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Tech talk #12: One more PSI please, an introduction to boosting

It has been some time now and likely you all guessed I was running out of topics. You got it wrong, plenty of topics, just lack of precious time. In recent history, I've got a couple of requests to advise in the matter of booster pumps. An interesting topic indeed given the fact you're about to pay top $$$$ for a booster pump; so best to get one that will suit your needs. In this article we'll have a look at types of boosters, specifications, how to choose one and some installation requirements. Our emphasis will be on air/pneumatic driven boosters for blending applications.

It is easy to comprehend that if you wish to fill an empty 12L cylinder to 200 bar with pure oxygen and you have available a 45 L supply cylinder filled to 130 bar with pure oxygen, this will become mission impossible: as the 12L cylinder fills with oxygen, it's pressure increases and at the same time, the pressure of the supply cylinder will decrease. The equalizing pressure would become 102 bar. Many similar scenarios will be encountered when partial pressure blending. So how do we get the pressure from 102 bar to 200 bar? In comes the booster pump.

So what are we talking about? A booster pump can be described as a machine which will increase the pressure of a fluid - within the context of this article: gases -. The booster is very similar to a gas compressor but in general has a simpler mechanism. The smaller units often have only a single stage to increase pressure of an already pressurised gas – two stage boosters also exist -. For divers or gas blenders this can include: increasing the gas pressure, transferring high pressure gas, charging gas cylinders and scavenging.

Increasing the pressure of a gas it is then. Within the scuba context this could be air, oxygen, helium, argon or mixed gases like EANx or TMx.

Warning: boosting oxygen and oxygen enriched systems possess a risk of fire and explosion since ignition and combustion hazards are present in all oxygen systems. Sadly oxygen related fire incidents have occurred in many industries. Because ignition and combustion hazards are inherently present in oxygen systems, proper guidance and training for using oxygen boosters is crucial to avoiding accidents and ensuring the safety of personnel and equipment. As per previous articles, oxygen is a serious fire hazard: it makes materials easier to ignite and their subsequent combustion more intense, more complete and more explosive than in air alone. Common causes are: mechanical impact, particle impingement, frictional heating, adiabatic compression, contaminants (e.g. hydrocarbons)... Therefore proper husbandry is of the highest order: ALL system components in contact with pure oxygen must be oxygen clean and oxygen compatible (in other words oxygen serviced), service booster pumps at recommended intervals and if possible avoid using your oxygen booster to boost other gases.

When choosing your dream booster, you should ask yourself the following questions:

- What type of drive does the booster have? For scuba applications air or pneumatic boosters are the most common (electric, hydraulic or manual driven boosters also exist).
- What type of booster is required for the application? Single stage, single acting; single stage double acting or two stage models are available.
- What is the maximum discharge pressure of the booster? What is the maximum pressure required in your cylinder to be filled? If the maximum discharge pressure of the booster exceeds the maximum cylinder fill pressure, a safety valve or automatic stopping device for your booster could be required.
- What is the flow rate of the booster?
    - What flow rate is required – output of the booster -? What is the required fill time?
    - Is it filling a cylinder? What cylinder size is to filled (water volume)?
- Supply gas?
    - What type of gas is to be compressed (media gas)? Not all boosters are suitable for oxygen applications. As well, different gases have different compressibility factors. Be aware that air pumps faster than helium. Oxygen, nitrogen, and air all pump at about the same rate, while pumping helium is the slowest and produces the most heat. These differences are attributed to the compressibility of different gases – see figure 1 - which in turn will be temperature and pressure dependent.

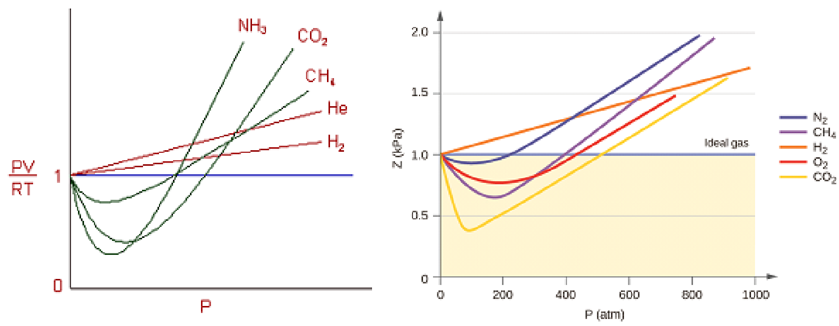

Figure 1

    - Is the supply gas at constant pressure?
    - Is the supply gas of decreasing pressure (most likely scenario for gas blenders)?
        - What is initial pressure of your supply cylinder? Does this exceed the maximum inlet pressure of your media gas to the booster pump? If the latter is the case, a pressure reducer will be required.
        - What is the minimum pressure of your supply pressure? Does this exceed the minimum inlet pressure of the media gas to the booster pump? If the latter is the case, you might not be able to boost all the gas available in your supply cylinder.
- Air drive, drive gas?
    - What air drive pressure available? What is the minimum and maximum inlet pressure of the drive gas to your booster? If your supply pressure is higher than the maximum inlet pressure, a pressure reducer (and safety valve) are required.
    - Air drive volume available? Depending on supply pressures of the media gas and the volume of media gas to be boosted a lot of drive gas can be required. Understanding the manufacturer's graphs will assist you in assessing the requirements. Knowing a

lot of drive gas can be required; using compressed breathing air is sometimes not that economical. In the latter case, a low pressure shop air compressor could bring the solution. Be aware that with an air-powered booster the drive gas consumption goes up logarithmically as the supply pressure decreases and the fill pressure increases.

- What is the application for your booster? With scuba in mind, this could be: using remaining pressure for recharging, air amplification, and transfer of gases into small cylinders...

How do booster pumps work is the first question to answer.

Single stage, single acting – see figure 2 -.

A booster consist of a large area reciprocating air drive piston directly coupled by a connecting rod to a small area piston. The gas piston operates in a high pressure gas barrel section. The gas barrel end cap contains high pressure inlet and outlet check valves. The air drive section includes a cycling spool and pilot valve that provide the continuous reciprocating action when air is supplied to the air drive inlet. The ratio between the area of the air drive piston and the gas driven piston (plunger area / piston area or pump ratio) approximates the maximum pressure the gas booster is capable of generating. Isolation of the gas compression chambers from the air drive section is provided by sets of dynamic seals. The intervening two chambers are vented to atmosphere. This design prevents air drive contamination from entering the gas stream. Cooling is provided by routing the cold exhausted drive air through an individual jacket surrounding the gas barrel. Check valves also allow for the equalization of upstream and downstream pressure prior to boosting, therefore the gas booster only needs to “raise” the upstream pressure to the required pressure and does not have to raise it from atmospheric pressure. Normally, start/stop control is accomplished by cutting off drive- or pilot air input.

Single stage, single acting models provide an economical means of boosting pressure where the volume is small and efficiency is not important.

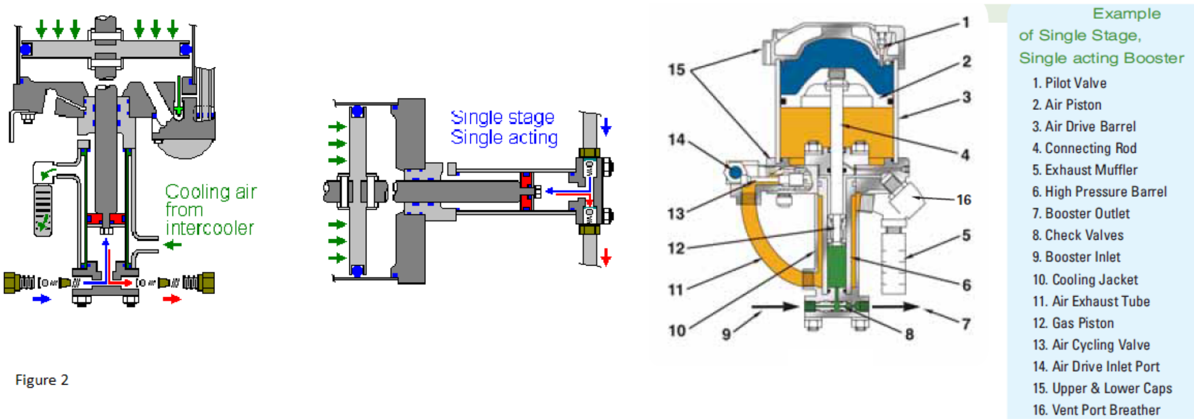

Figure 2

Single stage, double acting – see figure 3 -.

The drive section includes a pilot operated 4/2 way air cycling valve (spool) and dual air pilot valves to provide the continuous reciprocation. The spool leads the drive air alternately on the upper and bottom surface of the air piston. The spool is piloted through two 2/2 way valves or pilot valves which are mechanically actuated through the air piston in its end positions. The pilot valves charge and discharge the spool chamber.

Single stage double acting models not only pump twice the volume of an equivalent single stage model, but also require less air drive since the inlet gas pressure itself provides a substantial proportion of the required driving force. These models provide efficient means of boosting large volumes of gas at low to medium compression ratios.

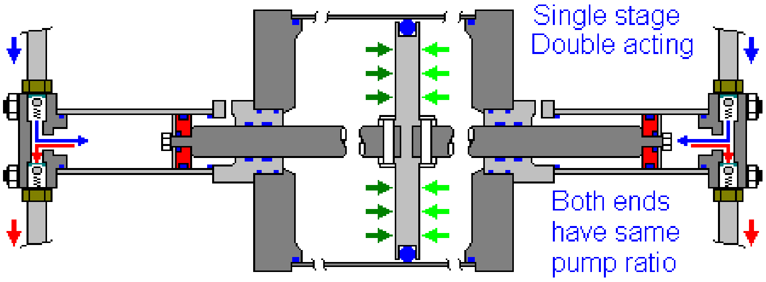

Figure 3

Two stage, double acting – see figure 4 -.

Two stage models provide an efficient means of boosting to a high compression ratio, since the ratio per stage is low. These models have interconnected gas pistons; they multiply supply pressure during the interstage stroke by the area ratio of the two gas pistons.

If the supply pressure is too high, the booster may have interstage stall. This may occur even though the outlet pressure is substantially less than the pressure obtainable on the output stroke. The interstage pressure is only dependent on air drive, minor ratio and major ratio. Thus the interstage stroke return force is independent of the supply pressure. A high supply pressure can oppose the interstage stroke return force causing interstage stall. If the outlet pressure is less than inlet pressure x major ratio / minor ratio, interstage stall will not occur. Cooling is provided by routing the cold exhausted drive air through an individual jacket surrounding the gas barrel and also through an intercooler on the interstage line.

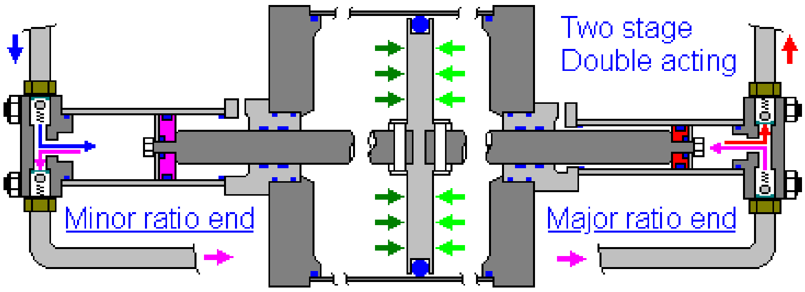

Figure 4

A little word about efficiency. Mechanical efficiency is about the same for all gas boosters, making it a nonissue in selecting among models. But gas booster buyers do need to consider volumetric efficiency. Volumetric efficiency relates to the gas booster's efficiency in moving the gas from stroke to stroke. Because all gases are compressible fluids, the volumetric efficiency of a gas booster varies widely from application to application depending on what compression ratio is encountered. To understand this, have a look at figure 5.

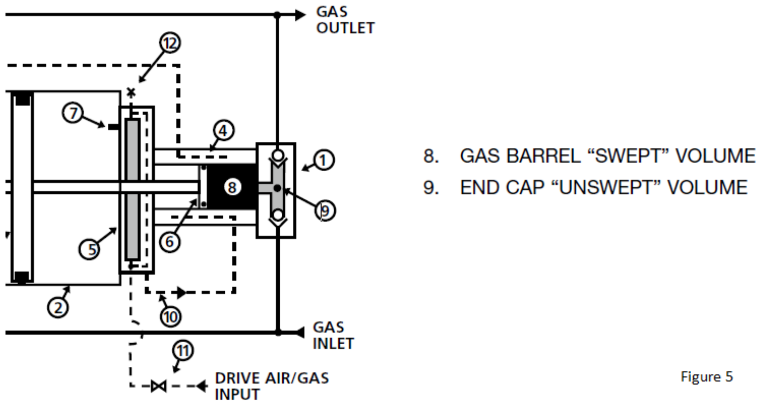

Figure 5

A gas piston cycle consists of a compression stroke and a suction stroke. During the compression stroke, the gas compresses from "swept" into "unswept" space; during the suction stroke, the gas flows back from unswept into swept space. If the gas is compressed to a very high ratio during the compression stroke, the unswept gas may come back during the suction stroke at a residual pressure high enough that the inlet supply pressure cannot open the inlet check valve. When this happens, volumetric efficiency and outlet gas flow reach zero, i.e., the unit has reached its maximum compression ratio.

At the other extreme, the gas in the unswept spaces is compressed very little by the compression stroke. In this case, as soon as the gas piston starts back on its suction stroke, the swept pressure immediately drops below the inlet supply pressure, the inlet check valve pops open, and a full charge of fresh gas is inhaled by the swept volume of the suction stroke. Volumetric efficiency reaches about 99%, meaning that the maximum amount of gas is moved from the gas supply to the outlet receiver during each cycle. Here the compression ratio is very low.

The graphs below – figure 6 A and B - illustrate the above. The compression ratio can be calculated as output pressure divided by the inlet pressure. The lower the input pressure, the higher the compression ratio given we try to achieve the same outlet pressure. From this graphs it can be seem the single stage models will be much less efficient for the same compression ratio compared to two stage models.

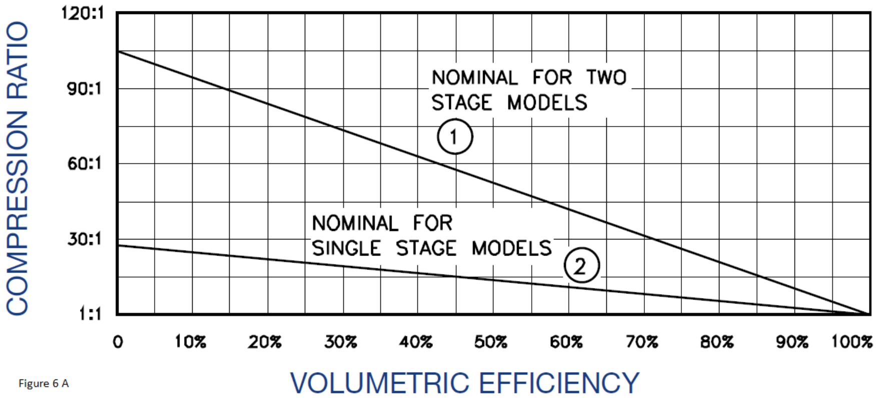

Figure 6 A

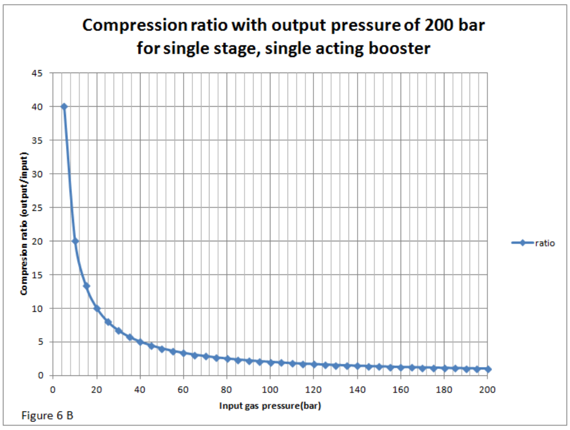

Figure 6 B

About time to put a system together. Figure 7 illustrates the components in relation to each other. But does it really needs to be this complicated? The answer is no: it could be nothing more than a small single stage booster pump mounted in a pelican case together with some whips to connect the supply cylinder, drive gas (scuba cylinder) and output gas (cylinder to be filled).

What will be required depends on your chosen booster and the application of the system. There will be 4 major components: the drive air section, the media gas section (gas to be boosted), the booster pump and the output section (receiver cylinder(s)). The drive air section could be powered by a low pressure compressor or by high pressure cylinder(s), the latter in turn charged by a high pressure compressor (not illustrated). Note as well that the output of the drive air section is fitted with a water trap/condensate drain. On the end of the drive gas line, there's a valve to turn the booster on or off. Depending on the pressure output of the drive air section, one cannot exceed the maximum drive gas inlet pressure of the booster; hence a pressure reducer could be required. If there's a maximum, I'd like to install a safety valve. The media gas section provides the media gas to the booster. Here as well a pressure reducer could be required if the pressure of the media gas supply is greater than the maximum allowable media gas input to the booster. The output of the booster is connected to the cylinders to be charged. Some boosters have very high outputs, therefore I'd like to install a safety valve on the output side of the booster to avoid over-pressurising the receiver cylinder(s) or to prevent 'exploding' the charging hose in case the operator is distracted and forgets to open the receiver cylinder valve. It goes without saying that all piping must be rated to match the design pressure (maximum pressure) of the system. On top of these basics, the system can be upgraded with options like stroke counters, air pilot switches to stop the booster when the output pressure reaches a set value or to stop the booster when the supply pressure drops below a set value, gas filters to stop contamination entering the booster (sometimes manufacturer recommended)...

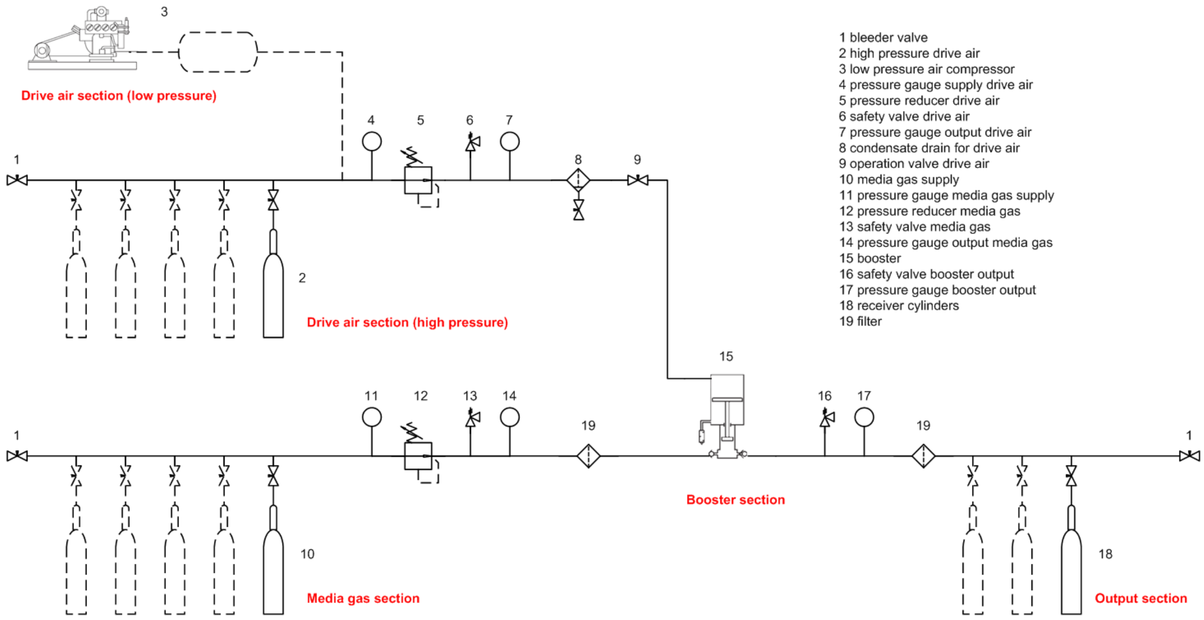

Figure 7

Time for the practical applications: can we boost any supply pressure to any output pressure? Not really, boosters have limitations – reference also made to the section of efficiency -. Important in this discussion is the fact that booster pumps can stall, in other words not being able to boost any further beyond a certain pressure. The two main factors are the inlet pressure of the drive gas and the supply pressure of the media gas. Reputable manufacturers will provide you with a formula to calculate the stall pressure(s) for a specific model. Single stage models have to cope with a static outlet stall pressure, whilst two stage models have to cope with both static outlet stall pressure and a maximum media gas inlet pressure to avoid interstage stall.

Let's take for example a Haskel AG-30 single stage booster: the static outlet pressure stall formula is 30 * Pa. The supply range of the drive gas is between 2.8 and 10.3 bar. Plotting this results in the following graph – figure 8 -.

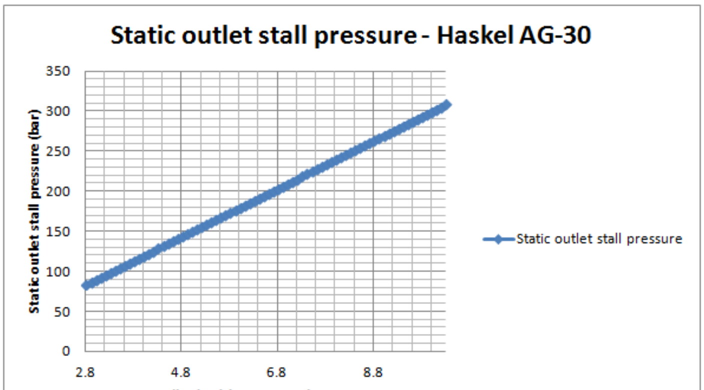

Figure 8

It is clear that if the drive gas pressure is low, the booster will stall at a much lower pressure compared to a high drive gas supply pressure. In this example, for the min supply of 2.8 bar, this is 84 bar and for maximum supply of 10.3 this is 309 bar. From a practical point of view this means that at a low drive gas supply pressure of 2.8 bar, we will not be able to boost higher than 84 bar and the maximum media gas supply pressure is 84 bar. If the media gas supply pressure is higher than 84 bar, we'll need to decant first or reduce this pressure.

How much drive gas does a booster use is a next logical question. Well it depends... not so easy to answer that one. I believe it's time to analyze some of the manufacturer's graphs first. The below graphs – figure 9 - represent the above scenarios for the Haskel AG-20 booster, the left one for a drive gas pressure of 10.3 bar, the right one for a drive gas pressure of 2.8 bar.

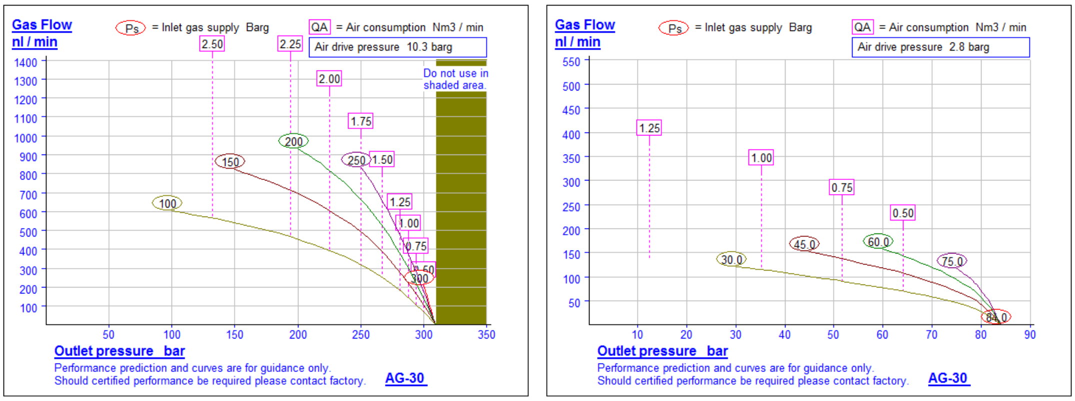

Figure 9

The vertical scale gives the output gas flow in l/min. The horizontal scale shows the outlet pressure in bar. On the graph you see multiple curves, each one for a specific inlet pressure of the media gas. The dotted lines connect the curves to a value: the air consumption in m3/min. Looking at the left graph of this figure 9, let take for example a media supply pressure of 100 bar and let's assume for now that this supply pressure remains constant. When we start boosting at 100 bar, the output would be 600 l/min and the drive gas required around 2.5 m3 or 2500 l/min. When reaching 150 bar output pressure, the output has decreased to 550 l/min and amount of drive gas required still would be around 2.5 m3/min. When we reach 200 bar output, the output decreased to 450 l / min and the drive gas required would now be around 2.25 m3/min. Hopefully you can see that:

- The amount of drive gas required can be considerable (high in other words). If this amount required cannot be delivered, the output of the booster will drop and hence the time to fill will increase.
- If the media gas supply pressure remain constant (same curve), as the output pressure increases, the output - flow/min - decreases. In reality, for scuba applications, the media gas supply pressure will drop, as this supply pressure drops, the output flow rate will drop accordingly.
- The higher the output pressure, the slower the output flow rate and the lower the drive flow rate required. However, given the lower output rate, the longer it will take to fill a cylinder, which then in turn will require more drive air despite the lower required flow rate.

Without software, estimating the time it takes to fill a cylinder and how much drive air is required will only be an approximation of the reality. For this example – fixed media gas inlet pressure and unlimited flow for the drive gas -, if our cylinder to be filled has a capacity of 12L and is to be filled to 200 bar, the computer simulation yields a fill time of 3 minutes and 5.5m3 requirement of drive air. To put this drive gas demand in perspective, this is the equivalent of 2.3 air cylinders with a volume of 12L filled to 200 bar. Note: for all the simulations in this article, I've assumed the media gas to be an ideal gas.

Let run a more realistic simulated scenario on the software for the same AG-30 pump. Let assume we have available a 40.9 L oxygen cylinder filled to 130 bar (our O2 supply in Thailand) and a 12L cylinder to be filled to 200 bar. Firstly we have to equalize the pressure between supply and receiver cylinder, this would result into 100.5 bar of oxygen in both cylinders. Now we can start boosting. After boosting the pressure of the supply cylinder would have fallen to 71.3 bar. The table below – figure 10 - lists the fill times, air consumption for different flow rates and pressures of the drive air. For a media gas supply pressure of 100.5 bar, our minimum drive inlet pressure is 6.7 bar to avoid stalling in order to reach 200 bar output pressure.

AG-30					
Pa (bar)	Flow (m3/min)	Fill time (min)	Average air used (m3/min)	Total air used (m3)	Cycles / min
10.3	∞	3	2.2	6.5	108
10.3	2000	4	1.6	6.3	80
10.3	1500	6	1.3	7.5	49
10.3	1000	11	0.9	9.5	25
10.3	500	39	0.3	13.6	7
8.5	∞	4	1.6	6.2	90
8.5	2000	4	1.5	6.2	87
8.5	1500	4	1.5	5.9	63
8.5	1000	8	0.9	7	32
8.5	500	20	0.5	9.1	13
6.7	∞	7	0.8	5.8	44
6.7	2000	7	0.8	5.8	46
6.7	1500	7	0.8	5.8	44
6.7	1000	8	0.7	5.7	35
6.7	500	16	0.4	6.3	15

Figure 10

This table – figure 10 - illustrates that for the same drive air pressure, the total fill time and total air consumption will increase as the flow rate of the drive air diminishes. If fill time is not too important, in this case, dropping the drive air pressure together with a low drive air flow rate will yield even a slightly lower overall air consumption.

Let run a another simulated scenario on the software for the same AG-30 pump. Let assume we have available a 40.9 L oxygen cylinder filled to 70 bar and a empty 12L cylinder to be filled to 200 bar. Firstly we have to equalize the pressure between supply and receiver cylinder, this would result into 54.1 bar of oxygen in both cylinders. Now we can start boosting. After boosting to 200 bar, the pressure of the supply cylinder would have fallen to 11.3 bar. For a supply pressure of 54.1 bar, our minimum drive inlet pressure is 6.7 bar to avoid stalling in order to reach 200 bar. The table below – figure 11 - lists the fill times, air consumption for unlimited flow rates and specific pressures of the drive air. Figure 12 shows you the output graphs for each one of the scenarios. The dotted red line in the graph shows what happens to the media gas supply pressure. These are some interesting results. As you can see, with a low media gas supply pressure, the total air consumption goes up by a fair bit (in the best case scenario we're using 7.8 air cylinders of 12 L filled to 200 bar). However, keeping the drive air inlet pressure low our drive air consumption stays the lowest in these scenarios. Compared to our previous example with high media gas supply pressure, the fill time has increased.

AG-30					
Pa (bar)	Flow (m3/min)	Fill time (min)	Average air used (m3/min)	Total air used (m3)	Cycles / min
10.3	∞	15	2.4	35.8	108
8.5	∞	18	1.9	34.1	89
6.7	∞	15	1.3	18.8	54

Figure 11

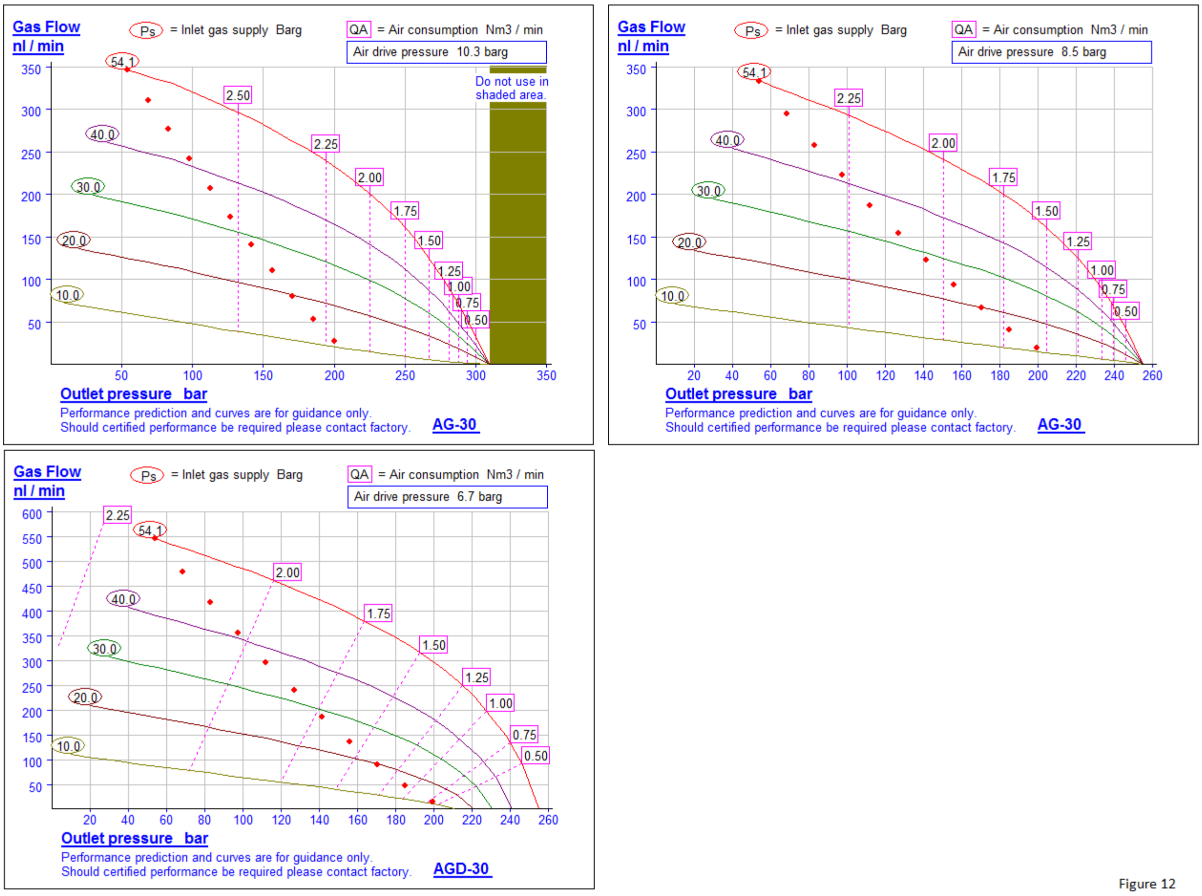

Figure 12

A little earlier in this article, I mentioned that single stage models have to cope with a static outlet stall pressure, whilst two stage models have to cope with both static outlet stall pressure and a maximum media gas inlet pressure to avoid interstage stall. Let’s put that into a practical example for the Haskel AGT-15/30: the static outlet pressure stall formula is 15 * Pa + 2 x Ps.

The maximum media gas inlet pressure to avoid interstage stall should be < 15 x Pa. It is important to note that this limitation for interstage stall does not apply if the outlet pressure is less than the maximum supply pressure times the area ratio of the two gas pistons. In other words the interstage pressure will not achieve interstage stall unless the outlet pressure is greater than the product of the supply pressure x the ratio. For the AGT-15/30 this ratio is 2 (30:15). A practical example: if the drive supply pressure is 10 bar, the maximum allowable inlet pressure to avoid interstage stall is 150 bar. Therefore, interstage stall shall not occur unless the outlet pressure is 300 bar or more. So from a practical point of view in scuba blending applications, this booster is very unlikely to create any issues. Should issues arise, interstage stall poses no harm to the gas booster and no safety hazard. To release the stall and allow the booster to cycle normally, simply throttle the inlet gas line. This manoeuvre reduces the gas incoming volume and pressure enough to prevent stall.

A theoretical representation of all those values for this particular pump for different drive air pressures is in the graph below – figure 13 -.

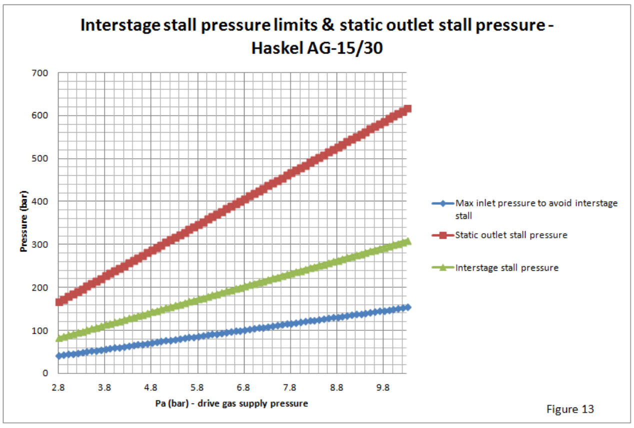

Figure 13

The performance curves of the GBT-15/30 are given in figure 14.

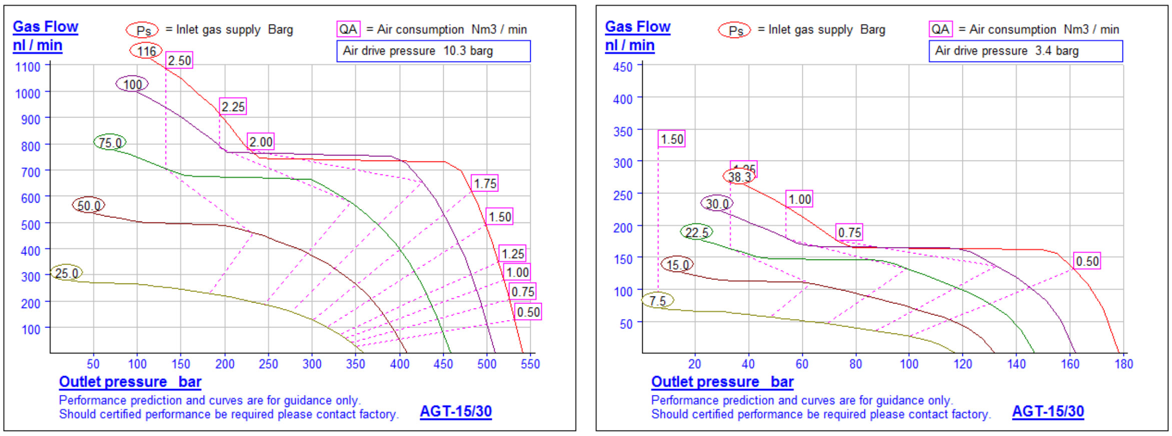

Figure 14

How much air thus this beast of a booster use? Let’s run a practical example, starting with a full 40.9 L oxygen bottle (130 bar) and fill some empty 3L rebreather cylinders to 200 bar. Our supply air drive supply pressure is 10.3 bar and the supply flow is unlimited. The table– figure 15 - shows what happens.

GBT-15/30								
P start media gas supply	P end media gas supply		Pa (bar)	Flow (m3/min)	Fill time (min)	Average air used (m3/min)	Total air used (m3)	Cycles / min
130	121.12	EQ						
121.12	115.33	BOOST	10.3	∞	1	0.6	0.6	86
115.33	107.66	EQ						
107.66	100.66	BOOST	10.3	∞	1	0.7	0.7	87
100.66	93.78	EQ						
93.78	85.99	BOOST	10.3	∞	1	1	1	89
85.99	80.11	EQ						
80.11	71.32	BOOST	10.3	∞	1	1.3	1.3	93
71.32	66.45	EQ						
66.45	56.65	BOOST	10.3	∞	1	1.7	1.7	96
56.65	52.78	EQ						
52.78	41.98	BOOST	10.3	∞	1	2.4	2.4	99
41.98	39.11	EQ						
39.11	27.31	BOOST	10.3	∞	2	1.9	99	3.8
27.31	25.44	EQ						
25.44	12.64	BOOST	10.3	∞	3	2.5	97	7.6

Figure 15

From the table we retain that as the supply pressure drops, the time to boost increases and so does the air consumption. Note that for the first boost session, the media gas supply pressure is 121 bar, which with a drive gas pressure of 10.3 bar is not a problem. However, if the drive gas supply would only have been 8 bar, this would not have been possible because of interstage stall.

To finish off in beauty, one more example for the CCR divers. You are the proud owner of a Haskel AG-30 booster and wish to fill your own oxygen 3L cylinders on the road. You have at your disposal a twin set that contains 4800 L of air (twin 12L @ 200 bar) and a 12L media gas supply cylinder of oxygen filled to 200 bar. After each dive, you return with 50 bar of oxygen in your 3L cylinder. How many fills can we achieve with this setup assuming the air flow rate of the drive gas is unlimited and the drive gas supply pressure is 10.3 bar? The 'theoretical' calculation reveals 4 times. See figure 16 below.

AG 30										
P start media gas supply	P end media gas supply		Pa (bar)	Flow (m3/min)	Fill time (min)	Average air used (m3/min)	Total air used (m3)	Cycles / min	Drive air volume start	Drive air volume end
200	170	EQ								
170	162.5	BOOST	10.3	∞	1	0.3	0.3	100	4800	4500
162.5	140	EQ								
140	125	BOOST	10.3	∞	1	0.6	0.6	104	4500	3900
125	110	EQ								
110	87.5	BOOST	10.3	∞	1	1.3	1.3	107	3900	2600
87.5	80	EQ								
80	50	BOOST	10.3	∞	2	1.3	2.6	110	2600	0

Figure 16

Time to wrap this one up. As you gathered, booster pumps are simple and complex at the same time – let's face it, they are a marvel of hydraulic engineering -. A fair few pressures and flow rates are to be considered for proper and efficient operation of the booster. Other factors – see list of questions – have to be evaluated prior to making your investment. Important to keep in mind is that booster pumps are not a piece of 'black magic' that will boost any pressure up. On top of that, boosters can use tremendous amounts of drive air, especially with low media air supply cylinders to be boosted to high pressures. In commercial blending applications, you will have to consider this drive gas expense. How much drive air that is required and the time to fill a cylinder is a big variable, however it will depend on:

- The size of the supply cylinder and its pressure: the higher the media gas supply cylinder pressure, the faster the booster will transfer gas. As gas is removed from the media supply cylinder, the supply pressure drops. The larger the media gas supply cylinder, the slower the rate of media gas supply pressure drops.
- The size of the receiver cylinder with its start and end pressure. The greater the capacity of the cylinder to be filled, the longer and the more gas (both media and drive gas) it will take.
- The flow rate and flow pressure of the drive air: a low air drive pressure, a low flow rate or a combination of both will make the filling process slow. Restrictions in the drive air supply line also will decrease the speed of filling. Therefore, large bore supply piping is recommended.
- The compressibility of the media gas and the temperature. Both the ambient temperature and the temperature of the booster are important. The greater the difference between the media gas supply and fill pressures, the more heat will be generated by the booster. The hotter the booster gets, the less efficiently it pumps.