FINITE ELEMENT ANALYSIS AND EXPERIMENTAL VALIDATION OF A NOVEL OXYGEN PRESSURE REGULATOR

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ABSTRACT: A regulator is designed and analyzed in the current paper for medical use in oxygen production centers. The conceptual design procedure starts with a research in the main elements, the operating principles of a pressure regulator and the existed technologies. The sizing guidelines and the important calculations that have to be made are also discussed. The regulator is designed and simulations take place in order optimize the design of the regulator. Stress analysis results are presented for the main body of the regulator, as well as, flow analysis to determine some important flow characteristics in the inlet and outlet of the regulator. Experimental validation takes place in order to monitor the specifications of the regulator in real time working conditions and compare them with the simulation results.
KEY WORDS: Pressure Regulator, Finite Element Analysis, Optimization, Stress Analysis, Flow Simulation.

1 INTRODUCTION

Originally, pressure regulator is principally a device that is used to reduce higher pressures of gasses or liquids to a more usable lower pressure. Its main function is to reduce a pressure and to keep this pressure as constant as possible while the inlet flow may differ. A regulator's exactitude and prowess in performing its function is determined by the combination of the four basic regulator components, designed into a specific regulator unit (loading mechanism, sensing element, control element, and relief valve). These components have to be designed according to mathematical guidelines, so that they work together harmoniously to give the desired results. Calculations are not only necessary for the good order of the regulator but also for the endurance in high pressures and the flow characteristics of the mean (Granger, 1995).

There is no much information published on pressure regulators due to the disquiet for leakage of proprietary knowledge. Zafera and Lueckeb studied the stability of gas pressure regulators (Zafera & Lueckeb, 2008). Their research investigated the consolidation of a concrete implementation of pressure reducer system. Areas such as palpitation in regulators and possible design amendments are presented that expunge the not steady throb modes. Kato et al. also investigated pressure regulators with high accuracy having quick response in pressure fluctuations (Kato et al., 2010).

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An effective adjustment of pneumatic palpitation isolation tables was presented. A regulator assembly was designed by the authors and the greatest characteristic of their design was the almost zero changes of pressure in the chamber that was detected by the transducer which changes the position of the servo valve, to preserve the initial pressure.

In another study, Kakulka et al. studied a pressure regulator having a piston as a sensing mechanism (Kakulka et al., 1994). The sensing mechanism consisted of a conical poppet piston-valve that adjusted the flow of the mean. The study dealt with the energetic results of limitative orifices and the upstream-downstream areas of the regulator. However, the friction and pendulousness effects inside the areas of the body of the regulator, were not taken into account in their research. Liptak also reports on the changes in the exit pressure by creating fluctuates in the supplied flow (Liptak, 1995). The author reports that any decrease in the fluctuations of the pressure abridges the consistency of the output of the regulator. This had as result, the regulator to make a lot of noise when it worked with oscillatory pressure cycling. For stabilization, a larger downstream pipe is recommended. Also, the noise was eliminated by expunging the fluctuations of the flow routes and keeping the flow of the mean at speeds not exceeding supersonic speed.

In this study, a new pressure regulator is developed and designed. The static behavior and the flow characteristics were determined through finite elements. More precisely calculations were made for the stress contribution in the main body of the regulator and additionally a flow analysis in order to determine some important flow characteristics in the inlet and outlet of the regulator.

2 PRESENTATION OF THE DEVELOPED CONCEPT

The pressure regulator that was developed was designed to be used in medical gas networks thus the primary flow mean is oxygen. Pressure regulator has been designed according to ISO: 9001 – ISO: 13485 for medical gas systems components. The developed model had to meet with some basic important requirements. The flow mean is oxygen, the inlet pressure is 200bar because this is the pressure that usually used in the gas-cylinders of the gas networks of hospitals. The outlet pressure has to be 10bar, because this is the inlet of the 2nd stage (of pressure reduce) gas stations, so then the O_2 can be used by patients. Every patient consumes about $0.42m^3/h$ O_2, so the maximum flow at 200bar should be over $200m^3/h$ for a large hospital.

Figure 1 presents the pressure regulator made of brass that was developed with explanation of the important spots. In Figure 1, the loading mechanism denoted with (1) is a spring-load mechanism. The spring is controlled by a plastic spigot on the top of the dome of the regulator. In the dome designed a small hole for extra safety, in case that high pressure goes accidentally to low pressure chamber and brakes the diaphragm. The sensing element denoted with (2) is a diaphragm from elastomer material (Ethylene Propylene) for sensitivity to pressure changes, simplicity and low cost. The control element denoted with (3) is an overpressure protection system developed to avoid the possibility of overpressure of the inlet pressure chamber. For this reason, a tiny hole was designed in the bottom of the pressure regulator. The working principle is based on the fact that for a certain amount of pressure the control element will cause the poppet to fracture the orifice. By this movement of the poppet the down exit is released and the compressed gas is getting out avoiding failure of the regulator. The safety valve denoted as (4) in Figure 1 was designed to protects the regulator from possible failure. In the case that the high-pressure passes from the high pressure chamber to the low pressure chamber, the spring of the valve is compressed in order to relief the extra pressure. Also certain slots for manometers and transducers were designed and denoted as (5) in Figure 1.

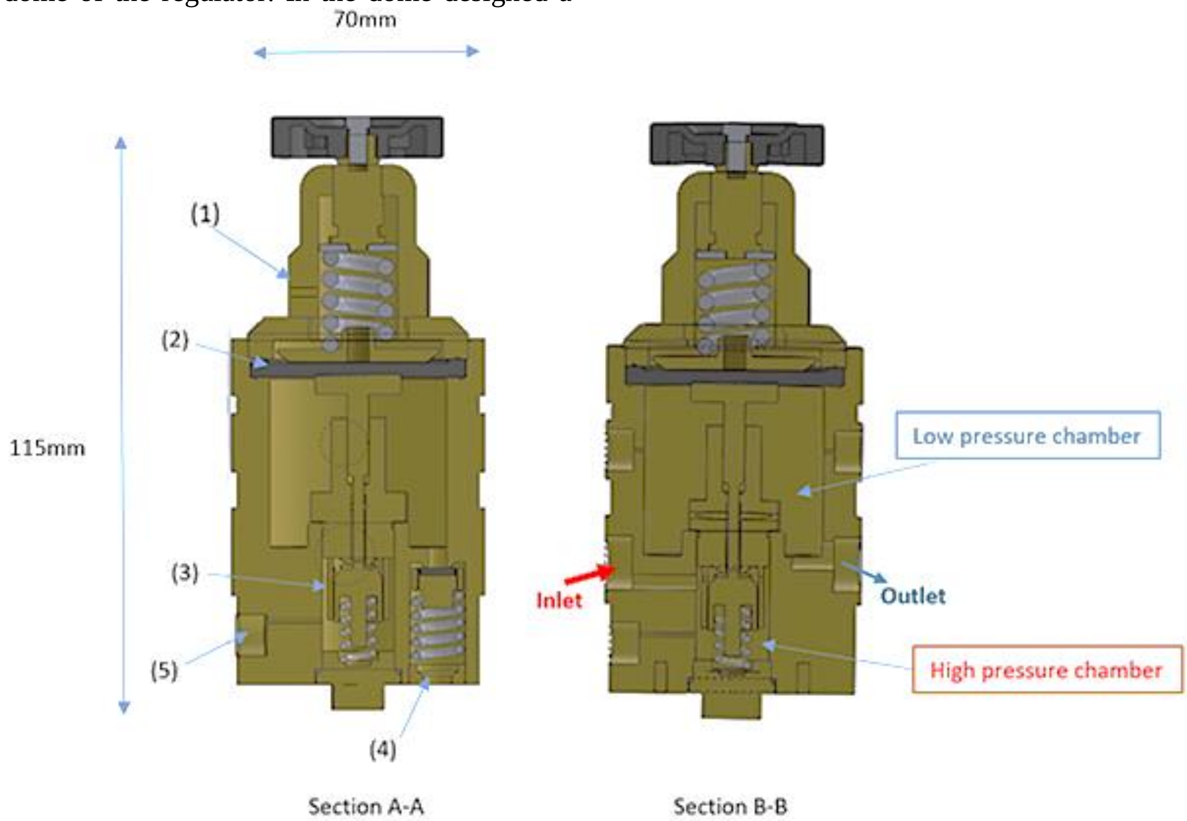


Figure 1. Intersections showing internaly the design of the pressure reducer

3 DESIGN SIMULATION

3.1 Stress analysis

The stress analysis was performed using finite element modeling. For the static analysis the internal chamber of the body of the regulator is set on high pressure. The purpose of the analysis was to show if the regulator can withstand a high gas pressure. The maximum pressure that is supposed to be applied in the regulator is 200bar. For safety reasons the regulator was simulated under a pressure of 300bar. The material that have been used for the analysis was brass having tensile strength of 0.478N/m^2, yield strength 0.239N/m^2, elastic modulus 1010N/m^2, shear modulus $34{\cdot}10^9$ N/m^2 and Poisson's ratio 0.33.

The boundary conditions that have been used for the analysis are shown in Figure 2. For the analysis 21747 nodes and 13047 elements have been used. The results have shown that the maximum stress that is applied inside the regulator is 1.07N/m^2 which is much lower than the yield strength of the material and the maximum displacement 0.012 mm. Figure 3 shown the stress and strain contours of the analysis. It should be noted that the applied pressure in the study was already higher than the pressure, thereby the results are somewhat conservative.

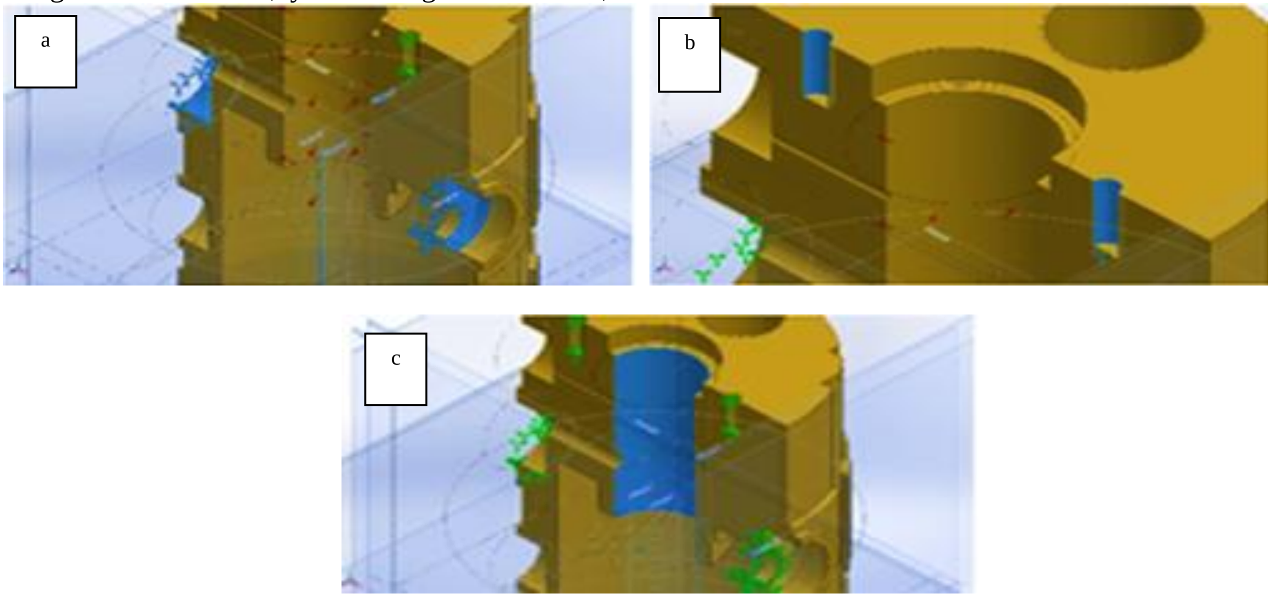


Figure 2. Boundary conditions used for the stress analysis of the pressure reducer with a) Fixes Inlet and outlet connections b) Botom is fixed with screws c) Chamber under high pressure (300bar)

3.2 Flow simulation

In this section, the flow simulations are presented. For the flow simulation study, the pressure regulator measured with the valve fully opened in order to see the maximum outlet flow rate through the designed orifices. The properties measured, as depicted in Table I, were the average flowrate in the outlet, the average outlet total pressure and the average temperature in the decompression chamber.

The results show that the values obtained from the analysis were inside the limits of the regulations. The flow trajectories are depicted in Figure 4(a). The pressure remains high in the high-pressure chamber and then passes through the control element that decreases the pressure with an adiabatic process. Then the O_2 expands in the low-pressure chamber that remains low until the gas exits the regulator. Figure 4(b) shows the temperature distribution inside the pressure regulator.

The temperature is about 293K (room temperature) when the oxygen inserts the regulator. Later the temperature decrease rapidly because of adiabatic expansion of the oxygen and then approaches again the room temperature.

Table 1. The properties measured in the flow simulation analysis

	Unit	Av. Value	Min. Value	Max. Value
Volume Flow Rate	m^3/h	241	240	241
Av. Total Pressure	[Pa]	1067482	958725	1155812
Av. Temp. (Fluid)	[K]	236	233	240

The lowest temperature is in the area that the pressure drop takes place and it is approximately 217 K. Figure 4(c) presents the pressure distribution inside the regulator. The oxygen enters the pressure regulator in high pressure 200bar. Pressure drop is occurred in the pressure reduction area. The oxygen exits the regulator having a 10bar pressure. In addition, inflow simulation analysis of the pressure regulator has shown that the proposed design seems capable to feed the system. The regulator functions with about 240m^3/h volumetric flow with the shutter fully opened, which is a very satisfying flow rate for a large hospital.

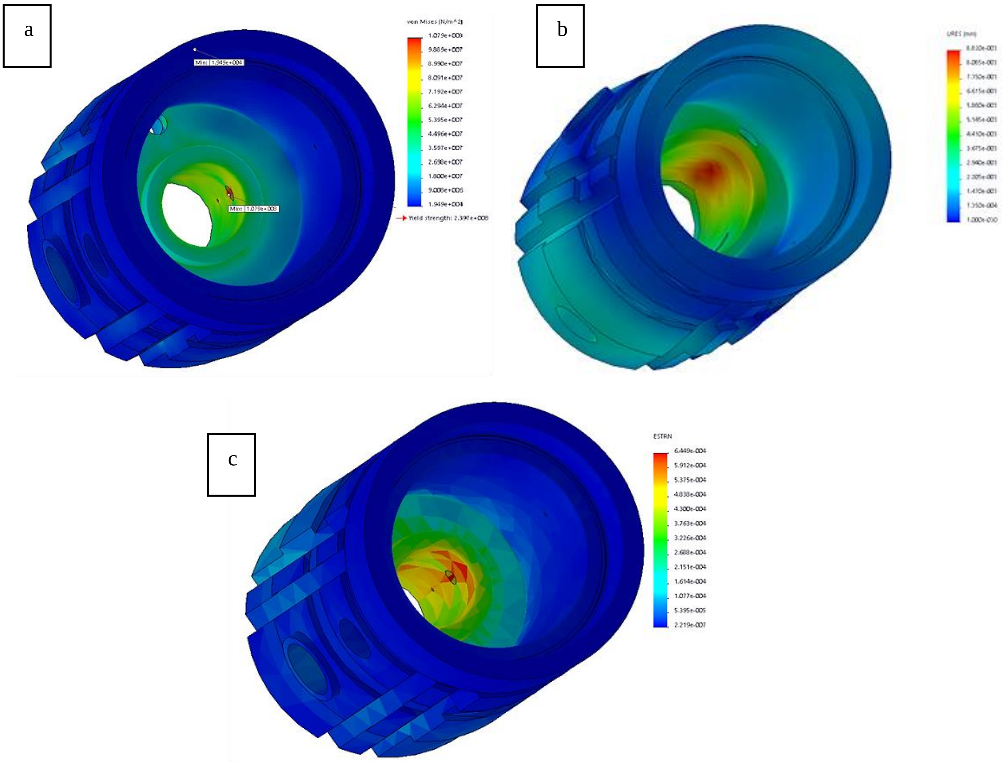


Figure 3. Stress contours of the pressure regulator showing: a) stress distribution b) displacement distribution, c) strain distribution

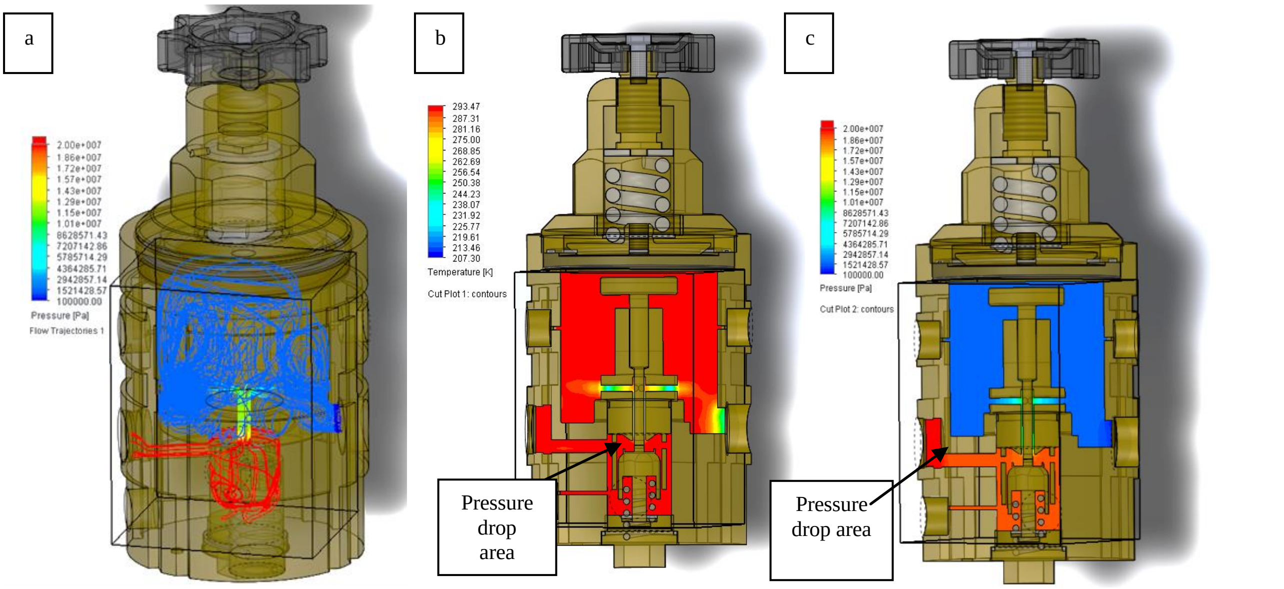


Figure 4. Stress contours of the pressure regulator showing: a)Flow trajectories b) Temperature distribution, c) Pressure distribution

4 EXPERIMENTAL VALIDATION

4.1 Hydrostatic test

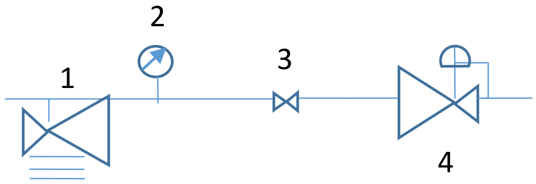
The first test was the hydrostatic test. It is used to test the maximum durability in vessels that contains gas that is in high pressure. For this test, the inlet of the pressure regulator (Device Under Test = DUT) is connected with the water-compressor. The compressor is an Enerpac multifluid hand pump, has a maximum capability of 500bars outlet pressure and water was utilized as a flow mean. All the other openings of the DUT, for this test, were sealed. The set-up for this test is presented in Figure 5.

The hydrostatic test took place inside the high pressure chamber of the regulator. To manage this, the loading mechanism adjusted to zero load. The shutter of the regulator was closed and so was the high pressure chamber of the regulator. After this step the pressure regulator connected to the water compressor in the inlet of the regulator. The test took place, according to EN 13480. The pressure was increased to a value of approximately 50% of the specified test pressure. Thereafter, the pressure was increased in steps of approximately 10% of the specified test pressure. The regulator was held at the test pressure for a period of at least 30min.

4.2 Pressure reduce and maximum flow rate test

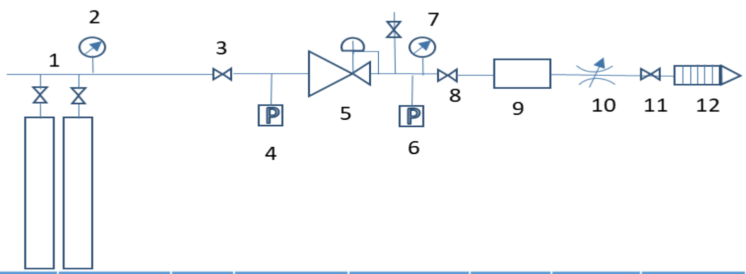
After the stress test of the regulator's body, the regulator was ready for a first basic working test. For safety reasons, the DUT was not tested with O_2 gas and so the results multiplied by the factor 0.996 to convert the results for the O_2 gas. The experimental setup can be found in Figure 6. First, the regulator tested with the spigot of the loading mechanism completely open (no load from the spring). Then the pressure of the inlet increased progressively from 0 to 200bars.

As the pressure increased, there was 0bar of air pressure in the outlet (low pressure) chamber. This meant that the shutter was designed well in terms of impermeability. For the second part of the test, the upper spigot was slightly turned in order to put a load to the upper spring. After that, the pressure of the inlet was increased progressively from 0bar until 200bars. In approximately 200bars of pressure the spigot was adjusted properly and the outlet pressure was managed to be controlled in about 8 bars.



1	2	3	4
Water hand-pump	Manometer	Switch	DUT

Figure 5. Test set-up 1



1	2	3	4	5	6	7	8	9	10	11	12
Array of gas cylinders	Manometer	Switch	Transducer	DUT	Transducer	Manometer	Switch	Flow meter	Flow controller	Switch	Silencer

Figure 6. Test set-up 2

Then the upper spigot turned slightly more in order to put more load to the shutter and make the orifice wider in the pressure reduce area. By doing this a pressure of 10bar in the outlet achieved and so the pressure reduction test passed with success.

Then the real flowrate of the regulator was tested in which the experimental setup remained the same. This time the regulator was pressed with 10bars inlet pressure with the shutter fully opened, just to see the maximum flow rate of the air in the exit, when the outlet pressure is 10bars. The maximum flowrate measured was 244 m^3/h.

4.3 Max flow vs stability

This test was performed in order to determine the maximum flowrate in 200bar inlet pressure and the stability of the regulator (pressure drop) of the exit pressure. The set-up in Figure 6 was also used for this test. The initial values for the regulator in this test were: a) inlet pressure of the regulator: 200bar, b) outlet pressure: 10bar (static) and c) flowrate: 0 m^3/h. For this test, all the switches and flow controllers were fully opened except switch 11. Switch 11 was rapidly changed from closed position to fully open in the beginning of the test. The bottle was gradually empty. In practice a pressure drop of 15% of the outlet pressure is acceptable, when inlet pressure is too low. The results of this test are shown in Figure 7.

	Inlet pressure (bar)	Outlet pressure static (bar)	Outlet pressure dynamic (bar)	Flow (m^3/h)
1	200	10	9,4	240
2	180		9,4	240
3	160		9,2	240
4	140		9,2	235
5	120		9,3	230
6	100		9,4	215
7	90		9,2	187
8	80		9,3	176
9	60		9,2	178
10	40		9,1	177
11	30		9	160
12	25		9	140
13	20		8,5	135

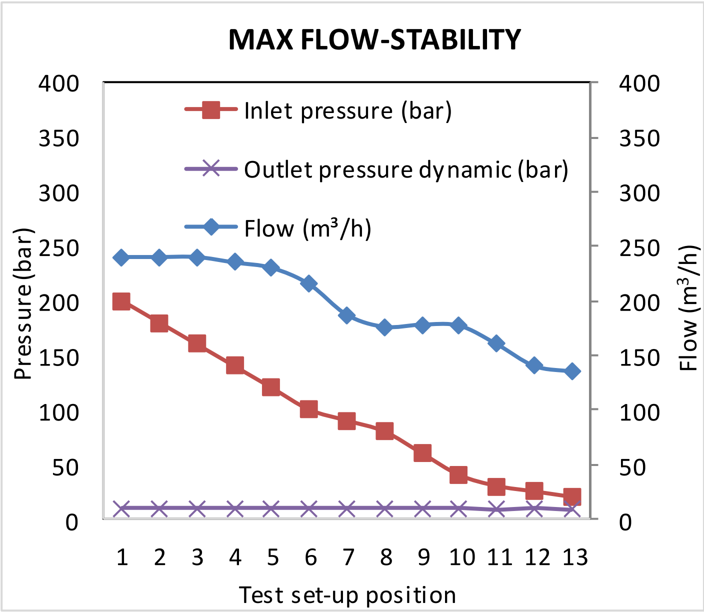


Figure 7: Test set-up 2

The results have shown that the maximum flowrate of the regulator is 240m^3/h at 200bar (inlet) and 9.4 bar (outlet). In general, the pressure drop in the inlet of the regulator is low and a maximum pressure drop of 1.5bar in the exit when inlet is 20bar which is normal.

4.4 Accuracy vs Capacity

The accuracy and the capacity of a regulator is determined by using Figure 8, which shows what happens to the outlet pressure of the regulator when flow is increased from zero to maximum with steady inlet pressure. This graph is also called "Direct Acting Pressure Regulator Operating Map". For this test the set-up of Figure 6 is also utilized.

As the flow increases the outlet pressure drops, this phenomenon is called droop. The accuracy of a regulator is determined by how much droop the regulator exhibits for a range of flow. The pressure that is required from the set point until to have zero flow on the (shut) exit of the regulator, is called Lock-up Pressure. The acceptable amount of local pressure is not determined by regulations but in general is acceptable for a <10% drop in set-up pressure from zero flow to 5m^3/h.

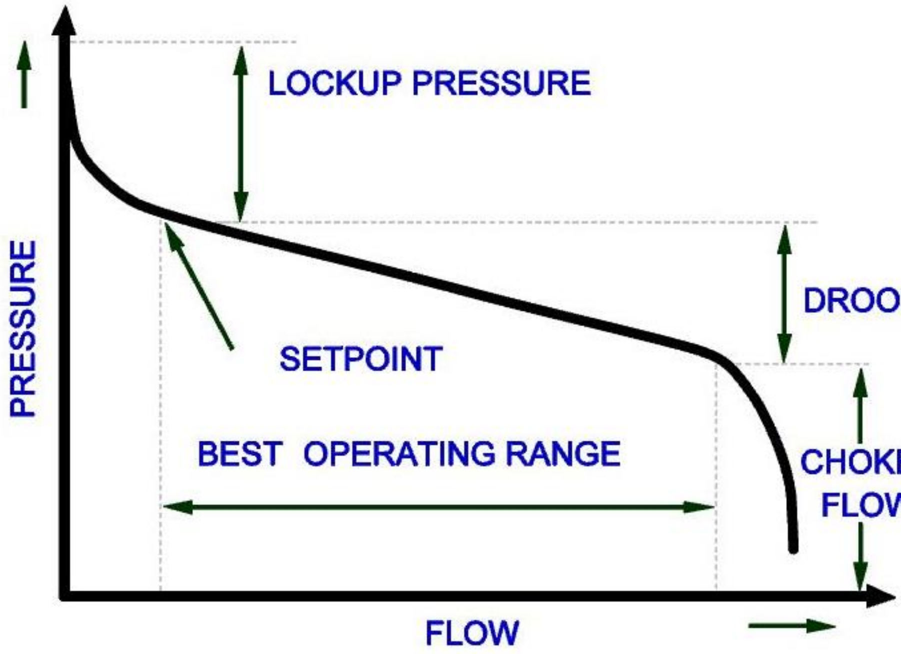


Figure 8: Direct Acting Pressure Regulator Operating Map

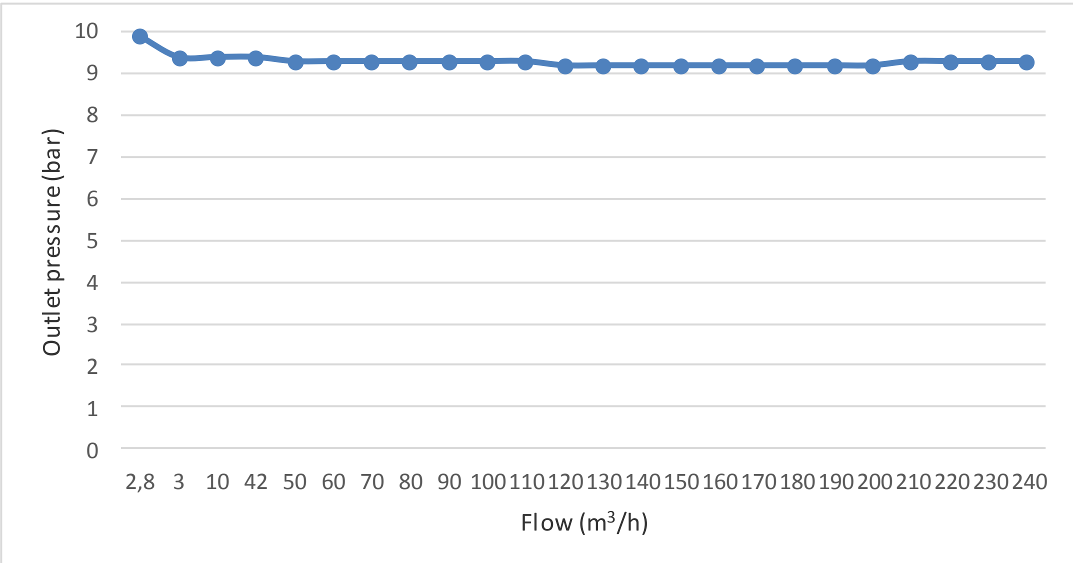


Figure 9: Outlet pressure vs increasing flow

The results in Figure 9 show that the regulator is accurate (very little droop) and capable (245m^3/h max flowrate). The lock pressure is 6% of the set-up pressure and it is as low as it should be. The operating range is satisfactory with very little droop until 240m^3/h. The test shows no chocked flow for the regulator. This means that the regulator can manage even higher flowrates and that the tubes that were used in the set-up of the test should be wider (in diameter) to see the limits of the capacity of the regulator.

5 CONCLUDING REMARKS

The simulation stress analysis has shown that the maximum stress that is applied in the chamber is 1.07 N/m^2 when the maximum yield strength of the material is almost two times bigger. The displacement is also very small. Inflow simulation analysis of the pressure regulator has shown that the proposed design seems capable to feed the system. The regulator functions with about $240m^3/h$ volumetric flow with the shutter fully opened, which is a very satisfying flow rate for a large hospital as mentioned. The lowest temperature is about 210K which is a normal value because of the adiabatic expansion that takes place inside the pressure drop area. Furthermore, the flow diagrams have shown how the oxygen is diffused inside the regulator and this gives to the reader a more realistic and comprehensible view of how a pressure regulator works.

The flow simulation analysis shows a complicated flow distribution of the flow inside the pressure regulator. This distribution changes by alterations of the shape of the internal orifices.

The prototype of the regulator was tested with great success. All the components seemed to fit together well. Furthermore, the tests also show satisfactory results. The first test was about endurance of the high pressure chamber in 300 bars and it was successfully passed. The body of the regulator endured the 300bar of pressure without any failure. Next it was the pressure reduce test that led to the conclusion that the pressure drop mechanism was well designed. The regulator was capable of reducing the pressure from 200 to 10bar. The same success had the test of the flowrate that gave $240m^3/h$ O_2. In this test the regulator tested with the valve fully opened to see if the openings of the regulator were enough to give high flowrates.

The regulator shows very good stability in decreasing flow from the gas vessels, with up to 7% pressure drop of the outlet pressure in low inlet pressures and even then, flowrates do not fall below 75 m^3/h.

The accuracy is also good with 6% lock pressure and very little droop which is an excellent result for this type of regulator. The chocked flow field does not appear in the diagram and this is a sign that it should be used with wider tubes to find the limits of this regulator. Future work will investigate how the shape changes affect the important characteristics of the regulator such as the stability of the regulator in pressure changes and the external flowrate.

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