POLISH HYPERBARIC RESEARCH 3(80)2022
Journal of Polish Hyperbaric Medicine and Technology Society

EVALUATION OF THE EFFECT OF NOZZLE DIAMETER ON THE BREATHING PERFORMANCE OF A DIVING BREATHING APPARATUS

Mateusz Banach, Zbigniew Talaśka

Department of Underwater Works Technology Naval Academy of Gdynia, Poland

ABSTRACT

The article was inspired by information in the literature regarding damage to medium-pressure diving hoses, which, as a result of the crystallisation of material on their inner surface and the detachment of particles, caused significant interference with the output of the pressure regulator. A dangerous consequent 'clogging' of the airflow in stage II of the breathing apparatus and an increase in the effort in the diver's lungs to overcome the increased breathing resistance resulted. This problem was investigated in the paper. Nozzles with reduced diameters were fabricated to simulate the deterioration of the automaton conditions. A suitably selected regulator from a domestic manufacturer's was used for the tests. A series of measurements was carried out in a breathing simulator for the established experimental conditions specified in the standard PN-EN 250:2014. Following the test, the results obtained were analysed and interpreted based on statistical description methods.
Keywords: mechanical engineering, diving technology operation, diving breathing equipment.

ARTICLE INFO

PolHypRes 2022 Vol. 80 Issue 3 pp. 39 – 60
ISSN: 1734-7009 **eISSN:** 2084-0535
DOI: 10.2478/phr-2022-0015
Pages: 16, figures: 18, tables: 0
page www of the periodical: www.phr.net.pl

Publisher
Polish Hyperbaric Medicine and Technology Society

Review article

Submission date: 09.02.2022 r.
Acceptance for print: 14.03.2022 r.

INTRODUCTION

The operation of diving equipment is inevitably associated with the occurrence of a wide range of events caused by the natural wear and tear and ageing of technical objects, as well as the occurrence of unforeseen emergency situations. The authors' attention was drawn to an article published by the Divers Alert Network Europe (DAN) [1], entitled "Invisible crystals and regulator failures." The international diving community was informed that the underlying cause of one of the diving accidents was degradation of the internal part of a medium pressure diving hose. This consisted of the precipitation of small crystals from the interior lagging of the hose. During the dive, the crystals moved towards the second stage of the regulator causing "clogging" disrupting the supply of breathing gas from the diving cylinder to the diver's mouth. As a result, there was a significant disruption to the dive which, thanks to the diver's good training, did not end in a serious accident. From the content of the article, it was clear that this was not an isolated incident.

Figure 1 illustrates the result of crystallisation of the inner lagging material of a medium-pressure diving hose connecting the components of an open-circuit breathing apparatus.

a) b) c)

Fig. 1 Example of crystallisation of structural material, flexible diving hose and result of clogging of the flow of breathing gas in the second stage of an open-circuit diving breathing apparatus [1,2].

RESEARCH PROBLEM

The effect of the occurrence of polymorphous crystallisation of the material used in the production of diving, flexible breathing apparatus hoses, and the unidirectional movement of the particles formed, is to reduce the nozzle clearance of the choke valve in the second stage. The result is an increase in the work output of the diver's lungs required to overcome increasing breathing resistances.

The information contained in the analysed literature led to the idea of reproducing the described situation under laboratory conditions. It was decided that a mapping of the "clogging" of the nozzle diameter cross-section in the co-operating throttling (reduction) valve of the second stage of the breathing apparatus could be achieved by using several nozzles with decreasing cross-sections.

It was assumed that the research problem would be to quantify the range of changes in the work of breathing that a diver would have to perform during use of the device in the event of an airflow disturbance through the nozzle.

In order to obtain an answer to the task thus defined, it was decided to carry out an experiment involving the following stages:

1. random selection of the components of a specific type of diving breathing apparatus from those in service at KTPP;
2. execution of additional nozzles with decreasing diameters;
3. subjecting them to a check of their technical and operational parameters on the basis of bench tests;
4. making the necessary adjustments;
5. preparation of the breathing simulator for testing and carrying out a check of its measurement system in accordance with the provisions of PN-EN 250:2014;
6. assembly of the breathing apparatus from the previously selected components and, on its basis, creation of agreed measurement groups in which the nozzles in the second-stage regulator's concurrent choke (reduction) valve will be replaced;
7. defining the experimental conditions and carrying out a series of measurements of the breathing operation in a breathing simulator;
8. analysis and interpretation of the test results obtained.

RESEARCH SUBJECT

It was agreed that a device from a Polish manufacturer would be used in the experiment. In terms of design, it was a split-stage, open-circuit breathing apparatus, supplied with air from a diving cylinder and allowing diving to a depth of 50 mH2O. In preparation for the bench tests, the components of the breathing apparatus with the best technical and operational parameters were selected. The breathing apparatus consisted of :

1) a first pressure-reducing stage with a pressure-

relieving valve plug operating on the overflow piston principle with a pressure-reducing range of 20 MPa to approx. 0.95 MPa (so-called reduced pressure);
2) a second stage with a simple, standard design and a coaxial pressure-reduction system without knobs for additional adjustment of the breathing parameters;
3) a flexible medium-pressure hose.

Figure 2 shows the components of the breathing apparatus selected for testing.

a) b)

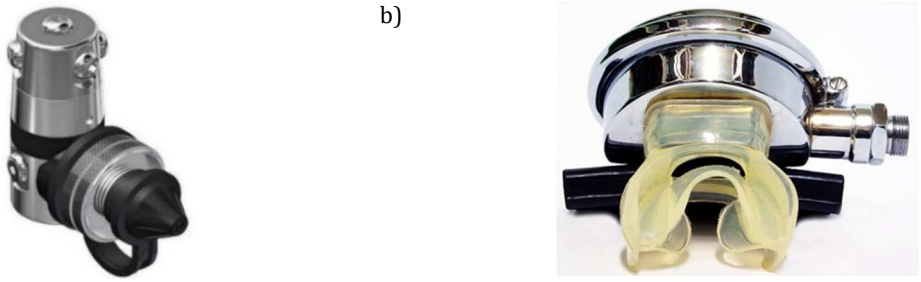

Fig. 2 Basic components of the breathing machine used in the experiment : a) first reduction stage, (b) second reduction stage.

FIRST PRESSURE REDUCTION STAGE OF THE BREATHING APPARATUS

In the first stage of preparation for the study, six units of first pressure reducing stages were randomly selected from those currently in use at the KTPP.

Fig. 3 shows the randomly selected first pressure reducing stages of the breathing apparatuses of the selected manufacturer.

Fig. 3 Randomly selected first stage reduction units selected for testing the breathing apparatus.

It was assumed that their technical condition and performance parameters were unknown, as a result of their use. By design, these regulators are not user-adjustable. Therefore, the criterion for verifying the correctness of their operation was to be a bench measurement of the reduced pressure, carried out under normobaric pressure conditions. The manufacturer's recommendation is that this pressure should be approx. 0.95 MPa. The manufacturer has specified a usable pressure range of 0.9 - 1.0 MPa.

Six randomly selected first reduction stages were subjected to a test to check the value of the reduced pressure on the bench, as shown in Fig. 4.

a) b)

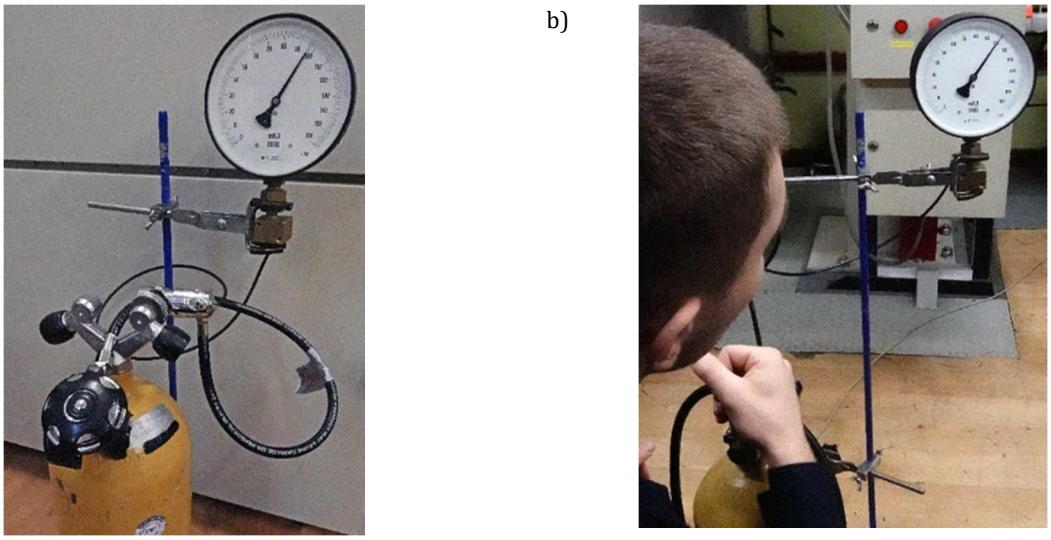

Fig. 4 Reduced pressure measuring station: (a) diving cylinder with a valve and the first stage of the regulator attached, and a board pressure gauge connected with the high pressure port, b) operator taking the measurement.

Fig. 5 presents graphically the results of tests to check the performance of the first stage regulators of the breathing apparatus prior to adjustment.

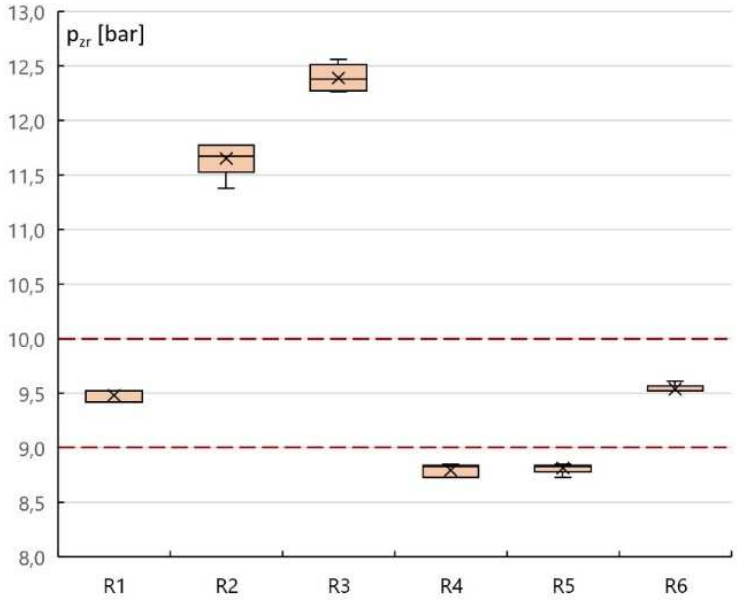

Fig. 5 Graphic representation of test results verifying the operation of the regulators of the first stage of the breathing apparatus prior to adjustment.

Examination of an important technical and operational parameter - the reduced pressure - showed that of the six first reduction stages randomly selected from service, only two were within the range required by the pro-ducer. The others failed to meet this requirement.

In the next stage of preparation for the tests, it was assumed that randomly selected first stage regulators would be subjected to adjustment. These activities were entrusted to an experienced diving equipment mechanic with the appropriate qualifications. The regulated parameter was the reduced pressure.

The results of the reduced pressure after the adjustment procedure are graphically presented in Fig. 6.

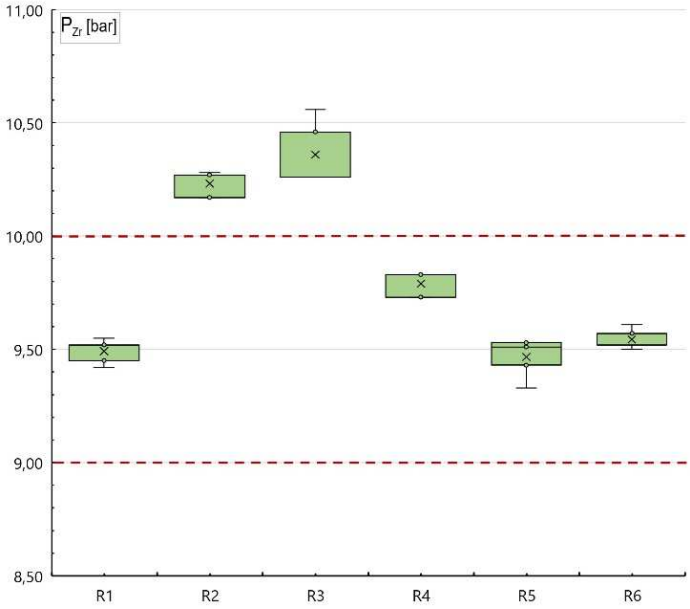

Fig. 6 Graphic representation of results of reduced pressure tests of the first stages of the breathing apparatus following adjustment.

Based on their analysis, it was concluded that the best technical and operating parameters were characterised by the regulator labelled R6. Ultimately, it was decided that this regulator, as part of the kit, would be used to carry out the experiment.

SECOND STAGE OF BREATHING APPARATUS

Three second stages of a breathing apparatus from a selected manufacturer were randomly selected from those currently in use at the KTPP.

Fig. 7 shows randomly selected units of the second stages of the breathing apparatus.

Fig. 7 Randomly selected second-stage units of a selected breathing apparatus.

It was decided that the form of selection of one second-stage device would be to measure the negative pressure value of inhalation. Verification of this technical and functional parameter was carried out using a measuring set consisting of an electronic differential pressure sensor connected to its mouthpiece. The manufacturer's preferred range of inhalation negative pressure values was up to 25 mmH2O. The measured values were then read out in a computer programme operating the measurement system of the breathing simulator.

Fig. 8 shows the set-up for measuring the negative pressure of inhalation in the second stage of the breathing apparatus.

a) b)

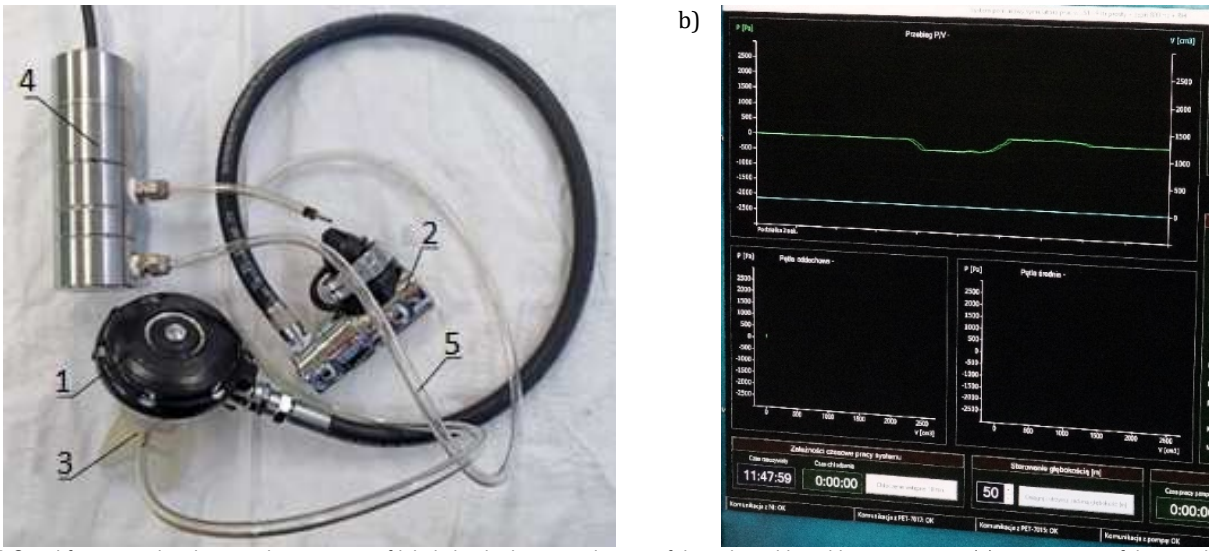

Fig. 8 Stand for measuring the negative pressure of inhalation in the second stage of the selected breathing apparatus : (a) components of the stand: 1 - second stage, 2 - first stage, 3 - mouthpiece adapted to measure negative pressure of inhalation 4 - electronic differential pressure sensor, 5 - flexible connection tube; (b) example measurement - the course of negative pressure of inhalation.

The compiled measurement results are presented graphically in Figure 9.

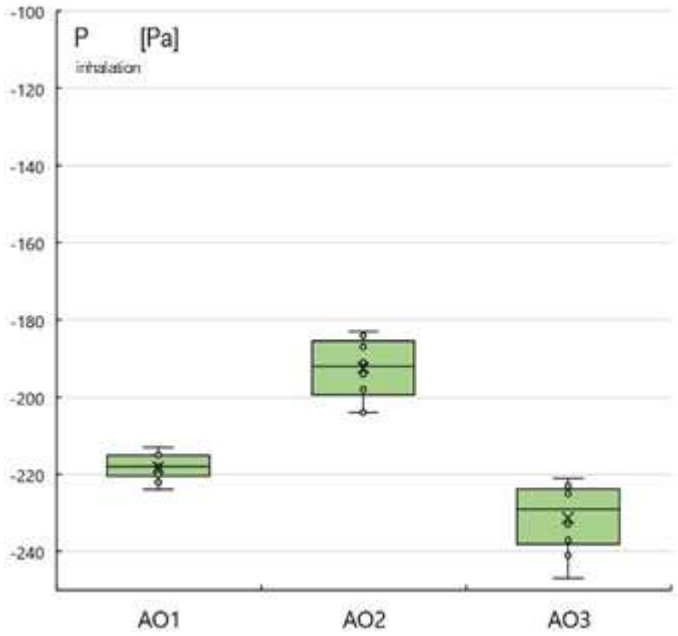

Fig. 9 Graphical representation of the results of the inhalation negative pressure test in the second stage of the selected breathing apparatus.

On the basis of their analysis, it was concluded that the second stage, marked AO1, was characterised by the best technical and operational parameters. It was decided to use this specimen for the experiment.

STAGE II PRESSURE REDUCING VALVE NOZZLES OF BREATHING APPARATUS

A necessary element for the experiment was the fabrication of additional nozzles for the concurrent reduction valve of the second stage of the breathing apparatus. The manufacturer assembles the nozzle in the valve body, part of which protrudes outside the housing of the so-called can. The dimension of the original nozzle diameter was: (Ø 4,5 ±0,01) mm. During comparative tests with other manufacturers, it was found that in similar designs of second stage breathing apparatus, the nozzle diameters were within the range (Ø 4,0 – 4,6 ±0,01) mm.

Fig. 10 illustrates the nozzle of a pressure-reducing valve fitted to the second stage of a selected breathing apparatus.

a) b)

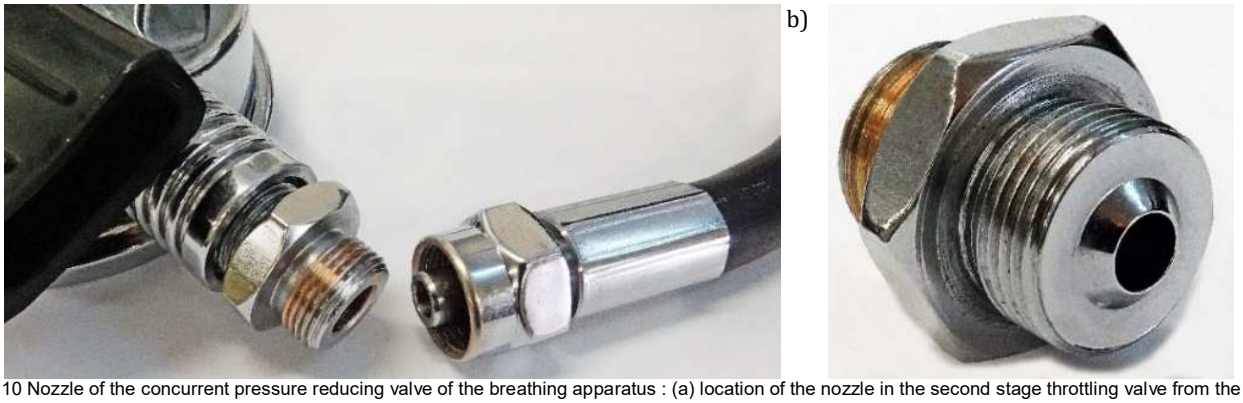

Fig. 10 Nozzle of the concurrent pressure reducing valve of the breathing apparatus : (a) location of the nozzle in the second stage throttling valve from the housing side; (b) appearance of the original nozzle from the contact side of the movable plug cutting off the flow of breathing gas.

It was considered that two additional nozzles with diameters: (Ø 4,0 ±0,01) mm and (Ø 3,5 ±0,01) mm would be fabricated to reproduce similar 'clogging' conditions, i.e. to reduce the breathing gas flow clearance caused by crystals. The nozzles are designed based on the dimensions of the original nozzle.

Fig. 11 shows the fabricated additional nozzles for the second stage of the breathing apparatus.

Fig. 11 View of additionally fabricated nozzles for the concurrent pressure relief valve of the second stage of the breathing apparatus.

TEST BENCH

The implementation of the experimental tests, on the selected type of breathing apparatus, required the use of a test bench i.e. a breathing simulator. Its configuration made it possible to carry out measurements of breathing work within the range of points defined in the PN-EN 250:2014 standard.

It consisted of the following components:

- a pressure chamber with a lid with a permissible working pressure of 2 MPa,
- a system for lifting the upper lid to close the pressure vessel,
- a breathing action simulator - breathing pump - including drive,
- control and manoeuvring console, consisting of: gas supply system for the chamber, measuring systems with sensors, computer with software for recording measured parameters in real time.

Fig. 12 illustrates the test bench, i.e. a breathing simulator.

Fig. 12 Test bench – a breathing simulator.

The pressure chamber made it possible to simulate the ambient conditions prevailing at a specific depth. It integrates all the components that work with it into a single unit, thus enabling measurements to be made of important technical and operational parameters of diving equipment in varying conditions of the aquatic environment.

The respiratory action simulator (respiratory pump) was the second most important component of the test bench. Its primary task was to imitate the human respiratory process as closely as possible to real breathing conditions. Measurement of the volume of respiratory gas pumped through the simulator, combined with measurement of changes in breathing pressure, allowed determination of the respiratory work a diver would be doing while breathing through a specific breathing device.

The realisation of the study, in accordance with the adopted objective, required appropriate steps to check the measurement system of the breathing simulator for correct recording of the results of the breathing work tests, in accordance with the requirements of EN 250:2014.

The instruments used during testing, which measure the required parameters, form a specific measurement system for the test bench. Its precision of indications directly affects the quality of the test results obtained [3]. This means that a properly functioning measuring system should ensure obtaining the best possible results after determining and eliminating errors generated in such categories as accuracy, repeatability, reproducibility, stability, linearity.

The instruments used during testing, which measure the required parameters, form a specific measurement system for the test bench. The precision of its indications directly affects the quality of the test results obtained [3]. This means that a properly functioning measuring system should ensure obtaining the best possible results after determining and eliminating errors generated in such categories as accuracy, repeatability, reproducibility, stability, linearity [4]. The breathing simulator prepared for use, together with a professional staff of operators, met all the requirements imposed by the PN-EN 250:2014 standard.

For testing, we adopted the provision of the standard para. 6.6.2., which specifies the general conditions of tolerance for the measurements to be made by giving a specific value [5, quote]:

„If not otherwise specified, the values should be within an error limit (deviation) of ± 5 %. If not otherwise specified, the temperature in the test room should be (24 ± 8) °C and the relative humidity at least 50 %. Temperature deviations for which no tolerance is specified should be ± 3 °C."

Furthermore, according to para. 6.2.4 of that standard, the test bench should provide the following conditions [5, quote]:

„The performance characteristics of the breathing simulation test equipment should be verified by using a calibrated orifice tester (...). The calibrated orifice tester should be inserted into the equipment under test in place of the breathing system (breathing apparatus) and the simulated breathing test equipment should be tested using air at 62.5 L/min (25 cycles/min, 2.5 L/(stroke)) at an absolute pressure of 6 bar. The recorded WOB (work of breathing) should be 3.3 J/l, the recorded inspiratory pressure should be -25 mbar and the recorded expiratory pressure should be +25 mbar."

According to the above, orifice-measured values of the work of breathing under norm-compliant conditions should be between the two limits: an upper limit of 3.465 J/l and a lower limit of 3.135 J/l.

Figure 13 shows the calibration nozzle and its mounting on the test bench.

Based on the procedures used at KTPP for checking the measurement system of the breathing simulator, a profile of its performance was adopted, as presented in Fig. 14.

The developed results of the measurement series are presented graphically in Fig. 15.

On the basis of the results obtained, it was concluded that the breathing simulator measurement system met the conditions set out in the above-mentioned standard and could be used to carry out the measurements in the experiment in question.

a) b)

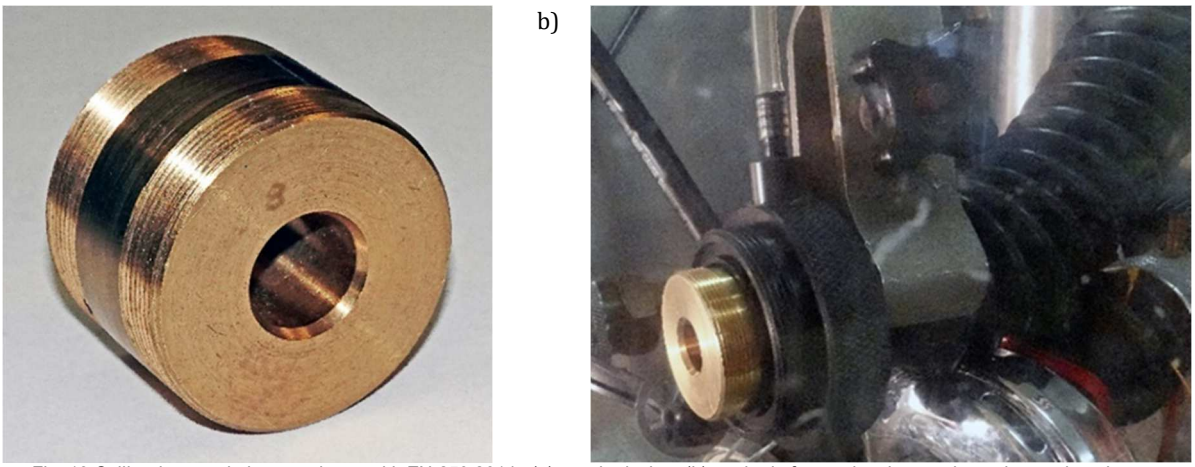

Fig. 13 Calibration nozzle in accordance with EN 250:2014 : (a) nozzle design, (b) method of mounting the nozzle on the test bench.

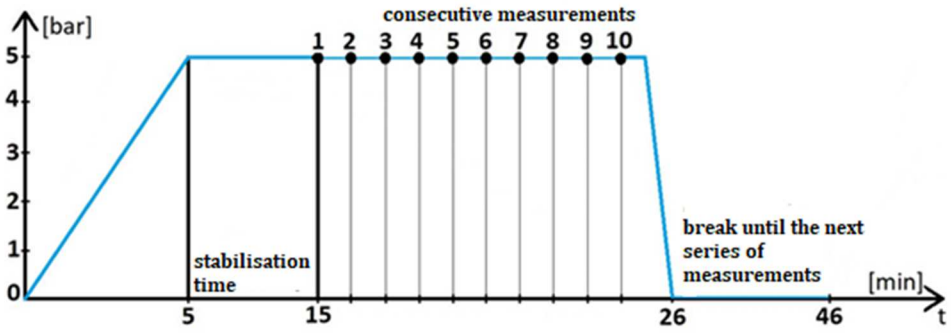

Fig. 14 Graphical progression of one profile (Pi) of the breathing simulator measurement system check with the calibration nozzle.

Fig. 15 Graphical representation of the results of checking the breathing simulator measurement system with the calibration nozzle.

RESEARCH

As a result of selecting the best components, one breathing apparatus was assembled from randomly selected specimens. As intended, before each successive series of measurements, the nozzle in the second stage pressure-reducing valve was replaced.

Fig. 16 shows the positioning of the breathing apparatus in the breathing simulator.

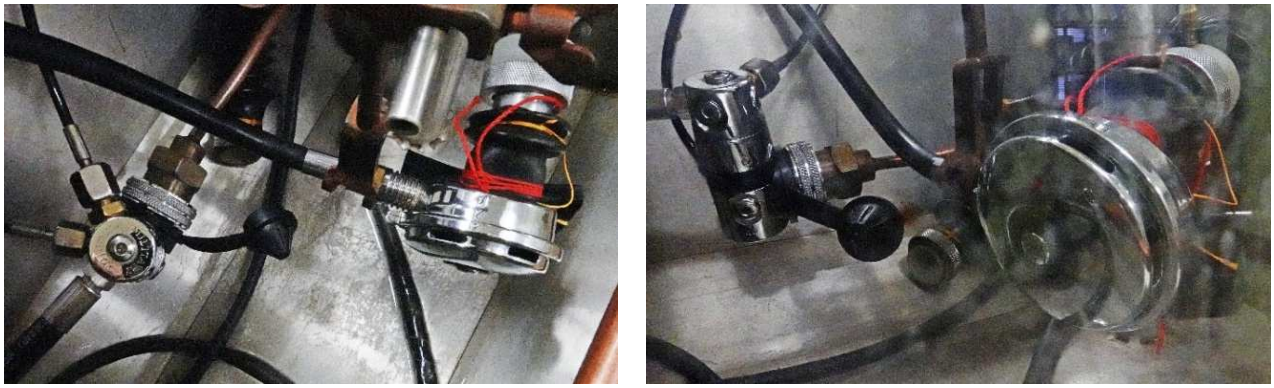

Fig. 16 Method of inserting a breathing apparatus into a breathing simulator.

The tests resulted in three series of measurements (Gi), the results of which are presented graphically in Figure 17.

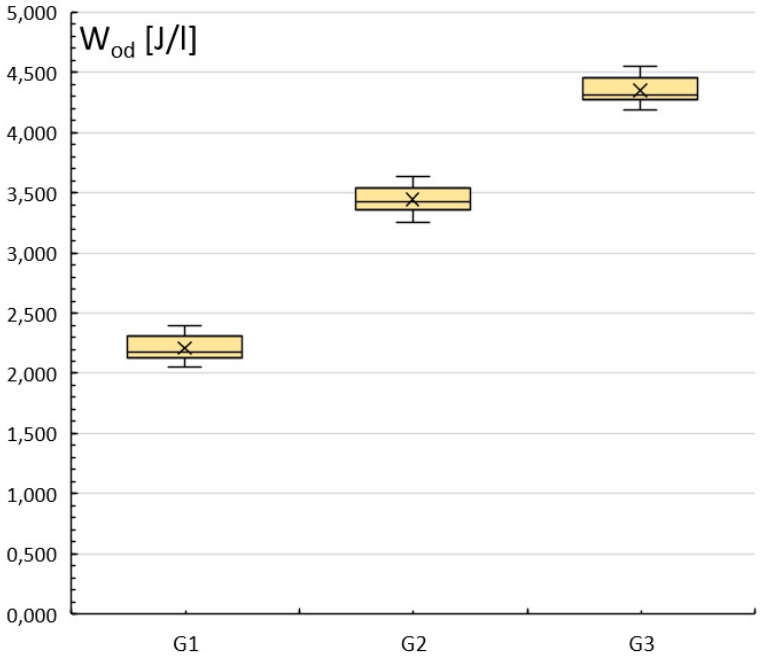

Fig. 17 Graphical representation of the results of the tests of the work of breathing in the three comparative groups.

Fig. 18 shows an example of a breathing loop for an automatic breathing apparatus with a nozzle with the dimension of (Ø 3,5 ± 0,01) mm installed in the second stage.

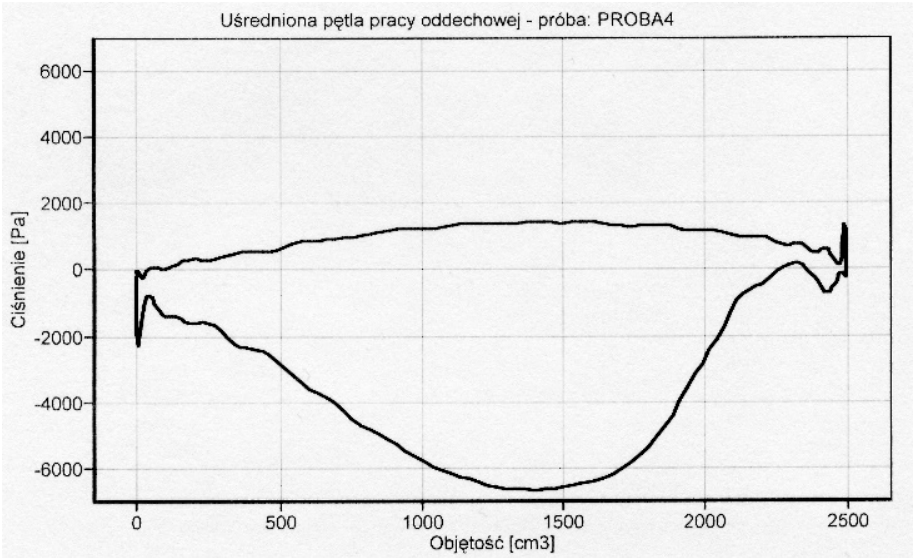

Fig. 18 An example of a breathing loop for an automatic breathing apparatus with a nozzle with the dimension of (Ø 3,5 ± 0,01) mm installed in the second stage.

CONCLUSIONS

The tests and results clearly indicated that simulated interference with the airflow by changing the nozzle diameters of the concurrent pressure reducing valve in the second stage of the breathing apparatus had a significant effect on the breathing work output. As expected, decreasing nozzle clearance resulted in an increase in the work of breathing. In the test groups, a factory-installed nozzle with a diameter of (ϕ 4,5 ±0,01) mm and two additional nozzles imitating 'clogging', with the diameters of (ϕ 4,0 ±0,01) mm and (ϕ 3,5 ±0,01) mm were used.

In accordance with clause 5.7.1. a) of EN 250:2014, it is assumed that for breathing apparatus without adjustable breathing resistance, the work of breathing should not exceed a value of 2.5 J/l. Taking into account clause 6.2.2, a value of (2.5 ±0.13) J/l is adopted as the basic reference point. This is the value determined during dynamic bench testing. It represents the essential limit of the diver's effort when using an open-circuit non-controlled breathing apparatus to a depth of 50 mH_2O.

The results obtained during the tests indicated that:

- for the nozzle diameter (ϕ 4.5 ±0.01) mm, assembled by the manufacturer of the device, the mean value of respiratory work was (2.21 ± 0.08) J/l;
- for a nozzle diameter (ϕ 4.0 ±0.01) mm (clearance reduced by 0.5 mm), the mean value of the work of breathing was (3.44 ± 0.08) J/l, which represented an approx. 38 % increase in respiratory resistance compared to the value specified in the standard;
- for a nozzle diameter (ϕ 3.5 ±0.01) mm (clearance reduced by 1.0 mm), the average value of work of breathing increased to (4.35 ± 0.08) J/l, which represented an approx. 74 % increase in resistance to breathing in relation to the value specified in the standard.

The literature on the subject indicates that a good design and high quality manufacture of the breathing apparatus, during bench tests and with the conditions for conducting them specified in the PN-EN 250:2014 standard, should ensure a breathing work value of 2.0-2.2 J/l [6]. The results obtained during the tests significantly exceeded the value indicated in the standard. From a performance point of view, an interference with the airflow through the nozzle in the second stage of the breathing apparatus, caused by accidental blockage of the nozzle by a material particle, should be considered as relatively large and highly dangerous to the health and life of the diver. From a practical point of view, this means that having a duplicated breathing apparatus in the water is an absolute necessity to increase diving safety.

REFERENCES

1. https://alertdiver.eu/pl_PL/artykuly/niewidoczne-kryształki-i-awarie-automatow
2. http://scubatechphilippines.com/scuba_blog/regulator-hose-diving-emergency/#Polymorphic_Crystallization
3. Greber Tomasz „Measurement system analysis (MSA)" Politechnika Wrocławska, Instytut Organizacji i Zarządzania StatSoft Polska Sp. z o.o. 2002 www. StatSoft.pl
4. Humienny Zbigniew, Kiszka Krzysztof „Metrology and interchangeability" Politechnika Warszawska Wydział Samochodów i Maszyn Roboczych Warszawa 2011 www. ipbmvr.simr.pw.edu.pl/spin/ ISBN: 83-89703-67-X
5. Polish standard PN-EN 250:2014 "Breathing apparatus. Open-circuit compressed air diving apparatus. Requirements, testing and marking" Polski Komitet Normalizacyjny Warszawa 2014 ISBN: 978-83-275-3214-5
6. https://www.diverite.com/wpcontent/uploads/library/Regulators/Regulator%20Performance%20Article%20By%20Mike%20Ward.pdf

dr inż. Zbigniew Talaśka
Akademia Marynarki Wojennej im. Bohaterów Westerplatte
81-103 Gdynia 3 ul. Śmidowicza 69
Kateda Technologii Prac Podwodnych
tel. + 58 626 27 46, fax. +58 625 38 82
e-mail : zbigniew_talaska@wp.pl