CONSTANTA MARITIME UNIVERSITY

Ph. D. PROGRAMME MECHANICAL ENGINEERING AND MECHATRONIC

Ph.D. THESIS

RESEARCH ON GAS TRANSFER IN DIVING TECHNOLOGIES

ABSTRACT

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Chapter I Introduction

The main objective of the PhD thesis is to identify the physical phenomena that occur in the diving activity during the transfer of respiratory gases and their influence on the safety of the divers.

We have found two major problems that characterize the circulation of respiratory gases:

1. Heat loss during the transfer of respiratory mixtures through the body of the diver, that can lead to an intense cooling, even down to death, if not properly managed.
2. External respiratory resistance to the human respiratory system, induced during the gas transfer through the breathing apparatus (pressure regulator).

The depth and duration of the dive are limited by several factors, including the diving comfort of the diver. Whether immersion is real or simulated, heat losses needs to be evaluated so that the choice of thermal protection system and the temperature of the respiratory mixture are adequately done.

The gas becomes denser with increasing depth (pressure), causing increased respiratory resistance. Knowledge of respiratory gas flow in various situations is necessary to control the physical and physiological phenomena involved, to choose a respiratory apparatus to reduce external resistance and implicitly the user's effort.

As a consequence, I consider the PhD thesis: "Research on gas transfer in diving technologies", to be useful and by being approached in an original way to broaden the knowledge in the field.

The objectives of the PhD thesis are:

- Establish the physical quantities and equations that characterize the two phenomena, namely the thermal losses through the diver's body and the flow of gases through the respiratory circuit of the diving equipment.
- Identifying the diver's heat balance equation and solving it.
- Experimental validation of the differential equation of thermal balance solution, by diving in the Hyperbaric Laboratory.
- Identifying a mathematical model for calculating the mass flow of respiratory gas delivered by the pressure reducer of breathing apparatus.
- CFD (Computational Fluid Dynamics) simulation - ANSYS Fluent gas flow through SCUBA (self-breathing, open circuit, diver).
- Experimental validation of theoretical calculations and numerical simulation (by CFD - ANSYS Fluent), regarding the flow of gases through the diver's breathing apparatuses.

Chapter II Current stage of diving technologies and gas transfers involved

The PhD thesis includes an analysis of the current state of diving technologies and gas transfers involved. After reviewing the main achievements in the field, I made a classification of the types of diving and equipment used. This classification highlighted the main respiratory gas circuits and gas transfers during diving.

We have established that the heat transfer through conduction and convection governs the heat loss of the diver in its work and consequently we have identified the laws to be applied.

To reduce respiratory effort induced by the breathing apparatus, I studied gas mass transfer through the specific circuits of the diving equipment. In the paper I also presented underwater equipment for contaminated waters, in its own design, made and tested at the Diving Center in Constanta.

As it can be seen, the effort to support the life of divers in optimal conditions during their activities is based on previous scientific discoveries in very broad fields: physics, chemistry, physiology, and engineering. The views of the specialists are not unanimous today in the hyperbaric field, leaving room for the theoretical and experimental study programs for the improvement of specific technologies.

The most important element is the respiratory gas. It is manufactured as a mixture of oxygen with one or two diluents gases, pressurized for storage, transferred through specific installations to the respiratory or pressurizing circuit of the hyperbaric chambers.

In the hyperbaric breathing process, the respiratory gas is transported to the mouth, then it is taken up by the inhale to the alveoli, where the oxygen is transmitted from the mixture, and then the cell metabolism products: carbon dioxide and carbon monoxide are taken up in the opposite direction, to be released in water or in the atmosphere, in the case of simulated dives.

Chapter III Thermokinetics of the transfer of respiratory mixtures

The study of the transfer of gas during diving is done by theoretical and experimental methods. That is why I studied rigorously the thermokinetics transfer of respiratory mixtures.

I started from the hypothesis that I can compare the body of the diver with a multilayer cylinder (muscle, skin, suit, water). For this I studied the Fourier equation for thermal conduction, the temperature field that crosses two concentric cylindrical walls and the application of the conditions of uniqueness, the free convection in open spaces. I have established the similarity criteria that apply to the convective heat transfer coefficient α.

The air stored in pressurized bottles is dry and cold. During the respiratory process, it is heated and humidified by the diver. For this reason I studied the properties of wet air and the heat flow received during evaporation.

At the international level, the thermal balance equations of the human body were solved only in dry hyperbaric environment.

The proposed thermal balance equation for the wet hyperbaric environment is a simplified model of a very complex phenomenon. The following hypotheses were adopted:

- For tissues, a reduced pattern was used, in which the conductive resistances of the skin layers have values depending on the diver's constitution and effort.
- Radiation was neglected due to low water temperatures.
- The body of the diver is in direct contact with the water in the wet suit, so we do not have evaporation.

Clearly, the hypothesis of comparing the diving body - water film - costume - water film with a multilayer cylinder of length equivalent to the height of the subject, over the hypothesis of walls with parallel flat faces, is closer to reality. This study can be continued with a more refined approximation of the human body (its segmentation in the head, trunk, limbs, etc.), so the results will be more accurate.

The study of the thermal balance equation of the diver's body in the wet hyperbaric environment provided an easy to use mathematical solution for estimating the body temperature according to the immersion stationary time. Thermal losses are added to the total lost energy of the diver during the dive. Managed inadvertently, they lead to a lower internal temperature of the individual, below the allowed limit for maintaining safety and health, leading to death. Information on the heat balance of the diver is useful to him because he can evaluate his own heat loss and consequently choose both the protective suit (thickness, material) and the diving time depending on the following variables:

- body and water temperatures;
- water pressure, corresponding to the depth of immersion;
- the main individual physiological features;
- respiratory characteristics (ventilated respiratory flow);

- properties of respiratory gas.

Some of these variables depend on water pressure (depth).

Chapter IV Research on thermal losses in transfer of respiratory mixtures through the diver body

Research on thermal losses in the transfer of respiratory mixtures through the diver's body was done by unitary dives with air and saturation with heliox and it has had as a main purpose the experimental validation of the previously provided thermal equation and its solution.

The evaluation of the thermal losses, both through the skin and respiratory, was done by testing 3 types of subjects: A (weak), B (normal) and C (corpulent), with suits with different thickness, in various diving conditions (water temperature, diving depth, exposure time).

Following the theoretical and experimental results, it is noted that between the calculated and the measured temperatures there is a difference of 0.5[^{0}C] in the dives with air and 1[^{0}C] in heliox saturation dives. I analyzed the initial assumptions and proposed a correction factor due to the simplifying assumptions, also taking into account that the tests were done under simulation conditions, by pressing the hyperbaric chamber at a rate that influences the body's reaction.

The final solution of the equation T (t) of formula (4.37) is the original solution.

$$T_{(t)} = \left[T_0 - T_a - \frac{\dot{Q}_m - l_{(p)}\rho_{(p)}x_{(p)}\dot{V}_{(p)}}{\frac{A}{R_{(p)}} + \rho_{(p)}c\dot{V}_{(p)}}\right] e^{\frac{\frac{A}{R_{(p)}}+\rho_{(p)}c\dot{V}_{(p)}}{mc_c}t} + \frac{\dot{Q}_m - l_{(p)}\rho_{(p)}x_{(p)}\dot{V}_{(p)}}{\frac{A}{R_{(p)}} + \rho_{(p)}c\dot{V}_{(p)}} + T_a - c$$

The correction factors are: $c_{aer} = 0.5$[^{0}C]; $c_{heliox} = 1$[^{0}C].

The proposed mathematical model is valid for diving in wet hyperbaric environment, up to 60m deep, for both: air unit dive and heliox saturation dive. The main variable is the time t[s].

$T_{(t)}[K]$ – body temperature; $T_0[K]$ - initial temperature; $\dot{Q}_m[W/m^2K]$ – metabolic flux density; $l_{(p)}[kJ/kg]$ - vaporization latent specific heat; $\rho_{(p)}[kg/m^3]$ - water density; $x_{(p)}$ - absolute humidity; $\dot{V}_{(p)}[l_N/s]$ - forced expire volume flow; $A[m^2]$ - body area; $R_{(p)}[m^2K/W]$ - thermal resistance of human body external layer; $c[J/kgK]$ mass specific heat of respiratory mixture; $T_a[K]$ water temperature.

Chapter V Transfer of gases through the breathing apparatus of the divers

The second proposed problem, the external resistance induced to the gas transfer through the breathing apparatus (second stage pressure regulator) to the human respiratory system, has been resolved from the determination of the flow conditions.

The air flow through the second stage pressure regulator is stationary and turbulent (Re> 10000) via tubes and nozzles with two main restrictors: A variable restrictor (between seat and cylindrical piston) and B fixed restrictor (cylindrical piston hole). The mathematical modeling of the flow through the restrictors of the respirators was made by following the notions of the theory of potential gas flow through tubes and nozzles.

For the study I have established a simplified model of a classical downstream flow, in which only the two pressure restrictors A and B, mounted in series (see Figure 5.21), were considered. In the 1st version, the B fixed restrictor is cylindrical and in the 2nd version, the B fixed restrictor is a conical nozzle. The variable section of A restrictor is critical, and the flow is also critical.

After establishing the flow conditions, I determined through calculations the critical mass flow provided by the device for the two chosen models. I calculated the external resistance to breathing induced by the second stage respirator at two differential pressures Δp = 5 [cmH2O] and Δp = 6.5 [cmH2O].

For the same model, the mass flow increased to the differential pressure Δp = 6.5 [cmH_2O], pressure which determined the increase of the x variable opening of the A restrictor. The B fixed restrictor geometry also influenced the mass flow provided by the device. The conical nozzle improved the parameters of the second stage: the flow increased and the external resistance was lower.

For a comparative analysis of the theoretical results, the second method of respiratory gas turbulence research was taken: CFD simulation (Computational Fluid Dynamics) ANSSYS Fluent. CFD simulation is a modern method that allows the calculation to be repeated on several nozzle designs and changing flow conditions so as to arrive at an ideal shape. The program used results in a wider visual view of the variation of several physical sizes: pressure, density, velocity, mass flow.
For both constructive versions I found:

- The input pressure passes after variable A restrictor from $9 * 10^5$ [Pa] to ≅ 10^6 [Pa] and drops sharply to $2 * 10^5$ [Pa], a specific phenomenon of the Laval nozzle.
- Densities also decrease with the pressure from 8-10 [kg / m^3] after the A first restrictor to ≅2 [kg / m^3] at the B fixed restrictor. From the exit of the B restrictor to the mouthpiece, more relaxes to the density at atmospheric pressure (1.23 [kg / m^3]).
- The speeds have supersonic values at the A restrictor and subsonic (200-300 m / s) at the exit of the B restrictor.
- Mass flows are lower by 13-18% than those calculated theoretically, the CFD numerical simulation more accurately reflects the phenomenon, as well as other losses.

Chapter VI Experimental validation of theoretical calculations and numerical simulation of gas flow through the breathing apparatus of the divers

In order to obtain viable results during laboratory experiments, I studied professional testers and standardized methods for checking underwater self-contained breathing apparatuses and chose a Scuba Tools professional stand purchased within a project of the Development Research Schedule of the Ministry of National Defense, where I worked.

The volumetric flow measurements were initially made on the original model, 1^{st} version, at the same time as the corresponding differential pressures. I kept the flow rates for the two differential pressure Δp = 5 [cmH2O] and Δp = 6.5 [cmH2O], under the conditions described in the thesis. After changing the nozzle from cylindrical to conical, I resumed the flow measurements under the same conditions. I calculated the corresponding mass flows and external resistance induced by the device. I compared the mass flows and external resistances by the three methods: theoretical calculation, numerical simulation and experimental verification.

Conclusions on mass flow:

- The theoretical values for the air flow were calculated for ideal gas, for a simplified model in which we took into consideration only two serial pressure restrictors: A and B.
- The surface of the first limiter is variable in time, but the smallest cross section of the airflow remains, thus fulfilling the conditions for a critical flow.
- The flow is stationary for the same environmental parameters and consequently the air mass flow depends only on the x opening of the A restrictor, caused by the differential pressure Δp.
- After the thin wall flow coefficients ($\alpha_1 = 0.7$ and $\alpha_2 = 0.8$) were applied to the mass flows, the highest values remain those obtained by the theoretical calculation.
- The conical section of the B restrictor determined a slightly higher flow rate in all three methods (theoretical calculation, numerical simulation and experimental verification). The increase of the mass flow from 1^{st} version to conical 2^{nd} version is 10 - 14%.

- The theoretical mass flows are in all cases up to 70-80% higher than the real ones, determined experimentally, due to the initial assumptions (ideal gas, adiabatic transformation, simplified model with only two pressure limiters, etc.).
- The mass flows resulting from ANSYS Fluent CFD simulation are 40-50% higher than those measured under real conditions.
- The performance techniques used in the numerical simulation make it possible to refine the calculations and to highlight the influence of the constructive form of the respiratory gas circuit restrictors through the apparatus.

Conclusions on external resistance

- Resistances calculated theoretically and by numerical simulation are lower than those resulting from experimental determinations.
- For the 2nd version with the conical section of the B restrictor, the resistance is lower for both differential pressure values Δp.
- All three methods: theoretical calculation, numerical simulation and experimental verification, show that the conical nozzle of the B fixed restrictor reduces the R_E resistance by ≅10-15% compared to 1st version with the circle section, by gradually reducing the speed.

The study revealed a practical method of determining the real flow coefficients, the passage of air through the restrictors resulting from the minimum openings in the thin walls, in the case of turbulent flow and with high pressure differences, the method described in subchapter 6.3. In the literature, real flow coefficients are not specified, except for laminar resistances or for low pressure drops ≈2 [bar] [Petcu D., 1970]. Real values of flow coefficients are approximately the same for different pressures at the same shape of the hole. The conical opening generates a higher flow rate, so a better flow.

Chapter VII Personal contributions

1. Personal contributions regarding the transfer of heat through the diver's body

- A synthesis of scientific approaches, internally and internationally, of mathematical modeling and of experimental validation regarding the research on the diver's thermal balance.
- The model of the multi-layer cylinder chosen for the body of the diver equipped in a neoprene suit, with a water film between the skin and the suit and immersed in the water. The mathematical modeling of the heat transfer during the transport of respiratory gas from the storage tank to the human respiratory apparatus was made in the wet hyperbaric environment.
- Determination of 2 $c_c\,[J/kgK]$ specific caloric values of the diver's body, equipped with a neoprene suit, for 2 thickness (5mm and 7mm) of the suit. . In literature, we only find value for the naked human body [Tarlochan F., 2005].
- Determining the differential equation of thermal balance of the divers in wet environment and its solving. The equation includes: the metabolic flux produced by the body, the loss of conductive and convective heat in the skin, and the heat loss at the respiratory level for heating and for humidifying the gas.
- The theoretical solving of the diver's thermal balance differential equation in the wet hyperbaric environment resulted in an original temperature solution T (p) (4.37).
- Experimental validation of thermal balance differential equation in wet hyperbaric environment, using atmospheric air and heliox synthetic respiratory mix at the Diving Center Hyperbaric Laboratory, in hot water and in cold water, with subjects having different physical constitutions and using diving suits of different thickness.

Future research directions

- Study of heat transfer through the diver's body when using other breathing mixtures (nitrox, hydrox, trimix).
- The evolution of the thermal balance equation for other types of wet and dry diving, for example the reaction of the body to rapid pressurization at 8-10 [m / min] speeds, compared to the standard pressurization speed of 1 [m / min].
- Refining the chosen model or multilayer cylinder by dividing the body into other geometric segments (head - concentric spheres, multi - ply cylinder trunk, limbs other smaller cylinders).

2. ***Personal contributions regarding the mass transfer of the gas flow through the breathing apparatus of the divers***

- Theoretical calculation of respiratory gas turbulence flow parameters through studied pneumatic mechanisms, focusing on mass flow and external resistance induced when inhaling from the apparatus.
- Geometrical modeling of the second stage, with the pneumatic devices chosen for study, by computer-aided design and numerical simulation of gas flow through SCUBA (open-air breathing apparatus) using CFD (Computational Fluid Dynamics) - ANSYS Fluent.
- Experimental validation of the theoretical calculations and numerical simulation (with CFD - ANSYS Fluent) of the gas flow through the breathing apparatus of the divers, using a professional stand at the Diving Center's Hyperbaric Laboratory and the establishment of a test plan adapted to the study requirements.
- The innovative solution for reducing the external resistance R_E during inhale in the device, by geometrically changing the second fixed restrictor nozzle (of the second stage) from cylindrical to conical.
- Experimental determination of real flow coefficients through openings in thin walls corresponding to the potential air flow for large pressure drops.

Future research directions

- Resume of calculations, simulations and experimental validations for certain depths (output pressures> 1 bar).
- Continuation of the study to obtain higher real flow coefficients in the studied cases and other thin wall hole patterns.
- Research approach through flow modeling, theoretical calculation, numerical simulation and experimental validation can be resumed on other types of pressure reducers used in diving technologies, as described in Chapter II, to improve their performance.

Chapter VIII General conclusions

1. ***General conclusions regarding heat transfer through the body of the diver***

Assumptions: The cylinder model with concentric layers for the diver's body, in which the conductive resistances of the skin layers have values dependent on the diver's constituent and effort, radiation and heat lost through evaporation have been neglected.

Information on the thermal balance of the diver is useful to him because he can evaluate his own heat loss and consequently choose both the protective suit (thickness, material) and the diving time, depending on the following variables:

- his (the diver’s) initial temperature and the water temperature;
- water pressure, corresponding to the depth of immersion;
- the main individual physiological features;
- breathing characteristics of the diver (ventilated respiratory flow);
- properties of respiratory gas.

The most important heat losses to be taken into account in the case of an immersion diver are those that occur through conduction and convection. They can be compared with the values recommended by the literature: [Hedge Alan, 2008]

- $\alpha_c \cong 230[W/m^2{}^\circ C]$ for standing in water;
- $\alpha_c \cong 580[W/m^2{}^\circ C]$ for movement in water.

The proposed mathematical model (equation 3.132) was validated for diving in wet environment up to 60m deep. It was applied using both air and heliox 95/5 respiratory mixture under the same water temperature and depth conditions to compare the results obtained in both cases. The main variable is time t [s].

Another aspect that needs to be emphasized is the quicker cooling of the diver's body when using the heliox 95/5 synthetic mixture, because of the specific heat at constant pressure of the helium almost 5 times higher than the air. [Goldman, 1971]

In both types of diving, the body temperature drops steeply in the first few minutes, but the decrease is slower over time, so after 2-3 hours the temperature stabilizes. The charts showed the most unfavorable situations with the fastest temperature drops in the body. In practice, divers are moving, production of metabolic heat is higher and thermal comfort is longer. Depending on the dive plan, the temperature T (t) which the diver's body can reach after the proposed stop time t [s] can be estimated and an appropriate thermal protection strategy can be applied.

How the proposed goals were met

- The mathematical modeling of the heat transfer through the body of the diver was done in the humid environment.
- The chosen model, the multilayer cylinder, is original and the results obtained by the experimental validation confirm the validity of the study.
- The physical quantities and thermal transfer equations that characterize the phenomenon studied were established.
- The thermal balance equation of the divers in the wet hyperbaric (simulated and real) environment is complex and follows the main ways heat is lost, heat which is produced by the body (metabolic heat):
  a. conduction and convection in contact with cold water;
  b. heating and air humidification by breathing.
- The solution of the thermal balance equation was experimentally validated by simulating dives with two breathing mixtures: air and heliox.

2. General conclusions about the flow of gas through the diver's breathing apparatus

Air flow through the second step respirator is stationary and turbulent (Re> 10000) through tubes and nozzles with two main restrictors: A variable restrictor (between seat and cylindrical piston) and B fixed restrictor (the cylindrical piston hole) Fig. 5.21. Resolving the reduction of external resistances was made by choosing a modified constructive variant of the B fixed restrictor from cylindrical in conical. The two models were compared by theoretically calculus, simulation and experimentation. The overall hypotheses of the study are:

- The flow conditions are stationary in the minimum cross section of the air flow through the 2nd stage circuit.
- The critical area of the A variable restrictor must always be smaller than the final cross section of the B fixed restrictor: $A_c < A_f$.
- The diameter of the cylinder in the A restrictor is equal to the cross section of the B restrictor.
- The flow is stationary for the same environmental parameters, so the mass air flow depends only on the x opening of the A restrictor, caused by the Δp differential pressure.

The theoretical calculation revealed:

- The mass flow rate provided by 2nd version of the opening (conical nozzle) is greater than the mass flow provided by 1st version (cylindrical nozzle), for both values of the Δp, the difference in pressure during inhale.
- Ideal gas calculations were performed for a simplified model in which only two pressure limiters: A and B, mounted in series, was taken into account, hence the large flow differences between the real values and the theoretical ones or those resulting from numerical simulation.
- The external resistance at inhale is lower for 2nd version than for 1st version for both values of the Δp, the difference in pressure during inhale.
- The theoretical calculation and numerical simulation for the determination of external air flow rates and resistances have been validated experimentally.

ANSYS Fluent CFD numerical simulation is a modern method that allows you to redo calculations on multiple nozzle designs and changing flow conditions so as to reach an ideal shape. To determine the geometric conditions favorable to the reduction of external breathing resistance of respirators, we used all 5 parts of the program, namely: Geometry, Meshing, Setting, Solution and Results. The calculated solutions were the better, the finer the mesh was made and the more computational iterations (see Figure 5.30). In this diagram we can see the coefficients k referring to the variation of the turbulent kinetic energy and ε which characterize the turbulence diffusion rate. They are given by the motion equations specific to the turbulent kinetic energy. In the 2nd version, with the conical section of the B fixed restrictor, the k and ε values decrease, indicating the decrease of the turbulence. Once the geometry of the mechanism is established in the program, the initial conditions are slightly changed through numerical simulation and a quick check of the results is made in order to be able to choose the optimal version. The values obtained from the simulation are similar to those calculated theoretically, only that the flows are about 13% lower. The numerical simulation has better reflected the real air flow through the studied circuits, rather than the theoretical calculation.

To validate the theoretical calculations and numerical simulation, a pressure regulator test stand was used, which is a professional complete from Scuba Tools. It was found that:

- Flows are progressively increasing until the critical value is reached.
- At higher differential pressure (6.5 cmH_2O), the flow rate is higher than that obtained for the same apparatus at a lower differential pressure (5 cmH_2O).
- For 2nd version (conical nozzle), the flow rate is higher than that obtained with 1st version (cylindrical nozzle) at the same differential pressure.
- The external resistance at the same inhale pressure is reduced for the 2nd version compared to the 1st version for both values of the differential pressure analyzed.
- Mass flows are significantly lower than those resulting from theoretical calculation and numerical simulation.

How the proposed goals were met

- A simplified model of the pneumatic gear of the second stage pressure reducer of the diver's breathing apparatus was established with two in-line pressure restrictors: one A variable (at the air penetration in the cylindrical piston) and one B fixed (at the exit air in the cylindrical piston) - see Fig.5.21.
- The flow of respiratory gas was mathematically modeled by the pneumatic mechanisms studied and also the theoretical calculation of the potential flow parameters through these mechanisms was made.
- The air mass flow rate provided by the breathing apparatus for two constructive versions of the B - conical and cylindrical fixed restrictor sections for two differential pressure (Δp = 5 cmH_2O and Δp = 6.5 cmH_2O) was compared.

- The CFD (Computational Fluid Dynamics) - ANSYS Fluent simulation of respiratory gas turbulence flow through the studied pneumatic mechanisms, resulting in the mass flows of the 1^{st} version and the 2^{nd} version, for the differential pressure $\Delta p = 5$ [cmH_2O].
- Testing performed at the Hyperbaric Laboratory on the two models 1^{st} and 2^{nd} validated the results obtained by theoretical calculation and ANSYS Fluent CFD simulation.

The working method for determining the real flow coefficients, resulting from the combination of the theoretical calculations and the experimental results, described at the end of subchapter 6.3, can also be used for other applications, where the turbulent flow of gas through the pneumatic mechanisms is made by restrictors (thin wall holes) that cause a large pressure drop with a number Re> 10000. Conclusions from theoretical studies, numerical simulation and experiments allow the development of a methodological approach to the engineering problems of gas flow through the breathing apparatus of the divers.

The objectives proposed at the beginning of the paper were fulfilled:

- I found an original solution for the diver's thermal balance equation.
- I have solved the problem of reducing external resistance R_E of the regulator by modifying the cylindrical fixed nozzle in a conical hole.

The result of the research, or the original, validated solution of the thermal balance equation, allows intelligent diving planning by choosing the appropriate diving suit, diving time and thermal protection measures to avoid thermal discomfort and no case of hypothermia (28^0C).

The information provided by this PhD thesis is a useful bibliographic material for the design and optimization of the pressure reducers studied to increase the efficiency of the diver's breathing apparatus.