Hydro-shift

Will hydrogen power keep the internal combustion engine alive? Richard Simpson visits a British company that is betting the farm on hydrogen as a diesel replacement

The case against using hydrogen as a substitute for diesel in internal combustion engines is a strong one, on paper at least. It retains all the inefficiencies and complexities of a reciprocating engine, with pumping losses, internal friction, and heat ejection robbing more than half of the input energy, while using a difficult-to-handle gas as a fuel.

Hydrogen fuel cells are far quieter and more efficient, but electric vehicle guru Elon Musk is disparaging about even them, dubbing them 'fool cells' because much less electrical energy is lost charging a battery than in the business of converting water to hydrogen and oxygen using a lot of electricity and then combining the hydrogen with atmospheric oxygen to produce a little electricity and a small cloud of steam.

It's difficult to counter the argument, therefore, that hydrogen power is highly entropic, and ultimately wasteful. As the world moves from fossil fuels, surely it's key to cut down on all kinds of waste?

That's the theoretical case. Out into the real world of farmyards, construction sites and quarries, it's very different. And JCB, specialising in farming and construction equipment since Joseph Cyril Bamford built his first tipping trailer in 1945, is firmly rooted in the real world. Most famous now for the backhoe loader which it pioneered in 1951 (generically, the JCB) the company produces 300 different types of machine across the construction, quarrying, material-handling and agricultural sectors, and makes a total of 400 diesel engines a day, with production equally split between plants in the English Midlands and India. Some 10% of production is supplied as loose engines to external customers.

That's all the more impressive given that JCB only commenced diesel engine production in 2004: a move made possible by the increase in volume driven by the commencement of manufacture in India and necessary by the takeover of incumbent supplier Perkins by JCB's rival, Caterpillar. Development of engines in-house had begun as far back as the 1970s, but volumes had always been insufficient to justify production. JCB's 2004 444 engine was a 4.4-litre, four-cylinder design with four-valve heads, and initially powered the company's 3CX and 4CX backhoe loaders.

Today's JCB diesel engines are compliant with Stage V emissions standards, representing a 98% reduction in harmful emissions over the 2004 units. But that's not sufficient for a future where most markets will be dominated by a 'green' agenda. The UK is committed to reducing carbon emissions to net zero by 2050, and that means shifting away from fossil fuels, starting now.

While JCB doesn't make truck engines, many of the challenges it faces in the search for a fossil-free power source are shared with the road transport sector, and the solutions could be easily transferable. So it's worth looking at JCB's progress down the carbon-free road.

FIRST STEPS

Just like the truck industry, the first step was into battery-electrics. This can be judged a limited success, as JCB now offers 14 different types of compact equipment using lithium-ion batteries, including a mini-excavator, and various types of material handlers and scissor-lifts. The machines make working in confined spaces and sensitive areas safer and less intrusive, but scaling the technology up to larger machines is problematic.

JCB's light plant only does a limited amount of work – typically around 300 hours a year – which leaves plenty of time to recharge. Like trucks, heavier plant works harder, both in terms of energy used and hours, meaning

recharging is more challenging. Add to that the greater weight and cost of batteries and the need to access powerful charging points, and the battery-electric option rapidly runs out of juice at weights of over six tonnes.

Arguments that increased scale of production will see the cost of batteries fall cut no ice with JCB engineers, who point out that this is not supported by their experience, or by their battery suppliers. Enter hydrogen as a means of storing energy. It's a transportable gas, hence can be taken to where machines are operating, just like diesel. Refuelling is as fast as filling up with diesel. And fuel cells can be used to turn it into electricity to operate heavy machinery.

So, in 2020, JCB built the world's first hydrogen fuel cell 20-tonne electric tracked excavator. Fuel cells provide electrical power with fast-charge/discharge batteries absorbing the massive fluctuations in load as the machine digs, slews and discharges. The machine works, but is subject to constraints that make it rather impractical. The fuel cells are very expensive and sensitive. For example, they are prone to contamination by volatile organic compounds (VOCs) – which are given off by hot tar – and susceptible to vibration, G-forces and heat. JCB acquired some used fuel cells out of London buses, and found that reconditioning them was an expensive exercise at about £10,000 a unit.

The conclusion was they were not really a sustainable proposition for use in harsh environments, and this is a lesson which the truck industry would do well to take on board before touting their suitability for uses such as tipper trucks.

There was also a lack of interest in JCB from the fuel cell makers, who, six years ago, were firmly fixed on the high-volume car market. Things have obviously changed since then, with batteries having won at least the first round in the battle to electrify the car market, and the fuel cell makers have now turned to lower-volume sectors including bus and truck.

WHERE WILL THE FUEL COME FROM?

On the green side of the debate, there are those who seek to portray hydrogen fuel as having 'fake' environmental credentials, as most hydrogen is currently made from fossil methane. However, JCB counters that much of this is actually a by-product of industrial plastics production, and that large and small-scale 'green' hydrogen production by electrolysis provides a means of using surplus electricity from unpredictable generators, including wind turbines.

BACK TO THE DRAWING BOARD

For JCB, it was back to first principles, and an examination of the possibility of adapting existing diesel engines to use hydrogen as a thermal fuel. The obvious advantage was that if the power characteristics of a diesel engine could be replicated by hydrogen, and the diesel engine's bottom-end retained, then the conversion from diesel machines to fossil-free could be completed with little other modification. And, unlike battery or fuel cell, the additional costs for each machine in mass production would be relatively low. Additional bonuses are the relative ease with which hydrogen can be stored and transported (either in bulk pressure containers or by pipeline), and fast refuelling times: comparable to those for diesel fuel.

Paul McCarthy, JCB's chief engineer at the hydrogen engine project, points out that there is history behind hydrogen

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as a fuel for internal combustion engines, dating back to 1807! However, there are huge challenges in handling and combusting the gas within the engine's cylinders.

The current prototype engines (pictured on p11 and as mounted at right) are direct injection, using repurposed common-rail high-pressure CNG injectors, and spark ignition. Compression ratio is more akin to a petrol engine than a diesel to avoid pre-ignition, but diesel-like torque characteristics are restored by using a large variable-geometry turbocharger (pictured, inset, p10): it's around twice the size of the units found on the parent diesel engines.

"Hydrogen disperses well in free atmosphere," McCarthy explains, "but its behaviour in a confined cylinder is very different, and counter-intuitive: it goes just where you don't expect it to. While its buoyancy is nine metres per second, it disperses at only 2cm per second in the confines of the cylinder. Unusually for a gas, it warms when it expands, too." JCB has been working with Aachen University to model the behaviour of hydrogen using computational fluid dynamic models.

It's already become apparent that the existing modified injectors will need to be replaced by dedicated designs, but intake air volume is key.

"The momentum of a large mass of air is essential to maximise the mixing of hydrogen," McCarthy adds. "Far more air is required than for a comparable diesel or petrol engine, but fortunately we've learned a lot about turbocharging since the 1990s, and all this knowledge has been applied to the hydrogen project."

Thorough mixing also plays a key role in preventing the formation of NOx from atmospheric nitrogen and oxygen in the cylinder, so EGR and SCR systems do not have to be installed.

"Temperatures and pressures are entirely different to anything you will

encounter in petrol or diesel," McCarthy explains. "For a start, the exhaust gas is pure steam."

Providing 'clean' ignition is also vital. Homogenised compressed charge ignition of hydrogen is perhaps a long-term goal for JCB, but for the moment efforts are centred on sparks. States McCarthy: "We need a single, well-defined spark to initiate combustion. We are currently working with our supplier to develop the fifth generation of hydrogen spark plugs."

The clean, steam exhaust is a bonus from an environmental point of view, but presents problems internally. "Keeping the water out of the lubrication oil is a challenge. The oil requires an additive to prevent emulsification: it needs to be a hydrophobic oil." While the oil remains perfectly clean in use (there is no carbon in the combustion process), it still degrades. "Water evaporation can strip additives from the lubricant, and it is still subject to the shearing stresses found in all engines," points out McCarthy.

As far as the purity of the fuel itself goes, the hydrogen combustion engine is far more tolerant than a fuel cell would be.

But possibly the biggest argument in favour of hydrogen as a fuel is an economic one. "With the exception of the pistons, the engine is the same as the diesel from the head gasket down," McCarthy asserts. This is vital in constraining costs. JCB's customers are essentially centred on the business of moving earth and rock, and neither of these substances have their value enhanced by a novel power source for the machines that move them. If the physical design of diesel machines can be largely carried over into the hydrogen ones, then the inevitable increase in capital cost is less than if all-new designs are introduced. And, significantly, that's an argument that can easily be applied to road transport, too. TE

HOW WILL THE FUEL BE TRANSPORTED?

While the national gas grid will eventually be converted to hydrogen, the fuel is currently transported in pressurised trailer-mounted tanks at 250bar: around three times as much volume is required as for the equivalent diesel. This requirement will fall when carbon-fibre vessels are introduced, which can contain gas at up to 600bar. Weight-for-weight, hydrogen has three times the energy of diesel.