Hyperbaric swimming simulator

Ryszard Kłos[a]

The Naval Academy, 69 Smidowicza Str., 81-103 Gdynia, Poland

[a]skrzyn@wp.pl

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Abstract. *This paper contains hyperbaric test facility equipped with swimming simulator description dedicated to diving apparatuses decompression research. This stand has been constructed within two scientific projects financed from research funds from the Polish Ministry of Sciences and Higher Education in 2009-2012 and it was realised in the Naval Academy of Gdynia.*

Introduction

Introducing of the new diving apparatuses to service is a complex problem for the sake of safety considerations. In this case establishing adequate and efficient decompression procedure is the most important problem. Decompression research needs hyperbaric test laboratory for establishing the adequate joined mathematical model for ventilation of diving apparatus breathing space and human decompression [4,5].

One of the main problems is to adjust and control with required accuracy an adequate effort to simulate swimming in the diving apparatus. It is realised in different ways. Frequently, it is used different constructions underwater cyclometers, but pedalling effort is different from the diving workload. In this article there is described a different type of ergometer. It is connected plate to a strain gauge (extensometer) to which have been pushed by diver during finning.

Description of test facilities. A diver engaged in physical activity in the swimming pool of the hyperbaric complex, is secured by a safety diver – Fig. 1. Throughout the experiment, the diver uses the diving apparatus while under water – Fig. 1d. On the workstation, there is a computer on whose screen it is possible to display the commands and parameters of oxygen pressure and content in the breathing mixture but these functions can be turned off individually – Fig. 1c. On the computer desktop, there are three buttons for quick communication. To communicate with the diver, we can use a wired communication system or a loudspeaker located in water, to issue commands directly to the diver in the aquatic environment. In the computer box, there is a camera for observing the diver's face; there are also cameras showing the correct arrangement of the diver under water and a general view showing both divers in the chamber – Fig. 1f.

Before immersion, the safety diver connects the one part of the inhalation hose with a quick coupler. In this way, the breathing mixture inhaled by the diver is taken for analysis. The maximum intake of the breathing mixture is $\dot{V} < 1 cm^3 \cdot min^{-1}$ and is directed to oxygen and CO_2 monitoring system. The analyzers which are part of an automatic measuring system of the breathing mixture inhaled by the diver. Similar measuring systems can be found in every chamber if the DGKN-120 complex – Fig. 2b. The results of measurements carried out at workstations measuring the composition of the breathing mixture, strain gauge, maintained pressure, conducting phase decompression, and maintained partial pressure of oxygen are monitored. The data is archived on any computer available in the measurement network of the DGKN-120 complex. All the systems are supervised by integrated software that can run on any of the Ethernet measurement network computer.

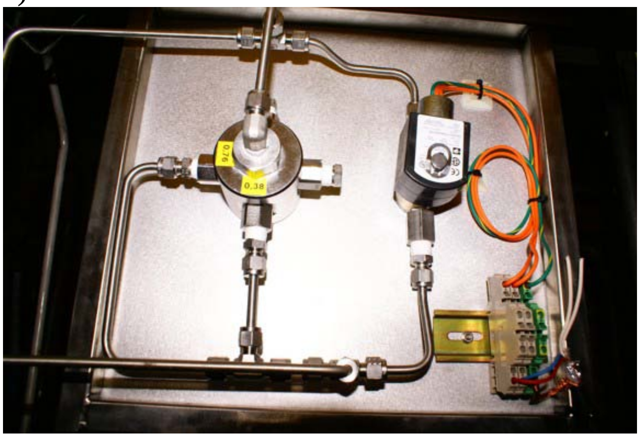
The DGKN–120 is also equipped with an automatic device for maintaining constant pressure, automatically conducting decompression, and maintaining permanent partial pressure of oxygen in the atmosphere of the hyperbaric chamber – Fig. 2c-d.

Fig. 1. Experimental Deepwater Diving Complex type DGKN–120 a) divers in the water chamber of the complex, preparing to dive b) a diver ready to dive c) computer with some indexes for the diver d) a diver on an ergometer e) DGKN-120 complex seen from above f) a system of observation and supervision of the experiment

a)

b)

c)



d)

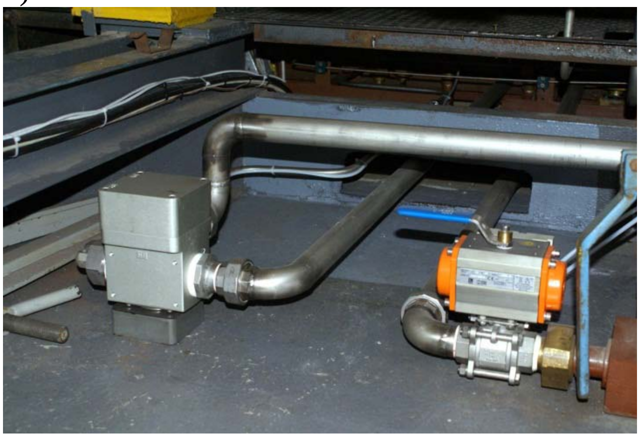


Fig. 2. Experimental Deepwater Diving Complex type DGKN–120 a) a view of the living chamber from the transition chamber b) an automatic system for measuring the composition of the atmosphere of the DZWONIEC and PRZEJSCIOWA chambers c) nozzle system for automatic oxygen dispensing into the DZWONIEC chamber's air d) an actuator of the automatic pressure maintenance system and the process of decompression (left)

While staying underwater, the working diver performs a simulation of swimming with flippers on while pushing a vertical plate connected to a strain gauge. The safety diver only protects the working diver, without performing any other tasks – Fig. 1c-d.

The safety diver, while underwater, can breathe air from the atmosphere or gas mixtures/oxygen from the built in breathing system equipped with a half-mask with an exhaust-driven system maintaining proper pressure difference outside the chamber. The length of hose allows the diver to move across the chamber.

If the safety diver breathed air from the chamber, he or she must be replaced before the start of decompression by another safety diver, because his or her decompression distribution will differ from the working diver's decompression due to different oxygen content in the inhaled breathing mixture. After replacing the divers, the first safety diver undergoes decompression in a separated chamber of the DGKN–120 complex with the possibility of employing oxygen decompression – Fig. 2a. The second safety diver undergoes decompression along with the working diver. The moment of the exchange must be carefully thought out by the person in charge of the dive so that this procedure is safe and convenient for the experiment.

Replacing the divers under pressure is possible, since all the chambers in the DGKN−120 complex may operate independently and have different pressures inside them. Each chamber of the DGKN−120 complex has two hatches and the space between them can be independently evacuated to atmospheric pressure or connected with the adjacent chamber to offset the pressure – Fig. 1e.

After decompression, experimental diver goes quickly to the living chamber, where he is examined to check the presence of intravascular free gas phase [3].

After the research is finished, the diver is kept under observation for at least 2–3 hours since the end of decompression, provided it is not noticed intravascular phase of free gas. If such a signal is recorded, the observation time is extended to 2 hours, counting from the moment the signal from the intravascular free gas phase fades out [3].

Method

Dimensional analysis. Dimensional analysis was used to establish function between exertion on a bearing plate and speed of swimming. Dimensional analysis is a method used for planning experiments and is a tool to find or check relations among physical quantities by using their dimensions. It based on similarity theory that determined the relationship between the physical parameters affecting the studied phenomenon and determining conditions under which physical phenomena are similar.

Any system or process within the system is characterized by many parameters. If some of them are correlated, it is possible to identify the system/process by a smaller number or a single parameter, based on the original features, among which there are strong ties.

Two phenomena are similar when some dimensionless units of physical parameters characterizing these phenomena are both equal. These dimensionless parameters are called modules, numbers of criteria Φ [2].

When determining a mathematical system model or defining a process taking place within it proves to be too complicated, common practice involves applying similitude models for such a determination and adjustment based on experiments, usually conducted according to a reduced scale.

The state of systems or processes occurring within them is influenced by a large number of parameters. Determining relations between those parameters is often quite laborious or impossible. The relationship between two examined variables may be modelled with the use of one curve. With three variables it is possible to plot a spatial graph, although in the majority of cases it appears to be unclear. Hence, such a dependency is often depicted as a bunch of curves dependent of one variable when the other parameters are fixed. Any further increase in the number of variables makes direct observation very difficult. If physical parameters of a tested system or the process taking place within it are grouped into dimensionless similitude modules Φ, the problem situation becomes simplified and the relations between the modules are easier to determine. Also a change in the numerical value of a similitude module may require only a change of one parameter of that module, which allows further simplification of the conducted tests. Therefore, *Similitude Theory* combined with proper *Design of Experiments* methods constitutes the basis for rational experimenting.

For a general algebraic mathematical model of a physical system expressed as a function: $f(\Theta_1..\Theta_2)=0$ can be described as a power function: $\{\sum C\cdot\Theta_1^{n_1}\cdot\cdot\Theta_k^{n_k}\mid C,n_i=const\}=0$. In the majority of technical problem situations it is permissible to omit less significant multipliers of this series, thus the equation may be expressed as follows: $C\cdot\Theta_1^{n_1}\cdot\cdot\Theta_k^{n_k}\cong 0$. The values of model variables are then replaced with dimensions, and next exponent equation systems are formulated for particular basic units and their values are defined. By grouping physical quantities of identical exponents we may obtain a criterial equation consisting of dimensionless numbers Φ, whose quantity is determined by *Bugingham theorem* [1].

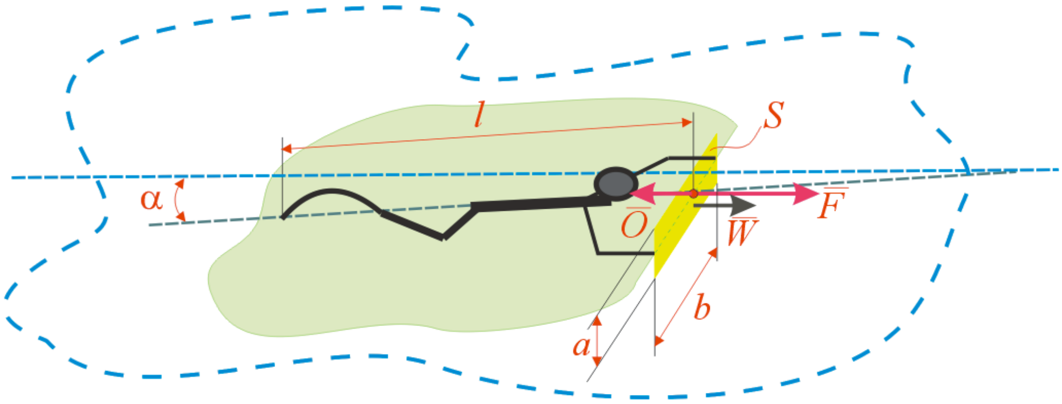


Fig.3. Force distribution during the diver's movement under water

The content of *Bugingham theorem* stems from an analysis of an algebraic mathematical model for a selected problem situation: a general analytic mathematical model binding k with the dimensions expressed in the units of the adopted physical unit with the help of basic dimensions l of the applied physical unit, may be expressed in the form of $k-l$ of dimensionless numbers Φ constituting a criterion of a similarity of phenomena [7].

Effort simulation. The diver's swimming position is maintained mainly through progressive movement; therefore his silhouette may be treated similarly to hydrofoil hull. When determining a simplified geometric shape of the border plane, at the first approximation it is necessary to assume that the diver's body length l constitutes a characteristic dimension in a swimming position where the arms are stretched forward and the fins are stretched backward. Substitute frontal resistance can be modelled as a plate with the area equivalent to the diver's cross-section $S = a \cdot b$. Hence, it may be assumed that the diver's silhouette has been replaced with a cuboidal box into which his body would fit completely – Fig. 3.

In the presented problem situation it was assumed that the diver's forward movement is parallel to a fixed plane constituting an approximate surface of a free surface of water. The diver's silhouette modelled with the cuboid produces an angle α in relation to the water surface, which also determines the direction of velocity vector $\overline{\upsilon}$ $\bar{\upsilon}$of the diver swimming underwater. The impact force generated by the diver with fins $\overline{F}$ works in the same direction and turns consistent with the velocity vector $\overline{\upsilon}$. The resistance force of the aquatic environment $\overline{O}$ is oriented to the opposite direction. Both forces constitute the resultant force $\overline{W} = \overline{F} - \overline{O}$ causing the diver's accelerated movement. When the forces counterbalance $\overline{F} = -\overline{O}$ the diver begins to move at a constant speed.

It is reasonable to assume water incompressibility for the established conditions, hence its density ρ remains unchanged $\rho = idem$. As it is known by experience, the distribution of pressures on the surface of the diver's body and the water resultant forces having an impact on the diver's body depend on the level of disturbance of water movement, thus they should depend on *Reynolds' number* $Re = \frac{\upsilon \cdot l \cdot \rho}{\eta}$, where η stands for dynamic viscosity.

According to the conducted analysis could be identified a set of eight variables which have an impact on the diver's movement in the defined swimming position underwater: W – resultant force, l – linear dimension constituting the length of the diver's silhouette, S – a replacement surface equivalent to the diver's cross-section producing frontal resistance during his movement, υ – velocity, α – diver's silhouette angle, ρ – water density, ρ – dynamic viscosity, Re – *Reynolds' number*, which may be limited to six items: W, S, υ, α, ρ, Re, providing for the dynamic viscosity η and the diver's body length l within the value of *Reynolds' number* Re.

The angle α and *Reynolds' number* are dimensionless variables and so they can be included in an unknown function of mechanical dimensionless quantities connected with movement in a liquid $f(Re,\alpha)$, which allows further reduction of the number of variables to five. According to the principles applied in the dimensional analysis it is possible to propose a final algebraic mathematical model as a following product: $const = f(Re,\alpha) = W^a \cdot S^b \cdot \upsilon^c \cdot \rho^d$. By replacing the variables with general dimensions constituting basic dimensions of the applied physical unit: $[W] = M \cdot L \cdot T^{-2}$, $[S] = L^2$, $[\upsilon] = L \cdot T^{-1}$, $[\rho] = M \cdot L^{-3}$, where: $M -$ mass dimension, $L -$ length dimension, $T -$ time dimension, the criteria for the model dimension calculation could be written as:

$$const = f(Re,\alpha) = M^a \cdot L^a \cdot T^{-2 \cdot a} \cdot L^{2 \cdot b} \cdot L^c \cdot T^c \cdot M^c \cdot L^{-3 \cdot c} \tag{1}$$

where: $a..d -$ numerical coefficients, $M -$ mass dimension, $L -$ length dimension, $T -$ time dimension, thus:

$$\begin{aligned} a + 2 \cdot b + c - 3 \cdot d = 0 & \qquad b = -a \\ a + d = 0 \;\Rightarrow & \;\; d = -a \\ -2 \cdot a - c = 0 & \qquad c = -2 \cdot a \end{aligned}$$

Taking for consideration the solution of the equation Eq. 1 for modelling process a given problem situation it is possible to write an approximate mathematical model in the algebraic form of the following product:

$$f(Re,\alpha) = W^a \cdot S^{-a} \cdot \upsilon^{-2 \cdot a} \cdot \rho^{-a} \tag{2}$$

where: $W -$ resultant force, $S -$ a replacement surface equivalent to the diver's cross-section producing frontal resistance during his movement, $\upsilon -$ velocity, $\alpha -$ diver's silhouette angle, $\rho -$ water density, $Re -$ *Reynolds' number*

After reduction and rearranging, the equation Eq. 2 may be transformed into:

$$W = \rho \cdot S \cdot \upsilon^2 \cdot f(Re,\alpha) \tag{3}$$

In the future experiments, it could be assumed that the angle α is not large and the function $f(Re,\alpha)$ which including system parameters $C_p = \dfrac{W}{\rho \cdot S \cdot \upsilon^2}$, could be treated as dimensionless no changing coefficient C_p: $W = C_p(Re) \cdot \dfrac{\rho \cdot \upsilon^2}{2} \cdot S$. The coefficient C_p is a function of the *Reynolds' number* Re: $C_p = f(Re)$.

Results

Assuming that the diver's with the rebreather together frontal resistance R may in the first approximation be replaced with a square horizontal plate with the frontal area of $S \cong 0.216\,m^2$, then using the model Eq. 3 for $C_p = idem$, the approximate frontal resistance R may be expressed as:

$$R \equiv W \cong C_p \cdot \frac{\rho \cdot \upsilon^2}{2} \cdot S \tag{4}$$

where: $R -$ impact force on the strain gauge plate exerted by a swimming diver [N], $C_p -$ a dimensionless resistance coefficient for the square horizontal plate $C_p = idem = 1.1$ (Troskalański A.T., 1954) [1], $\rho -$ water density, due to the approximate character of calculations the adopted value of water density is the density of distilled water $\rho = 1000\,kg \cdot m^{-3}$ [$kg \cdot m^{-3}$], υ – diver's speed [$m \cdot s^{-1}$].

Using the interrelation Eq. 4 it is possible to estimate the speed of swimming υ in a function of the diver's impact R measured with a strain gauge – Fig. 4.

Discussion

The calculations resulting from a dimensional analysis have been initially verified in experiments by comparing them with the results obtained during dives in a swimming pool of the length of 200 m. This swimming pool was created for model vessels in reduced-scale on their hulls testing. It is equipped with a platform bridge moving at a precisely assigned speed. The experiment consisted in divers following the platform while maintaining the same distance. Divers were equipped with heart and breathing monitors. The conformity was observed between results received from swimming pool tests in compared to monitoring of the same physiological parameters for the same divers who have performed effort with use the hyperbaric ergometer. The same compliance was obtained when juxtaposing the effort with the measured oxygen consumption during the diver's work at the hyperbaric ergometer. It appears that the proposed new method of simulating the diving effort is more appropriate in relation to real conditions as compared to using underwater cycloergometers for this purpose.

Further tests on determining accuracy of effort measurements would be interesting from the scientific point of view, however the hyperbaric ergometer may be used for research even without them. For instance, a cycle of implementation tests for diving apparatuses was carried out by taking only relative measurements of the divers' workload and referring them to oxygen consumption measurements, and then juxtaposing those values with the previously tested mathematical models concerning ventilation of the breathing space of a rebreather [4]. The results showed a surprising compliance [5,6], as such a high degree of conformity is not usually encountered in the complicated bio-technical systems such as the rebreather-diver system.

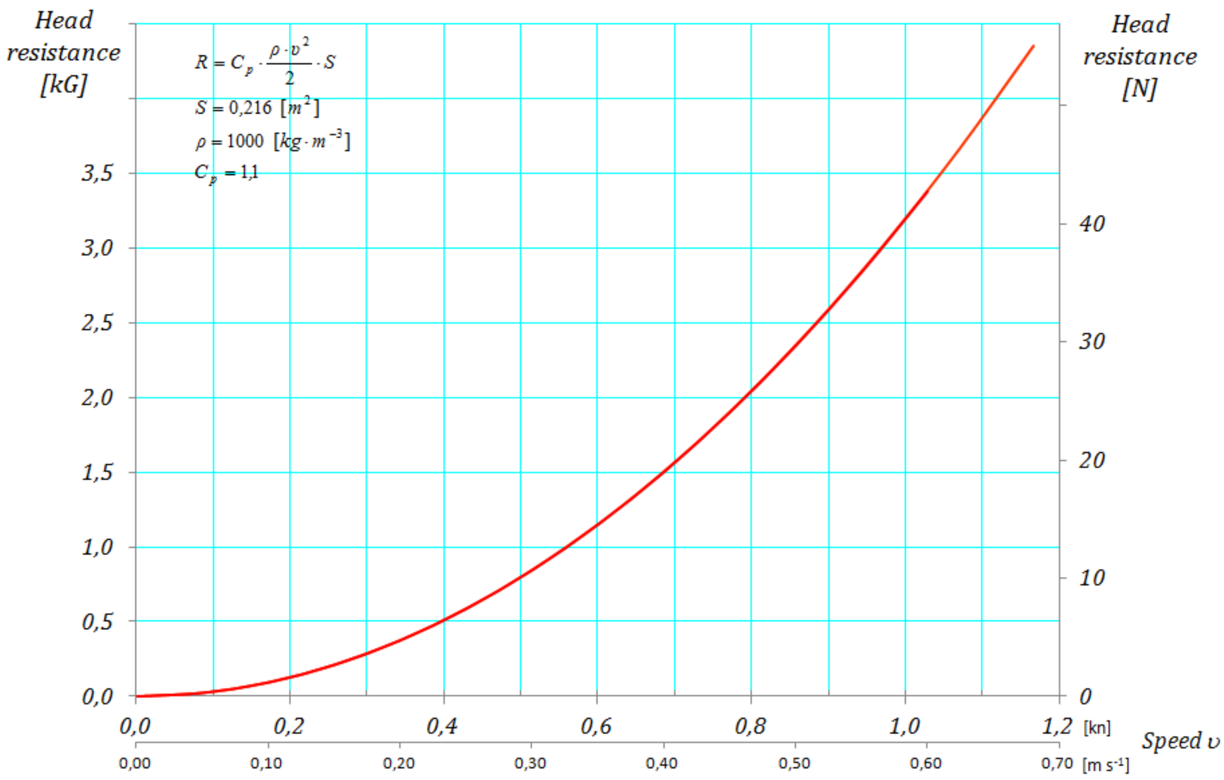


Fig. 4. The press force on ergometer bearing plate treats as equivalent of swimming diver's head resistance in function of diver's speed

Conclusions

Taking into account a high individual and temporal changeability of the biological conditions, e.g. the current level of training of a diver, from the practical point of view, further research on precise determination and validation of the impact function exerted by a diver on a plate in relation to the speed of swimming is not required.

The proposed method seems to be sufficient for conducting tests on diving apparatuses. The proposed construction of hyperbaric ergometer also has the advantage of not being located in a hyperbaric chamber completely filled with water as it is often the case in similar facilities in the world. This provides the possibility of an immediate exchange of a breathing mixture in an emergency situation, as it is enough if a diver rises to a kneeling position and removes the mouthpiece from his mouth. Also, the assistance of a safety diver is more reliable in situations when an experimental diver requires instant help.

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