Historically, NASCAR engines have been fed by a diaphragm-type pump, actuated via a pushrod from the engine's camshaft

Supply and demand

David Cooper brings us up to date on the latest trends in design, development and manufacture of fuel pumps for motorsport

In an internal combustion race engine, the fundamental mechanisms ensure there is a supply of air, as the piston acts to draw it in, but the fuel is a little less readily available, so there is a need to deliver it from a remote tank on the car to the fuel metering system and subsequently the combustion chamber. The type of pump used must be matched to the required flow and pressure characteristics – with carburation, port fuel injection or direct injection systems having differing requirements – while the design and development of the pumps is always driven by the desire to reduce static weight and parasitic frictional losses.

The vast range of engine and fuel metering combinations available across the motorsport world is such that there is a similarly wide variety of fuel pumps to meet their needs, from high-volume low-pressure pumps servicing carburetted engines to low-volume high-pressure pumps required to generate the very high pressures seen in the evolving generation of direct injection engines. There is a similarly broad combination of methods for achieving the desired fuel supply, either driving the pump mechanically from the engine or from a dedicated electric motor.

Mechanical piston pumps

Fuel pumps need not have a purely rotary motion; historically, NASCAR engines have been fed by a diaphragm-type pump, actuated via a pushrod from the engine's camshaft. While a traditional diaphragm pump is unlikely to be seen on a modern race engine, there are several modern piston-type pumps that are actuated in a similar fashion. Variable displacement piston pumps are perhaps the modern equivalent to the diaphragm pump, and retain the very low parasitic losses characteristic of such a pump (one manufacturer quotes less than a 0.5 hp loss on a 1000 hp engine).

Having a variable displacement, the pump is able to provide the desired fuel quantity and pressure without the need for a bypass valve, therefore removing the need to return fuel to the tank as in many other pumping systems, again reducing system weight and complexity. Typically designed to be a direct replacement for OEM mechanical pumps in dirt circle track or marine racing, they can be driven by the stock camshaft lobe without the need for further modifications. Made from billet aluminium and hard anodised, the piston rides on solid Teflon rings for minimum friction and wear.


Variable displacement piston pump actuated by pushrod from a camshaft (Courtesy of Race Pumps)

Depending on the configuration of the inlet system, a standard 3.5 bar (50 psi) pressure may be used on naturally aspirated or low-pressure turbo/supercharged applications, while a 10 bar (150 psi) pump is available for high-pressure turbo/supercharged engines. The 10 bar pump can either provide a constant pressure or be linked to the boost pressure in order to supply fuel at a certain pressure above that which exists in the intake manifold.

While these pumps typically supply a carburetted engine, where it is enough to deliver sufficient fuel to the carburettor fuel bowl, at the other end of the spectrum cam-actuated piston pumps are in use for applications with gasoline direct injection (GDI) fuelling systems. Again actuated directly from a dedicated camshaft lobe, these very compact single-piston pumps can maintain fuel rail pressures of up to 200 bar (2900 psi), with some variants able to maintain higher pressures still, and providing between 0.5 and 1.1 cm^3 of fuel for each revolution of the camshaft.

The precise fuel delivery can be controlled by selecting differing cam profiles, usually suggested by the pump manufacturer to suit different engine configurations. Either electronic fuel injection (EFI) or GDI systems may have an internal pressure relief valve in the pump (and so require no return fuel line to the tank) or more commonly be limited by an external pressure regulator on the fuel rail.

Despite the high demands placed on these high-pressure pumps, they weigh in at an impressively light 780 g, although that is not the whole story, as there is a requirement for a pressurised fuel delivery to the inlet of these pumps. This means one (or probably more) 'low pressure' electric pumps will be required to provide the pump with a constant 4-7 bar (58-101 psi) inlet pressure to ensure consistent operation. The general trend in this area is likely to see an increase in the system pressures used in direct injection race engines over the next few years, as manufacturers seek to optimise fuel efficiency and performance.

Electrical piston pumps

In addition to piston pumps driven by a direct mechanical linkage to the engine, there are also electrically actuated piston pumps available on the market. Driven by an electric coil/solenoid in one direction and returned by a built-in spring, they can operate at up to two cycles per second, and made up most of the electrically powered fuel pumps used during their early adoption in rally car racing in the 1970s.

The instant benefit of an electrically powered pump is of course the ability to place the fuel pump further from the engine and closer to the fuel tank. This helps to reduce fuel temperature, as the pump can be situated where the ambient temperatures are lower, while also reducing the vacuum which the pump has to pull to lift fuel from the tank, as it can now be much closer to the fuel source. Typically these pumps are used to supply the fuel bowl of a carburettor (much as their relatively low pressure mechanical counterparts) rather than any sort of injection fuel system.

Electrical rotary pumps

Most electrically powered pumps are, however, a rotary type. Modern units are usually brushless, and the electric motor is used to drive either a gerotor or roller cell-based pump mechanism, while electronics are packaged on the pump itself, often being cooled by the flow of fuel. Other types of rotary pump include a vane or turbine arrangement and screw or gear pumps.

A roller cell pump rotates an internal rotor in an eccentric fashion within the pump cylinder. As the rotor turns, a cylindrical roller flies out to create a small sealed volume of fuel between the bore of the pump and the slots cut into the rotor where the rollers used to reside. ▶

Cam-actuated compact single-piston fuel pump for direct injection systems (Courtesy of Bosch Engineering)

Pump elements of a roller cell-type electric fuel pump capable of a consistent 12 bar (174 psi) output (Courtesy of SF Motorsporttechnik)

A 12 V electric fuel pump with steel housing and nylon end caps (Courtesy of Glencoe)

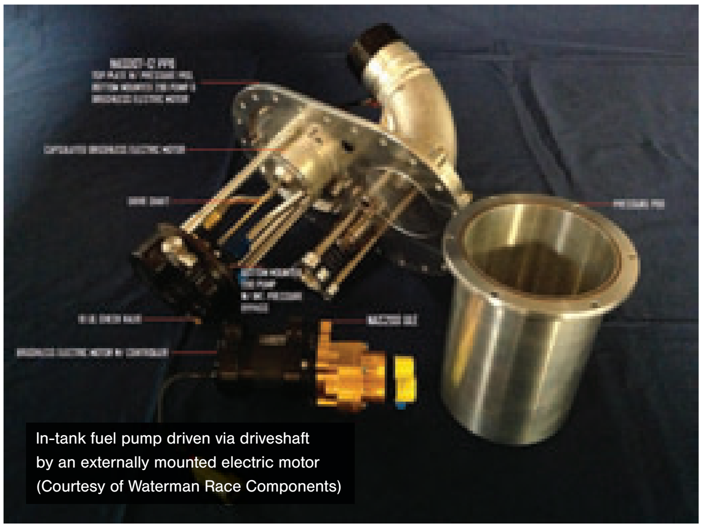
The gerotor, short for gear rotor pump, consists of a smoothed gear profile rotating within an annular internal gear ring; as the teeth mesh and traverse the perimeter a small volume of fuel is carried in the cavity volume.

These two pump types are generally referred to as positive displacement pumps, while others are known as flow-type pumps. In a flow-type pump, typically an impeller or vane arrangement rotates within a close-fitting housing in order to propel the fluid under pressure, providing a much more continuous flow characteristic than the pulsed delivery of most positive displacement units.

The pump can either be mounted 'in-tank', or 'in-line'. While an in-line configuration is potentially easier to access and replace, such pumps are typically larger and therefore heavier than a similar in-tank alternative. An average in-line pump weighs about 0.75-1.5 kg, while an equivalent in-tank pump can be as light as 0.35-0.45 kg. Overall, the trend is to adopt an in-tank configuration, with the pump mounted to a plate that usually drops in from the top of the tank.

The motor and pump are typically a single sealed unit which may be submerged in the fuel (where the volume of surrounding liquid ensures low pump temperatures), or a shaft may be used to drive a pump from a motor mounted onto the exterior of the tank. In-tank pumps may often have a collector pot or similarly named structure that ensures a local supply of fuel is maintained at the inlet of the pump regardless of the car's motion. This can be achieved by baffling a zone around the pump inlet, or by using a totally separate collector pot fed by a series of smaller scavenge pumps placed throughout the floor of the fuel tank to ensure continuous pick-up regardless of the car's movement.

Perhaps the most important benefit of an in-tank pump though is the minimal fuel lift required to prime the pump on starting. An in-line pump can be mounted conveniently outside the tank, but any significant height above the fuel level requires the pump to run dry in order to draw fuel. For a pump rotating at anything up to 5000 rpm, this momentary dry running most certainly increases the component wear, and if a significant period of dry running is needed to draw fuel over a considerable height then the pump may seize up altogether. One pump supplier notes that the steel internal components of failed pumps from such installations can be autopsied to show bluing of the steel surfaces, indicating excessive heat input through friction under dry-running conditions.



In-tank fuel pump driven via driveshaft by an externally mounted electric motor (Courtesy of Waterman Race Components)

The efficiency of an electrical pump can be measured by the level of current required to produce a given flow rate or pressure combination, with efficiencies of 40-45% energy conversion from electrical to hydraulic power suggested. Generally, if higher friction or a more inefficient motor are present, the current draw rises, with a typical in-tank solution drawing about 6 A to provide up to 9 bar (130 psi) for a standard EFI system. If the friction is higher and the pump less efficient, the current can rise to as much as 12 A. While such an installation will function, the excess heat generated will increase the potential for cavitation in the fuel as it is heated, leading to premature wear of components as well as requiring an increased gauge of wiring and higher capacity relays/fuses, in turn increasing the overall penalty of the installation to the whole car.

The objective therefore has to be for an optimal installation that allows the pump to operate comfortably within its limits – one supplier recommends a 30% overhead on pump capacity compared to the flow rate and pressure needed at the injector – without forcing the pump to lift fuel over any greater a height than is absolutely necessary. ▶

Although there is little difference in the weight of various options of pump for a particular installation, the benefits of a high-quality pump are readily apparent when comparing the variability in flow rates. Figures quoted in research for this article claim a variation of up to 7% in flow rates for some pumps compared to one of only 1-1.5% for a high-quality example that has been flow tested after manufacture.

Mechanical rotary pumps

While electrically driven rotary pumps are generally the technology of choice for modern EFI systems, requiring relatively low flow rates – no more than 450 l/h, or 2 gallons per minute (gpm) – and moderate pressures of, say, 3-12 bar (44-174 psi), their mechanically driven cousins are often used for both carburetted and injected systems where very high fuel quantities and/or high pressures are needed (up to 115 gpm at up to 650 psi, or about 45 bar)

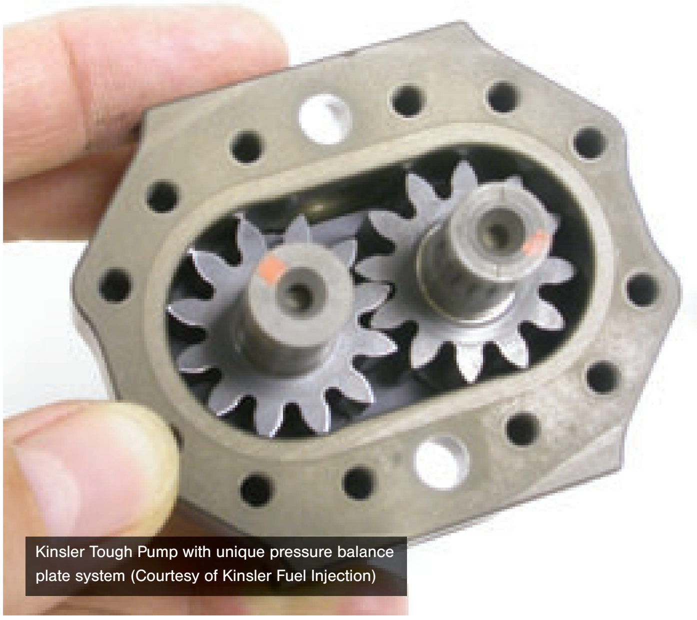
These mechanically driven pumps may have a gerotor or roller cell-type design, but more commonly they will use a pair of counter-rotating gears within a close-fitting housing, usually called a 'gear pump'. As the gears rotate, fuel is trapped between the gear teeth and the wall, travelling around either side of the housing from the inlet; as the teeth then mesh in the centre the fuel cannot return to the inlet and must instead leave at the outlet. Typical systems use about ten or 11 teeth on each gear and provide a pulsating fuel flow.

Mechanically driven gear pumps are the solution of choice where the high flow rates and high pressures quoted above are required, and find their most extreme application in high-horsepower drag racing with fuels such as alcohol or nitromethane where the air-fuel ratio desired requires a much larger volume of fuel than usually seen with gasoline or diesel. They may have a modular construction, featuring as many as four gear pump modules from a single drive input. Gear pumps may also be tuned by altering the gear width to vary the fuel volume that can be provided by each tooth cavity for each module. Running at camshaft speed, these pumps provide a very linear output of fuel that is always proportional to the demands of the engine.

Cavitation, or vapour bubble formation, is a significant problem in fuel pump design. The local presence of either low pressure or increased temperature around the geartooth-housing interface, particularly at high speeds, allows the fuel in that zone to vaporise and form a vapour bubble which remains entrained in the fuel flow. This bubble then travels through the fuel system, usually arriving at the same injector each time (a consequence of the fuel rail geometry and how the bubbles flow), inevitably causing not only a performance issue as it underfeeds one injector but also a reliability problem, as one set of components experience a different lifecycle from the others and inevitably wear out at a different rate.

To combat vapour formation, most pump manufacturers try to run the closest tolerances possible with the manufacturing techniques available, and so minimise the potential and severity of the bubble formation, although bench testing of pumps to analyse bubble formation is not always common.

One particular system, for which patents are pending, uses the pump's outlet pressure to force one of the pump sideplates against the gear faces and so give as near to zero clearance as the surface



Kinsler Tough Pump with unique pressure balance plate system (Courtesy of Kinsler Fuel Injection)

finish of the components will permit (the sideplate force is maintained by springs when the pump is not running). To achieve this, the manufacture of the high-alloy steel plate surface is critically important. It is given a high-hardness heat treatment and then ground to a 6 thou surface finish, after which a DLC coating is applied and the surface finish improved by a lapping operation until it is 2 thou with an end-to-end flatness of 1 thou.

This low-roughness surface finish also serves to drastically reduce the coefficient of friction of the surface, so reducing the torque required to turn the pump. As the plate is forced against the side of the gears, the gears also need to be able to withstand the wear, and ideally must do so without having a detrimental impact on the friction present in the pump; they therefore use a special polymer coating.

The design of the gear pump housing is also important, as any fixed sideplates cannot be allowed to flex significantly under fuel pressure when the pump is running, to avoid changing tolerances and increasing cavitation. To achieve this the sideplate/housings are often made from aluminium or steel, with reinforcing ribs and 12 or more fasteners to ensure the mating face remains as flat as possible.

While electrically powered pumps can be easily installed in a range of locations, mechanical pumps do need some direct linkage to the engine. They can be driven from the end of the camshaft, from a belt/pulley arrangement on the side of the engine or, to enable remote placement of the pump, a cable drive can be attached to either the camshaft or the drive pulley of the oil or power steering pumps. The benefit of a cable drive system is similar to an electrical drive, in that the fuel pump can move closer to the fuel tank to reduce the lifting effort, and away from the engine to reduce ambient temperatures. In an effort to reduce temperatures when the pump must be mounted to the engine, a phenolic resin spacer (which has low thermal conductivity) is usually used to isolate it.

Belt-driven fuel pumps offer notable advantages for tuning the fuel delivery characteristic, as the pulley ratios can easily be altered to determine the flow rate over the engine speed range. The belt drive ▶

Belt-driven gear pump, typically supplying carburettors (Courtesy of BLP)

also provides a wider variety of packaging solutions compared to a cam-mounted pump, as the pump can be moved (within reason) to suit the engine bay layout or the car's centre of gravity.

While mechanical rotary pumps come in all shapes and sizes, and are able to supply systems from low-pressure carburetted to high-pressure high-volume continuous injection, it is in the field of drag racing where the numbers always show the extremes of what is possible. A forced induction gasoline drag racing engine typically requires 7-8 gpm, while the difference in air-fuel ratios means that blown alcohol cars demand 18-20 gpm, and Top Fuel or Funny Car engines running at up to 110 gpm at fuel pressures as high as 45 bar (650 psi) and with more exotic fuels such as nitromethane.

Filtration

While the figures involved in drag racing pumps are undoubtedly impressive, sometimes it is the little things that count. Given the tight tolerances present between the moving parts of any fuel pump, maintaining these tolerances is vital to ensuring continued efficiency and longevity of the pump. As such, it is vital that fuel is filtered upstream before it can enter the pump.

Mechanical gear pumps are generally more tolerant of dirt ingress, although it is by no means beneficial to the pump, while electrically driven pumps can potentially be stopped by a build-up of dirt, given their lower torque and power compared to a pump driven from the engine. Of course, maintaining a pristine fuel tank is virtually impossible, as fuel may be contaminated with microscopic particles long before it arrives in the racecar's fuel tank, so an intake filter for removing particles (down to 30 microns or even smaller) is generally recommended to maintain performance of the pump and prevent a race-ending failure.

These filters can be in a 'sock' form attached to the inlet of an in-tank pump, or for out-of-tank pumps of all varieties an in-line canister-type filter is preferred. Filter elements can be either a washable stainless steel gauze, capable of filtering particles between 25 and 220 microns, or disposable paper elements for the highest level of filtration, spanning the 10-30 micron range.

Although filtering out the smallest particles possible is undoubtedly beneficial to pump life and performance, care must be taken not to restrict flow into the pump; not only would this reduce pumping efficiency but the low pressure created is likely to lead to the fuel boiling. Hence a filter with a fine mesh size but large area is preferred

Kinsler Monster Pump inlet filter with 148 sq in stainless mesh element (Courtesy of Kinsler Fuel Injection)

as the ideal method for ensuring a consistent and clean fuel supply to the pump and beyond into the engine.

Materials and construction

Most pumps, of whatever type, will usually adopt hardened tool steel internal pumping elements, inside either a steel or preferably aluminium machined housing for reduced weight, although magnesium can be used occasionally. For longevity, the wearing surfaces of the steel pump elements are likely to be heat treated and nitrided, while aluminium housings will be anodised or nickel-plated for the same reason and to protect the surface from corrosion.

Sometimes the internal pump elements may be manufactured from a high-performance engineering polymer such as PEEK (polyether ether ketone), which has excellent mechanical properties, low density and good chemical resistance. However, the high cost of PEEK components rules this out for the vast majority of applications where the weight benefit is simply not sufficient to justify its use. One manufacturer questioned for this article did confirm though that it has used PEEK for the wearing pump elements for the purposes of engine testing, in order to ensure that any metallic contaminants in the exhaust gas analysis cannot have originated from component wear in the fuel pump.

An electric pump may have the pumping elements mounted directly to the motor output shaft or, if customised for a specific application, the pump stage is likely to have its own dedicated shaft and bearings. While this may provide a benefit in terms of lifetime in higher pressure applications, it does however mean a slightly heavier installation.

The concept of a separate shaft and bearings also permits a change in components over standard items, allowing the use of hybrid ceramic bearings to reduce friction and wear at very high pump speeds for example. The use of ceramic bearings has several benefits – the materials are less susceptible to corrosive fuels and have a lower rolling friction and generally longer service life at higher temperatures. In high-temperature installations in particular, their inherently low coefficient of thermal expansion helps with maintaining the internal tolerances of the pump over a wider temperature range. Their use though increases the cost of the pump, so this option is only realistic where the application calls for one or more of the specific benefits.

As pumps generally form an interface between the fuel system and some other mechanical input, there is always a need to seal the fuel cavity at the interface. For this there are two main choices of seal: either a traditional O-ring type with retaining surfaces or a feather-edge type seal. While feather-edge seals provide a lower friction solution, an O-ring is a lower cost installation and service item. Buna-N seal materials are generally used in the US for gasoline and alcohol fuels, Viton for ethanol and EPDM (ethylene propylene diene monomer) materials for nitromethane fuels. Graphite-impregnated seals are a robust solution, easily able to cope with high shaft speeds and fluid pressures, while being impervious to almost all fluids.

PTFE is often used in preference to Viton materials as it provides a lower friction with a minimal stick-slip effect; it is also generally harder wearing and has a greater range of chemical compatibility. Elastomer/Viton-based materials are, however, better able to cope with radial movement of the shaft and maintain a seal.

The compatibility of sealing materials with bio-fuels such as E85 bio-ethanol, which is highly corrosive, is a potential issue for the use of these fuels not only in motorsport but the wider automotive sector. While some pumps can claim to be compatible with E85 – indeed, any pump will probably deliver any fluid – the problem is more one of longevity. A typical EFI gasoline pump can be expected to last up to 4000 h of running time without issue, but this may fall to only 500 h when used with E85. Undoubtedly this will improve with development; for the moment though, at least one supplier recommends flushing the pump with standard gasoline between races.

The use of methanol fuel with magnesium casings is also problematic, as when left static the fuel reacts and powders the surface of the magnesium, so nearly all manufacturers opt for an aluminium or steel solution to maintain compatibility. Methanol is also relatively corrosive, with manufacturers suggesting cleansing with methylated spirits at the end of each season and the use of pure silicone oil during storage of the pump to preserve seal life.

Conclusions

Regardless of the level of competition, the provision of a reliable and consistent fuel supply is essential. While the pumping methods themselves are based on a few largely unchanged concepts, the detailed implementation and attention to detail in perfecting the design and manufacturing processes of these pumps is second to none, with reliability as the watchword for all of the top manufacturers.

With the steadily increasing presence of alternative fuels such as bio-ethanol, and the uptake of GDI systems, this is by no means an industry standing still. The capability in terms of longevity, maximum pressures and flow rates can only grow as these applications expand.

Acknowledgements

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SOME EXAMPLES OF FUEL PUMP MANUFACTURERS AND DISTRIBUTORS

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