Solving the Problems of Gas Flow External Resistance through the Breathing Apparatus of Divers using Computational Fluid Dynamics *(Tamara Stanciu, Andrei Scupi, Dumitru Dinu)*	“Cercetări Marine“ Issue no. 47 Pages 249-259	2017

SOLVING THE PROBLEMS OF GAS FLOW EXTERNAL RESISTANCE THROUGH THE BREATHING APPARATUS OF DIVERS USING COMPUTATIONAL FLUID DYNAMICS

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ABSTRACT

The resistance to inhaling is the highest gas flow external resistance through the second stage respirator. The simplest formula for determining external resistance to inspiration is the one obtained by dividing the inhalation depression to the volume flow of gas. It can be influenced by the geometric factors of the device. We checked the variation of the gas volume flow in three design variants of the gas inlet in intake mechanism of the second stage pressure regulator by simulation with Computational Fluid Dynamics. We made the geometric modeling of three variants. After the meshing of the obtained fluid models, the required flow conditions were set. The mass flow rate, the gas density at the outlet of the pressure reducing mechanism and the fluid velocities were calculated. For the same flowing conditions and the same inhalation depression, we determined the external resistances in three chosen geometric variants of the gas intake mechanism. It can be concluded that the best shape of the inlets in the intake seat in second stage regulator is that of variant 1 with the circle section. For the piston, the recommended air flow direction port is that of variant 3 with conical section. To optimize gas flow through the restrictor, in the design of the breathing apparatus, we recommend that the inlet mechanism geometry be in variant 1, with 6 cylindrical slots, but the hole in the piston body to be conical, as in variant 3. Using Computational Fluid Dynamics we can run other simulations with different geometrical characteristics until we obtain an optimal shape.

Key-Words: external resistance, Computational Fluid Dynamics, gas flow simulation

AIMS AND BACKGROUND

Breathing in the underwater environment is influenced by the increase in environmental pressure, where the respiratory gas is delivered by the diver's breathing apparatus. The gas becomes denser and the flow resistance increases when passing through the pressure reducer mechanism. The solution of avoiding adverse effects caused by increasing breathing resistance in the underwater environment is to obtain the optimal geometric shape of the pressure reducer mechanism.

The purpose of the paper is to identify, by simulating the flow of the respiratory mixture with Computational Fluid Dynamics, the geometric shapes of the gas inlet mechanisms that reduce the respiratory resistance.

A second stage pressure regulator as schematically represented in Figure 1 takes up the intermediate pressure from the first stage and reduces it to ambient pressure, pressure at which the diver can breathe without causing a physiological incident. When the diver inhales, the pressure inside the second stage decreases, causing a diaphragm to depress and actuate a lever. This lever opens the valve allowing air to come into the second stage and to the diver. When the diver exhales, the diaphragm is extended and the exhaled gas leaves the second stage through exhaust ports located at the bottom of the second stage. The pressure needed to move the lever into the open position is called the cracking pressure. The lower the cracking pressure the less breathing resistance is felt by the diver.

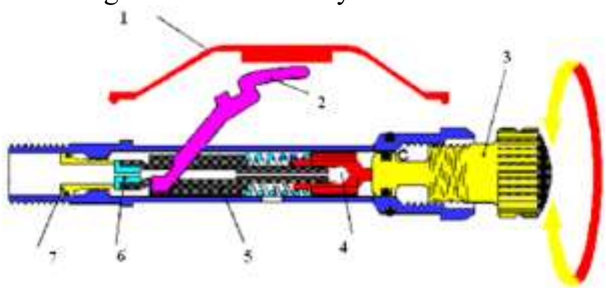

Fig. 1. Operating of a second stage regulator with cracking resistance control.

1. Diaphragm
2. Lever
3. Cracking resistance control
4. Counter balance cylinder
5. Poppet valve
6. Rubber seating
7. Seat

Regulators are tested in USA using the National Agency for Science, Technology and Innovation (ANTSI) testing system. This system evaluates regulators on human breathing simulation, scientific repeatability, test time, and complexity. Regulators are tested at several different breathing rates thus testing the regulator at different tidal volumes as well. The different breathing rates and volume are referred to as the RMV or respiratory minute volume. This RMV is measured in liters per minute. The amount of energy expended by a diver is measured in joules per liter, for 1 litre of respiratory air, known as the work of breathing or WOB.

Each manufacturer will test a regulator at their own chosen RMV. The results are generally compared to the goal set by the US Navy. The Navy prefers regulators that perform with a work of breathing at 1.3 [J/l] or less when breathed at 62.5 [l/min] RMV at 40 – 60 [mH_2O] using a $10.3 \bullet 10^6$[Pa] supply pressure.

We chose to study an unbalanced regulator Super Physalie, whose intake mechanism is represented in Figure 2.

The motion law of the mechanism is:

$$x = \frac{b}{B} s \quad (1)$$

x – piston opening

b, B - from the lever geometry

s – lever displacement

The functional feature of a breathing apparatus is the volume flow curve - the inhale depression. Each respirator is accompanied by the delivery of this characteristic, determined in terms of normobaric pressure. The theoretical curve has a profile similar to that in Fig. 3. As we can see the increase of the inhaled depression, the volumetric flow also increases, which when reaching a maximum value is blocked at this value under the conditions of constant normobaric pressure.

Deviations of this curve from its original shape also implicitly influence breathing resistance of the device. The functional feature changes under hyperbaric conditions. At the same inhaled depression value, the same device delivers respiratory gas at a volumetric flow different from the surface and depending on the environmental pressure (dive depth).

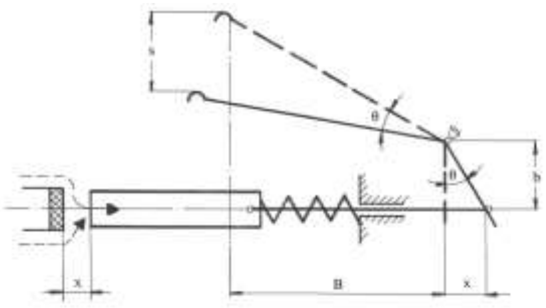

Fig. 2. Intake mechanism of the second stage regulator Super Physalie.

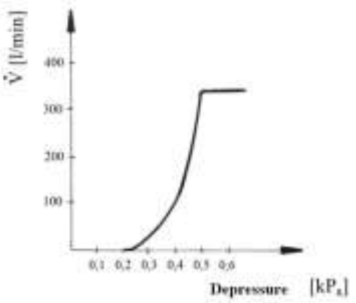

Fig. 3. Functional characteristic of the regulator in normobaric pressure.

As the absolute pressure of the medium increases, the density of the breathing gas increases and there is pressure loss on the circuit, losses which increase the external resistance and decrease the volume flow delivered by the apparatus to the same inhaled depression.

Breathing apparatus have in their geometry variable section restrictors classified into two large groups

a. With downstream opening (the gas flow direction and the section increasing are same), such as Super Physalie;

b. With upstream opening (the direction of gas flow is opposite to the section increasing).

This variable section restrictor is a convergent-divergent nozzle (Laval), whose role is to reduce the pressure of the feed gas. When passing through the minimum section, gas reaches critical speed and pressure drops. Due to this difference between the critical pressure and the outlet pressure, an expanding gas jet with variable pressure is formed through a wave system.

It is useful to study the flow through the Laval nozzle. The minimum section at which critical speed is reached, is the critical section and all the parameters involved are critical:

$V = a = c$, the speed of sound under critical conditions, ρ_C, p_C, T_C.

In the critical section, the maximum mass flow rate is reached and according to the continuity equation for a current tube in the permanent movement of a compressible fluid, the mass flow will be constant in any section of the tube.

$$\dot{m}_c = \rho_c \sigma_c c = \dot{m}_0 = \dot{m} \quad (2)$$

The distribution of speeds and pressures through the Laval nozzle is very well presented in Fig. 4

At pressure regulators, the variable restrictor is an orifice whose geometry causes the pressure drop and, implicitly, breathing resistance.

The external resistance to breathing that most influences the flow through the second stage respirator is resistance to inspiration. The simplest formula for determining external resistance to inhale is the one obtained by dividing the inspired depression Δp_E into volume flow $\dot{V}$.

$$R_E = \Delta p_E / \dot{V} \quad (3)$$

The external resistance to breathing, induced by the second stage of regulator, at the gas flow is influenced by the geometric factors of the device:

- Inner diameters
- The shape of the intake ports
- Law of movement of intake mechanisms

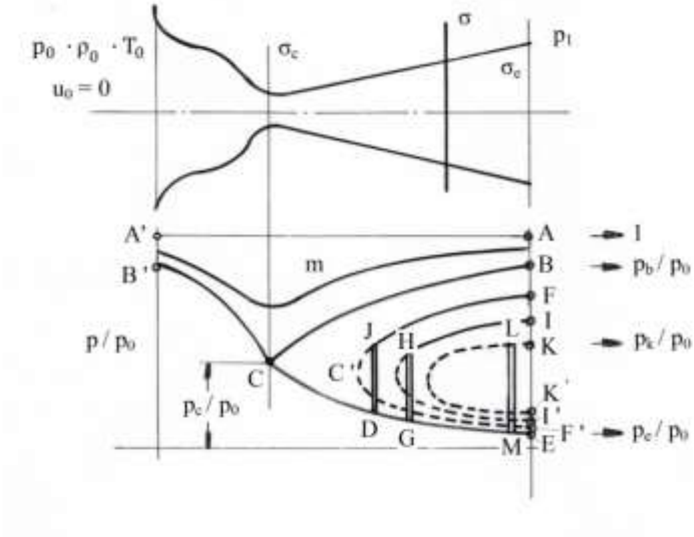

Fig. 4. Pressure distribution through the Laval nozzle.

Our study refers to the influence of the geometric shape of the intake ports of the breathing apparatus by simulating the flow of the respiratory mixture with Computational Fluid Dynamics.

EXPERIMENTAL

The constructive variants of respiratory gas intake mechanisms chosen for the study

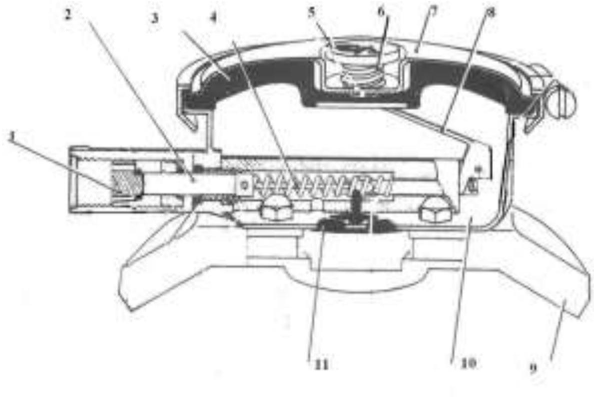

Fig. 5. Super Physalie regulator with downstream opening
1. Mobile intake seat 2. Poppet 3. Diaphragm.

Flow variations in several scenarios for changing the inlet of the gas intake mechanism can be determined by simulating potential flow through the ANSYS

Fluent program. The holes can be modified both dimensionally and in shape. We used the Super Physalie regulator in Fig. 5.

Variant 1 is the original intake mechanism of Super Physalie regulator, with a six-hole seat in the same circle (Fig. 6) and cylindrical piston gas outlet (Fig.7)

Variant 2: I replaced the six intake of the seat with four other equidistant ones, placed on the same circle, but with the square section 1x1 (Fig.8). The hole in the piston remained unchanged (Fig. 7).

Variant 3: The intake seat is the one with 4 equal holes of square section 1x1 (Fig. 8). The piston gas direction of the piston is conical (Fig. 9)

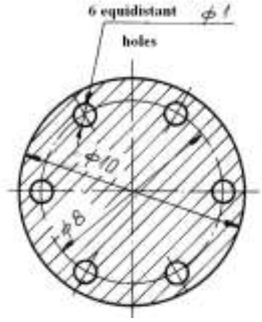

Fig. 6. Intake seat section variant 1.

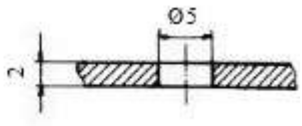

Fig. 7. Cylindrical piston hole section variants 1 and 2.

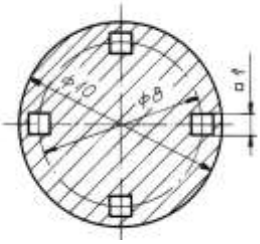

Fig. 8. Modified seat section, variants 2and 3.

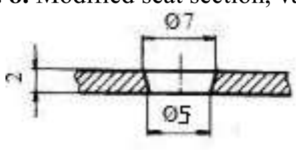

Fig. 9. Conical piston hole section variant 3.

RESULTS AND DISCUSSION

Solving the problems of external resistances in gas flow through the breathing apparatus of divers with Computational Fluid Dynamics program ANSYS Fluent.

We used all 5 parts of the ANSYS Fluent program, namely: Geometry, Meshing, Setting, Solution and Results, to determine the geometric conditions favorable to the reduction of external respiratory resistances.

We modeled each of the three variants of the mechanism, starting from the original model.

After the modifications made for variant 2 and for variant 3, we separated the three mechanisms. (Figure 11 for variant 1, Figure 12 for variant 2, and Fig 13 for variant 3)

Using operations specific to ANSYS Fluent, we simulated a cylindrical air stream to embrace these mechanisms and then remove them from the mechanisms (the Substract command). In this way we obtained the geometry of the fluid whose pressure is reduced in the three variants. (See Fig. 14 and 15)

We went to step two, meshing (see Fig. 16 for version 3).

We have established flow conditions:

1. Opening the piston x=1 [*mm*]
2. Inhale depression $\Delta p = 5[cmH_2O]$
3. Input pressure imposed $p_i = 9[bar]$
4. Output pressure $p_e = 1[bar]$
5. Respiratory gas: compressed air

The finer the mesh used the better the results are (see Fig. 17 for variant 2).

The results obtained were highlighted with the last part of the program, in the sections of interest, input and output, but also in planes parallel to the original coordinate axes. By simulating with the ANSYS Fluent software, we have suggestively showed the pressure, speed and density distributions in the sections of interest of the chosen constructive variants.

In version 1 (Fig. 18), the inlet pressure through the critical section passes from the range 9*10^5 Pa, after the restrictor to 1.5*10^5 Pa and a return to 4*10^6 Pa. At the piston outlet the pressure is 1.5*10^5 Pa.

In variant 3 (Fig. 19), the inlet pressure through the critical section passes from the field 9 * 10^5 Pa after the restrictor to 3 * 10^5Pa. There is a marked drop in pressure on the plunger contour after the area of the O-ring, 10^5 Pa and then a slight return to 2.5 * 10^5 Pa. The pressure is 10^5Pa at the outlet through the conical opening.

In variant 1 (Fig. 20) the speeds have a similar evolution, from 300 m / s at the entrance, to about 100 m / s at the exit. But when passing through the restrictor, a transient pass is made to the supersonic regime, specific to the Laval nozzle.

In Fig. 21 speeds are decreasing to the exit and have a substantial nonhomogeneity on the output contour, between 140 - 20 m / s.

For variant 3, the track of the gears is shown in Fig. 22. The velocity values are supersonic to the restrictor and subsonic (200-100 m / s) on the output contour.

Evolution of densities for variant 3 is shown in Fig. 23: between 9 [kg / m3] at input and 1.4 [kg / m3] at the outlet.

The mass flow is constant for the same flow conditions at the same apparatus. It depends on the opening of the restrictor (in this case we set x = 1mm constant for all three constructive variants chosen). Mass flows calculated with ANSYS Fluent are:

$Q_m = 5{,}225 \bullet 10^{-3}[kg/s]$ – for variant 1,

$Q_m = 3{,}13 \bullet 10^{-3}[kg/s]$ – for variant 2,

$Q_m = 4{,}44 \bullet 10^{-3}[kg/s]$ – for variant 3.

Knowing the mass flow, we calculated the volume flow

$$\dot{V} = Q_m / \rho[l/\min] \quad (4)$$

For each case, we calculated the external resistance at the piston outlet, with formula (3).

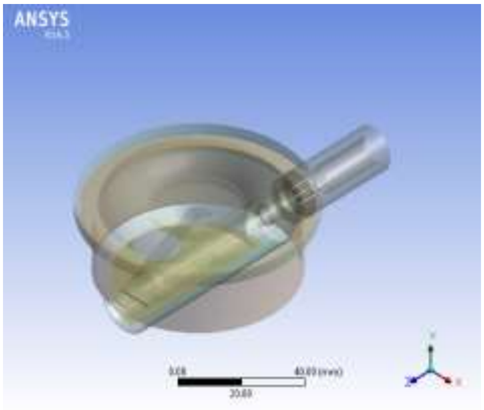

Fig. 10. Low pressure chamber of second stage Super Physalie.

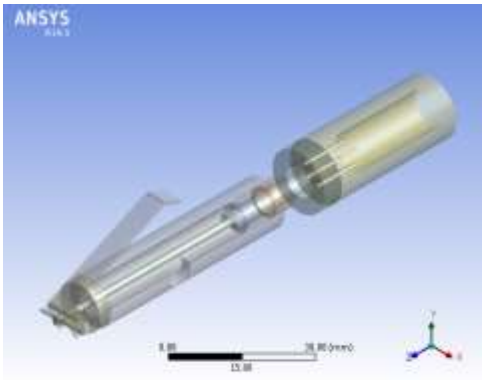

Fig. 11 Intake mechanism of variant 1 Super Physalie.

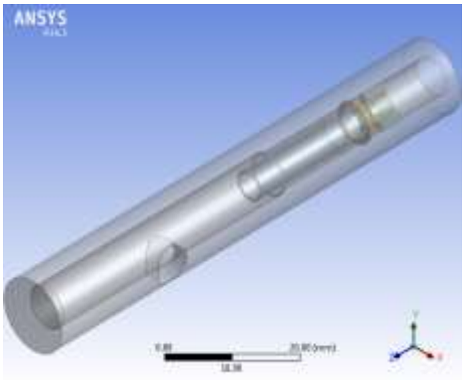

Fig. 12. Intake mechanism of variant 2.

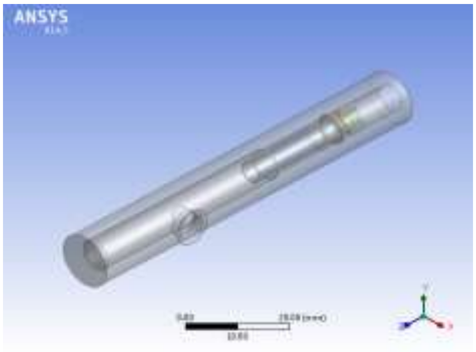

Fig. 13. Intake mechanism of variant 3.

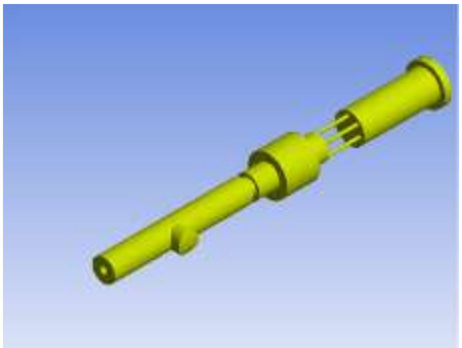

Fig. 14. Geometry of the air for variant 1.

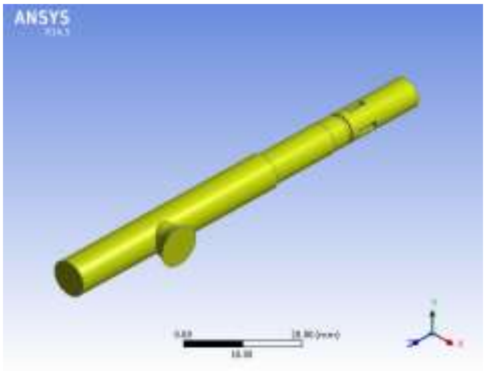

Fig. 15. Geometry of the air for variant 3.

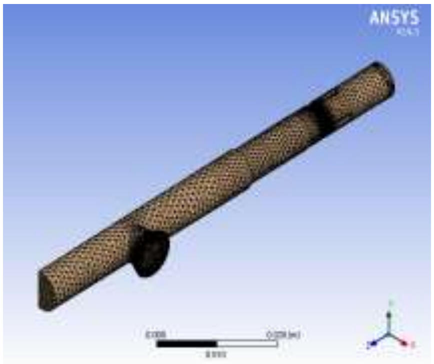

Fig. 16. The air circuit mesh in the intake mechanism for variant 3.

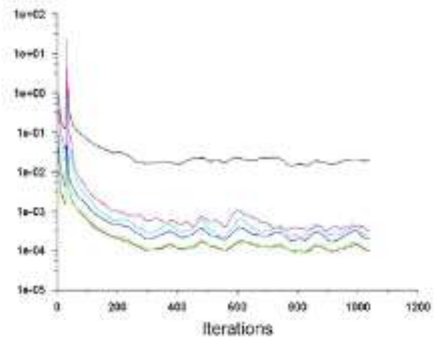

Fig. 17. Convergence of solutions for Variant 2 to 1000 iterations.

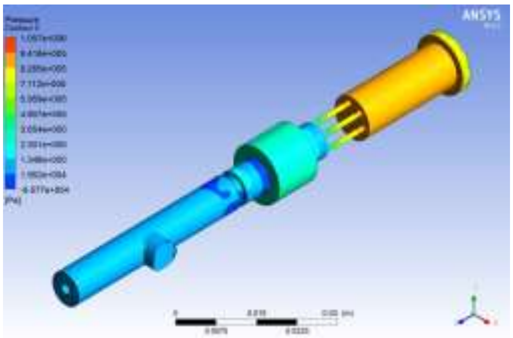

Fig. 18. Distributions of pressures on contour for variant 1.

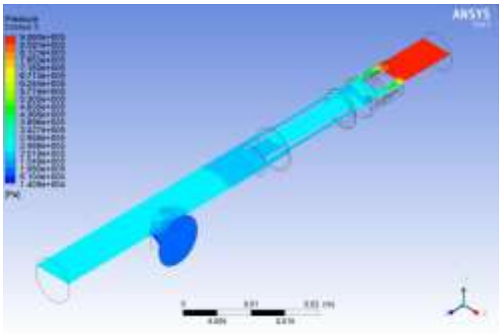

Fig. 19. Distributions of pressure on the contour, in a plane parallel to pl xz variant 3.

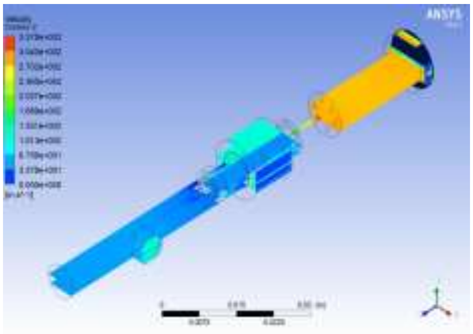

Fig. 20. Distributions of air speed in two planes parallel to pl xz, variant.

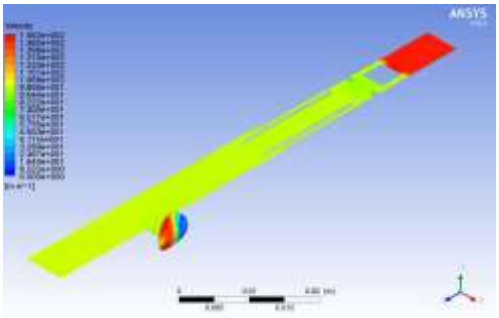

Fig. 21. Distributions of speed in a plane parallel to pl xz and to the air outlet, variant 2.

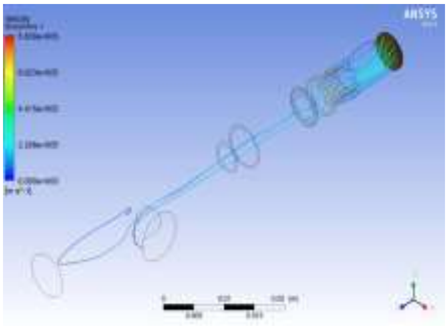

Fig. 22. Speed lines in a plane parallel with pl yz variant 3.

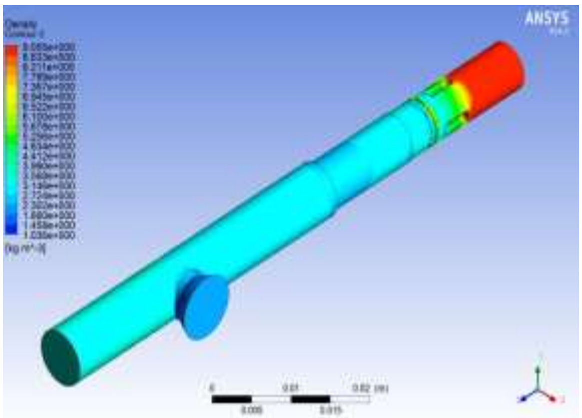

Fig. 23. Distributions of densities on contour and to the air outlet, variant 3.

CONCLUSIONS

Table 1 compares the results obtained for external inspiration resistance by simulating the flow through the three geometric variants of the pressure regulator intake mechanism under the same conditions.

The maximum values accepted in the literature for these resistances and measured at the outlet of the mouthpiece are up to $9-12[cmH_2O/(l/s)]$. The best external resistance is that of the original device, version 1.

Table 1. The results obtained for the external resistance to the inhale, by simulating the flow through the three geometric variants of the piston inlet mechanism.

Variant	$Q_m[kg/s]$	$\rho[kg/m^3]$	$\dot{V}[m^3/s]$	$\Delta p[cmH_2O]$	$R_E[cmH_2O/(l/s)]$
				$\Delta p[Pa]$	$R_E[Pa/(m^3/s)]$
Variant 1	$5{,}225\cdot 10^{-3}$	2,842	$1{,}84\cdot 10^{-3}$	5	2.72
				490.33	$266.74\cdot 10^3$
Variant 2	$3{,}133\cdot 10^{-3}$	2,418	$1{,}294\cdot 10^{-3}$	5	3.86
				490.33	$378.54\cdot 10^3$
Variant 3	$4{,}445\cdot 10^{-3}$	2,724	$1{,}63\cdot 10^{-3}$	5	3.07
				490.33	$301.06\cdot 10^3$

Observing the results obtained in Figures 10-23 and Table 1, one can conclude:

- The best shape of the holes in the intake seat is 6-point, equidistant, small diameter ($\phi = 1mm$)
- For the piston, the recommended airflow port is the conical one.

To optimize gas flow through the restrictor, in the design of the respirator, it is recommended that the geometry of the mechanism be with the 6 cylindrical slots on the intake seat as in variant 1 but the hole in the piston body be conical, as in variant 3. The simulation will be resumed in the ANSYS Fluent program in this geometric variant 4 and if the calculated external resistance is lower, experimental determinations will be made on a test stand to validate the theoretical results.

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