Expansion chambers

By Randy Norian

How expansion chambers work (basic theory)

I'm assuming that anyone who has made it this far knows the basics of 2 stroke engine operation. If you already know how chambers work, as well, skip this part and move onto the advanced stuff.

The exhaust system is critical to the operation of a 2-stroke engine. A 2 stroke relies on pressure changes in the exhaust system to help draw air through the cylinder- first to draw exhaust out and fresh charge into the cylinder, and then a moment later to cram any excess fuel mixture back in through the exhaust port, just before the piston seals the port shut.

A well-designed expansion chamber is worth at least a 25% power gain over a simple tubular exhaust on a 2 stroke, and I'd guess it's probably more like 50+ %. No matter what you do to the rest of the engine, the exhaust will make or break the package, and can be used to tune the engine's characteristics to a large extent.

There are a few basic underlying principles involved in all this exhaust pipe stuff. Here they are:

Waves and Reflections

Sound waves are just pressure pulses that travel through the air-- just like a shock wave traveling through a slinky. They travel faster or slower depending on the density and temperature of the medium (the stuff they're moving through). In fact, any pressure wave travels (propagates) through the air at the speed of sound. They're pretty much the same thing. Why don't low-pressure weather systems rush around at 600 mph, then? I have no idea.

Waves traveling down a tube will reflect back the way they came when they get to the far end. If the end of the tube is closed, there will be a positive reflection. Like a ball bouncing off a wall, the wave returning will look just like the one that made it. If the end of the tube is open, there will be a negative reflection, and you'll get a pressure wave that has the opposite value of the one that made it.   As it happens, anytime the pipe gets smaller it will reflect a partial + wave back , and any time it gets larger it will reflect a partial - wave back. Weird, but that's how it works, and that's one of the keys to understanding expansion chambers.

An example (skip this if you already get it):

Suppose we have a hollow tube, and at one end we introduce a +5 psi, (positive) pressure wave. (pop!!) We'll say this wave is short, maybe 0.1 inch long... At room temperature, the wave zips down the tube at about 1100 feet per second (fps).

If the far end of the tube is closed with a flat cap, the wave will hit and return (approximately) a +5 psi reflection back up the pipe, also 0.1 inch long. (pop!!) Now we try that again, but at the end we remove the flat cap and install a conical end cap 4 inches long. This new end cap tapers to a point, like a needle.

Again we introduce a 0.1" long pressure pulse into the pipe. (pop!!) It travels down the pipe and hits the start of the cone... as the pipe squeezes together, a long, but weaker + wave is reflected back up the pipe. The reflection begins as soon as the (pop!!) enters the conical section, so the original pressure wave is still moving down the pipe while a partial reflection is already beginning to travel back up. By the time our "pop" has reached the end of the needle, there is a 4" long wave already returning up the pipe (that's half the length of the returning wave).

Back at the front of the pipe, where all this started, we will be greeted by a weak poooooooooooop wave 8 inches long. It has all the energy of the original wave, but now it's spread out over an 8" length, so it is lower in amplitude.

The important thing is this: we can trade the amplitude (strength) of the returning wave for duration; Strong and short reflection, or weaker, but longer reflection. This is The Big Compromise in designing an expansion chamber.

Back to Pipes

The typical expansion chamber consists of a few basic parts. The head pipe, which has a shallow angle of around 1.7 degrees (3.4 degrees included) the diffuser (expanding section) which has an angle of around 7 degrees (14 degrees included) a belly or center section of constant diameter, the baffle (converging section) which is around 12 degrees (24 degrees included), and a stinger and muffler assembly, which varies widely but can be anywhere from 8 inches to 2 feet or more in length, and about an inch in diameter.

These are gross generalizations, pipes vary widely according to intended usage but these are ballpark specs for an RG500 exhaust.

A trip thru the exhaust/intake cycle

The exhaust port opens suddenly around 85 degrees after TDC. At that point, a high-pressure wave shoots into the head pipe. The pressure wave is traveling at around 1700 fps due to the high temperature and pressure in the exhaust pipe. The pressure moves down the pipe till it gets to the diffuser, the first major expanding section of the exhaust system. Part of the wave's energy is reflected back, in negative form, up towards the exhaust port, while the remainder of the original wave continues down the pipe.

The negative reflected wave reaches the exhaust port just in time to draw lots of fresh mixture up through the transfer ports and into the cylinder. In fact, it can pull so much fresh mixture that it actually fills up the cylinder and pulls the new charge right out the exhaust port and into the exhaust pipe. (This is obviously wasteful)

Now we get back to the original wave, reduced in strength but still moving down the exhaust pipe. It reaches the baffle cone (converging) and begins to reflect a + wave back up the pipe. The baffle cone is usually about 2X as steep as the diffuser and so creates a pretty strong, but short duration, pulse. This is often known as the "stuffing" pulse, and here's why: just as the piston is starting to close the exhaust port, trapping our excess fresh charge in the head pipe, the stuffing pulse arrives and literally crams a fair amount of it back into the cylinder.

With luck, the stuffing pulse holds out until the exhaust port is closed, and now we have much more mixture in the cylinder to be compressed than the motor could have pumped on its own. The exhaust system on a 2 stroke acts like a supercharger from the exhaust side, and it's this little trick that allows 2 strokes to make the tremendous power that they do.

More things to consider (advanced)

Once we know how the pipe works, we need to get a little more specific as to just when all this sucking and blowing occurs. When everything is right, it all goes just like the scenario described above.

Unfortunately, the vacuum and pressure pulses arrive back at the exhaust port at fixed intervals after the exhaust port opens-- this means that the timing will be right at some RPMS, and will be very wrong at other RPMs, leading to the notorious "all or nothing" power delivery that many expect from a 2 stroke power plant.

Determining the operating range of an expansion chamber

The most significant factor in this case is the placement of the baffle cone. The timely arrival of the stuffing pulse at the exhaust port is crucial to making good power. For this reason, most basic equations for analyzing expansion chambers simply deal with the 'tuned length' of the pipe. Jennings gave this formula:

Lt =3D Eo x Vs / N

Lt in inches
Eo is exhaust open duration in degrees
Vs =3D speed of sound in fps (Jennings uses 1700 fps as an average)
N =3D engine speed in RPM

For Metric fans, Robinson uses Lt =3D Eo x 42525/ RPM, where Lt =3D tuned length in mm

Lt is the distance from the edge of the piston to a point halfway down the baffle cone, if we pretend the baffle cone continues to make a point.   If we consider a stock RG500, this distance is about 84cm, (33 inches) and Eo is 188 degrees. Using Vs of 1700 fps, this formula predicts a peak power RPM of 9684 RPM.   This is a pretty good estimate, as my bike peaked at 9500 rpm in stock form.

Just to juggle things a little bit, let's raise the exhaust port, 2 mm on this motor. This increases Eo to about 196 degrees. Recalculating with the same pipe gives a new peaking RPM of 10100 RPM.

Obviously, there are a lot of things that affect the workings of the expansion chamber.

Wave timing

The diffuser section generates a vacuum pulse that helps to draw mixture up through the transfer ports. Just when this wave should arrive depends on what we want it to do. At 10,000 RPM, there are just 3.1 milliseconds (mS) from the time the exhaust port opens, and the exhaust pulse heads down the pipe, until the exhaust port closes prior to ignition. The useful vacuum pulse has a duration of about 7 mS. The stuffing pulse, about 5 mS.

These need to be timed precisely to arrive when needed. Keep in mind that the wave timing is for all practical purposes fixed, and the vacuum and pressure waves do their thing, with the same timing, regardless of engine speed.

Fresh mixture is pumped up from the crankcase through the transfers as the piston descends. After BDC, however, the rising piston wants to suck the mix back *into* the transfers.

Only the inertia of the flowing gas tends to keep it moving into the cylinder.., unless it's helped out by the timely arrival of a vacuum pulse at the exhaust port. The vacuum pulse can be as strong as -7 psi, and really pulls fresh mixture up into the cylinder from the crankcase.

Using a less aggressive diffuser will make a weaker but longer duration vacuum pulse, which will be in synch over a wider RPM range. At lower RPMs, the vacuum pulse arrives increasingly before BDC, and flow through the transfers after BDC is reduced. At low enough RPMs, there may be no vacuum available after BDC at all. As the pipe comes into phase, the vacuum pulse arrives just in time to keep the charge flowing before and after BDC, and helps to overfill the cylinder.

As RPMs increase too far, the wave will not begin to arrive until after BDC, and at high enough RPMs the transfers will close before the vacuum pulse is done, so some of the pulse is wasted.

Ideally, the fresh charge fills the cylinder and then spills out into the head pipe as the cylinder is 'overfilled'.

The stuffing pulse should be timed to arrive shortly before the exhaust port closes. At lower rpms, the pulse arrives too soon, before the cylinder is done filling. If the rpms are low enough it cannot only force exhaust gases back into the cylinder, it can prevent fresh mixture from moving up through the transfers.

As RPMs rise and the pipe comes into synch with the motor, the stuffing pulse will arrive just in time to push the fresh 'overfilled' mixture back into the cylinder before the piston seals the port shut, and power rises dramatically. As rpms increase further, the piston closes the exhaust port before the stuffing pulse can get there, and the supercharging effect is lost. At this point, the motor usually falls flat on its face.

Body waves
No, this is not a fashion consideration. Inside the pipe, the original pulse hits the baffle and heads back up towards the exhaust port. But what happens when it gets back to the diffuser section? To a wave traveling up the pipe, the diffuser represents a decrease in pipe size... and so part of the wave reflects back down the pipe, as a + wave. That wave then hits the baffle, and reflects back up the pipe, and so on and so forth. The result is a series of decreasingly strong waves resonating inside the center of the pipe. This is called the body wave.

The body wave is every engine cycle fed by a fresh exhaust pulse. At certain rpms, the body wave is in synch with the exhaust pulses coming from the engine, and it reinforces them. This can lead to an even higher, super peak in the torque. At other rpms, most noticeably just before the powerband begins, the body wave can be out of step with the motor, and can cause a terrible drop in torque output. This is often the cause of the 'pre-powerband hole' that bikes without exhaust valves get to enjoy. Adjusting the center section of the pipe to affect body wave timing can be used to tune out dips and spikes in the powerband.

Exhaust temperature
The temperatures of the gases in the exhaust pipe affect Vs (the speed of sound). Higher temps =3D higher Vs, and in turn, higher peaking rpm.

Several things, including ignition timing and pipe outlet restriction, affect the temperature in the pipe. Outlet restriction is affected by the stinger length and diameter. Pipe temperatures can also be altered by wrapping the expansion chamber with insulating material, or by using an isolative coating applied to the metal itself.

Backpressure
A certain amount of backpressure is desirable in the 2-stroke exhaust. Backpressure slows the speed of the exhaust gases flowing down the pipe, making it a little easier for the stuffing pulse to stop the flow, turn it around, and stuff it back into the cylinder. In fact, increasing backpressure usually seems to increase peak power. Higher backpressure also raises the density of the gas in the pipe, and also temperatures, (both of which raise Vs) and thus peaking RPM.

As always, though, there are disadvantages to offset the gains. More backpressure makes it easier for the stuffing pulse to do its job, and generally boosts peak power, but it also increases exhaust temps, and causes piston temperatures to skyrocket. Too much backpressure will melt pistons, for sure. Too much backpressure also puts drag on the motor, making it gain revs more slowly. Heat is a big killer for 2 stroke pistons, and it doesn't take a big problem to quickly allow too much heat to build up in the piston.

An engine that will be used for high speed, top end runs might use a pipe with less restriction to let the motor live under those conditions. A bike that will be used on a race course, with periods of on and off throttle, can often push things further because there won't be as much time for heat to build up.

Cone angles

It would be nice if we had great, strong exhaust pulses to pull and push mixture and out of the cylinder whenever needed. Only so much energy can be extracted from the exhaust pulse as it moves down the pipe, though, so we have to choose how much we want to use, and when. As mentioned before; steeper cones will create stronger pulses, but of shorter duration.

The powerband will be stronger, but the pipe will only be 'in phase', or what I call resonant, over a narrower RPM band. Not only that, the 'off-pipe' or anti-resonance, will be even worse. The pipe, which has potential to pull the most mixture into the cylinder, can also foul things up the worst at lower rpms. It's all a tradeoff, as usual.

There are other limits to how steep you can make the cone angles, especially on the diffuser side. Too sharp of a diverging angle can 'stall' the exhaust pulse, as it is not able to follow the rapidly diverging walls of the pipe. I'm not exactly sure what happens, but I picture it like non laminar flow across an airplane wing.

There are a few ways to help in this situation. One way is to ease the pipe into a steep angle by using a series of increasingly steeper cones- in fact, 2 and usually 3 stage diffuser sections are the norm these days.

Another way is to increase backpressure via the stinger outlet restriction, generally by using a smaller ID stinger. This is sort of a band-aid, however, and the drawbacks have already been mentioned.

Crankcase volume/ pipe diameter

Crankcase volume is another critical parameter to juggle, along with everything else in the pipe design game. Back in the old days, 2 stroke tuners relied on the descending piston to blow most of the fresh charge up into the cylinder. Without a strong vacuum pulse from the pipe to assist, tuners had to rely on kinetic energy in the transfer stream to keep things flowing after BDC.

To achieve this, and to get all that charge in the case up into the cylinder where we figured it ought to be, motors were designed with high crankcase compression ratios, as high as 1.7 to 1. "Stuffing the cases" was a common practice, where you would fill every nook and cranny of the case with epoxy or filler, in order to eliminate any wasted space.

Thus, when the piston descended, the charge would really squirt up through the transfers at terrific speed. Often the stream had such speed that it would quickly zip up the cylinder, loop around, and shoot out the exhaust port.

Eventually ideas changed and transfer ports became flatter at their entry into the cylinder. The idea was to let the incoming mixture streams collide gently in the center of the bore, and rise up, slowly and completely filling the cylinder. Crankcase CR dropped as they slowed down the transfer streams.

This hurt flow after BDC, so we began to rely more on the pipe to pull mixture after BDC. As it happens, it's easier to suck a big breath of air from a big room than a thimble, and crankcase volume increased so that the pipe could more easily draw mixture through the transfers. Modern motors have large cases, with crankcase CRs as low as 1.2 to 1. The RG500 has a case CR of about 1.47 to 1.

A fatter pipe can extract more energy from the exhaust pulse, and can generate stronger vacuum to pull mixture. However this only works to an extent, as a small case will frustrate this approach. You simply cannot take a deep breath from a small bottle. Fat, high-suction pipes will also pull more mixture out the exhaust port, and with older-style transfer ports (upward aimed transfers) an excessive amount of mixture will escape into the exhaust pipe--more than the stuffing pulse can push back in.

Internal stingers/ side exit pipes

Here's the basic idea. In a normal 2 stroke exhaust, the pressure pulse heads down the pipe, making its reflections, and traveling until it gets to the back of the pipe...at which point what's left of the pulse escapes into the stinger. Why should we waste this last little bit of pulse? Why not let the baffle cone continue down until it comes to a point, and extract all the energy out of that pulse where the gases are at their hottest and most highly compressed? Let all of the pulse bounce back up the pipe, and simply let the gases come out someplace else, like from the side of the pipe in the center. That's the premise for a side exit pipe. For some reason these have not really caught on, but rear-mounted internals stingers are not uncommon. On these pipes, the stinger simply extends into rear of the pipe a few inches.

The exhaust pulse is entirely reflected back up the pipe, and pressure is bled off the pipe from a point further up the exhaust, in this case, maybe 4 or 5 inches before the end of the baffle. I believe Spec II uses them on their RD350/400 pipes.

Internal stinger pipes are generally acknowledged to be a little quieter than conventional stinger setups; proponents of internal stingers say this is because more of the pulse is being put to work in the motor, and less exhaust energy is escaping out the back of the pipe.

Yet more things in the engine that affect pipe operation & design

A very experienced tuner told me to think of the expansion chamber like a turbocharger. The more heat and energy you put into it, the more you will get back from it (in terms of stronger wave action)

Compression Ratio

Increasing the compression ratio generally increases the energy released during combustion, because it's a good thing to squeeze the mixture very tightly before ignition. On the other hand, a side effect of higher CR is that more of the energy released is taken against the piston crown, and less escapes into the exhaust pipe. Less energy going into the pipe =3D weaker wave action. Weaker waves =3D less effective movement of fuel/air through the ports. So now what do we do? Our new, high compression heads are a double-edged sword. If the pulse heading into the exhaust is weaker, we can switch to a fatter pipe-- in an attempt to extract more energy from the weaker pulse we now have.

Kevin Cameron recently wrote an article on this topic (month, journal) and cited examples of race engines where compression ratio and pipe diameter are linked, a mysterious reduction in CR for a new model is accompanied by a reduction in pipe diameter, and vice versa. It's common knowledge that higher compression heads will give better midrange, while lower compression heads will often let a GP bike rev out harder on higher speed tracks, can it be because the LC heads allow the pipes to work better?

There are cylinder heads on the market (by Polini) that feature a floating combustion chamber that recedes at high RPM, this may not only address MSV (max squish velocity) but probably allows the motor to pull crisply in the midrange with a high compression setup, while retaining low compression rev-out characteristics at peak RPMs.

Ignition timing

Advance affects the expansion chamber primarily by altering exhaust gas temps. More advance generally reduces EGT, to a point. Retarding the timing makes the mixture burn later, and more heat escapes into the exhaust pipe. Higher EGTs raise Vs, and remembering the equation for Lt, the peaking RPM of the motor varies directly with Vs.

Simple version: retarding the timing at high RPMs will give you more overrev. This is no big secret, and my motor will pull hard for an extra 500 rpm or more simply by retarding the timing 4 degrees. The trick is to keep a good amount of advance through the upper-mid rpms, and retard timing after peak power to extend the rpm range of the pipe. Being able to rev another 500 rpms may save a racer several shifts per lap, so retard is an easy way to tune the exhaust system on the fly.

Blowdown

Blowdown refers to the interval between the opening of the exhaust port, and when the transfers open. Usually this is 31-35 degrees of crankshaft rotation. Blowdown is important because the high pressure in the cylinder has to bleed off before fresh charge can flow up through the transfer ports. 35 degrees of rotation doesn't seem like a long time for this to occur; yet 35 degrees is a very generous figure for blowdown. 30 degrees would be considered insufficient for a high rpm motor.

Generally, we'd like as much blowdown as we can get! Why not let the pressure in the cylinder fall as much as possible before trying to pump in that new charge? Well, have to move the exhaust and transfer ports further apart to increase blowdown (sort of), and there is a limit to just how far these ports can be relocated.

A modest engine may have exhaust opening at 86 degrees ATDC, and transfers opening at 118 degrees ATDC. That gives 32 degrees of blowdown, not a whole lot, especially for a high rpm motor. The only ways to increase that figure are to raise the exhaust port (reduces the power stroke) or lower the transfers (not the best idea for making more high rpm power).

However, these are not hard and fast rules. One tuner said that raising the exhaust port on a stock RG500 will help even in the midrange, because the stock porting setup is short on blowdown. Raising the port allows the exhaust to vent more completely before the intake cycle begins, and can result in better cylinder filling.

By that same token, too-high transfer ports will look racy on the spec sheet, but will drastically reduce blowdown timing, and will hurt top end performance. I have ridden motors with transfer ports too high, and they revved really high, but never seemed to pull very crisply. Just never came on the pipe really hard.

That's a bit of an oversimplification, though, because it disregards the SIZE of the exhaust port. A very wide exhaust port with 30 degrees of blowdown may well outperform a motor with a tiny exhaust port and 35 degrees of blowdown. We need to consider the exhaust Time-area, which factors in exhaust port size AND exhaust duration.

In general, you want as much exhaust port area as possible, and that's why we see large bridged exhausts or triple exhaust arrangements. These are tricks to get as much exhaust area as possible without overstressing the rings. In an ideal motor, we would have tons of exhaust area but a low port height, so we could have excellent low and mid rpm power, while retaining plenty of exhaust time area to support good top end power.

This doesn't impact the pipe directly, but the exhaust design needs to be in agreement with what the porting is trying to do. Bolting a super high rpm pipe onto a motor with mild porting will result in an engine that doesn't know if its supposed to be coming or going. Everything needs to be in synch and in step with each other in order for a 2 stroke to really get that terrific power peak.

Disc timing

On disc valve motors, the disc timing can interact with the pipe. One parameter especially strikes me. I mentioned earlier the problems with a small crankcase volume- high transfer velocity, and also a limited volume for the pipe to draw from. Well, that second one isn't strictly true- there is a way to trick a little more air into moving through the cases.

On an Rg500, the disc valves open about 147 degrees BTDC. The transfer ports, meanwhile, do not close (as the piston rises) until about 119 degrees BTDC. This gives us 28 degrees of crankshaft rotation where the engine is open all the way from the exhaust port to the carburetor!! An exhaust pipe with good vacuum late in the transfer event can pull mixture all the way from the carburetors- basically from a crankcase with no volume limit!

I have heard speculation that the Aprilia 250 GP bike uses this tactic to good effect. You never know!

Designing Two Stroke Exhaust Systems

There are all sorts of programs available that will help you to design an expansion chamber. Most of them do not worry too much about ignition timing, compression ratio, crankcase volume, disc timing, blowdown, port timings, exhaust size, projected exhaust and pipe temperatures, etc. All of these things have a bearing on how the pipe/engine package will function, but are often overlooked. It's fun to plug in a few numbers and have a little program shoot out a pipe design, but there is no substitute for a good analysis beforehand and some trial and error testing afterward!

I am not sure what would happen if I tried to design a pipe totally from scratch. It's certainly easier to take an existing design and build from there. The pipe design programs certainly can give you a starting point, if you're starting from scratch, but that's not something I have much experience with.