically a change in the exposure pressure has no impact on the value of the calculated time remaining to the beginning of the first ventilation. In the case of the model 2, one may clearly notice a negative correlation between the time remaining to the beginning of the first ventilation and hyperbaric exposure pressure in the chamber (fig. 1). With the increasing pressure, the values calculated with equation (2) will be decreasing, which follows from relationship (31). Equation (2) does not allow for the permissible content of carbon dioxide in the chamber's atmosphere, but the maximum permissible partial pressure of that component and its initial molar fraction in the atmosphere of the ventilated chamber. In this manner the boundaries of a safe composition of atmosphere in the decompression chamber are defined in terms of carbon dioxide, by determining when and in what initial conditions a maximum permissible content of this component will be reached. Together with the increase of exposure pressure the value will be reached with an increasingly lower molar fraction of carbon dioxide, which is clearly demonstrated in Fig. 1 and follows from the relationship (34) and has been demonstrated in figure 2.

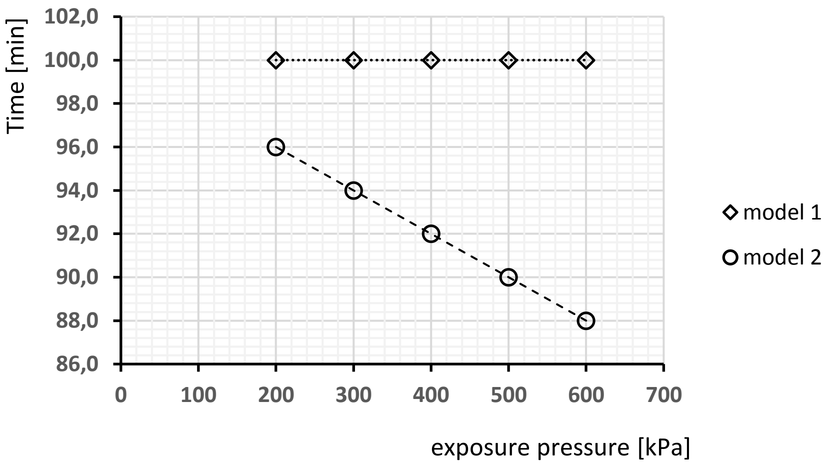

Fig. 1. The change of time remaining to the first ventilation in the function of exposure pressure changes in the decompression chamber ($\tau_1 = f(p)$) when $p = 200$[kPa], $C_{CO_2max} \in (0{,}25 \div 0{,}75)$ [%], C_{CO_2wyd} = 5[%], V_k = 10000 dm^3, p_0 = 100 [kPa], $\dot{V}_p$ = 15 [dm^3/min]; k = 2, $\dot{V}_{O_2}$ = 0,00075 [m^3] for $p \in (200 \div 600)$ [kPa] [own work]

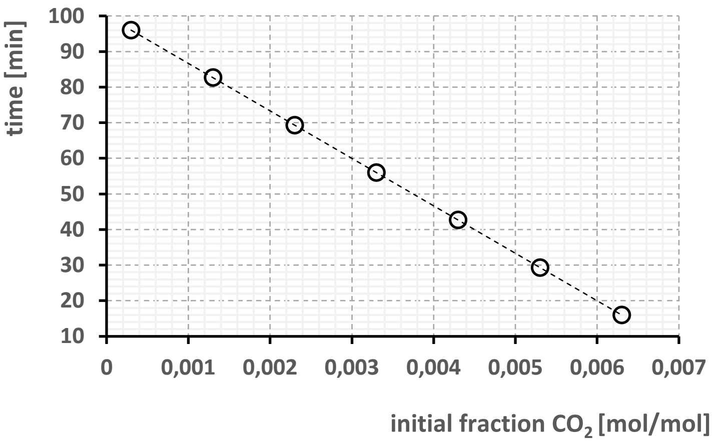

Fig. 2. The change of time remaining to the first ventilation in the function of changes in the initial content of carbon dioxide in the decompression chamber ($\tau_1 = f(x_1)$) when p_{CO_2max} = 1,5 [kPa], p_0 = 100 [kPa], $\dot{V}_{O_2}$ = 0,00075 [m³], V_k =15 [m³], $k = 2$, p = 200 [kPa], for $x_1 \in (0{,}0003 \div 0{,}0063)$ [mol/mol] [own work]

In the case of the remaining parameters ($\tau_1 = f(V_k)$) and ($\tau_1 = f(k)$) the differences between the analysed models are not significant (fig. 3 and 4). While the time values remaining to the first ventilation calculated by equation (2) are shorter than time values calculated by equation (1).

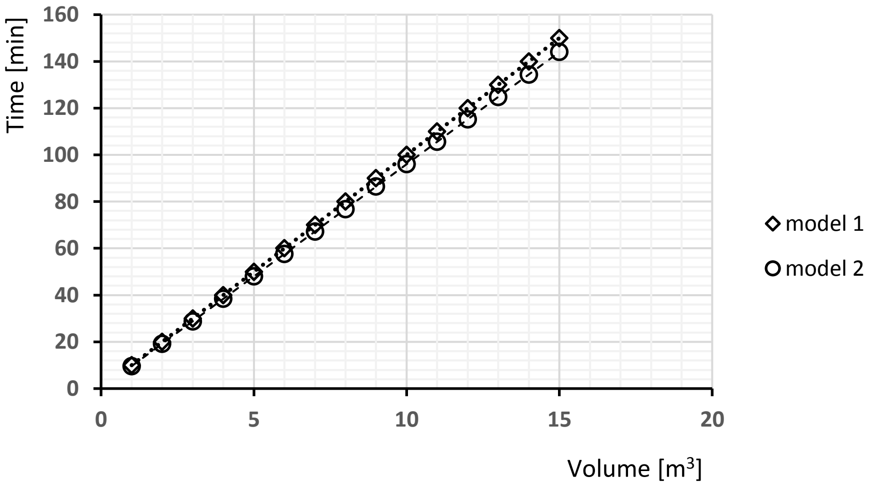

Fig. 3. The change of time remaining to the first ventilation in the function of changes in the volume of the decompression chamber ($\tau_1 = f(V_k)$) when $p = 200$ [kPa], p_{CO_2max} = 1,5 [kPa], p_0 = 100 [kPa], $\dot{V}_{O_2}$ = 0,00075 [m³], k = 2, x_1 = 0,0003 [mol/mol], C_{CO_2max}= 0,75 [%], C_{CO_2wyd} = 5[%],$\dot{V}_p$ = 15 [dm³/min] for $V_k \in (1 \div 15)$[m³] [own work]

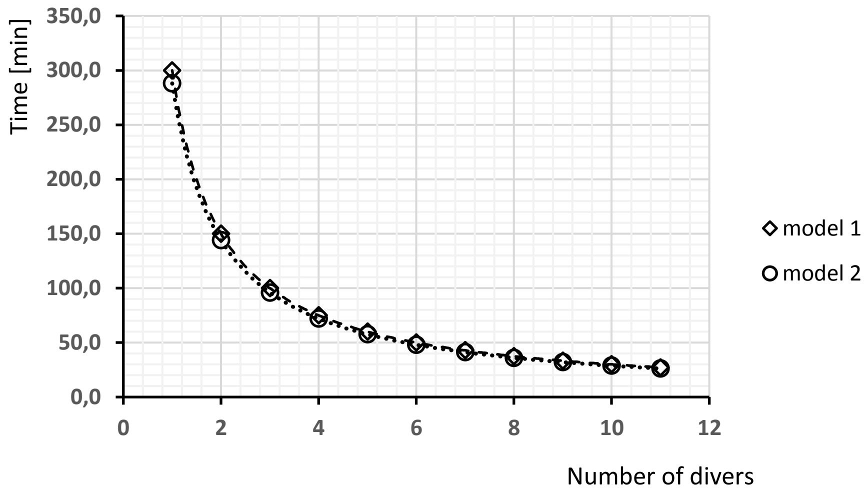

Fig. 4. The change of time remaining to the first ventilation in the function of changes in the number of divers in the decompression chamber ($\tau_1 = f(k)$) when $p = 200$ [kPa], p_{CO_2max} = 1,5 [kPa], p_0 = 100 [kPa], $\dot{V}_{O_2}$ = 0,00075 [m³], $V_k =$ = 3, x_1 = 0,0003 [mol/mol], C_{CO_2max}= 0,75 [%], C_{CO_2wyd} = 5[%], $\dot{V}_p$ = 15 [dm³/min] for [m³] $k \in (1 \div 11)$ [own work]

This follows directly from the fact that equation (2) allows for the initial state of atmosphere in the ventilated decompression chamber in the form of a molar fraction of carbon dioxide at the beginning of hyperbaric exposure in the chamber. The average time remaining to the first ventilation in the function of changes of chamber's volume is calculated with equation (2), and it is shorter than the time calculated with equation (1) by about 3 minutes. While with increasing volume of the chamber the differences increase reaching up to 6 minutes (fig. 3). In the case of the impact of changes in the number of divers the tendency is reversed, the average differences between time values calculated by equations (1) and (2) are also equal to approximately 3 minutes, but the largest differences occur with the smallest number of divers in the chamber (max. 12 minutes), which then decrease to about 1 minute with the maximum number of divers in the chamber (fig. 4).

Regardless of the demonstrated differences, both models have been employed in the Naval Forces of the Republic of Poland for years. However, model 2, which was developed with the advent of technical possibility of indirect measurements of carbon dioxide content in real time, is used more often, as it is safer in use. In addition, it indirectly contributed to the changes that took place in the construction of panels for monitoring the atmosphere of the decompression chamber on which systems for computerised analysis of atmosphere composition appeared. Model 1 is currently most frequently employed in the form of relationship (3) for a quick and approximate estimation of time remaining to the beginning of the first ventilation, which is later defined by equation (2).

REFERENCES

[1] Kłos R., *Matematyczne modele analityczne wentylacji obiektów hiperbarycznych*, 'Ergonomia', 1995, Issue 18, pp. 41–48 [Mathematical analytical models of ventilation in hyperbaric facilities — available in Polish].

[2] Kłos R., *Mathematical modelling of the normobaric and hyperbaric facilities ventilation*, PTMiTH Gdynia 2007.

[3] Kłos R., *Metodyka pomiaru składu mieszanin oddechowych w kompleksach hiperbarycznych*, PhD thesis, AMW, Gdynia 1990 [*Methodology of measuring the content of breathing mixes in hyperbaric complexes* — available in Polish].

[4] Krysicki W., Włodarski L., Analiza matematyczna w zadaniach PWN, Warszawa 1971 [*Mathematical analysis — problems* — available in Polish].

[5] Olejnik A., Wentylacja komory dekompresyjnej podczas powietrznych ekspozycji hiperbarycznych, PTMiTH Gdynia 2007 [*Decompression chamber ventilation during hyperbaric air exposures* — available in Polish].

[6] Olejnik A., *Metodyka wentylacji atmosfery komory dekompresyjnej podczas powietrznych ekspozycji hiperbarycznych*, PhD thesis, AMW, Gdynia 2004 [*Methodology of ventilating the atmosphere in the decompression chamber during air hyperbaric exposures* — available in Polish].

[7] *Prace podwodne*, praca zbiorowa, Wydawnictwo Morskie, Gdańsk 1971 [*Underwater works*, group work — available in Polish].

[8] Przylipiak M., Torbus J., Sprzęt i prace nurkowe — poradnik, PTMiTH, Gdynia 1981 [*Equipment and diving works — a handbook* — available in Polish].

[9] Talaśka Z., *Metoda ujednoradniania składu atmosfery oddechowej w komorze hiperbarycznej*, PhD thesis, AMW, Gdynia 1995 [*Methodology of homogenising the content of breathing atmosphere in the hyperbaric chamber* — available in Polish].

WPŁYW PARAMETRÓW POWIETRZNEJ EKSPOZYCJI HIPERBARYCZNEJ NA CZAS DO ROZPOCZĘCIA PIERWSZEJ WENTYLACJI KOMORY DEKOMPRESYJNEJ

STRESZCZENIE

W artykule przedstawiono analizę wpływu parametrów powietrznej ekspozycji hiperbarycznej na czas do rozpoczęcia pierwszej wentylacji liczony za pomocą dwóch modeli matematycznych. Badania przeprowadzono jako symulacje uwzględniające standardowe parametry ekspozycji. Wskazano różnice pomiędzy analizowanymi modelami i zdefiniowano, jaki jest wpływ zmian poszczególnych wielkości wejściowych analizowanych modeli na wartości wielkości wyjściowej.

Słowa kluczowe:
prace podwodne, komory dekompresyjne, inżynieria morska.