

Ian Bamsey considers long and short term options for kinetic and heat recovery systems in Formula One

# Recovery positions

In a speech he made at the Geneva Motor Show back in March, well before the scandal that threatened his presidency of the FIA, Max Mosley outlined the reasons for the introduction of Kinetic Energy Recovery Systems (KERS) to Formula One in 2009. He told his audience that KERS will make Formula One “at once more environmentally friendly, road relevant and at the cutting edge of future automotive technology”. He added that KERS as will be permitted in 2009 is “the first stage of a programme to divert the vast research effort at the pinnacle of motor sport towards energy efficiency”.

Mosley continued: “By bringing in rules changes which make

these technologies the only means by which a power advantage can be obtained, we can ensure that the outstanding engineers and huge budgets available to Formula One will be deployed on energy recovery technologies which are directly relevant to the car industry’s efforts to reduce CO<sup>2</sup> emissions as well as the average motorist’s fuel bill”.

Presented at Stuttgart’s Engine Expo in May were two examples of the sort of energy recovery technology system that we can expect to see in Formula One in the future. Flybrid exhibited its 2009-legal KERS system while heat2power revealed the sort of technology that could conceivably be exploited under yet-to-be-defined heat energy recovery system rules in the next decade.

## FLYBRID

The FIA defines KERS as 'a system designed to recover kinetic energy during braking... store that energy and make it available to propel the car'. The 2009 technical regulations confine such a KERS to a single system connected to the rear wheel drivetrain with its release of power at all times under the command of the driver. In addition the regulations state that the maximum power in or out of a KERS must not exceed 60 kW while the energy released on any one lap must not exceed 400 kJ. These measurements are taken at the connection to the rear wheel drivetrain, so more than 400 kJ may be stored to allow for losses between the storage medium and the measurement point. A figure of 60 kW equates to 80.4 bhp while the cap of 400 kJ allows that maximum level (a power boost of just over 10%) to be applied for (400/60) 6.66 seconds on each lap.

As we have described in the past, Silverstone-based Flybrid, led by Jon Hilton and Doug Cross has devised a mechanical flywheel system for Formula One in 2009. On the face of it, this is quite straightforward. A carbonfibre sheathed steel flywheel spins at 64,500 rpm within an aluminium container that, given a clever system for sealing the flywheel shaft provides a partial vacuum so as to minimise air resistance to flywheel motion. Careful attention is also paid to the bearing system in which the shaft runs, again to minimise the friction that saps flywheel energy. A connection between the flywheel shaft and the rear wheel drivetrain that can be de-clutched allows the flywheel storage system to be energised under braking and subsequently to reapply its energy to the rear wheels at the discretion of the driver.

The connection that Flybrid plans to use has been developed in conjunction with Xtrac and Torotrak and exploits the latter's 'Variator' variable ratio transmission technology as described in RET 023. Manipulation of its constantly variable transmission ratio controls energy storage and recovery. When the ratio changes so as to speed up the flywheel, energy is stored and when it slows the flywheel, energy is recovered.

The Variator is an alternative to the Van Doorne-type CVT, one that is lighter and more compact. It has enabled Xtrac to produce a connection to the rear wheel drivetrain that is at least 90% efficient while weighing no more than 11 kg complete with rotating components (5 kg worth) and lubrication system, including sump and pumps. A clutch comes between this power transfer unit and the flywheel assembly, with both connection devices electro-hydraulically operated under the command of a dedicated electronic control unit. The necessary hydraulic pressure is generated by a built-in hydraulic pump driven from the Variator. This entire KERS system weighs no more than 24 kg.

In theory the Flybrid flywheel could be employed instead as the storage medium in an electrical rather than purely mechanical KERS system. Its shaft would then carry a motor/generator, which would be linked through cable and voltage converters and controller to another motor/generator directly connected to the drivetrain. That approach clearly offers greater flexibility of packaging. Adding 24 kg to the rear of the Formula One car is a major issue under current conditions, although it should be noted that the aero regulations for 2009 are

## HEAT TO POWER

There are various potential means to reclaim energy from heat rejected to coolant or to the exhaust. We have mentioned in the past the BMW 'Turbosteamer' and we have looked more deeply at the Woodward Super Turbocharger (RET 020). At the Engine Expo French company heat2power revealed its patented exhaust heat regeneration system, giving us a further taste of the technology we can expect to see in the next decade, when Formula One takes another step in energy recovery system development.

In essence the heat2power system uses a supplementary 'hot air' engine (which it calls a 'heat engine'). In such an engine there is no fuel and no internal combustion. The piston is driven by the expansion of air that has been heated by an external source. The heat2power system puts a turbo-supercharger and a heat exchanger into the primary Internal Combustion engine exhaust system. The turbo compresses air, which is sent to the secondary hot air engine. The hot exhaust gasses from the IC engine first drive the turbine of the turbocharger, then pass through the heat exchanger downstream of the turbo, which is used as the external heat source for the hot air engine.

Skeptics might wonder if the post-turbo IC engine exhaust gas is significantly hotter than the compressed charge supplied to the heat engine. In fact heat2power's analysis claims that the gas temperature entering the exhaust heat exchanger is around 800°C (1472°F) and that the HX exit temperature is 370°C. The company claims to have done a lot of analysis of rival systems and of this new approach and it claims that its idea not only works, it works better than known alternative technologies, for example Organic Rankine devices. "The use of air makes our system simple and avoids negative effects of piston blow-by on lubrication," heat2power says. It further reports that the effectiveness of its system has been confirmed by simulations undertaken by "a major OEM".

So far we don't have the evidence of physical testing of the heat2power system applied in a race engine environment. In the absence of that, we will accept the figures offered by heat2power as an indication of what heat recovery technology might be capable of in the future. Even skeptics will find this food for thought.

## HOW IT WORKS

The heat2power exhaust energy regeneration system links an existing IC engine to a secondary hot air (or 'heat') engine. All of the exhaust gas exiting the IC engine passes through a turbocharger's turbine and then a heat exchanger, which causes a marginal loss of performance through increased backpressure and compromise of exhaust tuning potential. However, if heat2power's calculations are accepted, that is far more than offset by the power delivered by the secondary engine.

The turbine is part of a conventional turbo-supercharger unit that supplies compressed air to the heat engine rather than to the IC engine, sending it via a conventional air:air aftercooler. The heat exchanger is part of a separate 'hot air' circuit serving the secondary engine. It is akin to an air:air charge cooling device but, rather than passing air from the atmosphere so as to cool a ducted charge airflow, this device passes exhaust gas so as to heat air circulating within the hot air circuit. It thereby provides the heat engine's required external heat source. In theory this may be feasible: the devil is often in the details, and the implementation of this exhaust heat exchanger might prove to be quite a technical challenge.

The secondary hot air engine can have one or more cylinders. Each cylinder has four valves and a conventional piston that in turn drives a conventional crankshaft, from which power is added

to the drivetrain and from which the timing drive is taken. One of the four valves admits air compressed by the turbocharger another sends spent gas to the IC engine exhaust system downstream of the turbine and heat exchanger. The other two are transfer valves, one of which sends air from the cylinder to the exhaust gas heat exchanger while the other completes the hot air circuit, readmitting the air heated by passage through the heat exchanger.

The hot air engine has four operating cycles with normal exhaust and intake events controlled by the respective valves. During its compression stroke the intake air, which has been compressed by the turbo and then aftercooled is further compressed by the piston before the hot air circuit comes into play. The hot air circuit valves are then operated so that a slug of compressed air is sent around that circuit, through the heat exchanger. This heated air is then readmitted to the cylinder, and it is the expansion of that hot air that drives the piston on the power stroke.

The hot air engine is not throttled and is always operating at full power, so long as the IC engine's throttle is open, generating a flow of exhaust gas. However, a constantly variable transmission system is used to regulate the hot air engine's input to the drivetrain. Under deceleration, with the IC engine throttle closed the drivetrain can power the hot air engine, due to the direct connection between the two. The hot air engine can therefore add to the engine braking effect and it can be used to generate and store air pressure for subsequent reapplication.

## SYSTEM APPLICATIONS

The heat2power system can be used in conjunction with a KERS, each complementing the other. Exhaust heat recovery is effective when the throttle is open; KERS is more appropriate when exploiting closed-throttle time.

According to heat2power, in the case of a race engine the ratio of crankshaft power to thermal power loss through the exhaust can be as high as 1:1.8. Jack Kane points out: "the common rule of thumb for the distribution of the chemical energy contained in the fuel for a liquid cooled engine is approximately one third through various cooling systems (coolant, oil, external airflow), slightly more than one third down the exhaust pipe, and slightly less than one third delivered as usable power, varying with the thermal efficiency of the particular engine. In practice, it turns out that there is roughly 22-25% lost to cooling and roughly 45% lost down the pipe, in the form of (mostly) thermal energy and the remaining component in un-recovered chemical energy. So  $45/25 = 1.8$ , making that claim reasonable."

In other words, a 500 bhp race engine can actually reject 900 bhp worth of energy through its exhaust. According to heat2power its system can reclaim up to 30% of this loss at low engine speed. When the engine is operating between peak torque speed and peak power speed (the normal operating window of a race engine), it says that the gain can still be as high as 20%.

Thus, heat2power asserts that its system has the potential to reclaim under normal operating conditions some 20% of the 900 bhp otherwise wasted from a 500 bhp engine. In other words it can be expected to transform a 500 bhp race engine into a 680 bhp unit, through the addition of a small hot air engine with supporting turbo and heat exchanger systems. Note that no fluids are required for this simple secondary engine – perhaps not even lubricant if advanced coatings are fully exploited. It is further claimed by heat2power that its system weight is of the order of one kilo per 1.6 bhp generated. A gain of 180 bhp therefore equates to a system weight of 112 kg. Clearly there are weight and packaging disadvantages but the whole point of the system is that performance is increased for no increase in fuel consumption. On the face of it a regular turbo-supercharger system likewise

fundamentally different and that might influence weight distribution requirements.

In addition KERS efficiency has to be considered. Under 2009 Formula One regulations only the amount of energy flowing in and out of the system is measured not that stored so on the face of it any loss in transfer can be overcome by the use of greater storage capacity. Flybrid's Formula One mechanical flywheel system has a 440 KJ storage capability as 10% is considered sufficient margin to account for the losses of its system. Electrical systems will require a greater margin: given that twice the energy conversion is taking place perhaps twice as much? Whatever the answer this implies a larger/heavier flywheel unit that takes longer to fully charge. Flybrid has calculated that it will typically take 10 or 11 seconds of braking to generate the 440 KJ that its flywheel can store. That amount of braking is not an issue at the majority of Formula One circuits. However, there are some venues where it will be a struggle to capture the maximum permitted level of energy and here system efficiency will therefore play a role, too.

The electrical/flywheel approach is that being developed by Williams Hybrid Power for possible Formula One application, although in its case the storage unit's motor/generator will actually be combined with the flywheel itself (a carbonfibre wheel containing metal particles to allow it to be magnetized). The question mark here is how to cool the motor/generator when it is operating (Williams says at 100,000 rpm) within the partial vacuum needed to maximise performance of the flywheel.

That is not a problem for Flybrid, which has devised an innovative system for sealing its flywheel shaft so as to maintain the lowest possible air pressure within the containment vessel. Nevertheless, we should not underestimate the challenge of the weight and security of the containment system and of providing low air pressure and low friction flywheel shaft bearings. Flybrid believes that it has developed the highest speed hermetic vacuum shaft seal in the world. It has patented this and its rolling element shaft bearing system, details of which have not yet been revealed.

Flybrid has already proven the integrity of its flywheel system in FIA standard crash testing. A Formula One nose cone type impact test was undertaken at Cranfield University in the course of which the flywheel assembly was subject to a peak deceleration in excess of 20G. After the test the flywheel was found to be completely undamaged and it was still spinning at high speed.

While the mechanical flywheel system's flywheel output shaft has to be mechanically linked to the powertrain there is a certain amount of scope for packaging such a system, which in Flybrid's case in total accounts for no more than 13 litres of space. The flywheel could be mounted ahead of the engine (where the oil and fuel tanks normally sit) connected to the front of the crankshaft. However, the further it is from the final drive, the greater the overall system losses so the system may instead be carried over the transmission, subject to weight distribution implications. Flybrid anticipates that its flywheel will be mounted in a Formula One car such that the flywheel shaft is horizontal and running along the main vehicle axis.

Flybrid dismisses concerns over the gyroscopic forces generated by

mounting a 64,500 rpm flywheel on a Formula One car. The faster a flywheel spins the more kinetic energy it can store but also the greater the gyroscopic force. Energy stored is proportional to the square of rotational speed whereas the precessional forces are proportional only to rotational speed (not that squared). As a consequence the faster a flywheel spins the lower are the precessional forces for a given energy storage capacity. Flybrid is using a flywheel speed that it has calculated as the best compromise given the required storage capability and the consequent size and weight of the flywheel unit and its gyroscopic effect. In theory Flybrid could have employed a pair of counter-rotating flywheels but it considers that it has the precessional forces at a level that would not justify the additional complexity, saying that the maximum force the car will experience on track is 130 Nm.

In 2009 the Formula One grid is likely to see a mixture of electrical and mechanical flywheel systems and electrical systems using batteries and/or super capacitors as the storage medium. A hydraulic system would be legal but Flybrid has calculated that 10 litres of fluid compressed plus 10 litres uncompressed are required per 100 kJ requirement therefore the 2009 Formula One requirement would be for a pair of 40 litre fluid tanks. That is too great a space and weight requirement to make a hydraulic system feasible.

But will KERS be employed in Formula One at all in 2009?

Most involved in system development seem to agree that after packaging is taken into account the lap time gain on a normal circuit will be considerably less than one full second. However, even if it is only one third of a second, as some suggest, the field is so tightly bunched these days no team can afford to give up that potential gain. Moreover, with overtaking so difficult the start of the race is critical and here Flybrid has calculated that, having stored energy on the warm up lap a KERS will be worth a gain of something like 20 metres on the run to the first corner.

KERS has been touted as 'push to pass' but in truth overtaking tends to be done under braking rather than acceleration. In theory a KERS boost might be used to improve acceleration so as to set up an overtaking move into the following braking zone. In practice, teams are likely to have a strategy for KERS usage that maximises the lap time gain and sacrificing this in the hope of making an overtaking move could well be counterproductive. Interestingly, though, the majority of the lap time gain from KERS will be the effect of the system in shortening braking distances.

Flybrid has calculated that the system will provide up to 10% additional braking force in the early stages of a high speed braking event, before, with downforce tumbling, the car becomes grip limited and thus subject to wheel lock. It acknowledges the critical nature of the interface between KERS and the regular braking system, which these days is highly regulated and has to be mechanically controlled. Teams that do not get that interface right will find they have a car that is harder to drive, quite possibly eliminating the potential lap time gain and even slowing the car.

Running without a properly optimised KERS, or without a system at all will make a car more vulnerable to overtaking moves. We can assume that next year all the major teams will be using KERS – and striving very hard to get its implementation right! ■

## HEAT TO POWER

recaptures energy spent through the exhaust to increase performance and even with a charge aftercooling system taken into account it represents a lot less additional weight and complexity. However, the difference is that the conventional turbo system is designed to compress the charge air so that more fuel can be burned, thereby increasing power. The heat2power system doesn't just exploit exhaust gas energy it recaptures it so as to reduce the amount of energy wasted. According to heat2power its system is equally applicable to a turbo engine as to a naturally aspirated engine. Moreover, since it doesn't know what sort of engine it is dealing with it can be used with any type – compression ignition, two stroke, four stroke, rotary, alternative fuel and what-have-you.

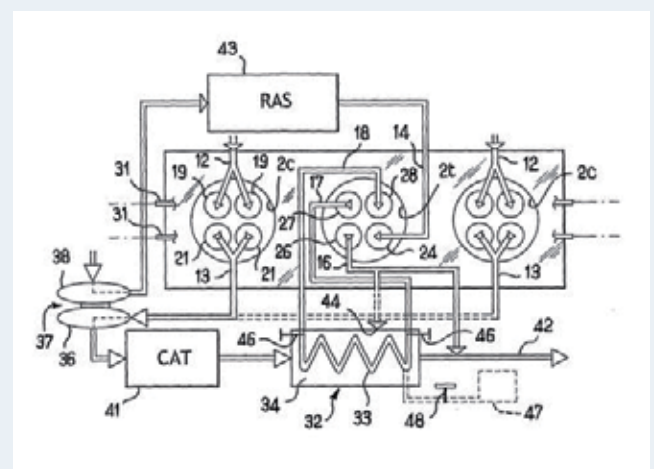
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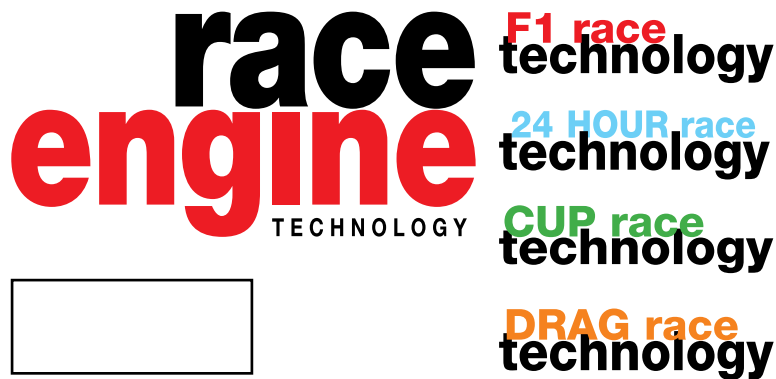
So, if heat2power's calculations are indeed correct, what might be the impact of this system upon a Formula One car?

Let us disregard for a moment the fact that the arrival of heat energy recovery systems is likely to coincide with new engine regulations. If we take the example of a contemporary Formula One car, this weighs 605 kg and exploits around 760 bhp. The same car hypothetically fitted with a heat2power system that recclaims 20% of wasted energy as described above in theory would produce 1034 bhp while pushing weight to 776 kg. Nevertheless, the car's power to weight ratio would have gone up, from 1.256 bhp per kilo to 1.332 and this for no increase in fuel consumption.

In practice, for reasons of safety the FIA is expected to peg power output at around the current level when this type of technology is introduced. It will do so by means of new engine regulations. So we can expect smaller, less powerful primary engines supplemented by kinetic and heat recovery systems to maintain today's performance level for significantly less fuel consumption. In fact there might well be a fuel flow metering device to govern this new generation of power plant. That will really sort the effectiveness of the potential energy regeneration systems as part of an integrated drivetrain package.

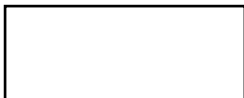
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