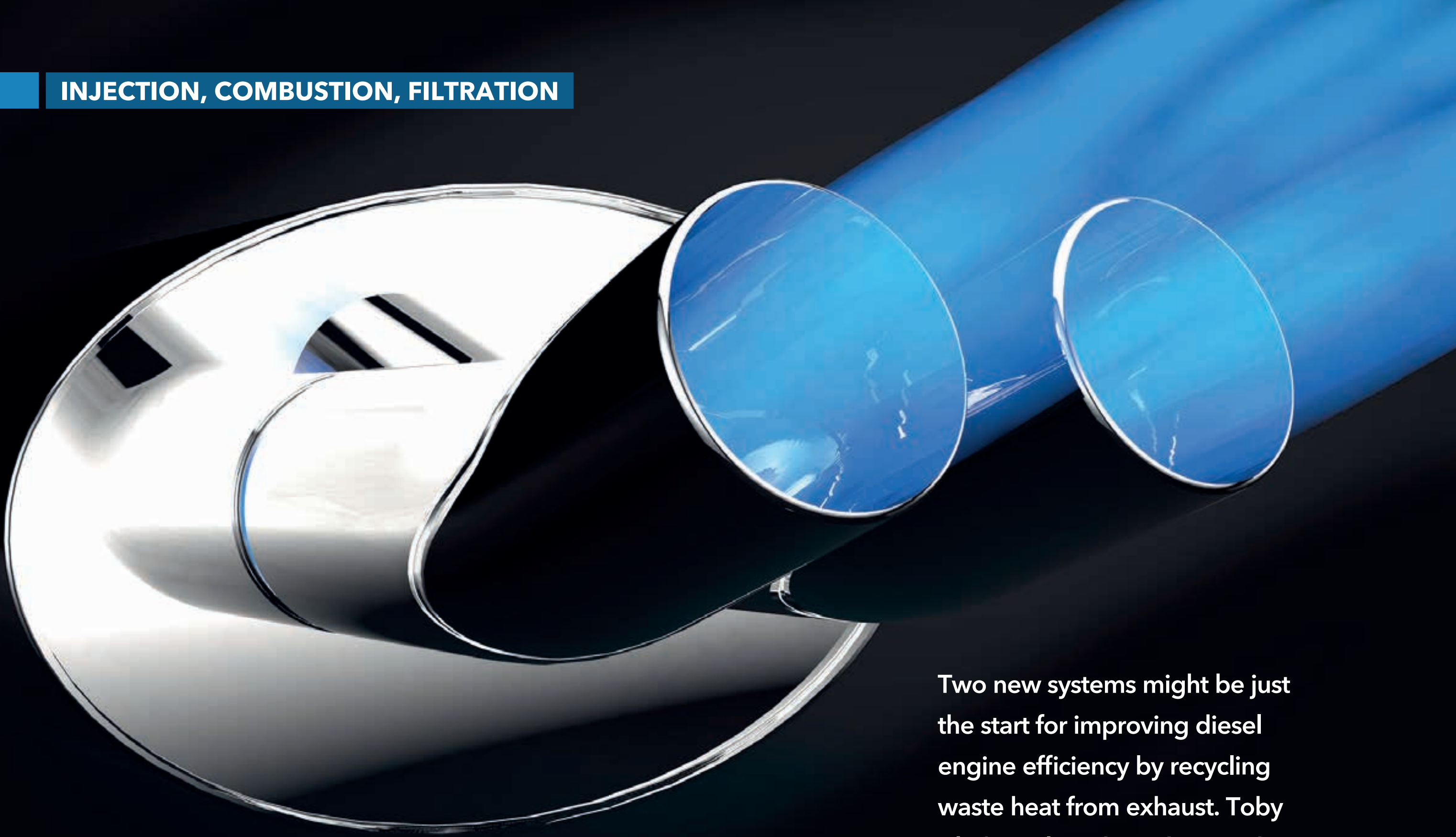

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Two new systems might be just the start for improving diesel engine efficiency by recycling waste heat from exhaust. Toby Clark explains how they work

Waste heat recovery

Diesel and spark-ignition internal combustion engines – as well as gas turbines and external combustion engines such as steam engines, vacuum engines and Stirling engines – are classified as 'heat engines': they turn heat energy (from burning fuel) into useful work. But the laws of thermodynamics mean that this process will always be inefficient; some of that heat energy will be wasted.

The earliest steam engines were miserably inefficient, turning just 1% or less of the fuel's heat energy into useful work; later engines improved on this dramatically, and large stationary steam turbines in power stations can be 40% efficient. Otto-cycle (spark-ignition) engines started off better and have improved steadily, while compression-ignition engines have always been even more efficient – Rudolf Diesel's first successful engine, in 1897, had a brake thermal efficiency (BTE) of around 26%.

An Otto-cycle engine is theoretically more efficient than a diesel, at the same compression ratio – but diesels always operate at a higher compression ratio, allowing them to extract more useful energy from the expansion phase of the two- or four-stroke cycle.

The most efficient conventional diesels today are the largest two-stroke ship engines: with bore and stroke measured in metres, and operating speeds of 100rpm or less, they can operate at up to 55% BTE, helped by high-pressure turbocharging, common-rail fuel injection, a relatively narrow rev range and low frictional losses. Somewhat smaller 'medium speed' four-strokes – still huge by roadgoing standards – are approaching similar efficiency.

Truck engines are unlikely to be as efficient: they must operate within strict emissions regulations over a wide range of speeds and loads, with variable temperatures and uncertain duty cycles. They also need much higher power density than a marine engine (which might weigh over 1,000 tonnes), so they rev much faster, increasing friction and internal pumping losses.

REMARKABLE

But given these limitations, manufacturers have done remarkable things, and modern heavy truck engines operate at up to 46% efficiency. Turbocharging makes excellent use of the energy of the exhaust gases, and turbocompounding (gearing down a turbine wheel driven by the exhaust, and connecting it to the drivetrain) can turn even more of this energy into useful work.

Still, while improvements in lubrication, geartrain design and fuel injection can all offer incremental gains, half the fuel's energy is still going out of the exhaust. Waste heat recovery (WHR) promises to extract some of this, and could see useful improvements in overall efficiency.

Numerous researchers have looked at harvesting waste heat using thermoelectric generators: solid-state devices which directly convert a

temperature difference into an electrical current. The idea is attractive – there are no moving parts – but the efficiency is low (usually less than 5%) and so the amount of energy that can be gained is small; the most likely application is for long-distance trucks working under constant load. However, new materials could improve efficiency and lower the cost dramatically, and research projects are continuing.

Most WHR systems operate using some version of the Rankine cycle; this is a thermodynamic process used to extract usable work from heat energy – and the principle on which most steam power plants (for example nuclear, gas- or coal-fired plants) are built. The four phases of the Rankine cycle are:

- Pump: the working fluid (usually water), at low temperature and in liquid form, is pressurised by a pump
- Evaporate: this high-pressure liquid is passed through a heat exchanger, where its temperature is raised by the heat source – it changes phase to a vapour, which is 'superheated' (that is, at a temperature higher than the liquid's boiling point)
- Expand: the high-pressure vapour is passed through an 'expander' – typically a turbine – which produces useful work, and its pressure drops
- Condense: the low-pressure vapour is cooled in another heat exchanger (a condenser), becoming a low-pressure liquid ready to start the cycle again.

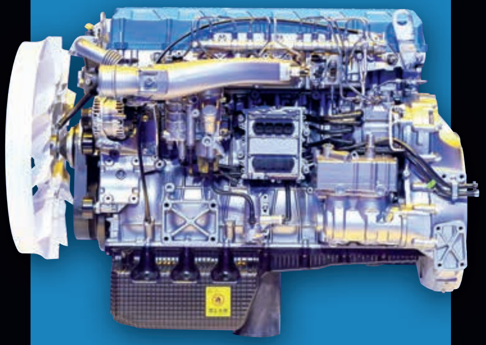
The process used in WHR is often called the organic Rankine cycle (ORC) when the working fluid includes organic chemicals such as ethanol (which evaporate more readily than water) – otherwise, it is not fundamentally different to the basic Rankine cycle.

First, BorgWarner has developed a generic organic-based WHR system, designed primarily for 'mild hybrid' vehicles using a 48V electric system to power ancillaries and provide limited propulsion energy. The BorgWarner system, diagrammed on p12, uses a turbine expander (pictured below, and driven by the superheated vapour) which drives both a 48V generator and a pump to pressurise the working fluid. The combined expander/generator/pump puts out a rated 7kW (maximum 13kW) and is remarkably compact, weighing less than 10kg and needing no separate lubrication.

BorgWarner also supplies heat exchangers in the form of evaporators (pictured above) to extract heat from both the tailpipe and the EGR system – effectively cooling the exhaust gases before they are recirculated – and a condenser to cool the vapour. Under high engine loads, the amount of heat entering the WHR system from the tailpipe evaporator can be excessive, so an exhaust flap valve (pictured at far left) is used to proportionally bypass this and keep the exhaust backpressure low.

With a dedicated control unit to manage the generator and bypass valve, the company claims around 3%-5% improvement in fuel consumption for the system.

Second, German component



THE WEICHAI 50% EFFICIENT TRUCK ENGINE

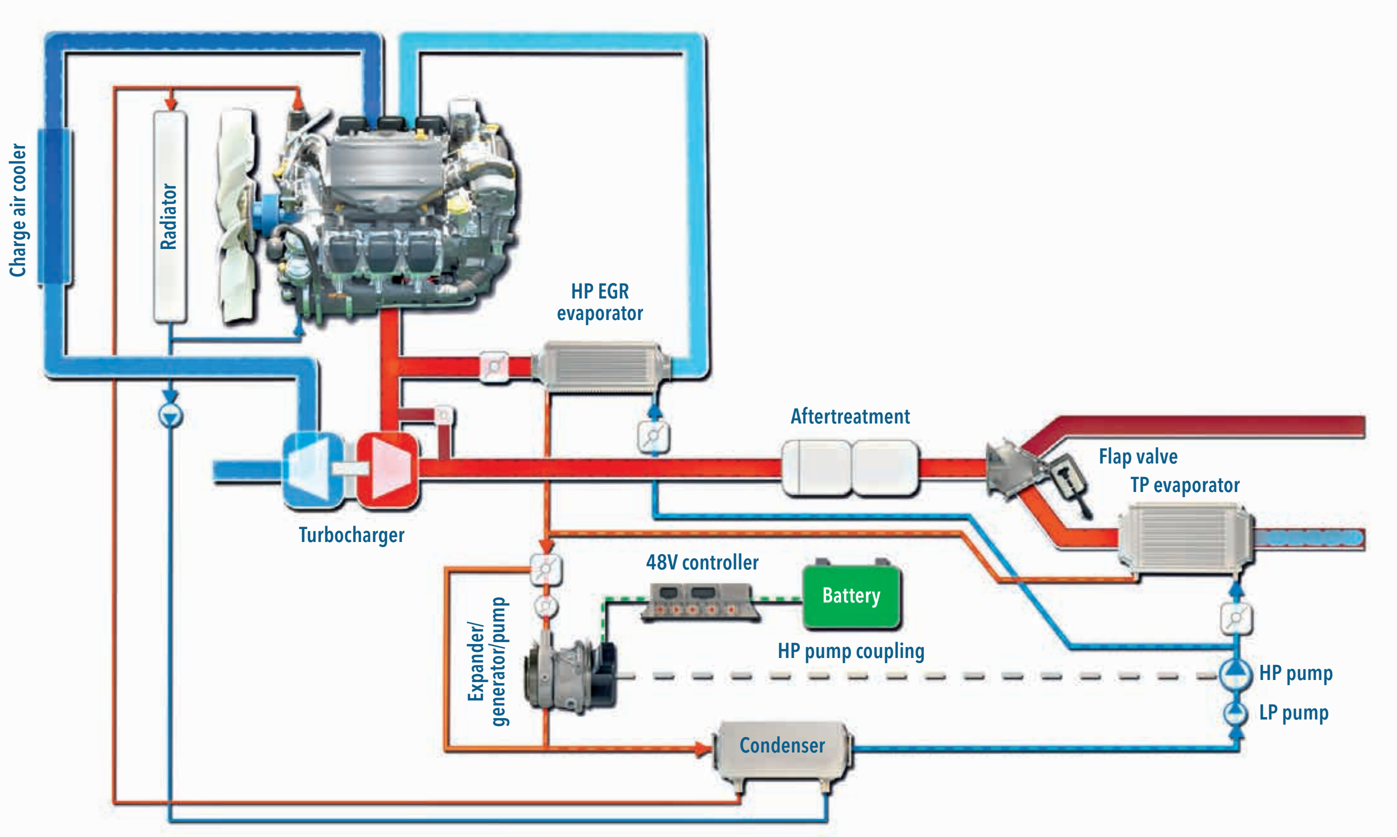
In September 2020, Chinese truck and engine manufacturer Weichai announced that it had developed a production-ready heavy-duty truck engine with a brake thermal efficiency (BTE) of over 50%. The German TÜV SÜD verified the result, stating that the engine had a BTE of 50.26% – although the exact operating conditions were not specified.

The engine is not unusual in layout: it is a 12.9-litre straight-six rated at 552bhp at 1,900rpm, uses a 2,500bar common rail injection system supplied by Bosch, and meets China VI/Euro VI emissions regulations. But hard technical details are difficult to come by; Weichai, which has been in operation since 1946, has reportedly spent $4.4bn on engine development in the past decade, and says that its engine takes advantage of five 'proprietary technologies'.

These are:

- 'Fields synergy combustion technology', which apparently increases combustion speed by 30%
- 'Harmonious design technology' to strengthen the engine and enable 60% higher peak firing pressure (PFP)
- 'Exhaust energy distribution technology', which seems to relate to EGR and turbocharging design
- 'Subzone lubrication technology', which 'uses several friction reduction technologies to reduce the overall friction by 20%'
- 'WISE control technology', which uses Weichai's own ECU, and involves more precise predictive models.

There is no sign yet that Weichai will launch its engines in Europe, but its plans include 'partnering with more global companies to move toward a goal of 55% thermal efficiency'.



manufacturer Mahle has approached the problem slightly differently. While its WHR system also works on the Rankine cycle, almost all of it is packaged into a single 55cm-wide box designed for easy installation into a variety of vehicles.

This 'Boost Box' contains a single evaporator, which is plumbed in after the exhaust gas aftertreatment. This evaporates the working fluid, which then goes into an expander – but the Mahle version uses an axial piston unit rather than a turbine. The expander drives a generator to power the electric condenser fan and feed pump – both also contained in the box. Excess electricity supplies a mild-hybrid battery system.

Michael Hötger, managing director of the eMahle division based in Berlin, says: "We packaged all the technology into one box. All we need is waste heat of 150°C and over for the WHR system to work." Mahle claims a fuel consumption reduction of 5%. Hötger says: "Within just one and a half to two years – a short timeframe when you think about the future – the WHR box has already paid for itself."

Systems like these are included in the $80m US Department of Energy-led R&D programme called Supertruck II, with the aim of dramatically improving the efficiency of Class VIII artic combinations. The teams involved – from Navistar, Daimler, Volvo, PACCAR (Kenworth) and Peterbilt – are all using 48V mild-hybrid architecture and WHR systems.

Navistar is using the BorgWarner WHR system, while Daimler has proposed an ORC-based system that combines the WHR fluid with the engine coolant (pressurised at 50bar) to extract heat directly, and using a three-cylinder reciprocating unit as the expander.

The PACCAR/Cummins ORC-based WHR system is more complex than some, with a dual-loop system taking heat out of the exhaust gases in two stages, and a 'dual-entry' turbine system from Cummins. It can apparently achieve very high BTE values, but the team says that "for optimum freight efficiency… the fuel savings under transient conditions don't outweigh the additional weight, and impact on aerodynamics. In addition, the cost and complexity of a highest-BTE WHR system remains a challenge for near-future commercialisation". TE

FURTHER INFORMATION

Volvo turbocompounding – www.is.gd/ufokef

Cylinder deactivation – www.is.gd/pepema

HOW DO YOU CALCULATE EFFICIENCY?

Brake Thermal Efficiency (BTE) is the usual measure of a heat engine's efficiency. It is defined as the useful energy **output** for a given period, divided by the energy **input** from the fuel, and is normally expressed as a percentage.

The energy **output** (in kWh) is calculated by measuring the power output with a dynamometer (a brake dynamometer, hence the B in BTE) over a period of time.

The energy **input** is calculated by multiplying the mass of the fuel used by its calorific value (also known as energy value or heating value) – this has various definitions, but the most useful is lower calorific value (LCV), which is typically (but confusingly) measured in megajoules per kilogram (MJ/kg). The LCV of diesel fuel is around 42.6MJ/kg – swapping the terms around, you can convert this to 84.5g/kWh.

So if your engine uses (say) 1.9kg of fuel to produce 10kWh of energy over a particular cycle, you would say it has a specific fuel consumption (SFC) of 190g/kWh. Under these conditions, its BTE is given by:

BTE = 84.5/190 = 0.445 = 44.5%