Understanding Constant Mass Flow (CMF)

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V2.1 01/12/2024

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Abstract: This text explains the principles of constant mass flow, how it can be achieved and why we use it in our rebreather designs.

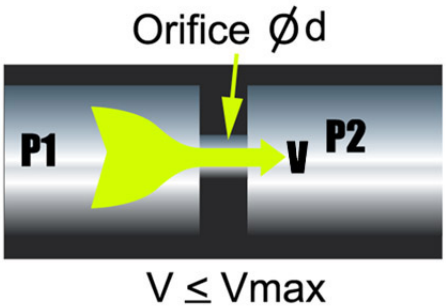
Disclaimer:

This text is a simplified explanation of the CMF principle, only to make it understandable related to the use of CMF in rebreathers.
The author of this article does not take any responsibility in case people use the information of this article for building/modifying rebreathers, or to dive outside the limitations of their training and certification.

Terms: CMF, orifice, nozzle, sonic speed, shocked flow,

1 Constant Volume Flow

When we discuss CMF, there is one law in physics we specifically focus on: when a gas is pushed trough a small hole, (also called orifice, or nozzle) the speed of that gas is limited: it can never be higher than a certain maximum speed: the sonic speed (Vmax) (1)



So, when the conditions to reach maximum or sonic speed are achieved, what ever you do, increasing the pressure at the entrance of the hole, decreasing, or even vacuuming on the exit side of the hole, the speed of the gas travelling trough the hole will not increase anymore, but stay constant at Vmax.

This means also, as the speed of the gas is limited, for an orifice with a fixed diameter, the flow (l/min) of gas trough the orifice is also limited, and can never increase once sonic speed is achieved: we have 'Constant Volume Flow'
(Because flow = speed of the gas x surface of the opening in the orifice)

$$\textbf{Volume flow } (m^3/s) = \textbf{surface orifice x gas speed}$$

$$= (\pi \times d^2)/4 \times v$$

Now when do we reach the maximum, or sonic, speed? We can apply a simple rule: sonic speed is reached when the inlet pressure p1 is at least twice the outlet pressure p2
or **p1 ≥ 2 x p2** (2)

Example:
p1 = 10 bar p2 = 1 bar: p1 must be min. twice p2 (2 bar) ➔ we have sonic speed
p1 = 10 bar p2 = 7 bar: p1 is less than twice p2 (14 bar) ➔ we have no sonic speed

This means also, with a fixed diameter orifice, as long as p1 ≥ 2 x p2, we have a **constant volume flow**.

2 Constant Mass Flow

Now we must be careful, earlier the statement is mentioned: 'volume flow' is constant once sonic speed is reached.
Please note that a "volume" of gas is not the same as "the amount" of that gas, or "its number of molecules" of that gas, or the "mass of that gas.
As we know that gasses can be easily compressed, it is clear that for a given volume, the amount of gas is linear with the pressure of that gas. Think of a scuba cylinder, although its internal volume stays the same, when the tank is fully charged, it contains more gas then when the tank is almost empty.
Going back to our volume flow, we can now understand when we do have sonic speed, thus a constant volume flow, there will be more gas molecules passing through the orifice when we have a higher inlet pressure "p1".

Our body uses oxygen for its metabolic processes. For a given, fixed work rate, we can assume that the oxygen metabolic consumption is constant. So when diving rebreathers we are not interested in what volume of O_2 goes through our orifice, but how many molecules of oxygen, (similar to how many grams / minute) flows into our system.

When we know the maximum volume of gas that can go through an orifice, and we want to know the MASS, or the number of grams/minute (gr/min) that flows through the orifice, we have to add another factor: the DENSITY of the gas (kg/m³ of gram/litres): **ρ**

So when we multiply the volume flow (l/min) by the density of the gas (gram/l), we get **gram/min,** and now here it comes:

Although the speed, and so the volume flow (l/min) is limited always to the maximum volume flow at sonic speed, if we want, we can get more molecules, more grams/min gas trough the orifice … by increasing the density of the gas. The denser the gas, the more molecules/litre, so even with a fixed volume flow, but having a 'denser' gas, the number of molecules/minute, or the 'grams/minute' (= the MASS flow) can increase.

In terms of our rebreather, when we talk about an oxygen flow of 0,6 litre/min, we actually mean 0,6 litre/minute measured at 1 bar, (surface conditions), which gives us roughly 0,86 grams/minute, as the density of oxygen at 1 bar is around 1,43 gram/litre.

Now how can we increase the density of the gas? Simple, by compressing it, or increasing the pressure of the gas

Mass flow = Volume flow x gas density

= surface orifice x v x ρ

p1 ↑ ➔ density ↑ (ρ ↑)

WHEN v = vmax AND orifice = fixed THEN:

Mass flow ↑ when ρ ↑
Or
Mass flow ↑ when p1 ↑

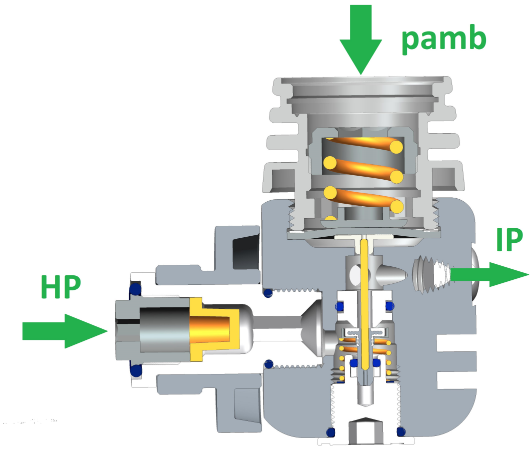
The density of the gas can be increased, by compressing the gas, (=by increasing p1).
So when p1 increase, the density of the gas **ρ** will increase, and the MASS flow, (density x volume flow) will increase.

Example: when we meet the conditions of sonic flow (Vmax), so that we have Constant Volume Flow, but we double the inlet pressure at the orifice, so we double the density of the gas, we will double the MASS flow through the orifice.

… ok enough theory, let's go to some practical examples

3 the 'standard' scuba regulator

Traditional, "standard" scuba regulators are made this way that they 'sense' the pressure of the surrounding water, and adjust there IP, so that the difference between the IP and the ambient pressure of the water (the pressure in the water when diving) stays constant: this is needed for the second stage, normally attached to this first stage, to operate correctly while diving.
This means that a standard scuba regulator will always increase it's IP with the water pressure it is sensing. Such a regulator has thus a compensated first stage. How does this compensation works? Let's have a look at the drawing below. If the central rod is pushed downwards, the regulator opens and allows gas to flow from the HP chamber to the IP chamber. When the IP reaches its pre-set value the regulator closes again. If we analyse what forces are trying to open the regulator and what forces are trying to close the regulator, we see that the big spring together with the ambient pressure on the membrane are trying to "open" the regulator. The intermediate pressure pushes on the other side against the membrane and tries to "close" the regulator. This means that the intermediate pressure is determined by the force of the spring and by the ambient pressure.

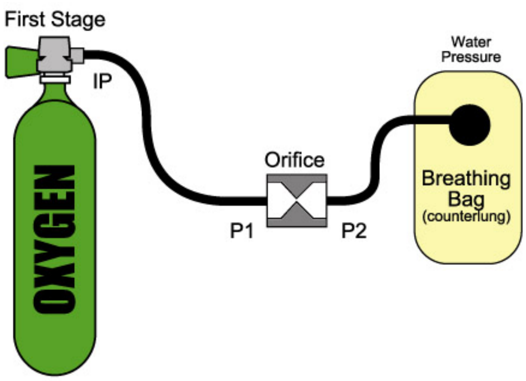


so we can say that with a compensated first stage, the IP (intermediate pressure) is depending on the ambient pressure.

Example: at surface (1 bar absolute) the IP of our regulator is 10 bars absolute, so the pressure difference is 9 bars
When we go diving, the water pressure increases with 1 bar every 10meters we descent, so the IP of the normal scuba regulator will also increase by 1 bar for every 10 meters of depth.
So with an IP set at surface at 10 bars absolute, when diving at 20 meters depth the IP will have increased by 2 bars till 12 bars absolute, or at 50 m till 15 bars absolute… and so on.
Note: not all first stages have a compenstation ratio of 1:1. So called "overcompensated" first stages will increase their IP a little over 1 bar per 10meters of water depth. This is because these are designed as open circuit regulators and the slight overcompensation helps to keep the regulators work of breathing with increasing gas density.

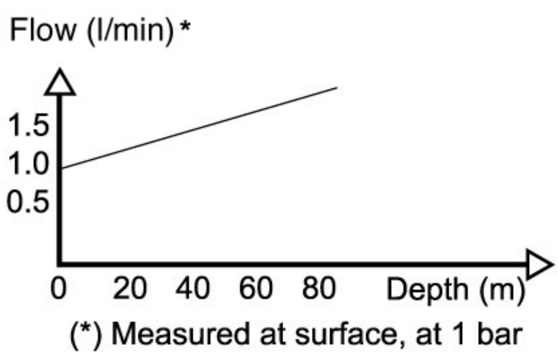
Now let's go back to our regulator/orifice/breathing bag

For the test we take a standard scuba regulator, the first stage, and connect it to an oxygen tank. The pressure at the outlet of the first stage, the intermediate pressure (IP) is set at 10 bar absolute pressure. To this outlet we connect an orifice with a fixed diameter, and the outlet of the orifice flows in the breathing bag of our rebreather



Suppose we choose the diameter of the orifice this way, that at surface, with the IP, or p1, set at 10 bars, we have a flow of 1 l/min (measured at the surface!!, so +/- 1.43 grams/min).
p1 is 10 bars, the outlet pressure (p2) is 1 bar (at surface), so P1 is more then twice P2, we have 'sonic speed', so we reach maximum volume flow.
Now we go diving with our rebreathers and we go to 20m depth. The absolute pressure in the water is 3 bar now, so p2 has increased with 2 bar, from 1 to 3, so the regulator has also adjusted (increased) it's IP with 2 bar, and so now p1 = 12 bar.
We still have maximum volume flow (as p1 = 12 is still more than twice p2 = 3), so the volume flow did not change.
But what happened: as p1 increased from 10 to 12 bar, the gas (oxygen) at the inlet has been compressed by 20% (from 10 to 12 bar), and so has become 20% more dense, so our MASS flow (volume flow multiplied by density of the gas) has increased by 20% also!
So now +/- 1.72 grams/min flows trough our orifice! If we could now measure the flow at surface again, we would measure 1.2 l/min!

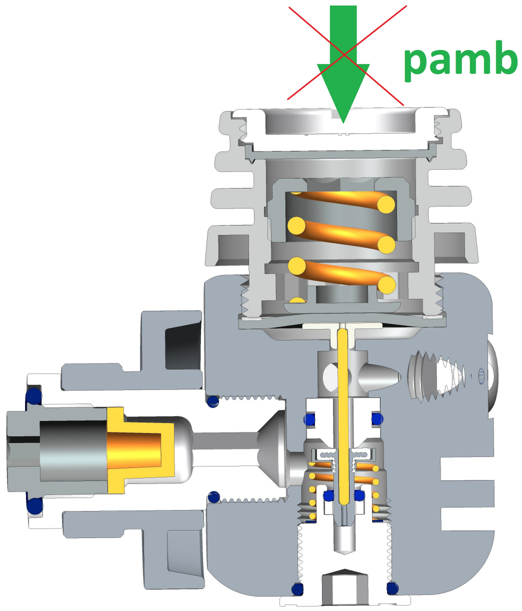
Now we dive to 50m: p1 = 15 bars, p2 = 6 bars, we still have maximum flow, (15 > 2 x 6), but the density has increased by 50%, and so has the mass flow, and we now have +/- 2.14grams/liter (equivalent to a flow of 1.5l/min at the surface)



We notice the deeper we go, using our system with a standard scuba regulator (that has a compensated first stage) connected to the oxygen tank, the mass flow of oxygen (and so the volume flow measured at 1 bar), increases when we go down: we do not have a constant mass flow of oxygen. Do we want this?....

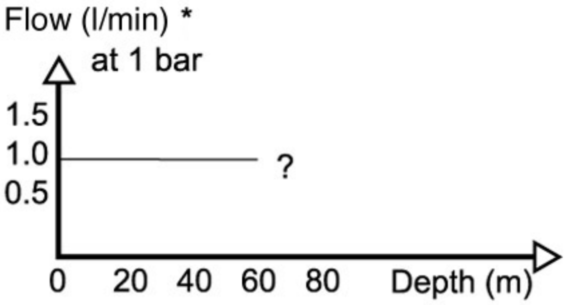
4 the 'absolute pressure regulator'

Let's now look at a different system: we modify our standard scuba regulator, so that it does not sense the water pressure anymore, so that it does not increase the IP when we descent in the water. (this can be done by mounting a special cap on the regulator, see white cap just above the big spring on the figure below), so that the water pressure does not get in contact with the 'sensing-membrane' of the first stage). If we would make again the same analysis, we would see that the IP of this regulator is constant as it is only determined by the force of the spring.



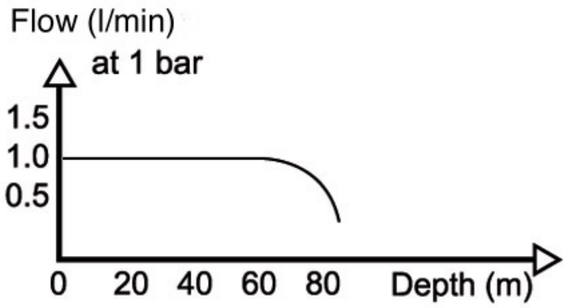
At surface the IP is set at 10 bar absolute, and using the same orifice, at surface we have the same volume flow of 1l/min. (+/-1.43gr/min)
Again we dive to 20m. The absolute pressure in the water is now 3 bar, but, since the regulator does not sense the water pressure, and so does not adjust it's IP, the IP, so p1, still stays at 10 bar absolute.
Do we still have maximum volume flow? Yes, as p1 (10 bar) is still more then twice p2 (3 bar): so the volume flow has not changed.
What happened to the mass flow? Since P1 did not change when descending from surface to 20m, the density of the gas flowing through the orifice did not change, so the mass flow through the orifice has not changed: we still have our 1.43 gr/min, (or 1l/min if measured at surface) **We have a CONSTANT mass flow.**

Now we descent further to 40m, the absolute pressure in the water is now 5 bar. p1 is still 10 bar, as our regulator is 'blind', and we still have maximum volume flow (as p1 (10) is twice p2 (5))
The density of the gas at the inlet of the orifice has not changed, (p1 always constant at 10 bars), so the mass flow has not changed, we still have constant mass flow (CMF)

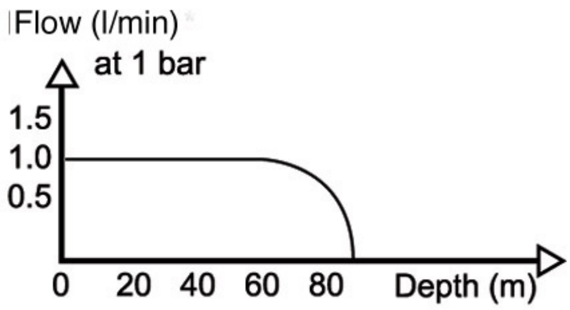


And this is what we want when we have oxygen flowing into a rebreather: we inject an amount of oxygen into the breathing bag, so that it just compensates for the basic oxygen consumption of our body (metabolic consumption) when we are at rest, or moving very slowly. And since our metabolic consumption does not change with depth, we don't want the oxygen mass flow into the breathing bag change when we descent or ascent: we want it to stay constant.
The extra amount of oxygen our body needs when we do more exertion can then be added manually in an mCCR, or electronically in the hCCR.
If the oxygen mass flow would increase when we go down, the mass flow would quickly become higher then our metabolic consumption, and so the ppO_2 of the gas would rise, and become hyperoxic, so we would have to 'flush it down' all the time with diluent.

Now what happens when we continue to go deeper with our absolute pressure regulator system: we descent to 60m. The pressure in the water is now 7 bar, the IP is still 10 bar, now p1 is not minimum twice p2 anymore.. (10 and 7): the condition to have sonic flow, and so maximum volume flow, is not achieved anymore! The speed of the gas trough the orifice has become less then max, so the volume flow has dropped, and since the density (determined by P1) has not changed, our mass flow has dropped! We don't have CMF any more



And while we go deeper, 70m, 80m … the pressure in the water p2 will increase and come closer to p1 (the IP), the velocity of the gas will keep dropping and so will the mass flow, until we reach 90m. At that point the pressure in the water equals the intermediate pressure (both 10 bar), there is no pressure difference over the orifice anymore, so no gas will flow through it, the mass flow has dropped to zero.



Now what does this mean when we dive a rebreather with an 'absolute pressure regulator' (so that we can use an orifice that delivers us a constant mass flow of oxygen over a range of depths): it means that the maximum operation depth of the rebreather is limited to the depth, where the IP equals the pressure in the water. (Because at that depth or deeper, no oxygen can be added to the system anymore, as also the manual add valves (MAV) will not give anymore flow when activated: the inlet pressure of the MAV is also the IP)

For the rEvo in mCCR or hCCR mode, we even limit the maximum operation depth to 20m less then the depth where the IP equals the water pressure: as the graph shows, at that depth there is still a reasonable mass flow through the orifice, and still enough differential pressure over the MAV to inject extra oxygen.

In the currentl rEvo setup we use an orifice of .0030" diameter, the IP is set at +/- 13 bars absolute (12 bars overpressure) and the flow at surface is +/- 0,6l/min : we get 0,86 grams / min. At a depth of 120m, the water pressure equals the IP, so the maximum recommended working depth of the rEvo in mCCR of hCCR mode is 100m.

Lowering the IP, to decrease the mass flow to mach the flow to a lower metabolic consumption, will also decrease the maximum operation depth of the unit: every bar the IP is decreased, the maximum recommended operation depth decreases with 10m.

In case we do not want to have any depth limitation, the first stage has to be a 'normal' depth compensated scuba regulator: so we change the unit from an mCCR into an eCCR by:

1) Blocking the orifice with blanking plug
2) Removing the 'cap' from the first stage, install the hydrostatic transmitter en envirmomentl seal
3) Set the IP to standard : 9 bar
4) Set the controller to "solenoid depth compensation : ON "

(1) note that this is an approximation
(2) the factor 2 is also an approximation: it depends on the type of gas, and can vary from 1.7 to 2.0