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The potential air flow through diver's breathing apparatus

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Abstract: The gas admission through the divers' breathing apparatus is done with a critical flow. The gas storage pressure is reduced to the value of the external pressure p_e. The paper approaches the gas-dynamic phenomena that occur when the gas flows through the second stage regulator, respectively: the variable restrictor A (between the seat and the cylindrical piston) and the fixed restrictor B (the orifice of cylindrical piston). The two main pressure restrictors can be considered Laval nozzles. Mathematical modeling of airflow through restrictors was done following the notions of the theory of potential gas flow through tubes and nozzles. The air flow was calculated numerically and by CFD simulation and was experimentally verified at a professional stand for the second stage.

1. Introduction

The diving specialists are constantly concerned with the safety of divers and improving their comfort in immerting, whether their activity is commercial or military. The gas becomes more dense with increasing depth (pressure), causing increased respiratory resistance. The anatomically dead volume also increases. Knowing the respiratory flow of gas in various situations is necessary to control the physical and physiological phenomena involved, to choose a breathing apparatus that reduces resistance to inspiration and expiration and thus the user's effort.

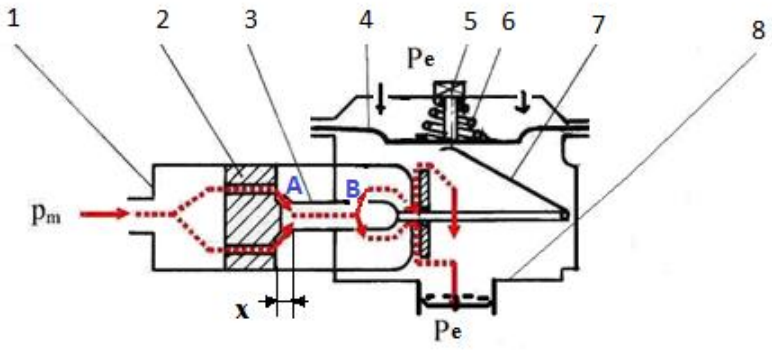

Figure 1 [1]

Unbalanced second stage regulator with downstream admission

1- casing, 2 – sealing seat, 3 –poppet tube, 4 – membrane, 5 –adjusting screw, 6 - spring, 7 – lever, 8 –exhale valve

The storage air pressure in the diver's cylinder is reduced, by the first stage, to an average pressure p_m. The gas passes through the medium pressure hose and reaches the second pressure regulator. The second stage regulator, showed in Figure 1, is unbalanced with downstream admission. Respiratory air is admitted in the second stage at the average pressure higher by 8.5 , above the outlet pressure p_e. The opening of the reducer is triggered by the inhalation of air at 5-6$\cdot 10^2[Pa]$ of vacuum, which moves the membrane (4), the membrane that pushes the lever (7). The lever actuates the poppet tube (3) by moving it again between the poppet tube and the seat (2).
In the point A is the first restrictor composed of the poppet tube (3) and its sealing seat (2) with variable flow area. The second restrictor B is the orifice in the poppet tube wall with constant flow area. Only the two series-mounted pressure restrictors A and B were considered (see Fig. 1).

2. Mathematical modeling of potential air flow through the restrictors of second stage

The paper approaches the gas-dynamic phenomena that occur when the gas flows through the second stage reducer, respectively: the variable restrictor A (between the seat and the poppet tube) and the fixed restrictor B (the orifice of cylindrical piston). Mathematical modeling of potential air flow through the restrictors of breathing apparatus was made following the notions of the theory of the potential flow of gases through tubes and nozzles. [1] The two restrictors can be considered Laval nozzles.
For the study we established a simplified model of a classic downstream flow regulator, in which we took into account 2 versions. In the 1st version the fixed restrictor B is cylindrical and in the 2nd version the fixed restrictor B is a conical nozzle. The variable area of the restrictor A is critical, the flow is also critical. The variable restrictor A is a convergent-divergent nozzle (Laval). The flow is stationary and turbulent. When the gas passes through the minimum section, it reaches critical speed and the pressure drops. Due to this difference between the critical pressure p_c and the outlet pressurep_e, an expanding gas jet is formed, which passes through a shock wave system. The minimum section in which the critical speed is reached is the critical sectionA_c, all the parameters involved are critical. [2]
Respiratory gas is air. The supply parameters of the second stage regulator have average values, respectively:
$p_m = 9.5 \cdot 10^5[Pa]$ – medium hose pressure
$p_b[kg/m^3] = 150 \cdot 10^5[Pa]$ – cylinder pressure
$\rho_m[kg/m^3]$ – medium density of the air in the hose
$k = 1.4$ - adiabatic index of air
$T_b = 293K$ - cylinder temperature
For an adiabatic and isentropic evolution, we determined the air density at the storage pressure:

$$\rho_b = \frac{p_b}{RT_b} = \frac{150 \cdot 10^5}{287 \cdot 293} = 178.37[kg/m^3] \quad (1)$$

The Reynolds number at the A variable restrictor is:

$$Re = \frac{\rho_b w d}{\eta} \quad (2)$$

w $[m/s] = 290m/s$ - air velocity in the critical area [1]
d $[m] = 0.005m$ – inner diameter of the cylinder
$R = 287[\frac{J}{kgK}]$ - air constant
$\eta = 1.745 \cdot 10^{-10}[Ns/m^2]$ - dynamic viscosity, μ, at 20℃ [3]
$Re = 10^{10} \rightarrow$ the flow is turbulent at restrictor.

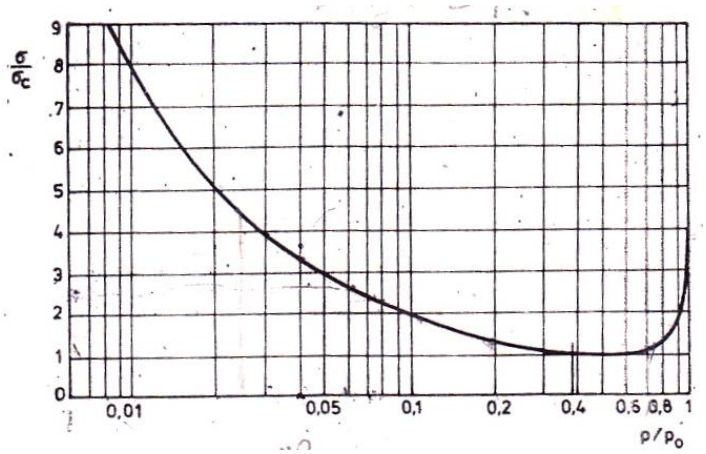

Figura 2 Diagram of pressures distribution [2]

The 1st version with the cilindrical orifice to the thin-walled piston, the B fixed restrictor
Knowing A_f, the area of the admission orifice, from the diagram (Fig. 2), results the area of the critical section, $A_c = 10.9 \cdot 10^{-6}[m^2]$, for the restrictor A. Piston displacement, for $\Delta p = 5 \cdot 10^2[Pa]$, opening differential pressure is x= $0.0007[m]$ at the restrictor A, for the critical pressure. [1]
In the critical section, the maximum mass flow $\dot{m}_c[kg/s]$ is reached, according to the continuity equation for a current tube [4].

$$\dot{m}_c = \rho_c A_c c \tag{3}$$

$\dot{m}_c$, critical maximum flow

ρ_c , density in critical conditions , respectively ρ_c, p_c, T_c .

A_c , restrictor's area in critical conditions, respectively ρ_c, p_c, T_c .

c, sound's speed in critical conditions, respectively ρ_c, p_c, T_c .

In a previous paper the maximum airflow was calculated for an ideal thermodynamic process, in which the flow rate coefficients through the two restrictors are:
$\alpha_{1t} = \alpha_{2t} = 1$
The calculated theoretical mass flow remains constant for this geometry and it is: [5]

$$\dot{m}_{t1} = \dot{m}_{t2} = \left(\frac{2}{k+1}\right)^{\frac{1}{2}\left(\frac{k+1}{k-1}\right)} \cdot \sqrt{k} \cdot A_c \cdot \frac{p_m}{\sqrt{RT_m}} = 0.025[kg/s] \tag{4}$$

For the 1st version, with the cilindrical orifice at the B fixed restrictor, the real flow rate coefficient is: $\alpha_{1r} = 0.7$.
Real flow for the 1st version at $\Delta p = 5 \cdot 10^2[Pa]$ is:

$$\dot{m}_1 = \dot{m}_2 = \alpha_1 \dot{m}_{t1} = 0.7 \cdot 0.025 = 0.0175[kg/s] \tag{5}$$

Piston displacement for $\Delta p = 6 \cdot 10^2[Pa]$ opening differential pressure is x= $0.0008[m]$ at the restrictor A, for the critical pressure. Critical area is $A_c = 12.6 \cdot 10^{-6}[m^2]$.
Real flow for the 1st version at $\Delta p = 6 \cdot 10^2[Pa]$ is:

$$\dot{m}_1 = \dot{m}_2 = \alpha_{2r} \dot{m}_{t1} = 0.8 \cdot 0.025 = 0.020[kg/s] \tag{6}$$

The 2nd version with a conical orifice at the B fixed restrictor
At $\Delta p = 5 \cdot 10^2[Pa]$, the theoretical mass flow is the one calculated for the 1st version, the geometry of the restrictor A is unchanged, as well as the flow conditions.
$\dot{m}_{t1} = \dot{m}_{t2} = 0.025[kg/s]$
The flow rate coefficient changes at the fixed restrictor B, for $d = 6 \cdot 10^{-3}[m]$: $\alpha_{2r} = 0.8$
The real mass flow for the 2nd version at $\Delta p = 5 \cdot 10^2[Pa]$ is:

$$\dot{m}_1 = \dot{m}_2 = \alpha_{2r} \dot{m}_{t1} = 0.8 \cdot 0.025 = 0.020[kg/s] \tag{7}$$

For $\Delta p = 6 \cdot 10^2[Pa]$, the critical area is $A_c = 12.6 \cdot 10^{-6}[m^2]$, resulting diplacement x= $0.0008[m]$
The theoretical mass flow is:

$$\dot{m}_{t1} = \dot{m}_{t2} = \left(\frac{2}{k+1}\right)^{\frac{1}{2}\left(\frac{k+1}{k-1}\right)} \cdot \sqrt{k} \cdot A_c \cdot \frac{p_m}{\sqrt{RT_m}} = 0.029[kg/s] \quad (8)$$

The real mass flow for the 2nd version at $\Delta p = 6 \cdot 10^2[Pa]$ is:

$$\dot{m}_1 = \dot{m}_2 = \alpha_{2r}\dot{m}_{t1} = 0.8 \cdot 0.029 = 0.023[kg/s] \quad (9)$$

3. CFD (Computational Fluid Dynamics) simulation of the flowair trhougt the restrictors of second stage regulator

For a comparative analysis of the theoretical results, we proceeded to the second method of studying the turbulent flow of respiratory gas through the studied pneumatic mechanisms: CFD (Computational Fluid Dynamics) simulation. Anssys Fluent is a general purpose numerical finite element modeling package that solves a wide range of mechanical computational problems. These problems include dynamic, structural analysis (both linear and nonlinear), heat and fluid transfer. [6]
CFD simulation is a modern method, that allows the calculation to be resumed on several models of nozzles and with changing flow conditions, so as to reach an ideal shape. In order to establish the favorable geometric conditions for reducing the external respiratory resistances of the breathing apparatus, we used all 5 parts of the program, respectively: Geometry, Meshing, Setting, Solution and Results. [7]
The program used results in a wider view of the variation of several physical sizes: pressure, density, velocity, mass flow.
We obtained the geometry of the fluid that goes through the two constructive variants and we made the meshing of these two models.
The imposed conditions have been set:

- turbulent and stationary flow (viscous);
- environment: fluid compressible air and its properties;
- variable density with pressure;
- the absolute inlet pressure imposed: $9.5 \cdot 10^5[Pa]$;
- the differential pressure imposed: $\Delta p = 5 \cdot 10^2[Pa]$.

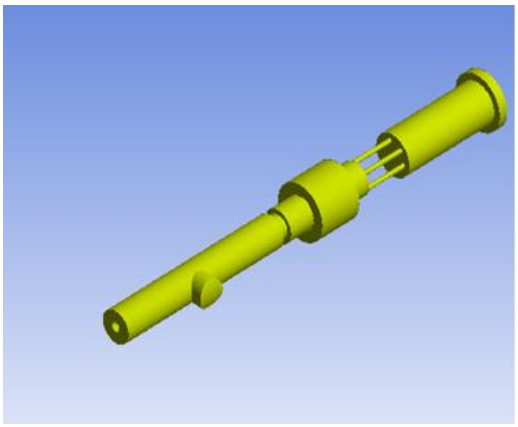

Fig. 3 The mass airflow rate for the *1st version* [8]

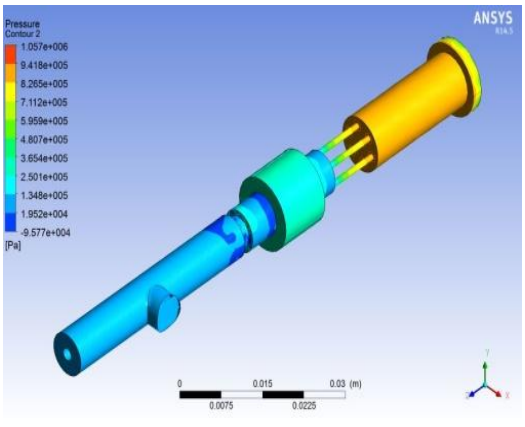

Fig. 5 Distribution of pressures in *1st version* [8]

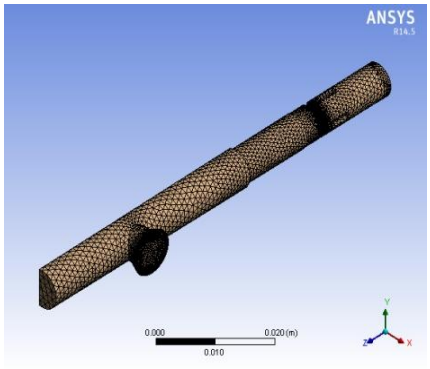

Fig. 4 Meshing of the mass airflow rate for the *2nd version* [8]

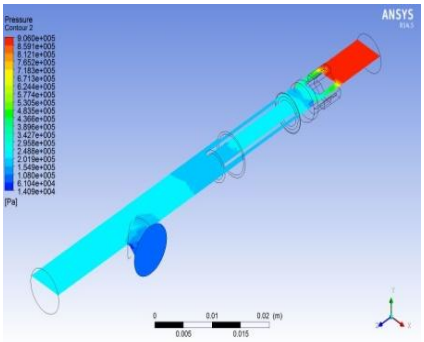

Fig. 6 Distribution of pressures in *2nd version* [8]

In both variants (cylindrical orifice and conical orifice), the sudden drop in pressure when passing through restriction A is very well observed, a fall which is specific to the Laval nozzle (see Figure 5 and Figure 6).

Anssys Fluent also allows the calculation of mass flows. The mass airflow is constant, for the same flow conditions at the same device. It depends on the opening of the restrictor A (in this case we set x = 0.7mm constant, for all the chosen constructive versions) and on the area of the fixed restrictor B.

The mass airflows calculated with Anssys Fluent are:

$\dot{m}_1 = 15.225 \cdot 10^{-3}[kg/s]$ for ***the 1st* version**, with cylindrical area ($d = 5 \cdot 10^{-3}m$)

$\dot{m}_2 = 16.433 \cdot 10^{-3}[kg/s]$ for ***the 2nd version***, with conical area ($d = 6 \cdot 10^{-3}m$).

4. Experimental validation of the potential mass airflows through the two versions of diver's breathing apparatus

The experimental verification was made at the Hyperbaric Laboratory of the Diving Center, for the two versions of the pressure regulator in Figures 7 and 8, at the professional Scuba Tools tester in Figure 9.

Fig. 7 *The 1st* version piston with cylindrical orifice [8]

Fig. 8 *The 2nd version* piston with conical orifice [8]

Fig. 9 Second stage regulator testing [8]

The supply of the tested devices was made from a bottle with $150 \cdot 10^5 Pa$, reduced to the average pressure in the hose measured p_m =9.5· $10^5 Pa$. The differential opening pressure was increasing $(1 + 6) \cdot 10^2 Pa$. It was measured on the differential manometer of the stand; we noted the volume airflow $\dot{V}$, recorded at the flow meter, corresponding to the differential pressures of 5· $10^2 Pa$ and 6· $10^2 Pa$ respectively. The masse airflow $\dot{m}$ $[kg/s]$ is:

$$\dot{m} = \rho \cdot \dot{V} \tag{10}$$

The values of the mass flows calculated on the basis of the measurements made are found in Table 1, chapter 5.

5. Results obtained and final conclusions

Table 1 Numerical air flow values calculated numerically, by CFD simulation and experimentally verified

	Debit masic $\dot{m}$ $[kg/s]$			
Calculation method	**The 1st version cylindrical orifice**		**The *2nd version* with conical orifice**	
	Δp =5· $10^2 Pa$	$\Delta p = 6 \cdot 10^2 Pa$	Δp =5· $10^2 Pa$	$\Delta p = 6 \cdot 10^2 Pa$
Numerical calculus	17.5*10^{-3}	20*10^{-3}	20*10^{-3}	23*10^{-3}
CFD Simulation	15,225*10^{-3}		16,433*10^{-3}	
Experimental verification	10,2*10^{-3}	11.3*10^{-3}	11,9*10^{-3}	12.7*10^{-3}

It can be concluded:

- 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 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.

Breathing gas flow modeling by the pressure regulators mechanisms of diver's apparatus, with CFD - ANSYS Fluent, has been shown to be useful in the ergonomic study of the design of devices used by divers. The simulation can also be resumed under operating conditions at required immersion depths (various outlet pressures).

The knowledge of the respiratory flow of gas in various situations, through the geometric study of the constructive versions, completes the possibility of controlling the physical and physiological phenomena involved.

The theoretical and experimental results obtained can be the basis for the elaboration of a program for periodic verification and adjustment of the pressure regulators in the divers' equipment.

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