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GAS FLOW IN UNDERWATER BREATHING INSTALLATIONS

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Rezumat: *Aparatul de respirație subacvatică cu circuit deschis poate fi un regulator cu una sau două faze, utilizat în scufundări, sau un regulator cu două faze, utilizat în instalațiile de suprafață furnizate. Aceste instalații sunt adecvate pentru locurile subacvatice, la o adâncime mică. Circuitul pneumatic al unui regulator cu două faze este alcătuit, în principal, dintr-un regulator de primă fază montat pe cilindrii cu aer și dintr-o a doua fază purtată de scafandru în gură. Cele două regulatoare sunt legate printr-un furtun de presiune medie. Circuitul se deschide atunci când depresiunea creată de inhalarea scafandrului, în corpul celei de-a doua faze, atinge o anumită valoare. Deschiderea celei de-a doua faze determină o mișcare tranzitorie, și anume o undă de expansiune care se propagă prin furtunul de presiune medie către regulatorul primei trepte. Se deschide regulatorul primei faze, iar aerul din cilindri este lăsat să curgă spre scafandru. Cu cât este mai lung furtunul, cu atât este mai mare durata propagării undei de expansiune. Investigațiile privind propagarea undei oferă date despre durata mișcărilor instabile de inspirație care influențează efortul respirator al scafandrului.*

Cuvinte cheie: undă de expansiune, mişcare instabilă, efort respirator.

Abstract. *The open circuit underwater breathing apparatus can be a one or two-stage regulator used in scuba diving or a two-stage regulator used in surface supplied installations. These installations are proper in underwater sites at small depth. The pneumatic circuit of a two-stage regulator is composed mainly of a first stage regulator mounted on the air cylinders and a second stage carried by the diver in his mouth. The two regulators are linked together by a medium pressure hose. The circuit opens when the depression created by the diver's inhalation, in the second stage body, reaches a certain value. The second stage opening causes a transient movement, namely an expansion wave that propagates through the medium pressure hose to the first stage regulator. The first stage regulator opens and the air in the cylinders is allowed to flow to the diver. The longer the hose, the greater the duration of the expansion wave propagation. Investigations on the wave propagation offer data on the inspiration unsteady motion duration which influences the respiratory effort of the diver*.

Key words: expansion wave, unsteady motion, respiratory effort.

1. Generals on Open Circuit Underwater Breathing Apparatus

Underwater breath is made heavy by the increasing density of the respiratory gas with the immersion depth and also by the external resistance to breathing added by the apparatus.

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The most comfortable and safe underwater breathing apparatus is the open-circuit two-stage demand regulator which can be used either in SCUBA or in surface-supported systems. The pneumatic circuit of a two-stage regulator is mainly composed of a first stage regulator mounted on the air cylinders and a second stage carried by the diver in his mouth. The operation principle and the construction type of the regulators are the same for the apparatus built in our country. But when using SCUBA, the air cylinders are carried by the diver, and when using surface supported systems, the breathing gas is stored under pressure in a tank at surface. Another important difference is in the first stage. The first stage of an open-circuit SCUBA is piloted by the hydrostatic pressure, in accordance with the depth. The immersion depth in air diving is limited by the nitrogen narcosis effect. The first stage of a regulator used in surface-supported systems isn't piloted, but is adjusted at the surface by handling a key which tightens or loosens an adjustment spring. The umbilical limits the diver's possibility to move. The advantage of the surface-supported system is that a greater amount of air can be used, which means a greater duration of diving. Another advantage is the audio station which equips the system and allows a continue connection of the diver to the surface team.

2. The Air Steady Motion Phase during Inhalation

Our investigations refer to the two-stage demand regulator and the surface-supported system built in our country and used in air diving. We have assumed that the two-stage regulator is an assembly of two variable nozzles linked together by a medium pressure hose, as in Figure 1.

Fig. 1. A two-stage demand regulator
represented as an assembly of two variable nozzles connected by a medium pressure hose.

A two-stage demand regulator reduces air pressure in the tank to the environmental pressure. Air delivered at the environmental pressure is a very important condition for a minimal respiratory effort of the diver. The pressure is reduced in two stages. First it is decreased to a medium value, *pm* [1]:

$$p_m = p_e + p_t \tag{1}$$

where p_e - environmental pressure (dependent on depth);
p_t - adjusted pressure (constant).

The relation (1) shows that pressure upstream the second stage is related to the depth. Consequently, the mass flow rate, $\dot{m}$ increases when the diver goes deeper and decreases when the diver comes up.

We must note that the medium pressure, irrespective of the depth, exceeds the environmental pressure with the amount of $p_t = 8 \div 9$ bar. So, the ratio between them is lower than the critical one (considering air as breathing gas) [2]:

$$\frac{p_e}{p_m} < \beta_{cr} = 0.528$$

That means the motion in the second stage inlet valve is critical for a large range of p_e. The gas accelerated through the linkage hose takes the critical values of the flow parameters in the minimal section in this part of the circuit (the variable section of the second stage inlet valve).

Then, the air expands with supersonic speed immediately downstream the valve. Shortly afterwards the motion turns into a subsonic one, due to a complex phenomenon which we assumed to be a normal shock wave [3].

The second stage regulator sets the value of the mass flow rate. Assuming a constant stagnation temperature during a diving, we can say that the mass flow rate, $\dot{m}$, depends only on the pressure p_m upstream the second stage and on the pass section area of the second stage inlet value, A2. This variable section depends on the amplitude of the dives demand, which means the vacuum created by the diver in the body of the second stage regulator [1]:

$$\dot{m} = C \cdot A_2 \cdot p_m \text{ [kg/s]} \tag{2}$$

where C - coefficient dependent on air constant ($R = 287.13 \ \mathrm{J}/\mathrm{kg \cdot K}$), ratio of air heat capacities (k=1.4) and on temperature.

3. The Air Unsteady Motion Phase during Inhalation

We have described above how the regulator works during the steady phase of the inspiration process. The unsteady phase of inhaling is important for the regulator’s sensitivity. This phase refers to the very beginning of inhaling, when the mass flow rate increases from 0 to a value m given by the relation (2) and equal in both nozzles. The differential pressure in the second stage body grows from 0 to a certain value Δp_{de} needed for the mechanism to open. The opening of this mechanism provokes an expansion wave that propagates through the medium pressure hose. As the wave propagates, gas particles are put into motion, their velocity rising from zero to a positive value. When this velocity takes the opening value v_d, upstream the hose, the first stage mechanism opens.

Pressure equation, written for the gas in the hose, gives the value v_d according to the stagnation values for medium pressure p_{mo}, and density ρ_{mo}.

$$\frac{k}{k-1}\cdot\frac{p_{mo}}{\rho_{mo}}=\frac{k}{k-1}\cdot\frac{p_{md}}{\rho_{md}}+\frac{v_d^2}{2} \tag{3}$$

where p_{mo} - medium stagnation pressure; p_{md} - medium pressure needed for the first stage to open, v_d - gas velocity corresponding to p_{md}.

The equation was written for an adiabatic transformation of a gas that means an isentropic movement [2].

Relation (3) shows that the sensitivity of the first stage mechanism, reflected by the opening pressure p_{md}, is related to the value v_d. The sensitivity of this mechanism is given by the differential pressure $\Delta p_{md} = p_{mo} - p_{md}$. Consequently, the sensitivity of the first stage inlet valve influences the duration of the unsteady movement of gas.

As the first stage mechanism opens, the unsteady movement lasts until the mass flow rate equilibrates through the two valves:

$$\dot{m}_1 = \dot{m}_2$$

In accordance with the discussion above, we can consider the duration of the unsteady motion t_n composed of three times:

$$t_n = t_{d_2} + t_{d_1} + t_e \tag{4}$$

where t_{d_2} – the duration asked for the second stage opening;

t_{d_1} – the duration asked for the first stage opening;

t_e – the duration needed for the mass flow rate equilibration through the two valves.

Due to the fact that the average duration of the inhaling in normal conditions of pressure, temperature and effort is one second [4], any little rising in one of the three durations in relation (4) results in the diver's breathing discomfort.

Applying twice the relation (4) for the same two-stage regulator, first used in a SCUBA and then in a surface-supported system, we can observe that the only difference is the time t_{d1} for expansion wave propagation, because the medium pressure hose is much longer at the diving system.

The equation of continuity written for an unsteady one dimensional movement in a constant cross section and tube, through which the gas evolution is isentropic, and the motion equation make a nonlinear system having pressure, *p*, and velocity, v, unknown. Both depend on space, *x*, and time, *t* [2]:

$$\begin{aligned} &\frac{1}{\rho a}\cdot\frac{\partial p}{\partial t}+\frac{v}{\rho a}\cdot\frac{\partial p}{\partial x}+a\cdot\frac{\partial v}{\partial x}=0 \\ &\frac{\partial v}{\partial t}+v\cdot\frac{\partial v}{\partial x}+\frac{1}{p}\cdot\frac{\partial p}{\partial x}=0 \end{aligned} \tag{5}$$

where $\rho=\rho_{(p)}$ gas density;

$a=a_{(p)}$ sound speed in local conditions.

A particular solution of this system (5) can be obtained by replacing the variables *x* and *t* with a single variable:

$$\eta=\frac{x}{t}$$

The two variables *x* and *t* are no more independent. The movement is considered to depend only on η, variable which has the dimension of a speed. The system (5) turns into an ordinary differential equations system.

The first solution: $\eta=v-a$ leads to the relation:

$$t=-\frac{x}{a_0-\frac{k+1}{2}\cdot\sqrt{v_2}} \tag{6}$$

where a_0 – sound speed in stagnation condition;

v_2 – maximum gas velocity.

The relation (6) describes a rarefaction phenomenon of the gas [2] which initially stood still. From now on we will take *t* for t_{d_1}.

At the initial moment $t=0$, the second stage valve opens and the gas in the hose begins to move to the low pressure second stage body, with the v_2 velocity.

The gas moves in the positive sense in Figure 1.

The velocity v_2 depends on the ratio between the downstream and upstream pressure of the second stage valve.

The expansion wave moves in negative sense of the O*x* axis, towards the first stage valve.

We have studied how long it takes to the wave to propagate through a hose of different lengths, *l*. Previously we’ve searched the variation of gas velocity v_d versus depth and temperature. The stagnation temperature does not notably influence the gas velocity v_d, as shown in Table 1.

Table 1. Temperature influence on velocity v_d

v_d, [m/s]				
***h*, [m]**	**273.15** [K]	**278.15** [K]	**283.**15 [K]	**288.15** [**K**]
0	8.86	8.92	9.02	9.10
10	8.44	8.51	8.60	8.67
20	8.09	8.14	8.23	8.30
30	7.77	7.82	7.91	7.98
40	7.49	7.54	7.62	7.69
50	7.23	7.28	7.36	7.43
60	7.00	7.05	7.13	7.19

At the same depth, velocity v_d has a small rising with the stagnation of the temperature. This rising is smaller as the depth increases.

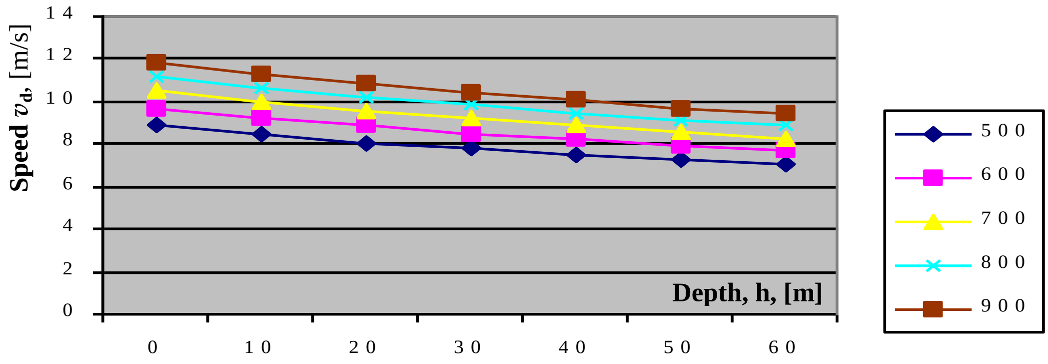

Fig. 2. Variation of velocity v_d, as a function of depth.
The curves are plotted for different values of differential pressure, Δp_{md} [mbar].

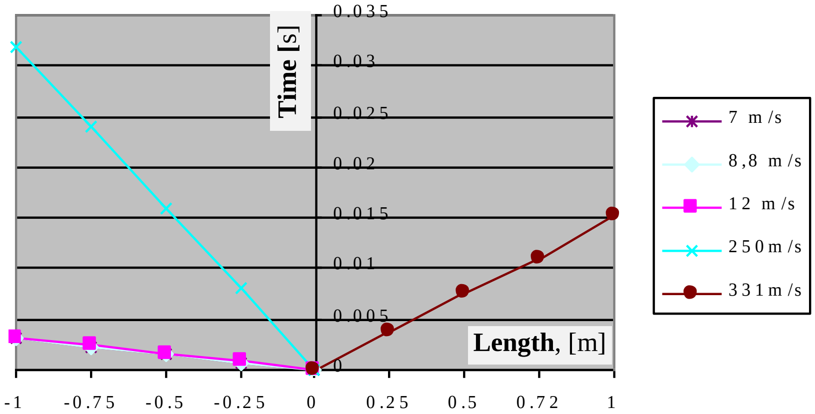

Fig. 3. Expansion fan for the hose of a SCUBA two-stage regulator .

We cannot say the same thing about depth. Gas velocity v_d corresponding to the opening pressure p_{md} varies with the depth of the immersion as it can be observed in Figure 2.

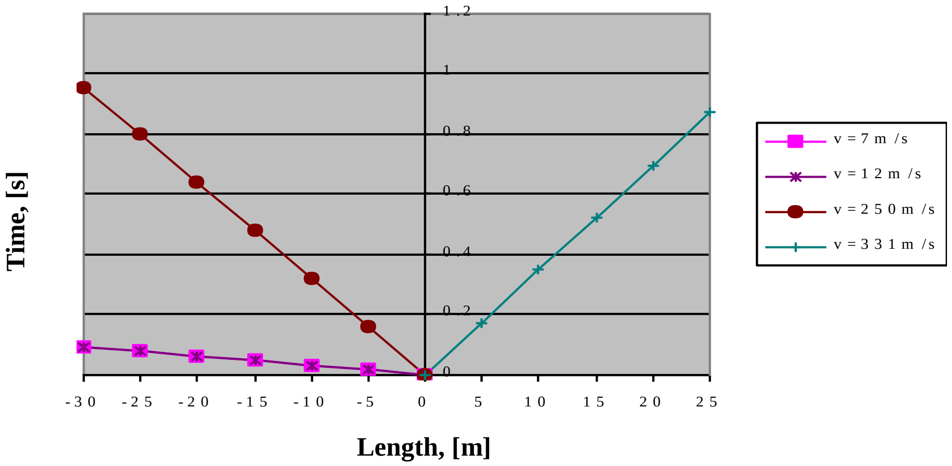

Fig. 4. Expansion fan for the hose of a surface-supported diving system S.

The expansion fan is represented in Figure 3 for a two-stage regulator with a hose of 0.7÷1 m in length, and in Figure 4. for a hose of 30 m long used in surface-supported system.

Calculations were made for a stagnation temperature of 273.15 K.

4. Conclusions

According to the particular solution of the system (5) that describes the expansion wave propagation, the time the wave reaches the first stage is directly proportional to the length of the hose.

The power consumed in the respiratory process had been evaluated at an average value of 12 w/l when the diver makes a medium physical effort [1].The value was experimentally obtained in stimulated air diving, for a 15 l/min ventilator volume flow rate. The divers used a two stage demand regulator with a 0.7 m long hose. At the same depth, the consumed power rises by 10% when using the surface-supported system, only because the hose is thirty times longer.

Taking into account that the Black Sea water freezes at a temperature lower than $0^{\circ}C$, the values presented above cannot be the worst case.

In order to choose an optimal length for our surface-supported system hose, we experimentally tried the same system with hoses with lengths between 20 m and 30 m. Obviously the breath was easier in the case of the shorter length. So the depth of immersion was reduced at maximum 18 m.

R E F E R E N C E S

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