Chapter 7.

Exhaust Fundamentals.

Exhausting Activities.

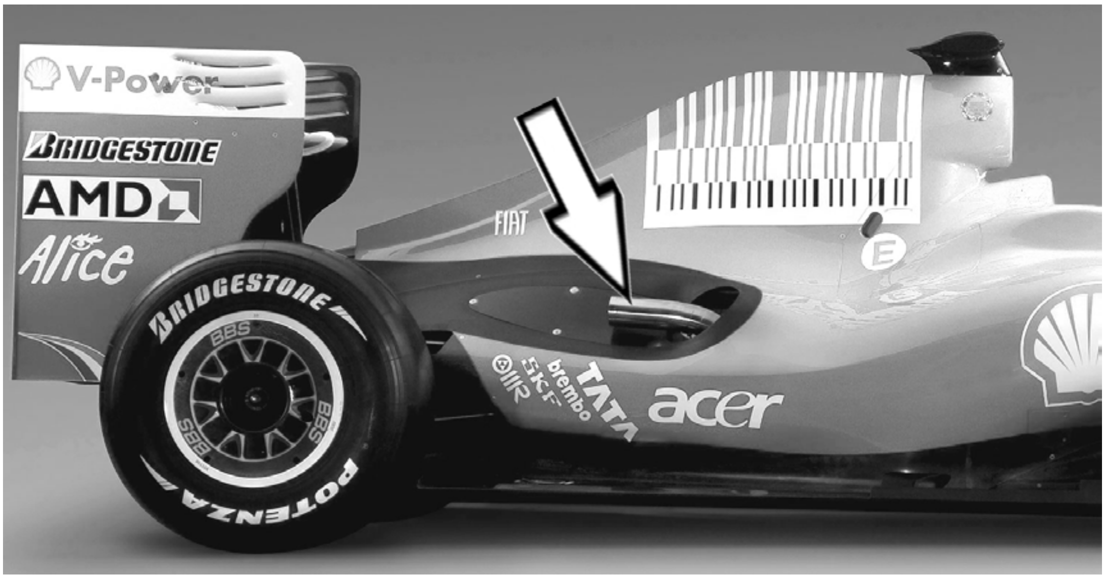

Fig. 7.1 2009 Ferrari F1 V8 exhaust tail pipe **(www.gurneyflap.com).**

It may seem a trifle odd to use a photo of a 2009 F1 Ferrari racing car to open a chapter with but the significance is the exhaust pipe indicated by the arrow. It is the only part of the engine visible to the outside world and is just a short tube about 16 inches (400 mm) long and barely 2.5 inches (65 mm) in diameter. Because the engine is a V8 there is a similar pipe on the other side of the car. Those two seemingly unremarkable exhaust pipes make an important contribution to the unseen engine managing to breathe in enough air to produce around 760 b.h.p. at nearly 18,000 r.p.m. How they succeed in doing that will unfold during the course of this chapter.

In fact the dynamics governing the exhaust system of an F1 racing engine are really quite straightforward having only one purpose and with no room for nonsense. It therefore provides a useful yardstick to return to when becoming mired with the complications and compromises that creep into the design of production systems.

That a pair of such modestly sized outlet pipes can be adequate for the tremendous volume of exhaust gas discharged by the engine at full power provides a clue that big bore exhaust systems with huge tailpipes may not always be needed for high power outputs. If the huge tailpipes so popular with go-faster youngsters for their noisy hot hatchbacks could give the Ferrari a few more horsepower then we can be certain that they would be used!

This chapter will explore high performance racing systems first in order to understand their dynamic behaviour. In the next chapter methods of silencing will be considered with the aim of retaining the benefits of dynamically effective systems whilst being acceptable for daily use in the real world.

Some History.

Historically most designers of multi-cylinder racing engines, even very successful ones, did not seem to give much serious thought to the potential of the exhaust system beyond ensuring that it offered mininum impedance to flow and that exhaust gases discharging from one cylinder could not pressurize another. This was reinforced by a widespread belief that exhaust flow from one cylinder could induce flow from the others in a sort of suction effect based on an imperfect interpretation of Bernoulli's principles regarding pressure and flow through passageways. It neglected the fact that the exhaust pressure in the branch pipe from a discharging cylinder would be likely to exceed that in any of the other branches at the time.

Even high powered aircraft engines like the Rolls-Royce Merlin had only minimalistic exhaust stacks, but for some installations these were carefully designed as 'ejector nozzles' to produce useful thrust at high speed, equivalent to over 150 b.h.p. at the propeller (Fig. 7.2). The discharge velocity of the exhaust gases had to be higher than the speed of the aircraft, to achieve which a backpressure of around 0.6 bar was required. A slight loss of shaft horsepower to the propeller was inevitable but the results speak for themselves in the annals of aviation history.

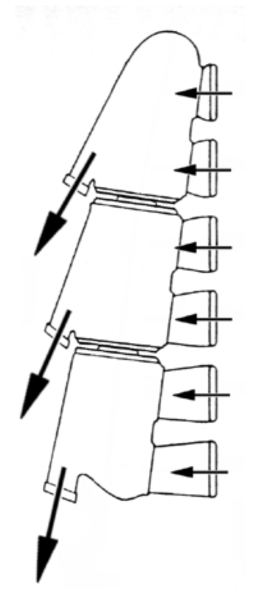

Fig. 7.2 Ejector exhaust of RR Merlin in Spitfire.

Of course, thrust is just a force and only becomes power when combined with motion, so at the range of speeds cars operate within there is not much potential for its exploitation, in the same way that torque at low engine speeds does not translate into much power. Nevertheless exhaust egress has often been used to augment aerodynamic performance of racing cars by re-invigorating boundary layer flow near the point of breakaway. This is really rather an indirect use of thrust, yet it does show the importance of maintaining an open mind about potential performance gains that may never appear on the dial of any dynamometer.

Perhaps not so surprisingly, dragsters again are a special case where the huge volume of exhaust gas generates around 1000lbs of downward thrust, utilized to aid traction. Should one cylinder start to misfire during a race the proportionate thrust imbalance can cause problems with directional stability, quite apart from the other more obvious consequences.

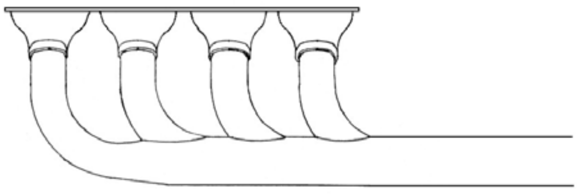

Fig. 7.3 Typical primitive exhaust manifold from before the 1960s.

By around 1960 it was becoming apparent that multi-cylinder systems for racing which properly exploited exhaust gas dynamics could reap large performance gains. Coventry Climax were an early and very successful exponent of this line of development, particularly with their little V8 that was the most successful GP engine of the 1962-65 period. Surprisingly, examples of simplistic exhaust technology (Fig. 7.3) still appeared in top level racing for a number of years and persisted on the legendary 4 cylinder Meyer-Drake Offenhauser right up to its final attempt at the Indianapolis 500 race in 1983, after winning it on 27 previous occasions.

The story was different in motorcycle racing where very effective single cylinder systems first appeared in the 1930s using tuned length pipes with megaphone type diffusers – yet even these arrived almost by accident having been originally devised as a method of extending a simple but effective straight pipe system to comply with a regulation on minimum length.

Astute designers soon recognized the potential, even if they did not properly understand the reasons for it, and began to find good results as a consequence of empirical development. Even when multi-cylinder motor cycle engines began to take over they still mostly remained loyal to single cylinder exhaust technology with separate systems to each cylinder, despite the attendant weight and packaging handicaps. Clearly the advantages were very convincing and still prevail on many modern racing motor cycles.

Top fuel dragsters are another branch of motor sport where separate tuned length pipes – one per cylinder – remain in common use. Here, however, producing a merging system capable of surviving the intense vibration and stress to which it will be subjected is a very tough design and materials problem that cannot be easily tested in simulated conditions. Individual pipes are between 2.5 and 3 inches in diameter and each one handles the gas volume appropriate for 800 to 1000 b.h.p. - in half an engine cycle.

The Exhaust Process.

After the struggle to get fuel and air to fill the cylinder and then burning it, the time comes when the resulting expansion reaches a point where it becomes more beneficial to start to discharge the gases than allow them to cause negative work against the piston on the next upward stroke. For this reason pressure must start to be released well before the piston reaches the end of the downward power stroke so the exhaust valve of even the most mundane engine will have started to open by the time the crankshaft is still 40 degrees before BDC (Fig. 7.4). A racing engine will generally start its exhaust process around 90 degrees before BDC but there have been some extreme cases opening 15 degrees earlier than that. Of course it must be remembered that because of the angular deflection of the connecting rod the piston will be much nearer to the end of its stroke than these figures might suggest. For clarity inlet and exhaust valves will be referred to in the singular having equal meaning for engines with two, four, or five valves per cylinder.

As an exhaust valve starts to open the cylinder pressure in a full throttle condition will still be very substantial (i.e. circa 100 p.s.i.) which has two effects which can be very significant: firstly there will be a substantial load acting on the valve head in opposition to the lifting force from the camshaft, adding to the severe stress the valve mechanism will be under at high engine speeds; secondly the pressure ratio across the valve will be more than enough to create sonic choked flow even allowing for the increased speed of sound at the elevated temperatures. The issue with the valve gear pressure loading has no further relevance here to the exhaust process under discussion, which clearly starts with a very violent discharge into the exhaust port.

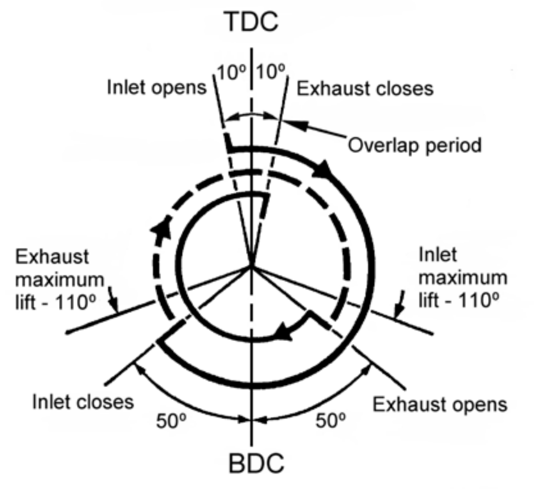

Fig. 7.4 Valve events diagram.

As the valve lifts further off the seat the sonic discharge will reach a peak level of mass flow after which the increasing curtain area between the valve and the seat will allow the velocity to drop as the cylinder pressure continues to fall. In the meantime the pressure in the port will be rising to reach a peak value somewhere just before BDC and this can be considered to be the point at which a strong positive pressure pulse is launched into the exhaust system. Note that the ‘particle velocity’ of the gas stream itself will be dependent on pressure differences and passage dimensions whereas the pulse velocity will always be the speed of sound.

There is a common perception that the cylinder pressure should be relieved almost entirely by the time the piston reaches BDC to minimize negative pumping work as the piston rises to scavenge the cylinder on the exhaust stroke. Because the cylinder pressure is falling throughout this period, pressure remaining after BDC is the consequence of still higher pressure before BDC, which will have contributed to the power stroke. In fact what matters is the difference of pressure acting on the piston in the early part of the exhaust stroke compared with that at the final part of the power stroke. Despite involving quite a segment of crank rotation, the angular movement of the connecting rod does not translate into much piston motion around BDC and the resulting poor mechanical advantage ensures that any residual pressures do not contribute much either positively or in opposition. Consequently the timing of the exhaust opening point has a relatively insignificant effect on engine performance.

The valve will still be gaining lift for some time after BDC and will reach fully open somewhere around 70 degrees after BDC by which point the cylinder pressure will certainly be down to just a few p.s.i. above atmosphere where it stabilizes briefly because of the effect of the upward acceleration of the piston and the now closing valve. Finally the combination of the piston slowing and dynamics in the out-flowing gas stream causes the pressure to drop to around that of atmosphere.

The next diagram (Fig. 7.5) shows how the cylinder pressure now leads onto the inlet phase which was discussed in the previous chapter. It also illustrates how the pressure in the cylinder relates to the opening and closing of the inlet and exhaust valves during the process of scavenging spent gases and filling with fresh charge as the piston moves between TDC and BDC and back again.

22 pages follow.