New automotive fuel injector actuator technology rivals piezo-electric performance at solenoid cost

A N Dames, H J Meanwell, J A M Dilley, A H Burrell & J W Evett
Sentec Ltd, England

ABSTRACT

Anticipated automotive gasoline engine emission regulations associated with Euro 7 may be met by precision fuel spray preparation and injection, or by the use of gasoline particulate filters (GPF). Currently, only piezo-electric gasoline direct injection (GDI) injectors can meet these requirements, but at a cost precluding their use in most future engines. Sentec has developed a flux switch actuator technology, called Exactus, which provides performance rivalling piezo-electric actuators at a price comparable to a solenoid. Exactus may be employed in injectors designed for homogeneous or stratified charge strategies, which offers the potential for increased economy and reduced fuel pressures.

1 INTRODUCTION

Future automotive gasoline engine emission regulations such as Euro 7 may be met by precision fuel spray preparation and injection, or by the use of gasoline particulate filters. GPFs are expensive and may impact fuel economy(1), so high performance injection is the preferred fuel system strategy for downsized turbocharged engines. However, to deliver this goal the fuel system will need to provide multiple precise injections, fast response, and an extended dynamic range starting below 1mg per pulse at high fuel pressures. The injector should provide feedback to support matched cylinder to cylinder performance and OBD data.

Currently, only piezo-electric GDI injectors can meet these requirements, but at a cost precluding their use in most future engines. A new, low cost, high performance actuator technology is required, which will enable engine designers to meet the forthcoming regulations without resorting to gasoline particulate filters.

Sentec has developed a flux switch actuator technology, called Exactus(2)(3). It uses low cost standard electromagnetic components, but provides performance rivalling piezo-electric actuators. Prototype Exactus GDI injectors have already been tested by the automotive industry with outstanding results.

Sentec has a partner in the natural gas direct injection field of use. However Sentec is working on diesel applications in addition to gasoline direct injection.

This paper presents the technology’s working principle and performance test results including: shot to shot repeatability, dynamic range, opening/closing speed, closed loop performance, closely spaced multi-pulse injection and flow rate control using Exactus’ stable partial opening capability.

2 WORKING PRINCIPLE

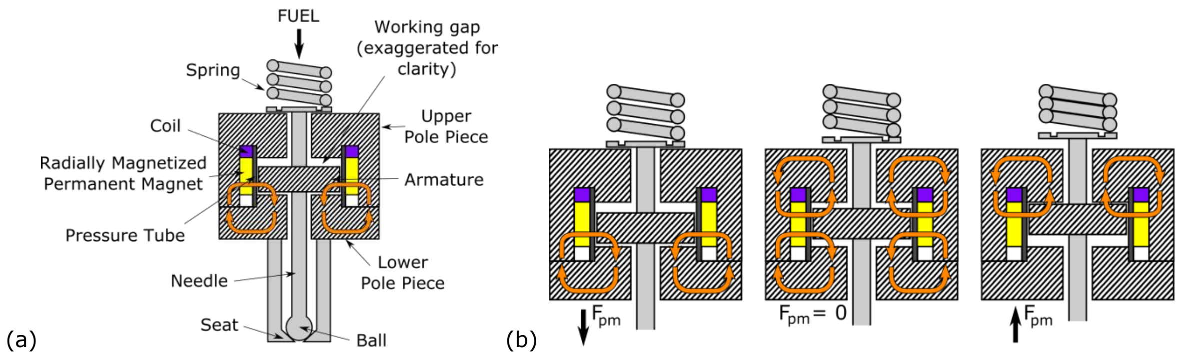


Figure 1. (a) schematic of injector actuator construction with Exactus technology. (b) Flux paths from the permanent magnet, from left to right: armature near lower pole; armature in the centre of the gap; armature near the upper pole.

A schematic of an inward opening injector with an Exactus actuator is shown in Figure 1(a). Please note that the working gap above the armature is exaggerated for clarity. In reality the gap is much smaller than the radial thickness of the magnet. Standard GDI solenoids have one active pole surface generating force in the direction of the injector axis, but Exactus has a form similar to that of a double-acting solenoid with pole surfaces on both sides of the armature. This enables Exactus to generate twice the force of an equivalent single-pole actuator. However, Exactus differs from a double-acting standard solenoid in that no second coil is required, and no current is needed to keep the injector closed. This is a consequence of the permanent magnets employed.

We first consider the influence of the permanent magnets without the mechanical spring or current-carrying coil. The flux from the radially magnetised magnets enters the armature from the side then passes through the gaps above and below the armature. The magnetic circuit is then completed when the flux travels through the relevant pole and up (or down) the outside of the actuator body and back to the magnet. There are therefore two relevant flux paths (being above or below the armature) as illustrated in Figure 1(b). The flux is shared between the gaps: the smaller gap receives more flux as this is the path with lowest reluctance. Taking the situations in Figure 1(b) in order from left to right, when the armature is closer to the lower pole, the majority of the flux passes around the lower path; the force from the magnets therefore acts to anchor the armature to the lower pole piece. When the armature is positioned centrally between the pole pieces, the flux is shared equally between the two paths and the net force on the armature is zero. Finally, when the armature is closest to the upper pole, the majority of the flux passes around the upper path and the magnetic force acts to push the armature upwards onto the upper pole. A stiff linear magnetic spring is produced by the arrangement of the components illustrated. This linearity is a key benefit of the design.

Figure 2(a) shows the paths taken by the flux from the permanent magnets and current carrying coil. For the current direction shown, the flux produced by the coil always takes a clockwise path down the outside of the actuator body, and up through the lower pole, armature and upper pole. (The flux from the coil does not pass through the magnet as this is a high-reluctance region.) When the armature is closest to the lower pole (Figure 2(b) left), the majority of the permanent-magnet flux is passing around the lower path. However, driving current in the coil effectively cancels the flux in the lower path and reinforces the small amount of flux around the upper path. The result is a force urging the armature upwards. When the armature is closest to the upper pole (Figure 2(b) right), the current-driven flux continues to reinforce the majority of the permanent-magnet flux which now passes around the upper path, resulting in a large magnetic force anchoring the armature to the upper pole. However with the armature raised, the mechanical spring is compressed and provides a mechanical force urging the armature downward. Therefore, when the hold current in the coil is removed, the armature is driven home to the lower position. (Reversal of the current direction can be used to speed the closure process further.)

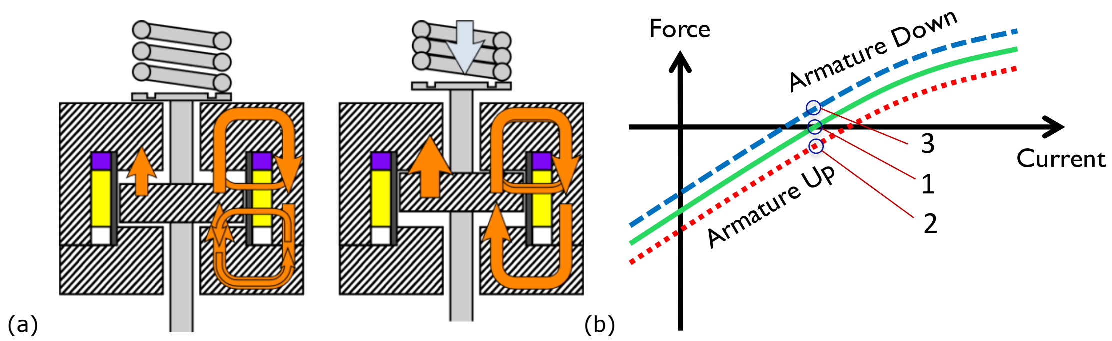


Figure 2. (a) Illustrations showing the paths taken by the flux from the permanent magnets and coil in situations L-R: when the armature is close to the lower pole piece; when the armature is close to the upper pole piece. (b) Diagram of force on the armature against current in the coil for different armature positions, see text for explanation.

If the mechanical spring is chosen to be stiffer than the magnetic spring constant, the displacement can be varied linearly with hold current and the result is a stable controllable valve capable of variable lift. As shown in Figure 2(b), different levels of current achieve stable equilibrium at different lift levels (armature positions) where the forces on the armature balance. For a given current, the armature will reach equilibrium (F=0) at a given lift level (solid green line, 1). If the armature drifts up (dotted red line, 2), the resultant force will be to urge the armature back down, while the converse is true if the armature drifts down (dashed blue line, 3). Therefore the partial lift is stable and self-correcting.

3 EXACTUS-BASED FUEL INJECTORS

We have described the Exactus actuator technology which provides for a stable controllable variable fuel valve lift which is proportional to current and where force is substantially linear with displacement. These benefits make it ideally suited to fuel actuation applications, where the variable lift capability allows the technology to provide a linear fuel delivery to pulse width curve over the whole dynamic range. The flux-switched nature of the design allows a very fast response, opening or closing in as little as 100μs for small strokes, with 150-250μs possible for full strokes depending on load; this compares favourably with the 400μs typical switch time of conventional solenoids. This fast response, in combination with small lifts, allows multi-injections of repeatable deliveries with performance similar to a piezo.

The solenoid current or back-EMF can be used to provide excellent performance feedback as the actuator is magnetically close-coupled, which enables closed loop control of the injector, making possible injector to injector delivery matching and compensation for lifetime wear. The controllability of Exactus allows pulse shaping to provide soft landings at the fully open and fully closed positions, which allows bounce removal, acoustic noise reduction and may increase the injector lifetime. Nevertheless, the actuator can be operated satisfactorily with conventional peak-and-hold drive profiles, see Figure 4 and accompanying text.

Additionally, Exactus provides for a very compact actuator design with a high force per unit cross-sectional area, while reverse currents applied to the single coil can be used to provide additional closing forces. Exactus designs can be capable of over 700N peak-peak forces (or over 400N with unidirectional current) within a 21mm diameter housing.

The actuator can be incorporated in both inward and outward opening fuel valve designs, and in both wetted and non-wetted armature configurations. Application specific designs can achieve a wide range of lifts: 25 to 800μm within a 21mm overall injector diameter. The cost of Exactus technology is comparable with a standard solenoid actuator, while partial lift control can be obtained with a standard GDI drive ECU.

4 PERFORMANCE

Performance testing has been carried out on several prototype injectors incorporating Exactus actuators. An outward-opening prototype is shown in Figure 3. The valve used in the prototype was taken from a commercially available BMW GDI piezo injector which has had the piezo actuation component removed and which has been modified to allow a fuel supply to be attached. The Exactus actuator is assembled and clamped inside a thin-walled tube of 21mm diameter, which is then clamped to the valve component as shown in Figure 3. The clamps allow easier assembly and disassembly for development purposes. If the design were assembled with welds then the injector would fit existing engines.

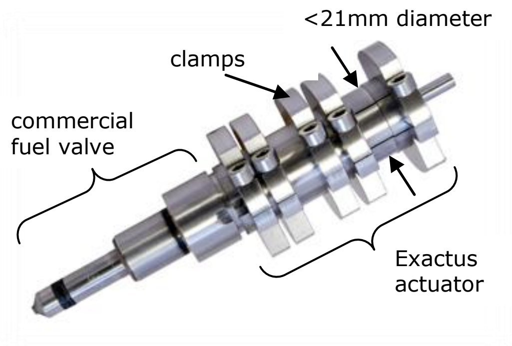


Figure 3. Prototype injector including commercial fuel valve component and clamps.

The technology has been extensively modelled by Sentec. Both static and dynamic processes have been modelled using FEA packages (COMSOL Multiphysics) and Simulink/Matlab. FEA modelling of the static case is used to optimise the magnetic circuit and includes air gaps expected due to part tolerances and the non-linear BH magnetic material properties. Following the static optimisation, dynamic FEA models are used to simulate behaviour when driven by a simple drive circuit; these simulations include magnetic, spring and hydraulic forces, and crucially include eddy current effects in the magnetic circuit. These simulations allow predictions of opening/closing times, peak currents, energy consumption and electrical coupling of armature position, as well as an exploration of sensitivities to various manufacturing tolerances such as part positioning, spring stiffness and preload, coil resistance and permanent magnetic field strengths (among others). The Simulink/Matlab models also include an eddy current model and allow fast optimisation of the drive parameters and simulation of operation under closed-loop control.

4.1 Shot to shot repeatability and dynamic range

Figure 4 shows the mean fuel delivery per pulse and repeatability against pulse width when driven with a standard GDI driver (in open loop mode). The data were provided by a major vehicle manufacturer who tested the prototype in their injection test laboratory.

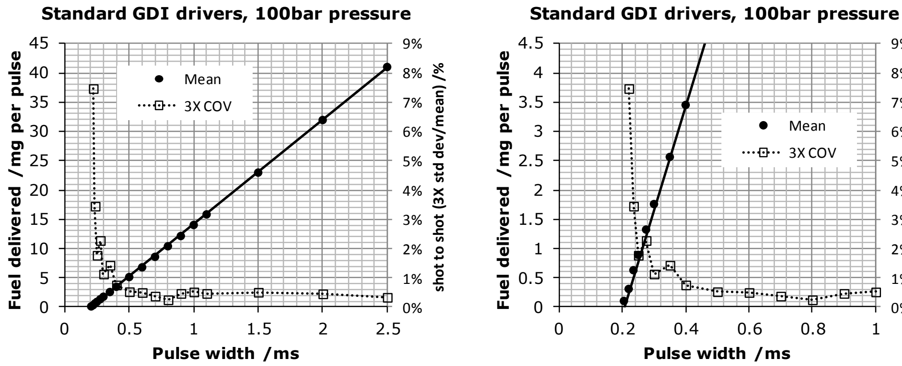
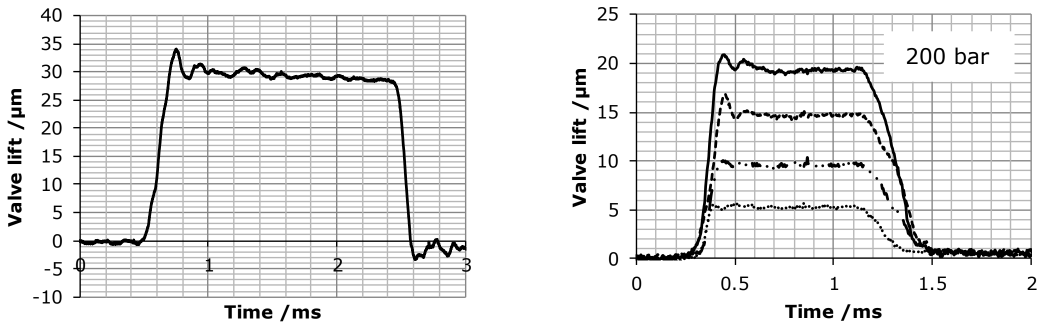


Figure 4. Mean fuel delivery per pulse and repeatability against pulse widths up to 2.5µs (left) and for low pulse widths up to 1µs (right).

The data show linear behaviour at full lift down to 0.2ms pulse widths at 100bar pressure; similar performance is achieved at higher pressures. Conventional injectors show an S-shape excursion between 3 and 5mg in corresponding fuel delivery linearity plots; this is not present with Exactus technology. A further advantage is the extremely low shot-to-shot standard deviation in delivery, which is approximately 4 times better than conventional injector technology when operating at 1mg. With delivery rates of about 18g/s at 100 bar and 25g/s at 200 bar with this implementation of the technology the dynamic range is from over 100mg per pulse to below 0.5mg per pulse, offering a turndown ratio of over 200.

4.2 Flow rate control

Figure 5(a) shows an example of the fast opening and closing times possible with Exactus technology; the plot shows experimental data recorded for a 30µm pintle lift which opens and closes in under 200µs. By operating the actuator with a stiff mechanical spring (in comparison with the magnetic stiffness), the injector is capable of stable partial lift. Figure 5(b) shows experimentally recorded lift profiles for a prototype Exactus injector operating in partial lift mode.



(a) (b)

Figure 5. (a) Experimentally recorded lift profile showing an Exactus injector with opening and closing times of under 200µs. (b) Experimentally recorded lift profiles for an Exactus prototype injector operating in partial lift mode.

Operating the injector at a lower lift point allows linear and highly repeatable fuel delivery even below 0.3mg/pulse. Unlike a conventional solenoid, which operates ballistically at low pulse widths leading to non-linear operation with a poor repeatability, Exactus can be operated repeatably to a defined lower lift point. The result is a family of linear fuel delivery curves for each lift point; examples are shown in Figure 6 for short pulse widths up to 400µs.

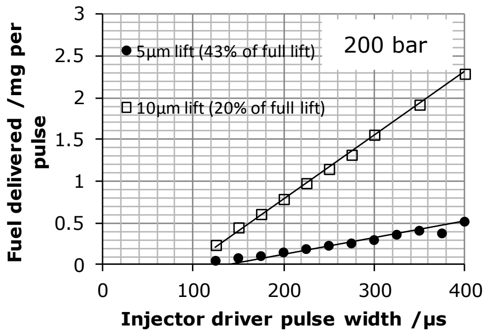


Figure 6. Fuel delivery linearity curves for low pulse widths using Exactus technology operating in partial lift mode with 200bar fuel pressure.

4.3 Closed loop performance

Operating the injector with closed-loop control can bring improved performance through compensation for lifetime, operating conditions and production variables; this also allows injector-to-injector matching. For example, production variations in armature position within the gap or spring preload can be corrected in operation. Closed-loop control can also correct dynamically for changing operating conditions (such as cylinder or fuel pressures) and can compensate for slower component drifts over the engine lifetime.

Feedback to the closed-loop process can be provided by external sensors such as lambda or cylinder pressure sensors, however one can also monitor the current or back-EMF in the actuator coils in a so-called “sensorless” approach. Since the Exactus actuator is a relatively linear and closely coupled system with constant magnetic reluctance, the back-EMF or current provides excellent piezo-like feedback and this makes it easier to use these signals to provide input to the control process.

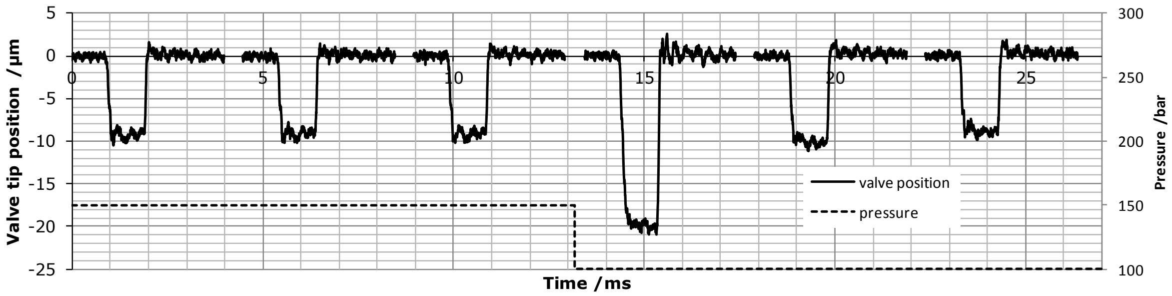


Figure 7. Valve tip position for consecutive pulses with the closed loop control in operation. The pressure is manually changed from 150bar to 100bar between the third and fourth pulses pictured above.

Figure 7 shows the operation of a prototype injector with closed loop control. The injector was operated in partial-lift mode with a lift of 10µm, and the injector tip position was monitored with an eddy current sensor during the injection process. Successive injections at 150bar were recorded, before the pressure was reduced manually to 100bar. The reduction in pressure causes a reduced load on the injector which consequently opens further in the subsequent injection, but this is immediately corrected using feedback from the 2-wire drive connection to the drive coil only. The valve tip position is used as a diagnostic only, and does not form part of the feedback to the closed-loop.

4.4 Multi-pulse operation

Multiple injection events per combustion cycle are used for some homogeneous or stratified combustion applications.

Operating engines with lean stratified combustion can result in improved fuel economy; this requires multiple very closely spaced injections over a short period of time, just prior to the sparking plug being activated(4). Multiple short injections allow local enrichment near the spark plug, allowing operation with leaner mixtures to be used. Exactus flux-switched technology can operate fast enough to provide such injection profiles. Figure 8(a) shows the delivery profile as measured by spray momentum from fuel impinging on a piezo force transducer, where the injector is operated to provide 5 injections within 1ms. The hydraulic dwell between each injection is 90us.

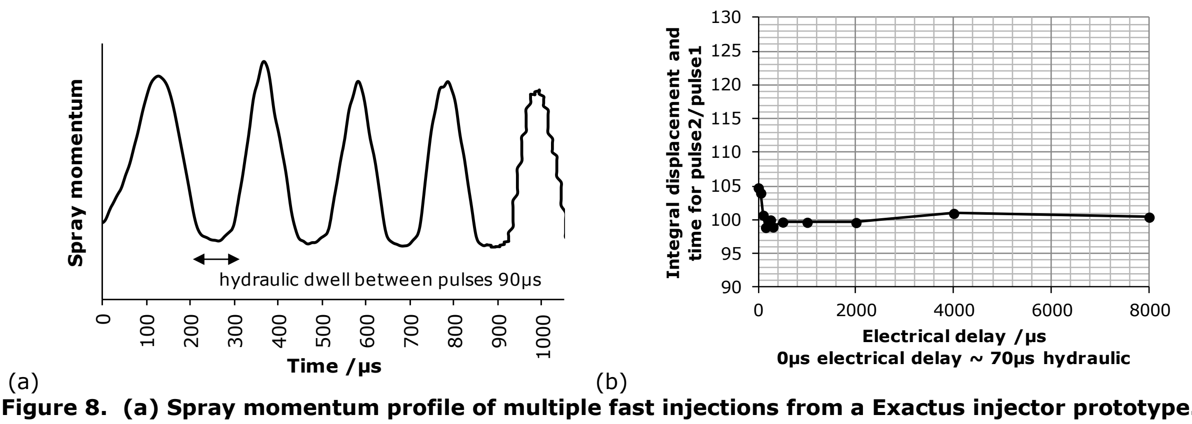


Figure 8. (a) Spray momentum profile of multiple fast injections from a Exactus injector prototype. (b) Fuel delivery in first and second pulses of a dual-pulse injection event with de-energization.

Longer delays between injections may be required for some homogeneous applications which reduce particulates by using multiple injections(5). Multiple injections may be used when the engine is cold when starting. Figure 8(b) shows the result of operating the injector to provide two closely spaced injections. The injector is operated in partial lift mode (60% of full lift) to provide dual pulses equivalent to 5mg fuel. The injector tip displacement was measured with an eddy current sensor and the integral of displacement with respect to time is used to provide an estimation of fuel delivery. The result of this is shown in Figure 8(b) which demonstrates that the second pulse delivers within 1.2% of the fuel of the first pulse for delays above 100µs, with a maximum error of +5% at 70µs hydraulic dwell (0µs electrical delay); the two pulses are effectively operating independently.

4.5 Permanent magnet use over temperature

Exactus technology incorporates a ring of radially magnetised permanent arc magnets, which are crucial to the injector performance. Since the injector will be required to withstand an extended temperature range, it is important to consider how permanent magnetic materials such as SmCo are affected by high temperatures(6)(7). Standard grade SmCo magnets have working applications up to 350°C, but even at temperatures below this it is important to ensure the magnetic design does not allow the magnets to become demagnetised enough to impact injector performance adversely.

The magnetic losses considered fall into three categories: thermally-driven reversible and irreversible losses, and losses due to a combination of high temperatures with demagnetising fields. We first consider reversible thermally-driven losses. Both B_r (the flux output) and H_{ci} (the resistance to demagnetisation) change with temperature, but these changes are reversible; there is no permanent loss in magnetic flux output when the temperature returns to its original state. For SmCo2:17, B_r changes by –0.035%/°C, and H_{ci} changes by –0.2%/°C (compared to –0.11 %/°C and –0.4 to –0.6 %/°C respectively for NdFeB). For an operating temperature range of –40 to +120°C, this implies a change in B_r of ~5.64% over the whole range.

At high temperatures, irreversible losses are caused by thermally activated reversal of individual magnetic domains; this loss increases logarithmically with time and temperature. This can be mitigated by a thermal stabilisation procedure: by baking the magnets at 50°C above the maximum operating temperature, the least stable domains reverse and the remaining magnetisation is stable over time(7). The maximum operating temperature is defined inconsistently for different magnet suppliers; the susceptibility of magnets to temperature depends on both the magnetic circuit and the dimensions of magnets, so application design is critical to this behaviour. To determine the maximum operating temperature, the load line of the magnet must be determined based on knowledge of the magnetic circuit, and also the maximum demagnetising field present. The Exactus actuator drive coil generates a small demagnetisation field due to the circuit design. The load line adjusted for the demagnetisation field can be compared to the BH curves of the magnet to determine the maximum reliable operating temperature.

Sentec has investigated the magnet performance experimentally and have seen negligible impact on the actuator performance over the temperature range tested (up to 180°C, and 150°C with a 30 amp fault current). In addition we have completed automotive designs that allow the magnets to operate above 200°C.

5 CONCLUSION

We have described the working principle of Sentec's Exactus actuator technology and its application in fuel injectors. We have reviewed the capabilities of the technology, including linear delivery behaviour, stable partial lift and fast multiple-pulse injection. Finally, we discuss the operation of the permanent magnets over temperature and time. Exactus provides piezo-like performance using standard peak and hold injector drivers but within a size and with a cost comparable to a standard solenoid GDI injector. Exactus may be used in opening inward or outward gasoline direct injection injectors in advanced homogeneous or stratified combustion applications which may remove the need for gasoline particulate filters. In addition future combustion strategies being developed may benefit from Exactus' piezo-like capabilities.

REFERENCE LIST

1. Mikulic I, Koelman H, Majkowski S, Vosejpka P. A study about particle filter application on a state-of-the-art homogeneous turbocharged 2L DI gasoline engine. In 19 Aachener Kolloquium; 2010; Aachen.
2. Dames AN, inventor; Solenoid Injector. patent EP2499646A1. 2012 September 19.
3. Dames AN, inventor; Solenoid Injector. patent EP2721333A2. 2014 April 23.
4. Husted HL, Piock W, Ramsay G. Fuel Efficiency Improvements from Lean, Stratified Combustion with a Solenoid Injector. SAE Int. J. Engines. 2009 April; 2(1).
5. Rivera E. Fuel Injection Technology Trends. In Proceedings of the 2014 CRC Advanced Fuel and Engine Efficiency Workshop; 2014; Baltimore, Maryland.
6. Liu JF, Walmer MH. Thermal Stability and Performance Data for SmCo 2:17 High-Temperature Magnets on PPM Focusing Structures. IEEE Transactions on Electron Devices. 2005 May; 52(5).
7. Liu J, Vora P, Dent P, Walmer M, Chen C, Talnagi J, et al. Thermal Stability and Radiation Resistance of SmCo Based Permanent Magnets. In Proceedings of Space Nuclear Conference; 2007; Boston, MA. p. 2036.