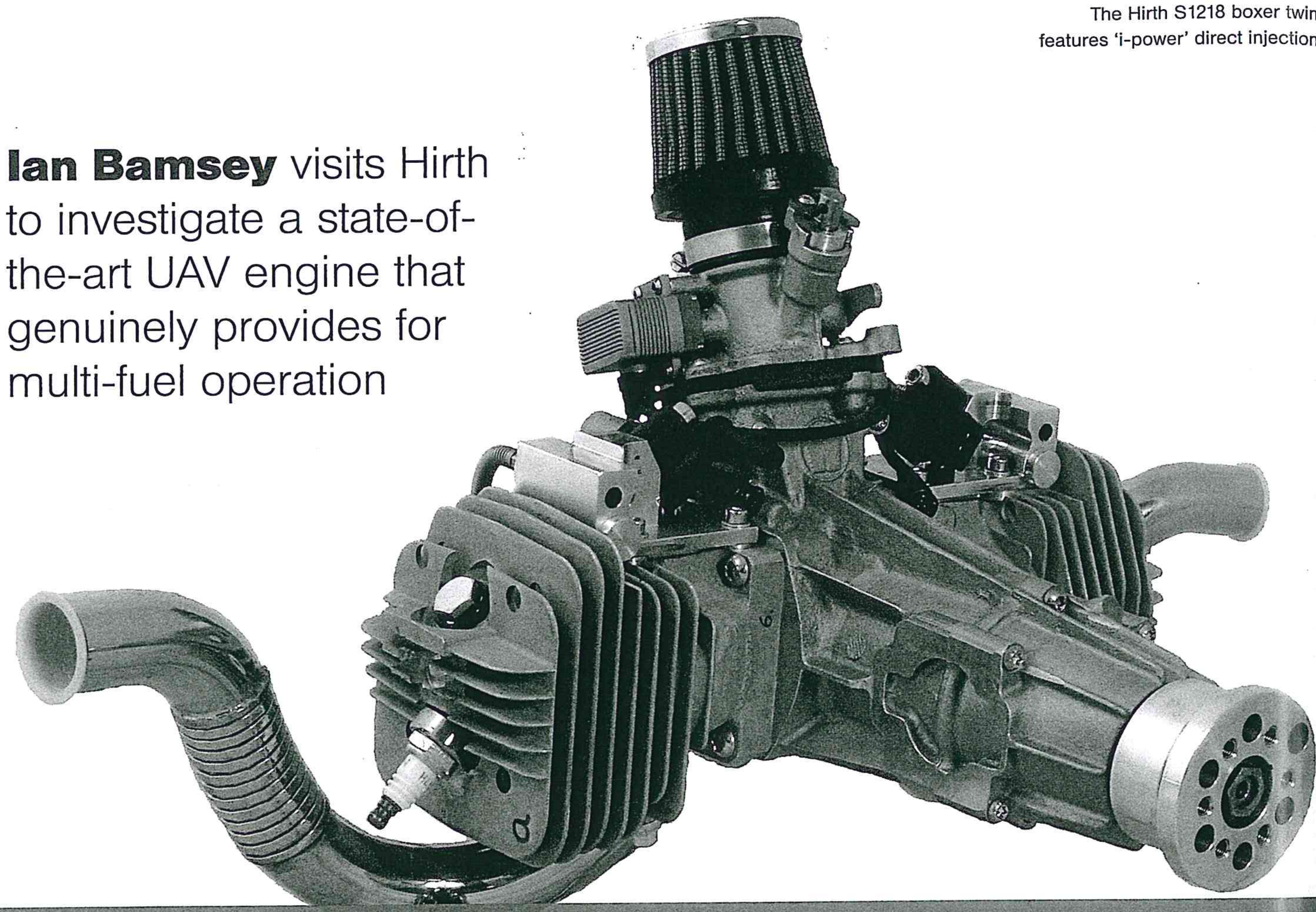
The Hirth S1218 boxer twin features 'i-power' direct injection



**Ian Bamsey** visits Hirth to investigate a state-of-the-art UAV engine that genuinely provides for multi-fuel operation

# Fuelling freedom

Hirth is one of the world's leading suppliers of two-stroke engines – over the past 70 years it has delivered more than a million of them to customers globally. Not surprisingly then, this well established engineering company based near Stuttgart in Germany is a major player in the growing market for engines for small unmanned aerial vehicles.

Here we investigate a state-of-the-art UAV engine from Hirth, its 183 cc twin-cylinder two-stroke, project S1218. It bristles with innovative technology, which allows it to burn all forms of kerosene-based fuel, however low the octane rating, making it invaluable for military deployments. The direct-injected Hirth flat-two is a flyweight power unit that provides 15 bhp and can operate missions of 14 hours' or more duration. That is standard-setting performance.

A comparable diesel engine would require a far stronger structure to contain the greater combustion pressures, which would add weight and there would be more vibration. The UAV market is heavily influenced by power-to-weight ratio – in simple terms, less weight is longer flight time. Hirth concentrates on two-stroke technology, which is ideal for the power density requirement of UAVs. "We can get 120 Nm per litre without turbocharging," notes technical manager Dietrich Kehe. "We are totally focused on two-strokes, and are experts in the technology."

Launched at the Orlando AUVSI show in May 2014, the S1218 introduces Hirth's innovative i-power system, the development of which began a couple of years ago. S1218 is based on project S1212, which has the same base engine and has been proven in combat use in Afghanistan and elsewhere.

The key aspect of i-power is that it allows the engine to ignite all forms of kerosene (paraffin) based fuel. Often the basis of aviation jet fuel, kerosene is far less flammable than gasoline (petrol). In the distant past kerosene was used as an inexpensive fuel for tractors; in that application the engine was started on gasoline and would only switch over to


The S1218 powers various UAVs, including the BAT seen here taking off

kerosene once it had warmed up. Its hot exhaust was routed around the intake to heat the kerosene to help vaporise it, so that it could be spark-ignited.

Modern kerosene-based fuels on which a UAV might be asked to fly include the civilian Jet A and Jet A1 and the military JP-5 and JP-8 blends. JP-8 is similar to A1 and is the regular NATO airforce fuel, whereas JP-5 is a fuel developed in 1952 specifically for use in aircraft stationed on carriers, where the risk from fire is particularly high. JP-5 isn't as flammable as JP-8 and A/A1; as Kehe notes, "It is almost impossible to burn JP-5 outside of an engine!"

## i-power

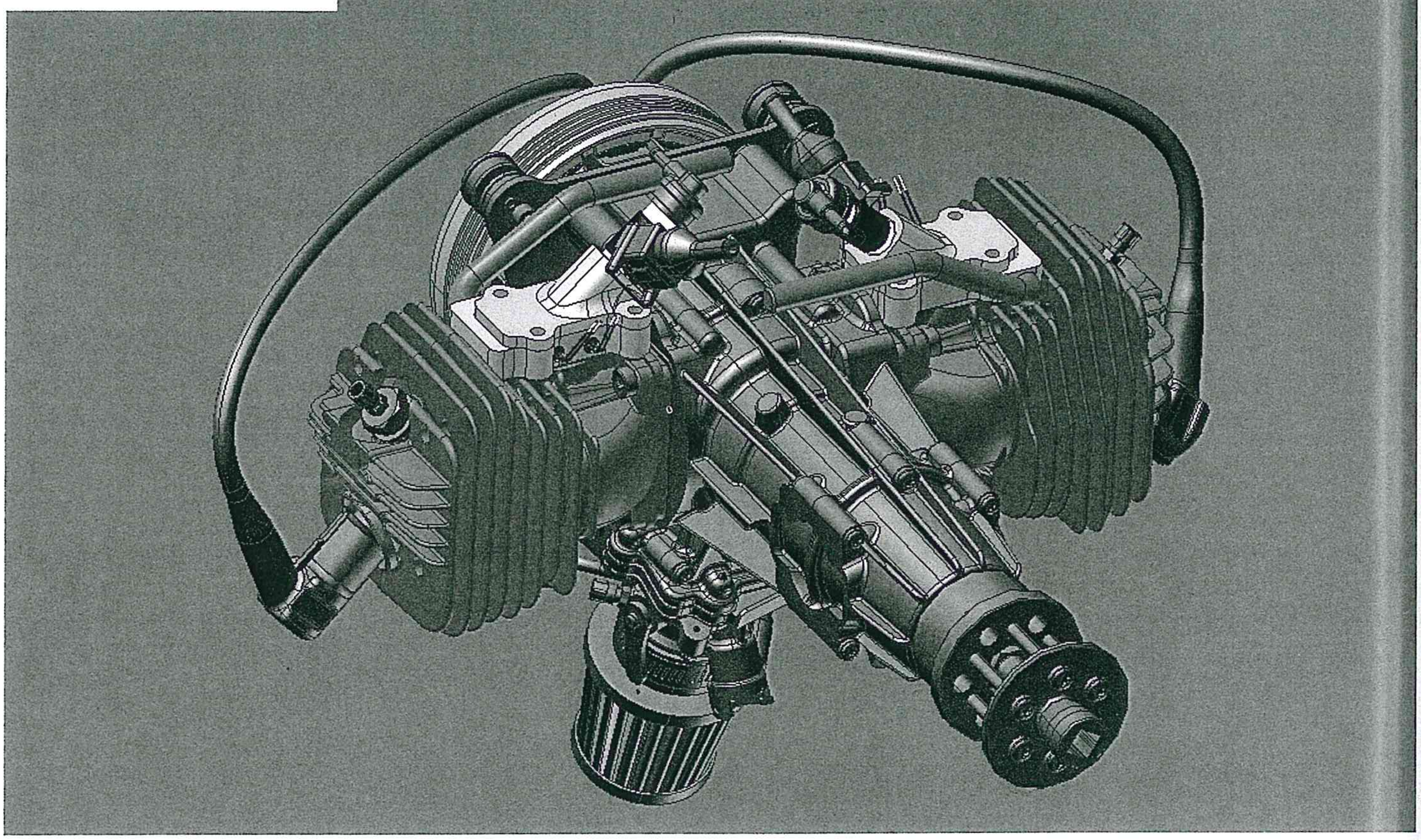
A two-stroke engine has exhaust and (incoming charge) transfer ports accessed via windows in the bore wall, the opening of which are controlled by the action of the piston skirt. As the piston descends on the power stroke, it opens the exhaust port windows on one side of the cylinder and then the transfer port windows on the other side. The ports remain open while the piston reverses direction at bottom dead centre, until its return on the compression stroke brings its skirt back up to close them again.

> The key aspect of the i-power system is that it allows the engine to ignite all forms of kerosene-based fuel

The transfer ports allow in a fresh charge that has been pre-compressed in the crankcase, and unavoidably there is a lot of overlap with the action of the exhaust. The challenge of simultaneous charging and scavenging is aided by tuning the unsteady gas dynamics via exhaust geometry, which in effect pushes any fresh charge trying to escape back into the cylinder. It is also aided by the design of the transfer ports, which turbulates and directs the incoming charge, again to minimise overlap loss.

In the case of a Hirth i-power engine, there is an extra window in the cylinder, above the height of the exhaust and transfer ports. That window opens into an aluminium resonance tube. As the piston's descent opens it, hot and high-pressure exhaust gas rushes into it. The gas runs down the tube to the end, where it is reflected back to the cylinder. The length of the tube is a function of the rpm operating range – in simple

Underside view of the Hirth S1218



## If we have [uncontrolled] ignition in one area, it cannot spread so fast that you have a knock issue

terms, if revs are higher then the tube will be shorter. The flow has to be reflected at the appropriate time.

A fuel injector is located near the top of the tube and is angled, and its operation is timed such that it sends a slug of fuel into the flow of escaping burnt charge. Kehe says, "You spray the fuel into the tube as the window opens, and the fuel has most of the length down and all of the length of the tube back to become vaporised. Because of the very hot exhaust gas it vaporises very easily. You shoot back vaporised fuel into the cylinder, which is ready to ignite [mixing with the fresh charge air that has come into the cylinder through the transfer ports]."

It follows that only air is pumped through the crankcase and the transfer ports, while the opening and closing of the window to the resonance tube – which introduces the fuel to the combustion chamber – is controlled solely by the piston. The timing of the injection into the tube is controlled by the engine management system (EMS) operating a regular Bosch solenoid-type injector with a fuel pressure of only 3.0 bar.

"Normal direct-injected gasoline engines use high fuel pressure, which means heavy components and the complication of a high-pressure injection pump," Kehe says. "With this system we don't need that. Plus, with additional preparation time – our 'pre-vapouring' of the fuel – the droplets are smaller and the charge will burn faster. We only need the injector to meter the fuel at the right time and in the right quantity."

The fuel is timed to arrive in the combustion chamber after the exhaust port has closed, avoiding loss of fuel through scavenging. On the other hand, an apparent drawback with mixing the fuel with exhaust gas is that the resultant charge will contain a proportion of exhaust gas. Kehe however says that in fact this is an advantage, since it has the effect of reducing knock sensitivity.

"Kerosene-based fuel is extremely sensitive to knock, so its effective octane rating is very low – in fact it is not rated at all," he explains. "With our use of exhaust gas to vaporise the fuel you get a damping effect. Even if we have [uncontrolled] ignition in one area, it cannot spread so fast that you have a knock issue; it is damped by the presence of the exhaust gas."

There is still the challenge of cold starting though, which is notoriously

## Anatomy: Hirth S1218 UAV engine

- Flat twin
- 54 x 40 mm = 183.2 cc
- Naturally aspirated two-stroke
- Multi-fuel, including kerosene-based
- Aluminium structure
- Linerless with nickel silicon carbide coating
- Two main bearings, roller
- Steel crankshaft, two pins
- Steel con rods
- Light alloy pistons; two rings
- Four transfer ports per cylinder
- Two plugs per cylinder
- CDI ignition
- Reed valve
- Compression ratio undisclosed
- Maximum rpm, 6500

The S1218 is a boxer twin that has an all-aluminium construction with linerless cylinders that have a nickel silicon carbide bore coating. The heads are integral, and each cylinder is attached to the crankcase by four bolts with a paper gasket at the crankcase interface.

The crankcase is split laterally (not, as might be expected, longitudinally). Beyond the front and rear sections is a nose section that extends out to the propeller. Thus does the three-section crankcase support the crankshaft and the propeller, which is mounted to the very nose of the crankshaft.

Liquid sealant is used between the crankcase sections. Each side carries a roller main bearing in its wall. The crankshaft runs in just those two bearings, although it carries two pins, phased at 180°. Each con rod, which carries needle roller bearings top and bottom, is H-section. A steel piston pin, optionally DLC coated, runs directly in a light-alloy piston, which has a full skirt to control the various ports.

The exhaust is stainless steel. The upper centre section of the crankcase incorporates the common intake port, within which is located the reed valve. The EMS-controlled butterfly is located above the reed valve, while an air filter is used upstream. The EMS also controls twin-plug CD ignition and Hirth's i-power direct injection system.

Ready to run, the S1218 weighs 7.6 kg (including just 67 g for the EMS), excluding propeller assembly and an e-machine on the rear of the crankshaft. The e-machine is either a permanent magnet starter/generator or simply a generator, according to customer choice. It supplies all the electrical requirements of the craft, including the engine ignition and EMS. The wiring is according to customer requirement.

The S1218 is designed to be mounted semi-stressed in the airframe, using four bolts only. These are positioned at the rear, so the engine and propeller assembly is cantilevered, and the thrust comes through the engine structure to the airframe

To strip and rebuild a S1218 takes about six man-hours.

**Some key suppliers to this engine**

**Head/cylinder castings:** Gilardoni
**Crankcase casting:** MH Gusstech
**Crankshaft:** in-house
**Reed valve:** Moto Tassinari
**Pistons:** Mahle
**Rings:** Mahle
**Piston pins:** Mahle
**Circlips:** Mahle
**Con rods:** in-house
**Big-end bearings:** FAG
**Big-end bearings:** Koyo
**Main bearings:** FAG
**Main bearings:** Koyo
**Gaskets:** Pilz
**Ignition system:** undisclosed
**Spark plugs:** NGK
**Fuel injectors:** Bosch
**Engine management system:** undisclosed
**Servo actuators:** Volz Servos
**Throttle:** in-house
**Oil pump:** Dellorto
**Oil filter:** Mikuni
**Alternator:** customer-specific
**Exhaust:** undisclosed
**Air filter:** K&N
**Air filter:** Pall
**Fuel pump:** undisclosed

**Dynos:** Schenk
**Dynos:** Magtrol
**QC equipment:** Mitutoyo

difficult with kerosene-based fuel. "The military likes to operate at temperatures as low as -30 C so you do need a cold-start strategy," remarks Kehe. "For the first few cycles you have to prepare the fuel in a different way; after that you have the hot exhaust gas, and the injection performs normally.

"So we have a special cold-start mechanism – that is our 'trick', which we haven't patented. It is a strategy to vaporise the fuel before we put it into the engine. I wouldn't like to reveal more than that!"

In addition to fuel preparation, the duration of the spark is an important aspect of i-power engine control. The S1218 uses CD ignition, and the EMS provides control not only over the timing of the spark but also its duration, according to the burn rate of the fuel. The spark duration can be as long as 1 s if required.

Using i-power, an engine can run on any fuel, with a change of mapping in the case that gasoline rather than kerosene-based fuel is used. That makes it a genuine multi-fuel engine, and the next development will be to use a vibration-based knock sensor, so that it isn't even necessary to change the mapping.

The one drawback with this multi-fuel approach however is that the compression ratio has to be a compromise when running on gasoline. Running on gasoline, ideally it is approaching 10:1. "For a two-stroke it makes no sense to go higher than 10.5:1," remarks Kehe. "There is no gain in going higher; you only stress the engine more. Around 9.5:1 is about the limit for an air-cooled two-stroke; only with water cooling do we go to 10.5:1."

On the other hand, says Kehe, even at 9.5:1, "on kerosene-based fuel there would be so much knocking it wouldn't even run". All he will say about the compression ratio for running on kerosene-based fuel is that it is well under 9.5:1 – "somewhere between 5:1 and 9.5:1". The engine will run satisfactorily on gasoline at this lower compression ratio but, he says, "If you optimise the compression ratio for gasoline you will gain performance, including enhanced fuel efficiency."

If an engine is to be run solely on gasoline then the base of each cylinder is machined as a means of adjusting compression ratio. Also, there are different chamber forms in the head, providing different squish areas as appropriate for the low- and high-compression versions of the engine.

### S1218 base engine

The S1218 is a flat-twin operating as a boxer, which means its con rods are on individual crankpins phased at 180° so that they 'box' together and apart again during each 360° revolution. Since the two cylinders flank the crankcase, air is fed into the centre of it, so it follows that it has to go through the transfer ports on both sides at the same time, and that both cylinders have to fire at the same time.

In theory, this configuration eliminates unbalanced forces in the reciprocating parts of the drivetrain, but having the crankpins offset from each other causes an unbalanced moment on the crankshaft. No vibration dampening is used to offset that; Kehe notes that this would not represent a useful addition of weight.

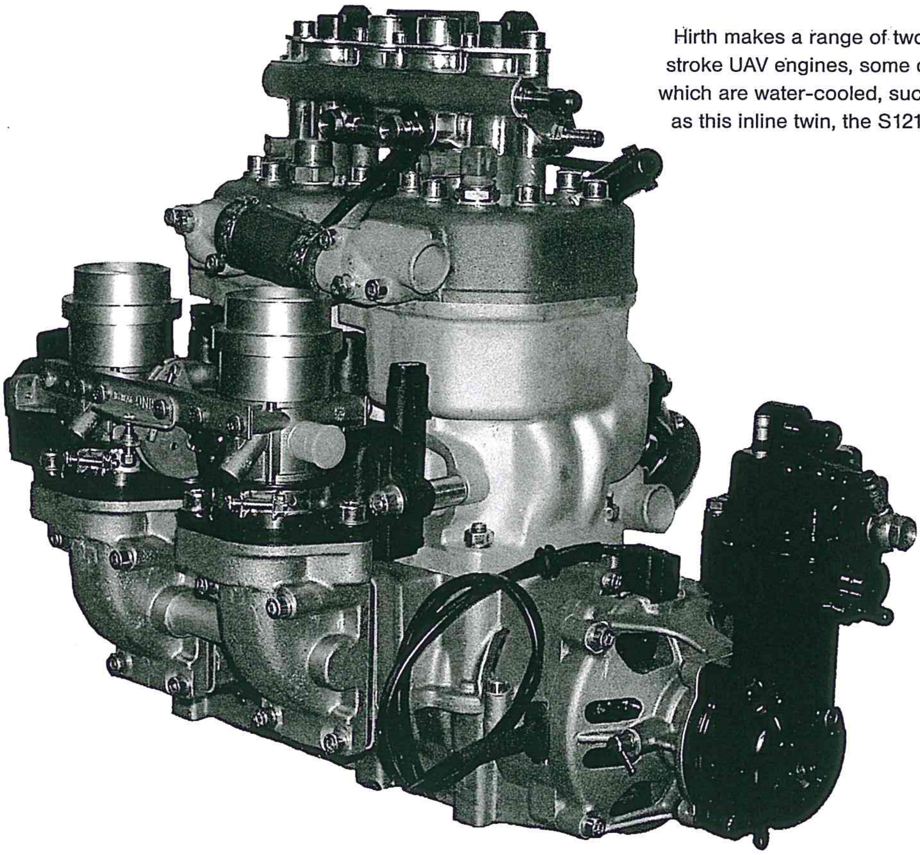
Engine assembly at Hirth

> Weight is saved by using a combined cylinder and head, which also overcomes the problem of head sealing

A small weight penalty is introduced by the fact that each cylinder has twin plugs that fire simultaneously, simply as a flight safety measure. However, weight is saved by using a combined cylinder and head, which also overcomes the problem of head sealing. It allows each head/cylinder to be sealed to the crankcase by means of a simple paper gasket.

The S1218 has an all-aluminium structure with linerless cylinders. This is a lighter option than using an iron or steel liner and, given the use of low-expansion 4032 alloy aluminium pistons, it avoids the need to warm the engine up before launching. In some military applications, to minimise the possibility of the operator being detected, as soon as the engine starts running the UAV needs to be sent on its way.

Kehe notes that two-strokes are very sensitive to back-pressure, and that exhaust design is consequently a compromise between noise suppression and back-pressure. "If the customer wants an extremely quiet engine then we can also use a separate silencer cartridge,



Hirth makes a range of two-stroke UAV engines, some of which are water-cooled, such as this inline twin, the S1214

There is no lambda sensor but the exhaust-exit temperature is measured using a thermal probe

but packaging is always a problem."

A catalytic converter doesn't come into the equation. Given the associated temperature level, there would be too great a risk of fire.

A single central reed valve-controlled inlet feeds the charge to both cylinders via the crankcase. Each cylinder is then fed via four transfer ports. "With our 6500 rpm maximum operating speed there is no need to go for more than four transfer ports," explains Kehe.

Since the crankshaft carries roller (main) and needle (big-end) bearings there is no need for a pressurised lubrication system. Oil is metered into the charge air in the intake manifold and travels with the flow to lubricate both the bottom and the top end. An electric solenoid-type oil pump controlled by the EMS meters fuel into the incoming charge air one small shot at a time. The pump is pulsed at a frequency that corresponds with the engine speed and load.

Each piston has a crown that is only very slightly domed, while the squish area formed by the chamber in the head is considered crucial in terms of avoiding knock. Since there are no valves in a two-stroke cylinder head a large squish area can be provided. "You have to be careful – if you overdo it, you get knocking. If you make it too 'soft' then you don't get any benefit from it," Kehe says.

The light-alloy piston carries two identical steel compression rings which have the plain working surface "recommended by Mahle for use with its Nikasil-type bore coating," according to Kehe. They have a 1.2 mm tall working face and taper back within a groove that has a matching taper. Essentially the floor is flat while the roof tapers down towards the inside. This influences the 'angle of attack' of the working face in the dynamic situation.

Doubling the number of rings clearly increases ring-generated friction but it helps with wear. It is the rings rather than the bore where most wear occurs, so the twin-ring solution tends to extend maintenance intervals.

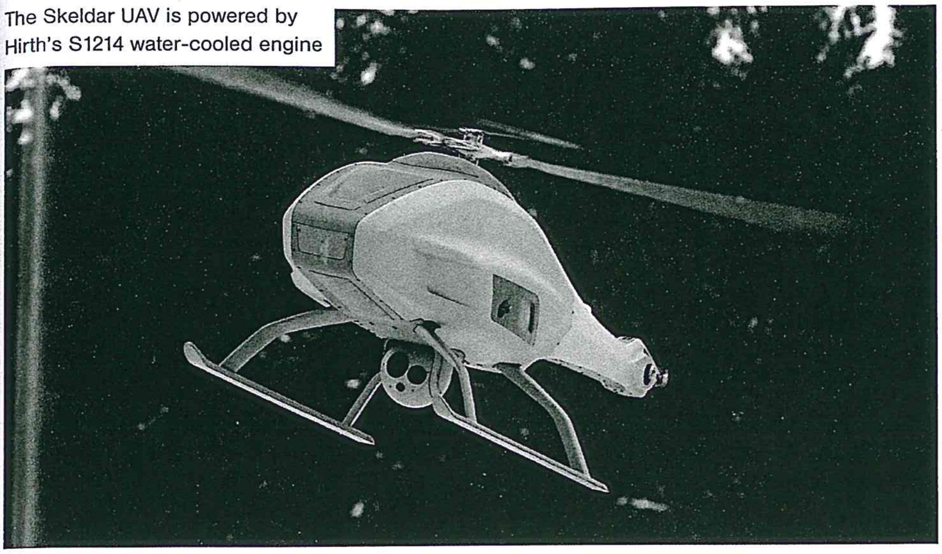
## Engine operation

Hirth's own EMS runs the injection and ignition, and also controls the fly-by-wire throttle (a butterfly, the opening of which is servo-operated). Engine control is closed loop, the EMS reacting to mission parameter requests from the autopilot and to various engine sensors to obtain the requested rpm (propeller speed) at any given time while keeping the engine within safe operating conditions.

There is no lambda sensing but the temperature of the exhaust exiting each cylinder is accurately measured using a thermal probe. "That is a key engine sensor on a two-stroke," remarks Kehe. "We also read crankshaft position, throttle position, intake air temperature and pressure above the throttle, cylinder head temperature and other [undisclosed] temperature readings."

If necessary the engine can run in 'limp home' mode without any input to the EMS aside from crank position. The normal operating engine speed range is 3500-6500 rpm, and the engine is designed to run no faster than that because of the implicit increase in wear and noise. That 6500 rpm limit also assists the challenge of running on kerosene-based fuel, and allows many customers to mount a propeller directly on the nose of the crankshaft.

Some UAVs using this engine have the propeller driven via reduction gearing instead, in order to spin a bigger propeller



The Skeldar UAV is powered by Hirth's S1214 water-cooled engine

at lower rpm. That provides more thrust for a given horsepower, and in practice it is a more efficient solution. "That is an optional extra that we recommend," notes Kehe. "Customers who accept that option are always happy with the result."

When using a direct-drive propeller, a representative cruising speed is around 4500 rpm. If the engine is used in this way for most of a mission, flight time can be expected to exceed 12 hours. In fact, depending on the UAV in question, its fuel load and mission parameters, Kehe says a representative figure is 14 hours-plus.

"Typically a mission will start with 10-20 minutes of wide-open throttle [WOT] running for the take-off plus the climb to the required altitude," he explains. "Then the throttle will be backed off, normally to run at a constant speed that will represent something in the region of 65-80% of maximum power. So it is stressed within that amount of maximum at all times. That is a lot of stress."

The cylinder head operates at a temperature of up to 280 C. Measured 110 mm downstream of the exhaust port window, exhaust gas temperature is typically around 680 C at WOT and up to 720 C at part load.

Ignition timing is normally in the region of 30-25° BTDC, regardless of fuel type. "Advancing the ignition can help, but not beyond 25°," remarks Kehe. "That is a typical two-stroke thing". He adds

> A mission will typically start with 10-20 minutes of WOT running for the take-off plus the climb to the required altitude

that all engines supplied by Hirth are mapped so as not to run into knock. "The mixture preparation provided by our resonance tube technology – and the way the engine is designed and mapped – means we can avoid knock, even when using kerosene-based fuel."

As is typical of a two-stroke, maximum torque for this engine is very close to maximum power – in this case it is just 200 rpm lower, and maximum power is 15 bhp at the 6500 rpm limit. Given that kerosene-based fuel is hard to burn, fuel consumption is a function of the type of fuel used. Using kerosene-based fuel, a representative figure at WOT is around 360-380 g/kWh; in cruising mode it would be more like 280-300 g/kWh.

It all adds up to a state-of-the-art UAV engine, and one with a remarkable multi-fuel capability. □

## Hirth the company

Owned by Siegfried Göbler, Hirth employs 50 people at its base near Stuttgart in Germany in the business of the design, development, building and testing of two-stroke engines. It supplies engines for UAVs, including aircraft and helicopters, as well as karts, hovercraft and portable fire pumps.

Hirth makes most of each engine in-house, including machining structural components from raw castings. The manufacture of built-up crankshafts using the well known Hirth-type couplings is a core technology. These are forged outside the company but are machined and assembled in-house. Hirth offers a 1000-hour warranty for each of its press-together crankshafts, the hand assembly of which – using special tools – is a highly skilled task.

Outsourced are altitude chamber (Porsche) and climatic chamber (Beru) testing. In-house facilities include five-axis machining and a quality control room maintained at a constant 20 C. To ensure repeatability, components are kept there for 24 hours before checks. The company has various test cells for sub-assemblies as well as complete engines. All engines are tested on one of the in-house dynos before delivery to the customer. Most are supplied as a package complete with the mounting frame – the approach is that of 'plug and fly'. Full documentation is always provided with each engine.