
# 75 YEARS OF SPORT DIVING
## HOW DOES A SINGLE STAGE REGULATOR WORK?

FEATURE **PATRICK VAN HOESERLANDE**

The Mistral single-stage regulator is for most of us, a bit like a Ford T – we may have heard of it, or read about it, but very few have dived with it.

The legendary Mistral regulator. Photo by Dirk Deraedt.

The Mistral single-stage regulator is for most of us, a bit like a Ford T – we may have heard of it, or read about it, but very few have dived with it. I hear some people think they have dived with a single-stage Mistral! That was also my reaction before I immersed myself in the matter to write this article. Until recently, I believed a single-stage regulator (figure 1) was tantamount to a big round thing attached with two hoses, connected to a mouthpiece. Thanks to the absence of annoying air bubbles that escape from the mouthpiece into my field of view, my diving experience with such a device was surprisingly quiet. I was ignorant then.

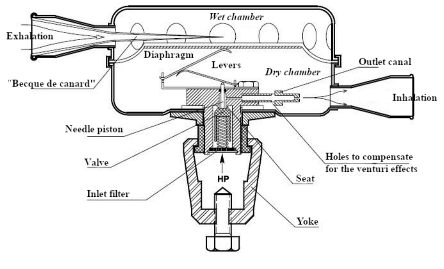



Figure 1: A single stage regulator.

Through my research, I discovered that there was a model very similar to the one used by Jean-Jacques Cousteau, later baptised the "Mistral", that was in fact a two-stage regulator. Yes, they both look alot alike and resemble my above-mentioned visualisation of a "single-stage", but that large shiny thing on the back can also include two stages, as shown in figure 2. The second stage is unlike the modern version, not integrated in the mouthpiece but tucked away under the large lid. There is no connection for medium pressure, they felt no need for it at the time, and thus only the technical specifications or a complete dismantling of the regulator can reveal the number of stages: one or two? I'm not sure of the number of stages I dived with years ago.

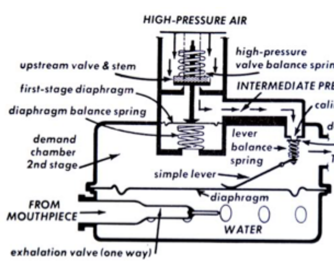



Figure 2: A two-stage regulator in one casing.

You can recognise a single stage regulator by the typical 'whoosh' sound it makes when diving with it. This distinctive sound is produced by the venturi, but I have not yet confirmed this myself. It is on my to-do list for the next article in which I – as a two-stage diver – will try out the old model and share the experience with you.

Before diving with the regulator, I wanted to technically analyse the device and understand its operation. I sought to go deeper than the normal dive course and transcend the few lines you normally find on the topic, to a less vulgarised explanation. First, here's a general description of the regulator because general knowledge of the modus of operation is the basis for better, more detailed understanding, and not everyone likes physics. Right?

If you think that using the internet for its specialised sites and Wikipedia to catch up on technical explanations is a piece of cake, then you are heading for disappointment. Dozens of sites later – different pictures, drawings, pdf-files – I could not find an explanation on how the regulator worked. The first problem that I struggled with when I looked at the diagrams, was the exact function of the exhalation valve – 'becque de canard' or duckbill – situated in the exhaust part of the casing. I did not immediately see how it could close the unique stage when exhaling. I was obliged to analyse a technical cross-section to draw up the formulas when I desperately asked colleague-diver, Dirk Deraedt for support. He had found extensive work on regulators and other dive equipment in French. I should have done my research in French considering the nationality of the duo, Cousteau-Gagnan.

In any case, the book he had found was 'Principes des détendeurs de plongée 2006' by Henri Le Bris and it was the starting point I was looking for. This is a fantastic reference and I used it to write this article. If you are interested in the nitty-gritty details of your dive equipment and you understand French, I strongly recommend reading it. It is free and available online.

## THE POPULAR EXPLANATION

As promised, I will start with a simple explanation that forms a good basis for understanding the more detailed description that follows. Before we start, I first want to highlight a few peripheral parameters that support the study. As a diver, we know that the length of a snorkel is limited, among other things, by the relatively weak power of our chest muscles. During our evolution as mammals, we did not need to develop strong upper body muscles because they are not needed for life in an atmospheric environment. Although this makes sense in a Darwinism way, the result is that we can barely overcome pressure differences of a few dozen centimetres of water pressure, or a few hundredths of a bar. If we compare that with the pressure in a scuba tank, we get a good idea of the big change between the input (hectobars) and the discharge pressure (centibars) of a single-stage regulator.

In Cousteau's dive tank, due to limited technical possibilities and physiological limits of the time, there was barely 150 bar in his tank and thus a single-stage regulator was enough to make scuba diving possible. If he would have had a 300 bar composite tank on his back, we would most probably have to wait for the birth of sport diving to invent the modern two-stage regulator. A single-stage is not able to safely overcome the large adiabatic cooling caused by such a high pressure drop.

We can use the simplified representation of the regulator in figure 3 to explain its operation. This regulator was the most widely used of the two types, as illustrated in figure 4, and is also the type of the Aqua-Lung regulator. "Aqua-Lung" was the name given to the original design as patented by Emile Gagnan and Jacques Cousteau in 1943. Today the name "Aqualung" sounds a bit old-fashioned and we prefer the use of the term "SCUBA".

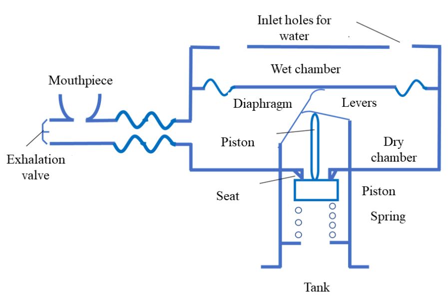



Figure 3: The components of a single-stage regulator.

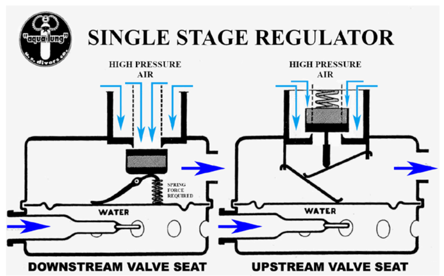



Figure 4: Different types of regulators according to the position of the piston.

Let us study the drawing of figure 3. At rest, the high pressure in the dive tank pushes the piston against the seat, preventing air from flowing into the dry chamber of the regulator. This means that the force of the spring, together with the force exerted on the valve, is at least, in balance with the force of the water pressure on the diaphragm and transmitted by the levers.

If the diver inhales, the pressure in the dry room drops, resulting in the diaphragm lowering. If the force (via the levers) on the valve is large enough, it will open and air from the tank will enter the dry chamber. This will continue to flow until the equilibrium is restored. That is when the diver stops breathing and the pressure is reestablished.

On expiration, the air flows to the exhalation valve following the path of the least resistance. This valve is a duckbill shaped rubber piece in the wet room. The air bubbles escape easily through the large holes of the wet room and do not affect the movement of the diaphragm. When the diver stops breathing, the regulator is ready for the next cycle.

Of course, there is another phenomenon that can disturb the balance of forces, and that is a change in depth. Imagine that our diver is descending deeper. This increases the pressure in the wet room, that is, after all, in direct contact with the surrounding water, causing the diaphragm to move downwards. If the change in depth is large enough, the piston will move too and let air through. The amount of air will be just enough to restore the balance. The air pressure in the dry room will then be equal to the new ambient water pressure.

The value of the high pressure in the tank also plays a major role. After all, the equilibrium is dependent on this pressure and thus a drop in pressure in the tank will decrease pressure difference necessary to move the piston.

For the sake of leaving no stone unturned, I must mention that this pressure difference also reduces with increasing depth. There are combinations of pressure in the tank and dive depth where the tank simply empties itself. This also means that the shallower you dive, the harder it is to breathe. In fact, a single stage regulator is set to operate ideally for a certain depth (along with a certain pressure in the tank).

## THE TECHNICAL EXPLANATION

The above explanation is enough for an initiation course, but not for a specialised article on this topic. The following information will focus on the detailed operation and for that we will have to use some formulas. These are based on the laws of diving physics that I assume you are familiar with as a reader. If not, then this is a good time to open your course book on that chapter and to keep it at hand in case you need it. We will limit ourselves to the static operation of the regulator because the dynamic study would take us too far into the details and yields little extra insight.

For our study, we use a simplified, theoretical model that is close to reality. Figure 5 contains the necessary number of physical characteristics of the regulator.

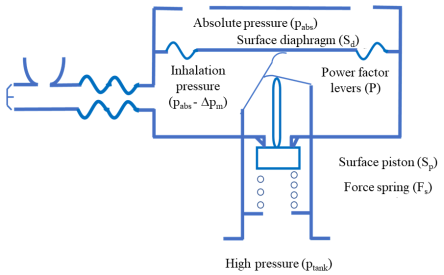



Figure 5: The physical characteristics of a single-stage regulator.

**The force by which the piston presses against its seat consists of:**

- The force of the spring: $F_s$
- The high pressure ($p_{tank}$) pushing against the surface of the piston ($S_p$): $p_{tank} \times S_p$
- The pressure in the dry chamber ($p_{abs}$ - $\Delta p_m$, with $\Delta p_m$, the pressure drop during inhalation) against the surface of the diaphragm ($S_d$) transmitted and augmented by the levers (P): $(p_{abs} - \Delta p_m) \times P \times S_d$

**The force that pushes the piston away from its seat is the combination of:**

- The pressure in the dry chamber against the surface of the piston ($S_p$ with the assumption that the surfaces on both sides of the piston are equal): $(p_{abs} - \Delta p_m) \times S_p$
- The absolute pressure in the wet chamber ($p_{abs}$) against the surface of the diaphragm ($S_d$ with the assumption that the surfaces on both sides of the diaphragm are equal) transmitted and augmented by the levers: $p_{abs} \times P \times S_d$

**At equilibrium the two opposing forces must be equal:**

$(p_{abs} - \Delta p_m) \times S_p + p_{abs} \times P \times S_d = F_s + p_{tank} \times S_p + (p_{abs} - \Delta p_m) \times P \times S_d$

**Further work leads to:**

$p_{abs} \times S_p - \Delta p_m \times S_p + p_{abs} \times P \times S_d = F_s + p_{tank} \times S_p + p_{abs} \times P \times S_d - \Delta p_m \times P \times S_d$

$\Delta p_m \times P \times S_d - \Delta p_m \times S_p = F_s + p_{tank} \times S_p - p_{abs} \times S_p + p_{abs} \times P \times S_d - p_{abs} \times P \times S_d$

$\Delta p_m \times ( P \times S_d - S_p ) = F_s + ( p_{tank} - p_{abs} ) \times S_p$

$$\Delta p_m = \frac{F_s + (p_{tank} - p_{abs}) \times S_p}{(P \times S_d - S_p)}$$

Usually $S_p$ is negligible in relation to $P \times S_d$ and the same is true for $p_{abs}$ compared to $p_{tank}$. If we take this into account, we obtain:

$$\Delta p_m = \frac{F_s + p_{tank} \times S_p}{S_d} \times \frac{1}{P}$$

With $\Delta p_m$, the pressure difference required by inhalation in order to unlock the piston, or in short, the pressure drop for inhalation.

## WHAT CAN WE CONCLUDE FROM THIS FORMULA?

- The inhalation pressure drop decreases with a decrease in tank pressure. This means that the regulator must be correctly adjusted to prevent the tank from fusing when the high pressure due to air consumption becomes very low.
- The inhalation pressure drop is inversely proportional to the surface of the diaphragm. This explains the big dimension of this membrane.
- The ambient or absolute pressure, as long as it is negligible with respect to the cylinder pressure, has no influence on the inhalation pressure drop. This is not the case at great depth with an almost empty tank.
- When the high pressure decreases, the inhalation effort decreases (necessary inhalation pressure drop decreases).

**Numerical example:**

$S_p$ = 0.04 cm²; $F_s$ = 20 N; P = 40; $S_d$ = 65 cm² and $p_{tank}$ = 150 bar.
Then you get $\Delta p_m$ = 3.08 mbar (3.08 cm water).

## DIVING ON PAPER

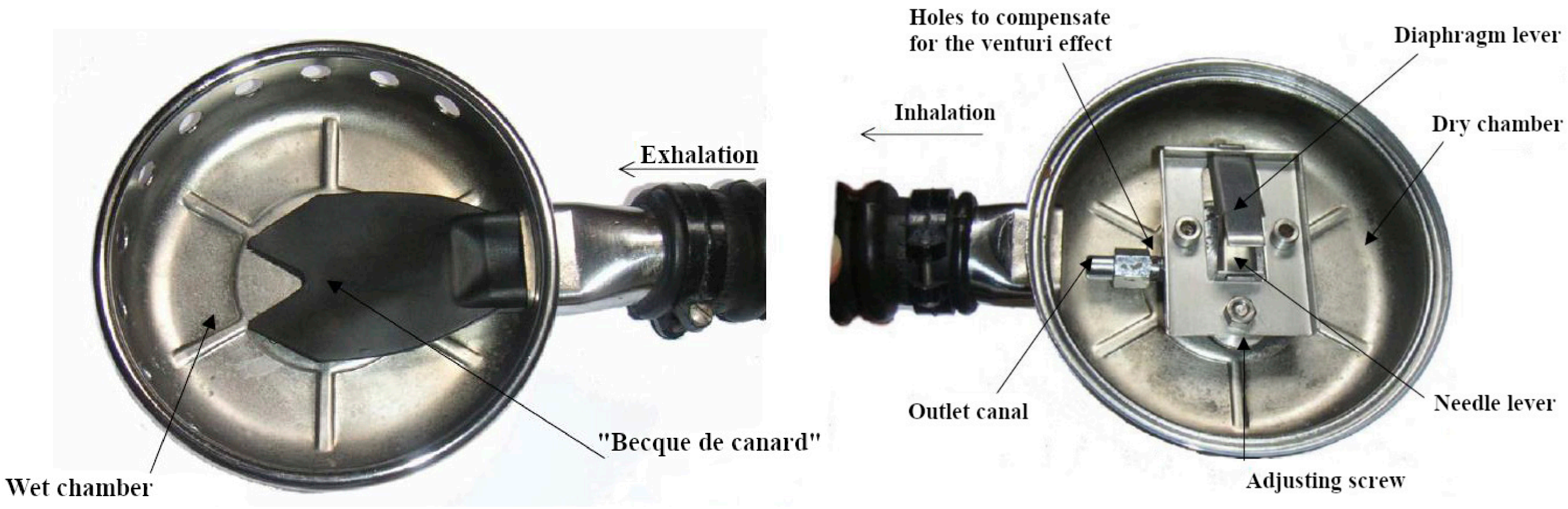
Now that we have a better understanding of the operation and its consequences, there are a few interesting things about a single-stage regulator. To be completely honest, what is stated below is in most cases also true for all regulators mounted on a diver's tank regardless of the number of stages. Sometimes single and two-stage regulators are lumped together, while they involve two different approaches. However, as most single-stage devices are equipped with an inhalation and exhalation hose, this confusion is not illogical.

Why a second hose? The first Aqua-Lung prototypes just had one hose, but Cousteau soon discovered that the regulator went into free flow when the mouth piece was held higher than the regulator. No surprise when you look at the result of the example above. The solution of adding an exhalation hose connected to the wet chamber ensures that the pressure at the outlet is equal to the ambient pressure at the level of the regulator. This extra tube did not appear to be the perfect solution because air simply wants to rise, but it was better, and when the regulator went into free flow, the air escaped through the wet room instead of bubbling before the diver's eyes. The latter is an advantage of the back mounted regulator with twin hoses; bubbles are ventilated at the back and do not disturb the diver's visual field of view. Also, the bubbles stay clear of the ears, making it less noisy. The real 'monde du silence' – silent world - as Jean-Jacques described it.

The double hoses solution does however come with its disadvantage. Due to the low pressure in the hoses, their diameter must be big enough to allow a flow sufficient enough for normal breathing. The resulting large volume of air in the two hoses have the tendency to pull the mouthpiece up. If you are going to dive with a single-stage, then you should add a bit more weight than diving with your modern regulator. If you should lose the mouthpiece, it will go up and constantly flow. Of course, this effect can be reduced by adding weight to the casing when designing the mouthpiece. The large hoses also provide extra resistance in the water when you swim or encounter a current. Due to the resistance, it pulls on the mouthpiece. It's clear that if the mouthpiece is not properly clamped between your teeth, then chances are you will lose it.

As previously mentioned, a single-stage regulator does not work well when there is high pressure in the tank. A large pressure drop can cause problems by the sudden cooling of the air (allegedly Cousteau did a dive with a Mistral mounted on a 330 bar dive tank) but this formula will also make breathing very difficult.

Another disadvantage is that no intermediate pressure is available. There is no means to attach a second regulator. If you want to do this, you need an extra tank.




The famous single-stage Mistral. Photo by Herwig Van Cotthem.

Because you do not have a back-up regulator, you must, in the case of an emergency, share your air with your one and only mouthpiece. Due to the sensitivity to free flow, this must be done in a very disciplined manner. You could opt to rotate your mouthpiece resulting in the folding of both hoses in order to prevent air from escaping. The two hoses also make it difficult to pass the mouthpiece to your buddy and the absence of a purge valve means that discharging water is far from child's play. An alternating breath as you rise to the surface together with your buddy, requires dexterity and a lot of practice.

The final disadvantage is that the respiratory comfort strongly dependends on the position of the mouthpiece in regards to the regulator's fixture. A variation of a few centimetres has a big effect on the comfort. The effect is greater than that of a modern two-stage regulator and completely the opposite as figure 6 nicely shows. However, the greater breathing effort could have a positive effect on air consumption. The robust design and simplicity of the regulator ensures that the single-stage breathing apparatus is a very reliable device.

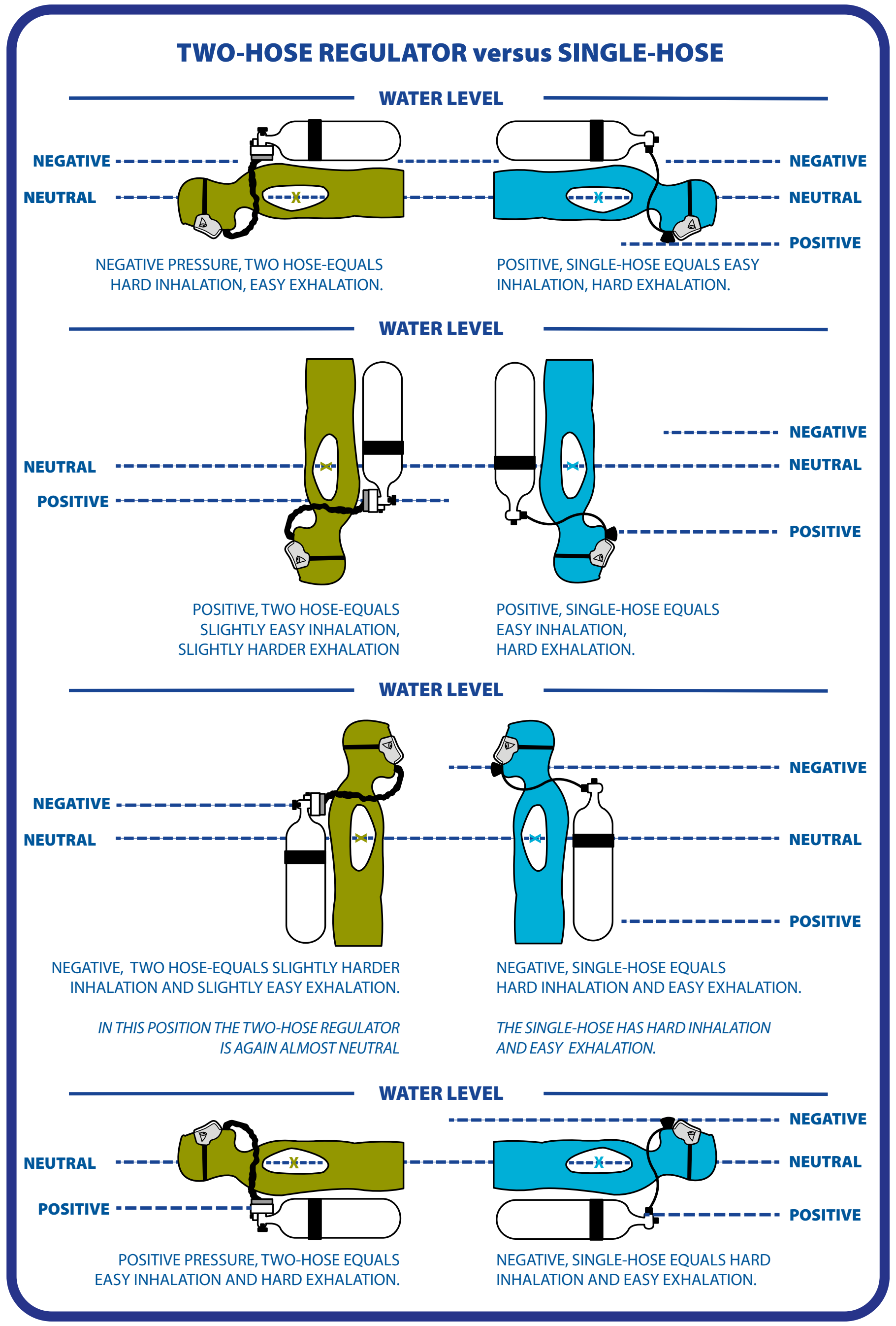



Figure 6: Breathing comfort in function of the position of the diver.

Equipped with the above theoretical analysis, we are prepared for the real thing: a dive with a single-stage regulator. It was not easy to lay my hands on a working specimen, and it took some time to find one. Wondering how the dry, technical analysis will correspond to the underwater experience? Then read part 3 of this series in the upcoming June issue.