Two-Stroke Exhaust Systems

The two-stroke internal combustion engine has been around with since Sir Dugald Clerk's pioneering gas engine of 1881. Twice as many power strokes promised big improvements over 4-stroke gas engine designs, but the actual gains were very modest. It turned out that having twice as many power strokes meant the time available for emptying and filling the cylinders was so much shorter that both the inlet and exhaust ports needed to be open at the same time. Naturally, this situation lead to some fresh charge getting lost out the exhaust and some exhaust staying behind to become mixed with the fresh charge.

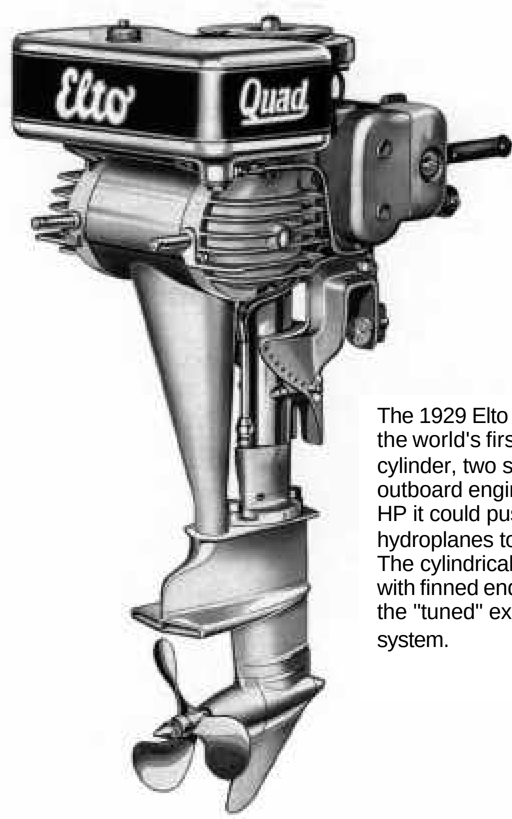
In the 1890's Joseph Day designed the lightweight 2-stroke engine where the crankcase is used as a pumping chamber for the fresh mixture. Now the 2-stroke had it's small power advantage, plus a new and big power to weight advantage over other engines, so it was ideal for applications where weight has a large effect on performance.

For most of the 20th century we became used to finding a two-stroke engine in applications like lawn mowers, chain saws, outboard engines, motor cycles, light aircraft and go-karts. Then in the 1960's, as any student of racing will know, the two-stroke suddenly took off as a high performance engine. In racing classes where any type of engine was allowed, limited only by engine capacity, the two stroke engine has reigned supreme ever since. Today the best two-strokes are demonstrated by Grand Prix 500cc racing motor cycles where power output exceeds 350 horsepower per litre, compared with the current top 4-strokes, Formula One cars, at around 260 horsepower per litre.

While many evolutionary improvements occurred during the two-stroke's first 70 years, the single change that brought about the sudden power superiority was exhaust tuning, or the design of exhaust systems that actually help clean and fill the cylinders, not just take the spent gasses away.

Even in the early days technicians knew that the two-stroke's exhaust system had a considerable effect on the engine. Leaving the muffler off would make some machines go much better, while others went noticeably worse. Experimentation with exhaust system shapes often brought rewards without us understanding why. Production engines started to show unusual shapes in the 1920's.

See the example sketch of the 1929 ELTO (Evinrude) 18 HP outboard. This horizontally opposed 4 cylinder two-stroke was a high performance engine of the day, winning many races. The cylindrical chamber at the rear the engine, with finned end caps, is the exhaust manifold. It's nearly as big as the engine itself. A lot of experimentation had arrived at this shape, but just why it worked was not really understood.



The 1929 Elto Quad was the world's first 4 cylinder, two stroke outboard engine. At 18 HP it could push racing hydroplanes to 45 mph. The cylindrical chamber with finned end caps was the "tuned" exhaust system.

In an age when most boats had less than 10 HP and rarely traveled at more than rowing speeds, 18 HP and 45 MPH (72 KPH) was race winning stuff.

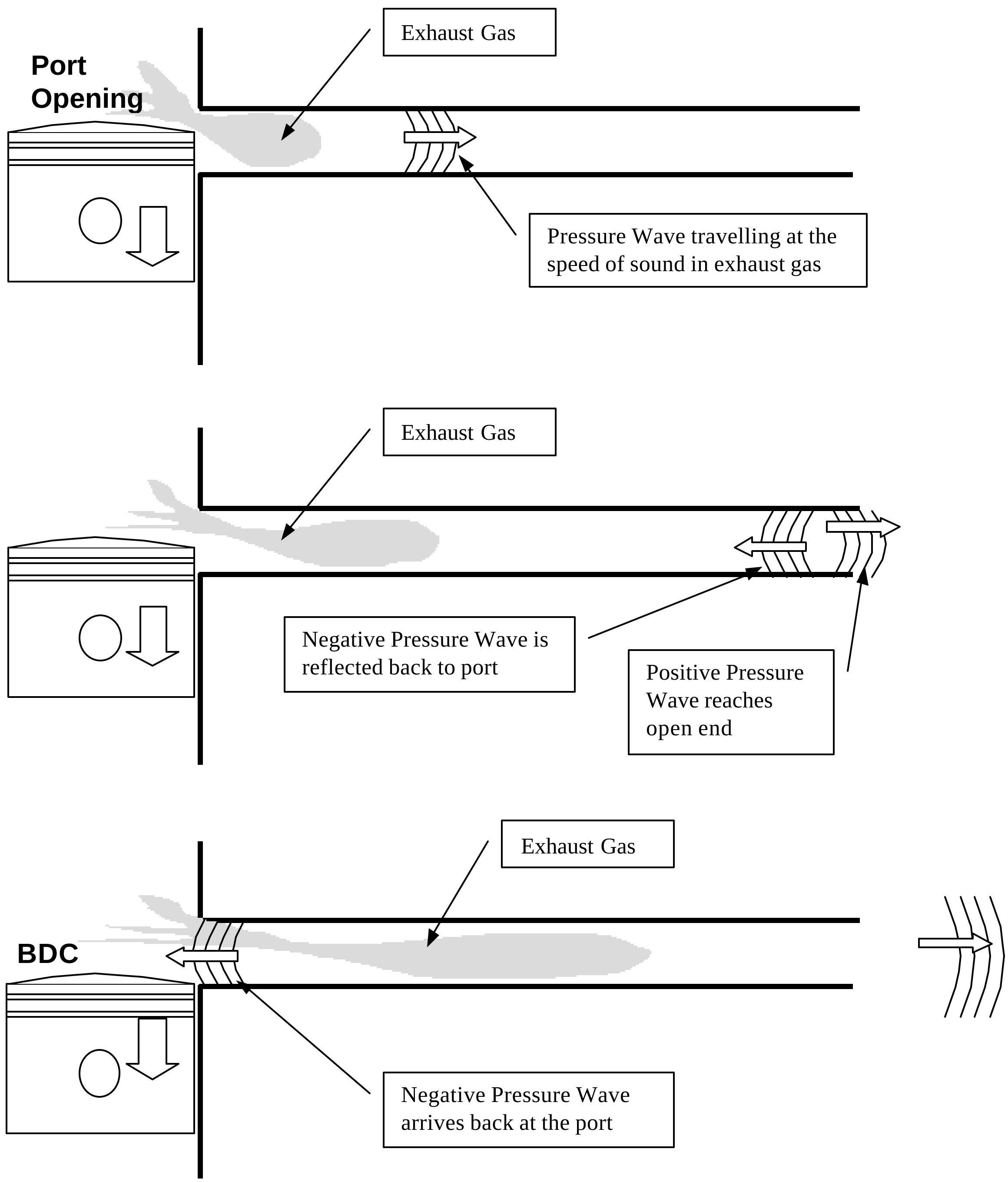
In the 1950's racing motor cycles started to appear with the first really visible tuned exhausts, "megaphone" type exhaust systems. They were very noisy, and used lots of fuel, but were also quite fast threatening the dominance of four-strokes at that time.

By this time engineers were starting to understand what was really happening in the exhaust system and how they could use it to advantage. The text books of the day followed the "slug of gas" theory, where it was believed that the rapid transit of the exhaust gas down the pipe just after the port opened, must have been creating a negative pressure behind it, and so helping to empty the cylinders. But it was not long before engineers reasoned there had to more to it than that, because the gas flow is too slow.

To demonstrate take an example engine with a 500cc cylinder and peak power at 6000 rpm, quite common in modern marine engines. The exhaust port will open about 98 degrees after TDC, and the exhaust pipe will be around 40 mm in diameter. A few quick sums will show the exhaust port is open for 0.0045 seconds at that rpm and if the engine was 100% efficient, all 500 cc's of exhaust gas would be evacuated in that time.

At first the gas speed is quite rapid, about 300 KPH right at the port, however because the port is open only briefly, the "slugs of gas" once out in the pipe rapidly run into previous "slugs" and mingle to form a more uniform flow. That computes to an average gas speed in this size of exhaust pipe of just under 40 metres per second or 140 KPH, fairly quick but not really quick enough. During the time the exhaust port was open the "slug of gas" could have traveled up to 400 mm, if the pipe was completely empty, but because it's not the average distance is less than 200 mm.

Typical wave behavior in a parallel sided pipe.



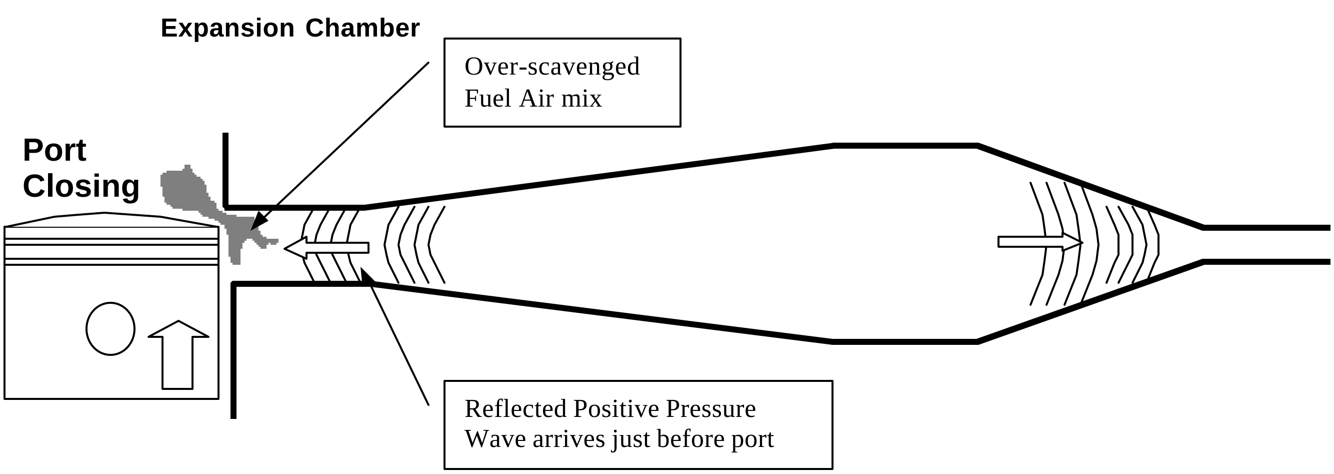
The breakthrough was in understanding how pressure waves, or sound waves, travel along the exhaust pipe and can change the pressure in the system. When the exhaust port opens the still quite high pressure in the cylinder causes a positive pressure wave to travel along the pipe, at the speed of sound. When it reaches the open end of the pipe some of it is reflected back as a negative pressure wave. If this negative pressure wave arrives back at the port when the port is fully open (BDC), pressure at the port is lowered, pulling any remaining exhaust out and also pulling the fresh charge up from the crankcase. If the pipe is the right length to match the sound wave's speed to the desired engine speed, then there is sudden increase in cylinder scavenging at the rpm where they coincide.

A straight sided pipe reflects a relatively weak and very brief wave, because too much energy is lost into the atmosphere. A diverging pipe (megaphone) reflects a much stronger wave and over a much wider range, which is just what we need for a high performance engine. These megaphone exhaust systems were so good at "vacuuming" the cylinder that they also pulled a lot of the fresh charge out into the exhaust, hence the very high fuel consumption of these early racing two-strokes.

An example of this type of system is shown in the picture of Starflite III a hydroplane that set the worlds outboard speed record at 123 MPH (198 KPH) back in 1960. The V4 1.5 litre two-stroke engine was based on the Evinrude 75 HP outboard motor of the day and produced about 120 HP. The exhaust system used 4 megaphones and is bigger than the engine. Noisy but very effective.

Engineers then reasoned that if they could find a way to push back into the cylinder the over-scavenged fuel-air mix which had been pulled out into the exhaust system, just before the exhaust port closed, then they'd really have a tuned exhaust system. One that helped to both empty and fill the cylinders, the best of both worlds.

Some tuners, while experimenting with megaphone systems had already discovered this by accident when trying to reduce the noise. By placing a reverse megaphone, or a converging pipe, on the outer end of existing exhaust megaphones, some engines gained more power, and surprisingly, used less fuel.



What happened is the original positive sonic wave, created when the port opened, (some of which had been reflected as a negative wave), had continued on through the system until striking the converging cone, or baffle cone as they are often called. Here, because it's almost a closed end to the pipe, the reflected wave will stay as a positive, and by virtue of having traveled further, will arrive back at the exhaust port later. If the arrival time is arranged for best effect it will be about 40 degrees before the port closes and the over-scavenged fuel-air mix is pushed back into the cylinder.

If you know the speed of the sonic waves, then calculating the system shape should not be difficult, except that's it is very dependent on the temperature of the exhaust gas through which is it travelling. As the exhaust moves away from the port and expands its temperature drops, when it reaches the baffle cones and the pressure rises a little the temperature goes up. And of course the temperature of the exhaust gas emerging from the port varies a lot with power output and rpm.

At sea level and 15 degrees C, sound waves travel at 340 metres per second. At high power outputs exhaust gas temperatures approach 600 C and sounds travels at over 500 Metres per second. Varying the temperature in the exhaust to deliberately change the wave speed and consequently the rpm at which the system works best is today a common practice on marine engines where plentiful cold water is available.

Twin expansion chambers fitted to a twin cylinder 950 cc Seadoo Rotax engine, by US speed equipment maker Factory Pipe. The pipes are water jacketed and water injected by an electronic controller to vary the gas temperature and get the sonic waves to arrive at the right time over a wider RPM range. Engines with this setup can produce over 160 HP (120 kW).

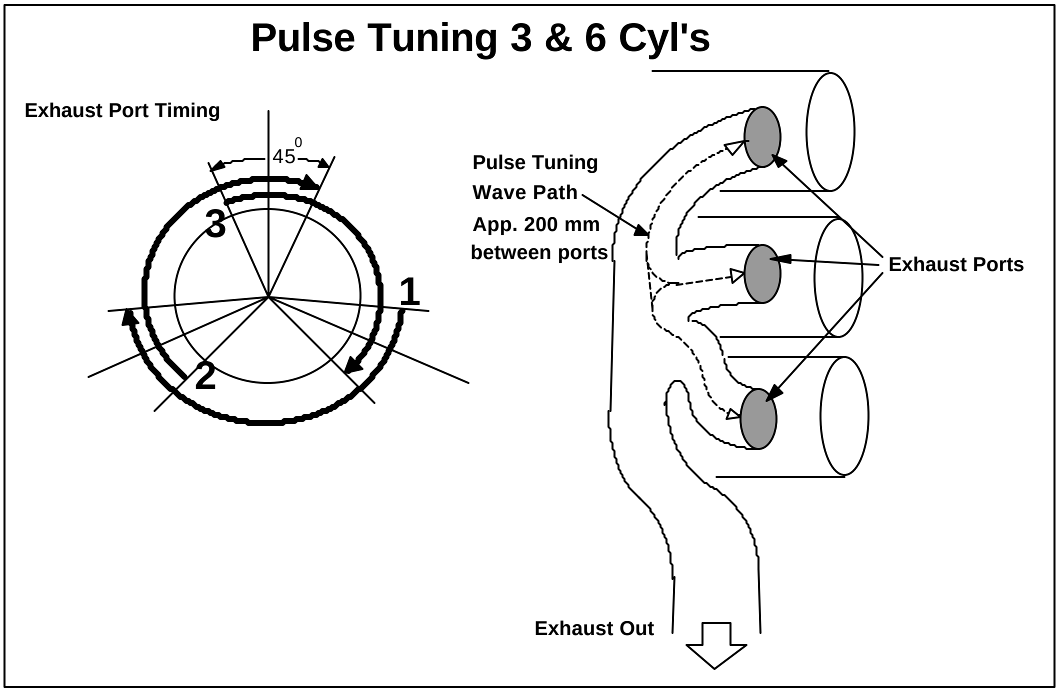
Using our example engine quoted above, to get a positive wave arriving back at the exhaust port a little before closing, requires the wave travel a total distance of 2.6 metres. That means the expansion chamber needs to be 1.3 metres from exhaust port to the middle of the baffle cone. This is for best results with exhaust port duration 164 degrees at 6000 rpm.

If we now inject some cold water into the system about half way along (can't inject water too close to the port or the wave action can push water back into the cylinder) and reduce the temperature, then the optimal rpm for our example 1.3 metre long chamber will be lower, enhancing mid range power. If the temperature were to drop by, say 100 C, then the rpm at which our example system works best now drops to 4800. Combine this with power valves in the exhaust port, to change port timing, and a modern expansion chamber can be very effective over a wide rpm range.

There's no doubting these expansion chamber systems work well, but as the photo shows they do take up a lot of space. One and two cylinder engines are not much trouble, but what do you do with 3, 4 or even 6 cylinders? Most vehicles just don't have the room for several expansion chambers, but there is a way to get the same benefits on multi-cylinder engines without all the bulk - pulse tuning.

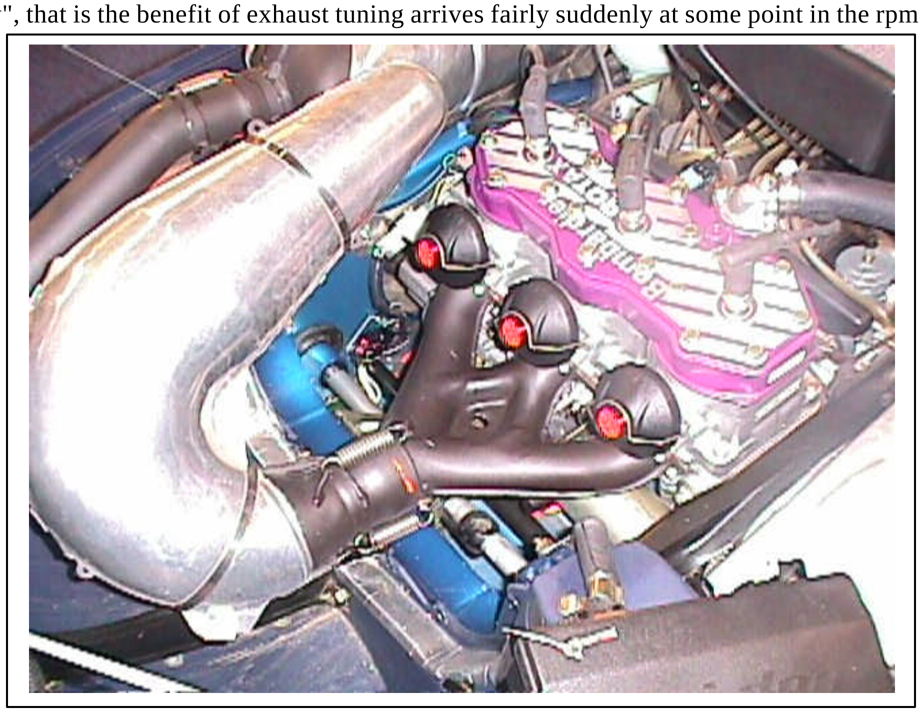
We still need a negative wave to arrive about BDC and then a positive to arrive just before port closing. The divergent cone (megaphone) that provides the negative wave is not very big and several cylinders can share one because the wave travel time is short. It’s the positive wave that's a problem because it usually travels much further and can then arrive when another cylinders negative wave is present in the system, canceling the benefit. Instead, pulse tuning gets it's positive, plugging pulse by using the opening of another cylinder's exhaust port, not the far end of the exhaust system.

On a 3 cylinder engine (or half a V6) the exhaust port timing is nearly ideal, with some overlap between exhaust port open periods. When one cylinder's exhaust is opening, and radiating a strong positive wave into the system, another cylinder's port is just closing. Therefore the positive or plugging pulse is present at the right time without needing to travel a long distance. The sketch shows a typical 3 cylinder engine where the overlap between exhaust port open periods is about 45 degrees. Only about 200 mm of travel distance is required for the positive wave to arrive at the right time. That's why a 3 cylinder, or V6, outboard can have a quite sophisticated tuned system, but it all hides neatly out of sight under the cooling water jacket.



Some vehicles have a little more room and display a more obviously tuned system. The photo shows a Bombardier Ski-Doo snowmobile powered by a 110HP, 3 cylinder 700 cc Rotax engine. This vehicle allows room for a larger more complex system. The exhaust manifold still allows for the short distance between exhaust ports for a pulse wave, but adds a much larger expansion cone to a provide stronger negative wave, and very possibly it also augments the positive wave at certain speeds.

The CVT transmissions used in this type of vehicle is also part of the equation. This type of exhaust system can make some engines "peaky", that is the benefit of exhaust tuning arrives fairly suddenly at some point in the rpm range and with conventional fixed gearing would make the machine difficult to drive.



What about 4 cylinder engines? Here an exhaust port opens every 90 degrees, so the pulse wave arrives too early if we use a short manifold like that on 3 cylinder set-ups.   So a longer system is needed, and on V4 engines this is arranged by having alternate firing cylinders on opposite banks of the V. The pulse wave then travels to the common join point between banks of the V before moving to the cylinder on the other side.

The V4 Pulse tuning sketch shows the type of system used on modern Evinrude and Johnson outboard motors, called a "U tube" exhaust. Here the exhausts of port and starboard cylinder banks don't meet until part way down the engine's midsection. The resulting length for the pulse wave to travel means it arrives at the right time for strong mid range torque. The negative wave is provided by two smaller divergent cones (megaphones), one for each bank.

Today a modern two-stroke engine without a tuned exhaust system is just about unthinkable. Even your humble chainsaw or brush-cutter today has a system that can greatly affect engine performance, but as we have seen above, those sophisticated systems don't always look like it.

Perhaps this small article will have helped to explain just how carbon build up and corroded or broken exhaust parts could be the real reason behind that lack of performance, or high fuel consumption complaint that has been troubling you.