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Rotary Valve 4-Stroke Engines for General Purpose Power Equipment and Unmanned Systems

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ABSTRACT

A rotary valve 4-stroke combustion system has been applied to engines for unmanned air vehicles (UAVs) and general-purpose power equipment. The RCV rotary valve system can operate on a range of fuels and at high levels of power, together with typical 4-stroke exhaust emissions and fuel economy. The DF35 and DF70 engines, for UAVs and unmanned hybrids, are based around a 35 cc cylinder configured as a single or boxer twin, with either air or liquid cooling. The fuel injected DF engines achieve 63 kW/litre on either gasoline or kerosene-based fuels such as JP8. The 25 cc multi-position general purpose CK1 engine is configured into a brushcutter package. CK1 has completed development for volume production, achieves 48 kW/litre.

Recent small engine developments are application specific. Small two wheelers and garden equipment originally used basic 2-stroke engines for cost and power to weight reasons. Exhaust emissions regulations have resulted in new low emissions small engines and a move towards battery/electric systems. However, there are many situations where battery electric systems will not be viable. With a requirement for net-zero carbon emissions in 2050, future small engine will need to achieve: low exhaust emissions, low fuel consumption, high power to weight, and have an ability to run on net-zero carbon fuels, such as synthetic aviation fuel. Combining the multi-fuel capability of the DF engine with volume production technology of the CK1 engine, the RCV rotary valve combustion system provides a viable technology for future small engine applications.

INTRODUCTION

Small internal combustion engines (ICE) are used on lightweight two wheeled vehicles, portable lawn and garden equipment, and unmanned air vehicles. These applications have traditionally favoured 2-stroke over 4-stroke engines for cost and power to weight reasons. However, this position has changed over the last 30 years with legislation to reduce toxic tailpipe exhaust emissions for improved air quality. The market today includes a mix of low emissions 2-stroke and 4-stroke engines, with an increasing uptake of battery/electric (BE) systems. With the global effort to reduce carbon emissions to net-zero by 2050, it is necessary to consider attributes that small engine need to have where BE systems are not viable.

In global two-wheeler markets, poor urban air quality and the introduction of exhaust emissions legislation resulted in 2-strokes being replaced by heavier, less powerful 4-strokes. Taking the two-wheeler market in Taiwan as an example, 2-strokes had 60 % market share in 1995 [1] and with increasingly tight emissions regulations had disappeared by 2010. In the entry level 50 cc sector, less powerful 4-strokes engines were not able to achieve the same vehicle performance, so consumers then moved on to 100/110 cc 4-strokes. These themselves are now being replaced by battery/electric (BE) scooters, while the 125 cc and above market is currently increasing, Figure 1. In Europe the 50cc category for mopeds has also disappeared where emissions regulations currently at EU5 are expected to become tighter and possibly consider real driving emissions (RDE) reflecting real use rather than a laboratory test cycle [2].

Small off-road engine (SORE) exhaust emission regulations were introduced in the 1990's for portable forest and garden equipment. With challenging requirements of power, weight and cost, the market did not shift from 2-stroke to 4-stroke as might have been expected considering two-wheeler trends. Some manufacturers developed a new generation of low emissions 2-strokes with stratified scavenging combustion systems and/or exhaust catalysts, while others introduced mini-4-stroke engines. With such a mix of technologies in the market, Favre et al [4] looked at a representative range of handheld engines in relation to emissions behavior. They found that regulated emissions levels did not directly relate to the combustion principle (2-stroke or 4-stroke), but the technology used for improvement. The future of the SORE category will also depend on regional regulations. CARB for example, will require most applications to be zero emissions by 2024 [5]. However, in markets where small engines continue to be used, a future challenge will be control of particulate emissions relating to unburnt oil and fuel in the exhaust gas [4].

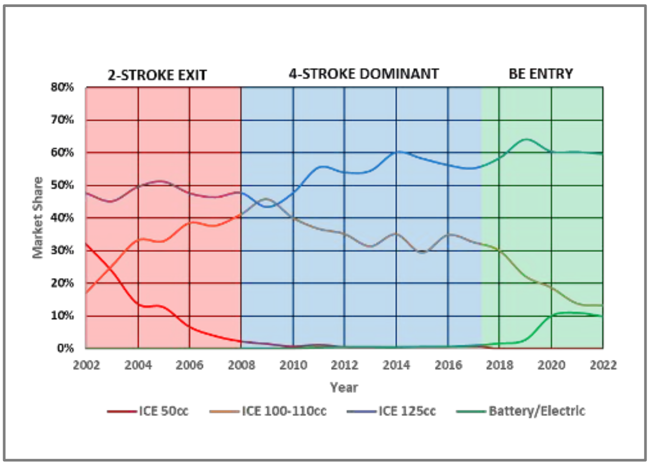


Figure 1. Small powered two-wheeler technology trends in Taiwan 2002 to 2022 [3].

Small UAVs or drones for surveillance use BE propulsion, but these systems have limited range or flight duration. The use of an ICE can either extend flight durations from 30 minutes up to 20 hours or allow a pay load such as for agricultural crop spraying. These ICEs are predominantly 20cc to 100cc 2-strokes derived from either hobby aircraft or garden equipment. To provide fueling control over a range of environmental conditions and altitudes, UAV engines use electronic fuel injection. For military use, there is also a requirement to operate on kerosene-based fuels such as Jet A1, JP5 or JP8, known as heavy fuel (HF). Such fuels have low volatility, so difficult to ignite when cold and have a low octane rating resulting in combustion knock limited performance [6]. Small engine HF conversions can result in a 5 to 15 % decrease in power with corresponding increase in fuel consumption [7].

With BE propulsion there is not only a trade-off between weight, cost, and range, but also the practical issue of access and availability of power for charging. This is a particular issue in off-grid locations and when there are power outages due to extreme weather events, natural disasters, or power generation/distribution failures [8]. In the future reliable alternative power sources will still be needed including portable generators with small ICEs.

For passenger cars, manufacturers are offering hybrids as a way of significantly reducing vehicle fuel consumption. For two wheelers, Ramanchandra et al [9] show that in terms of well to wheel CO_2 emissions, there are significant reductions (>50%) with an ICE hybrid or BE system. The difference between hybrid and BE, depends on how the electricity is generated [10]. On handheld tools, battery size, cost and weight currently limits BE to the lower output categories. To address such issue for professional use, Vogiatzis et al [11] have looked at hybrid powertrains for handheld tools indicating that up to 30% reduction in BSFC might be possible with a 2-stroke hybrid and 50% with a 4-stroke. For quadcopter drones, hybrids are now available that can extend the flight duration for crop spraying or surveillance from 30 minutes to over 4 hours operating with an ICE hybrid using gasoline [12, 13].

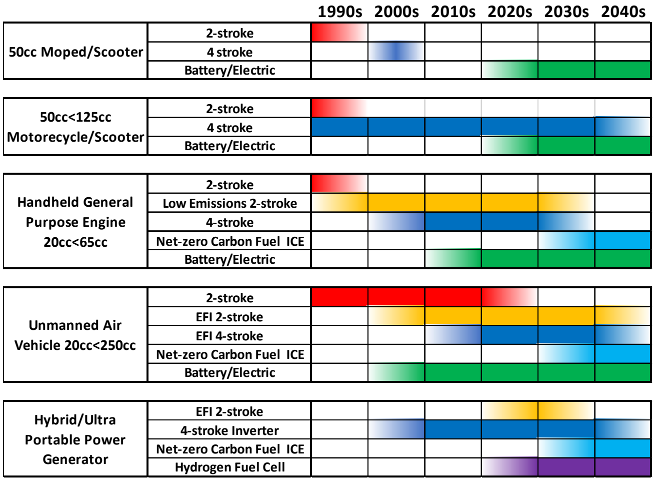
For each application where small engines are in use today there are ongoing development challenges driven by requirements for both low tail pipe emissions and reducing Carbon emissions to net-zero. The McKinsey report on “The Net-zero Transition” highlights some of the changes required and challenges in meeting net-zero [14]. In relation to current small engine applications, the choice of energy source will to a large extent depend on trends in transport sectors and related infrastructure. Forward projections to net-zero are based on the following generalised assumptions:

- Road transport for people from ICE to BE
- Road transport for goods from ICE diesel to ICE net-zero carbon fuel
- Air transport for goods and people from Avgas / Jet A1 to sustainable net-zero carbon aviation fuel
- Electrical power generation away from fossil derived carbon fuels to ICE net-zero carbon fuel or hydrogen fuel cells

Air transport is major challenge for BE systems due to the trade-off between energy storage density and range. In the short to medium term, it is expected that alternative net-zero carbon or other fuels will be used. Of these synthetic biofuels (from treatment of biomass) and synthetic fuel (from captured CO_2) are drop in fuels in that they can be used in existing ICE propulsion systems with existing distribution infrastructure [15]. Hydrogen is also a potential fuel for ICE use, but implementation is not straight forward due to fuel handling challenges and whether a Hydrogen infrastructure is established. Exploring the use of Hydrogen in ICEs, Rana et al [16] identify that a Hydrogen ICE is likely to produce 17% less power and be prone to abnormal combustion with combustion chamber hot sports.

Taking into consideration recent trends and forward projections for transportation, Figure 2 presents possible scenarios for products currently using small ICEs over the next 25 years. The relative take up of BE systems for consumer products such as two-wheelers and handheld products will depend on up-front cost and regional emissions regulations. For professional handheld products and unmanned air vehicles, an ICE provides clear benefits over BE systems today in terms of power, weight, and range. This has resulted in hybrid configurations for UAVs where the related technology could be applied to ultra-portable power systems to improve on the power density of 4-stroke invertor generators currently in widespread use [17]. Essential requirements for future ICEs are likely to be as follows:

- Show sufficient benefits against other technologies where BE is not viable
- Low tailpipe exhaust emissions including particulates from unburnt oil
- Sufficient power to weight for the application to be viable
- Capable of operating on a range of fuels including net-zero carbon synthetic fuels
- Low cost through volume production



		1990s	2000s	2010s	2020s	2030s	2040s
50cc Moped/Scooter	2-stroke	🟥					
	4 stroke		🟦				
	Battery/Electric				🟩	🟩	🟩
50cc<125cc Motorecycle/Scooter	2-stroke	🟥					
	4 stroke	🟦	🟦	🟦	🟦	🟦	🟦
	Battery/Electric				🟩	🟩	🟩
Handheld General Purpose Engine 20cc<65cc	2-stroke	🟥					
	Low Emissions 2-stroke	🟨	🟨	🟨	🟨	🟨	
	4-stroke		🟦	🟦	🟦	🟦	
	Net-zero Carbon Fuel ICE					🟦	🟦
	Battery/Electric			🟩	🟩	🟩	🟩
Unmanned Air Vehicle 20cc<250cc	2-stroke	🟥	🟥	🟥	🟥		
	EFI 2-stroke		🟨	🟨	🟨	🟨	🟨
	EFI 4-stroke			🟦	🟦	🟦	🟦
	Net-zero Carbon Fuel ICE					🟦	🟦
	Battery/Electric		🟩	🟩	🟩	🟩	🟩
Hybrid/Ultra Portable Power Generator	EFI 2-stroke				🟨	🟨	
	4-stroke Inverter		🟦	🟦	🟦	🟦	🟦
	Net-zero Carbon Fuel ICE					🟦	🟦
	Hydrogen Fuel Cell				🟪	🟪	🟪

Figure 2. Future small engine application scenarios towards 2050.

ROTARY VALVE ENGINE TECHNOLOGY

For over 20 years, RCV Engines Limited has been involved in the development and manufacture of rotary valve engines. RCV first entered the model aircraft market building up a range of six engines from 10cc to 22cc. These engines use a rotary valve incorporated into a rotating cylinder geared to the crankshaft, Figure 3. Application of this rotating cylinder concept to larger cylinder sizes (up to 125 cc) raised several issues without showing significant enough benefits [18]. A change to a fixed cylinder and evolution of the rotary valve, provided an opportunity to develop the DF UAV and CK general-purpose engines described in this paper.

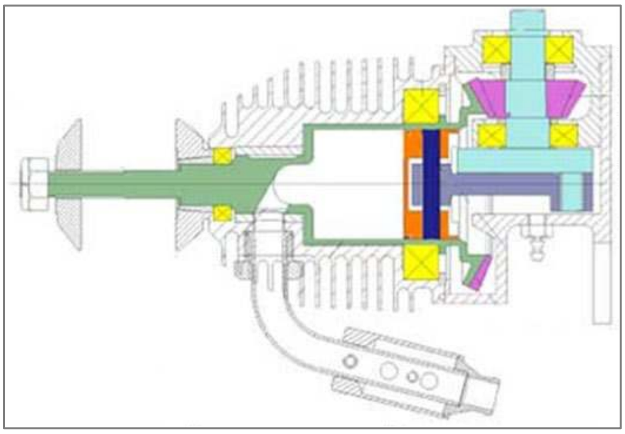


Figure 3. Section through the RCV SP "Rotating Cylinder Valve" model aircraft engine.

To avoid any confusion with "rotary wankel" engines, a "rotary valve" 4-stroke engine has a conventional crankshaft and piston group with a rotary valve to control induction and exhaust flow events. On the RCV concept shown in Figure 4, a rotary valve is driven at half crankshaft speed using a gear train comprising; a bevel gear pair at the crankshaft, and spur gear pair above the valve. On a standard 4-stroke, poppet valves control inlet and exhaust events using a camshaft and valve actuation mechanism, the valvetrain. As these valves are closed using springs, there is an associated friction loss, and the system can also be speed limited depending on the dynamic performance of the valvetrain. When running at high engine speeds valvetrain dynamic issues can lead to valve bounce and even catastrophic engine failure. The rotary valve system has relatively low friction and can operate at high speeds without such dynamic issues.

Figure 4. RCV rotary valve timing drive.

The rotary valve itself features cut away portion with an opening that exposes each port to the cylinder resulting in unrestricted flow paths, Figure 5. Valve timing is set by the radial position of the ports relative to the valve opening. The effective valve area is dictated by the width and height of each port, together with the valve opening width. Valve opening/closing rate is dictated by port height and valve outside diameter. As the valve rotates, it exposes the spark plug during the compression stroke with a compact central combustion chamber formed by the valve cut away.

This vertical valve configuration uses a single Aluminum alloy valve component running in a Nickel Silicon Carbide plated bore coaxial with the piston/cylinder bore. The valve system relies on maintaining a sliding clearance between the valve and valve bore surface. The surface of the valve cut away sees both the cool inlet charge and hot exhaust gasses, while the valve bore has asymmetric thermal loading due to the port layout and spark plug position. During development, thermal finite element analysis was used to understand the hot shape of the valve/valve bore and optimise the system for different operating conditions such as: cold start at -20°C, fast warm up, and full power hot ambient conditions, Figure 6. As with a piston/cylinder group, development requires extensive durability and abuse testing. For the RCV rotary valve, reliable operation has been achieved with consideration of several details such as the specification of the cylinder and valve materials, the cooling strategy, the cold clearance range and using an external diametral profile on the valve.

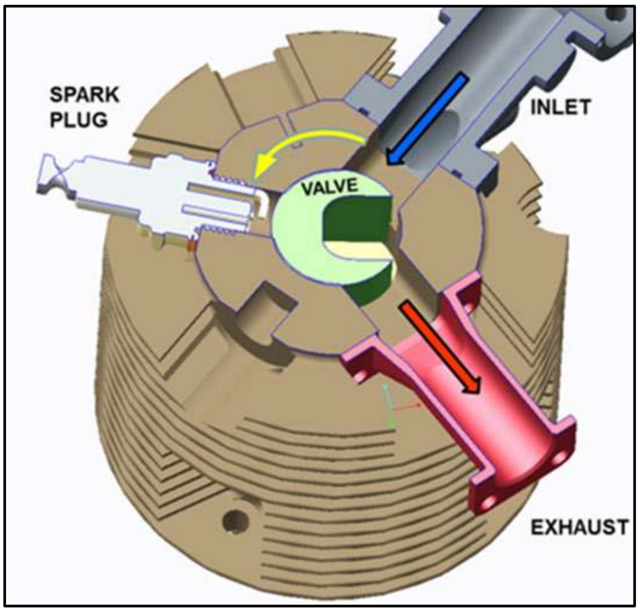


Figure 5. RCV DF engine – section through the rotary valve, ports, and sparkplug.

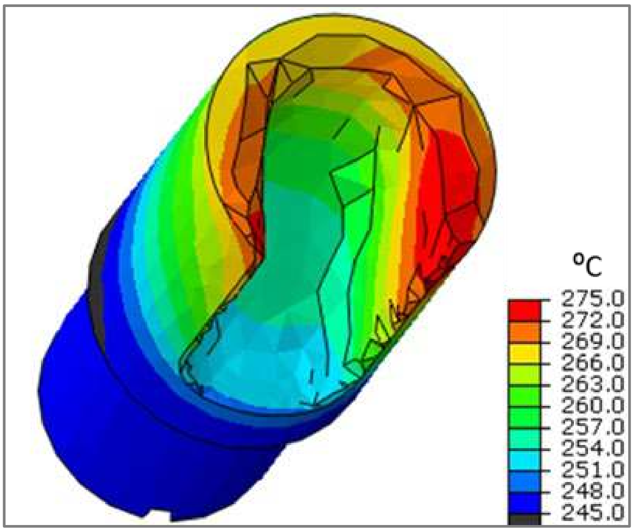


Figure 6. Valve thermal analysis example showing temperature distribution.

The result is that engines using this vertical valve system show strong power sustained up to relatively high engine speeds. The engine can operate over a wide range of air fuel ratios and is not detonation limited when operating on low octane fuels. There are several reasons for this:

- Large effective valve area, Figure 7.
- Absence of very hot surfaces.
- High turbulence generated by the valve opening/closing edge
- Controlled squish above the piston
- Compact central combustion chamber

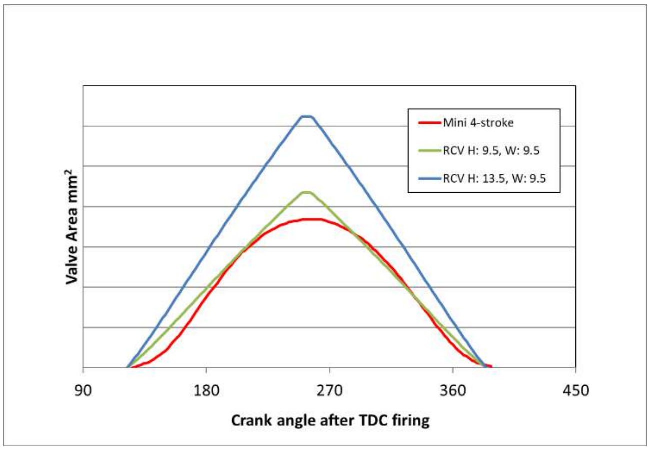


Figure 7. Rotary valve – effective exhaust valve area compared to a mini-4-stroke.

Heavy Fuel Operation

In response to a US Department of Defense Directive, there has been a requirement to operate 1 to 10kW engines used on UAVs on low octane (or knock index) heavy fuels. HF challenges for small engines have been well summarised by Ausserer et al [6], specifically:

- Vaporizing the fuel particularly for starting due to relatively low volatility compared to gasoline
- Creating a homogeneous air fuel mixture for consistent combustion
- Abnormal combustion or knocking due to the low octane nature of HF

On the RCV DF engine, the cylinder and inlet port are fitted with cartridge heaters for HF cold starting, Figure 8. These are put on until a threshold cylinder temperature is reached at which point the engine can be started. The pre-heat phase typically takes 2 minutes at 20 °C ambient with start in less than 2 seconds of engine rotation. This HF starting strategy is reliable and tested to -20 °C. Starting can be achieved with carburettor or fuel injection and using a range of HFs as well as diesel.

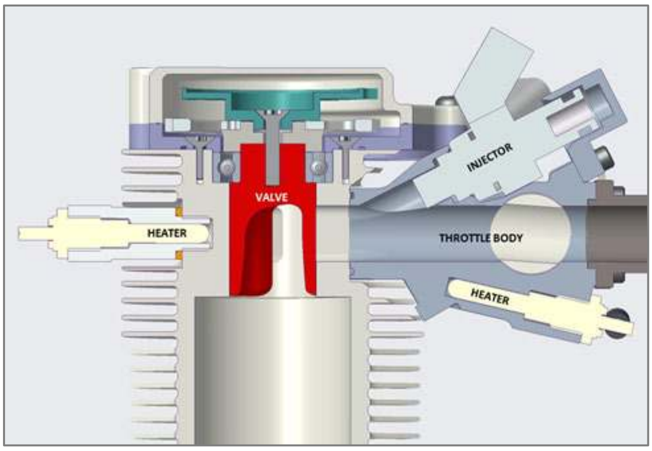


Figure 8. Section through the DF35 throttle body.

For some technologies, creation of a homogeneous air fuel mixture for consistent combustion relies on specialist fuel injection technology [7]. With the RCV combustion system, a conventional small scooter/motorcycle injector is used at 3 bar fuel pressure. The fuel spray targets the hot rotary valve for enhanced vaporisation and the valve itself also generates significant turbulence. As a result, reliable combustion is achieved across a range of Air Fuel ratios, Figure 9.

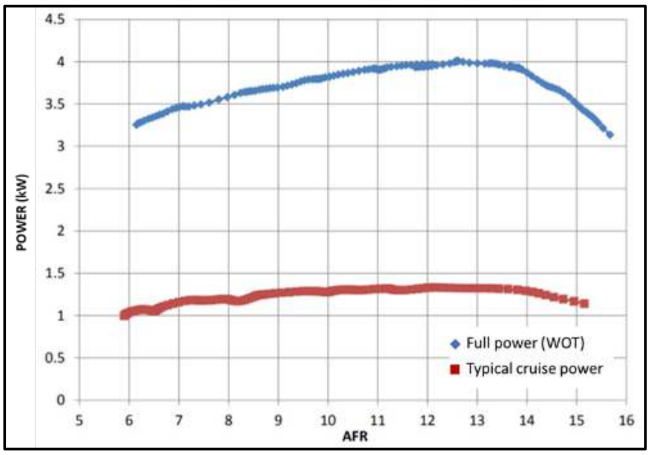


Figure 9. RCV DF70 combustion system response to AFR on JP8 fuel tested with a 12 x 8 propeller.

In terms of abnormal combustion, detonation or knock, an evaluation on n-Heptane fuel confirmed that the RCV combustion system has low detonation sensitivity. Detonation borderline (DBL) occurred with ignition advance some 20° beyond minimum advance for best torque (MBT) under normal operating conditions. This characteristic is attributed to the compact central combustion chamber [19] and uniform combustion chamber surface temperatures. Such a lower octane capability is a documented feature of rotary valve engines [20]. As such, the RCV rotary valve combustion system is not knock limited on HF and produces similar power and BSFC to gasoline operation.

DF UNMANNED SYSTEM ENGINE RANGE

UAV applications originally used engines sourced and adapted from hobby aircraft or general-purpose equipment. This approach is still used but where performance consistency, reliability and heavy fuel operation are required, then dedicated engines or propulsion modules are generally produced in low volumes. There are also a wide range of vehicle types from fixed wing air vehicles, helicopters to quadcopters, each with a unique layout and set of operating requirements. A fixed wing UAV will use full power for take-off and climb, then spend a long time at part load cruise. The engine can be cooled by air flow over the air vehicle. A helicopter operates at higher loads and speeds, when hovering there is no airflow over the engine, so an external fan is required or liquid cooling. A helicopter also requires a remote self-start capability achieved with a starter generator. A quadcopter might use electrical propulsion with a central hybrid module generating electrical power, where the ICE will also self-start and need a self-contained cooling system. To accommodate these diverse requirements, RCV has developed the DF engine range specifically for UAVs with a flexible modular approach.

The DF engine range is based around a 35 cc cylinder unit that can be configured as a single, boxer twin or boxer four, Figure 10. For a specific engine, the port layout set up arranged for either clockwise or anti clockwise engine rotation to suit the air vehicle installation and type of propeller used. Typically, the engine will be supplied coupled to an alternator or starter/generator with a suitable mounting kit. RCV has found that this flexible configuration architecture approach, allows the most suitable layout to be provided around a set of common core engine parts and ECU. A general specification for the DF35 and DF70 is shown in Table 1.

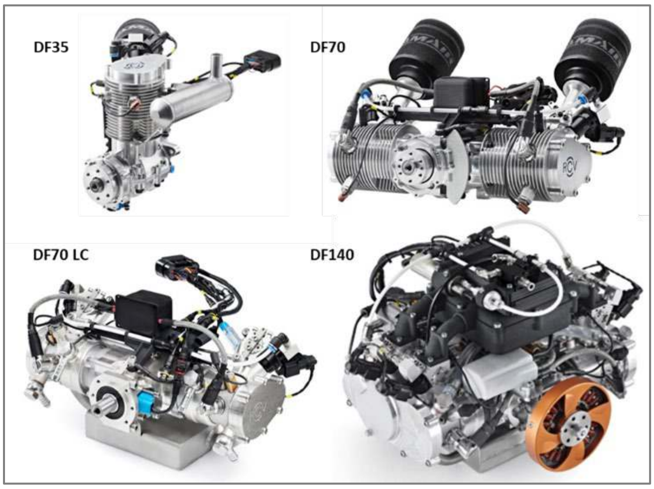


Figure 10. RCV DF Engine Range.

Table 1. DF35 and DF70 general Specification

Model	DF35	DF70
Engine type	Rotary valve 4-stroke	
Cooling	Air-cooled or liquid-cooled	
Bore x stroke	34 x 26 mm	
Cylinders	1	2
Displacement	35.3 cm^3	70.6 cm^3
Valve diameter	20 mm	
Maximum power	2.2kW/9500rpm	4.2kW/9500rpm
Maximum torque	2.4Nm/8000rpm	4.3Nm/8000rpm
Fuel type	Gasoline or Kerosene with oil (50:1)	
HF cold starting	Installed cartridge heaters	
Ignition system	High energy inductive	
Fueling system	Electronic port injection	
Dry weight*	2.1 Kg	3.0 Kg

* Weight includes base engine, ECU, fuel system, wiring and standard exhaust. Generator, propeller, and cowlings not included.

Typical power and BSFC characteristics for the DF35 engine are shown in Figure 11 with open inlet and simple exhaust muffler

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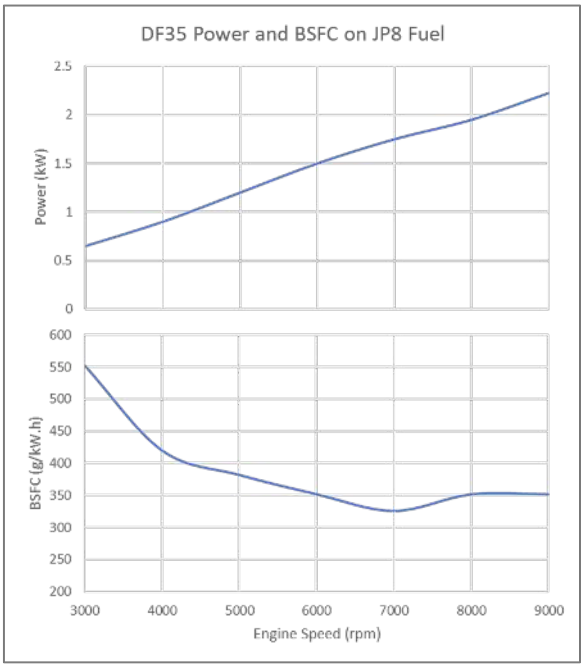

Figure 11. DF35 full load power and BSFC on JP8 fuel.

To support the DF engine range, a dedicated ECU and fueling system has been developed, Figure 12. The fuel system uses a lightweight pump driven by a brushless DC motor with spill back pressure regulator. The pressure regulator can be set to give fuel pressures between 2 and 5 bar with fuel pressure monitored and compensated for by the ECU. Load mapping is by manifold pressure or throttle position, with atmospheric temperature and pressure monitoring for altitude compensation. The ECU features twin injector and ignition drivers and servo drivers for cooling control (fan, air flap or coolant pump). The system features field proven control software/user interface with an inbuilt data logger. The ECU is supplied with standard fueling maps so that the operator can easily switch fuel types, such as changing from gasoline to JP8.

Figure 12. RCV EFI Engine Control Unit.

The air cooled DF35 is a popular choice for fixed wing UAVs offering good all-round performance and economy in addition to running on heavy fuel. The DF35 engine has been flight tested at altitudes up to 4500m (15000ft) and even used for the UK Royal Air Force's first drone flight for the using net-zero carbon synthetic aviation fuel [21], Figure 13.

Figure 13. DF35 flight test on net-zero carbon synthetic aviation fuel.

The liquid cooled DF70 is a popular choice for hybrid applications. These include quadcopter UAVs, unmanned boats, and military motorcycle demonstrator. For the motorcycle, an existing electric motorcycle was converted with the hybrid module replacing part of the battery pack, Figure 14. The system was designed with starter generator to produce 2kW of electrical power at 2000m altitude with a low noise signature, less than 70 dBA at 3m. For this application the ECU had switchable fueling maps for gasoline and JP8 as well as diesel for back up use. The DF70 combustion system can run on diesel but there is some white smoke following cold start and power/economy down by around 5%. With specific development, there may be room for improvement.

For applications requiring higher power, a four-cylinder DF140 (Figure 10) has been tested to establish a route for achieving higher outputs from the DF engine concept. The boxer four arrangement allows a common airbox and exhaust collector to be used for a compact engine package. Through customer demand a larger DF220 has now been built based and tested around a 55cc cylinder module. Pre-production versions producing 14 kW are now on customer evaluation.

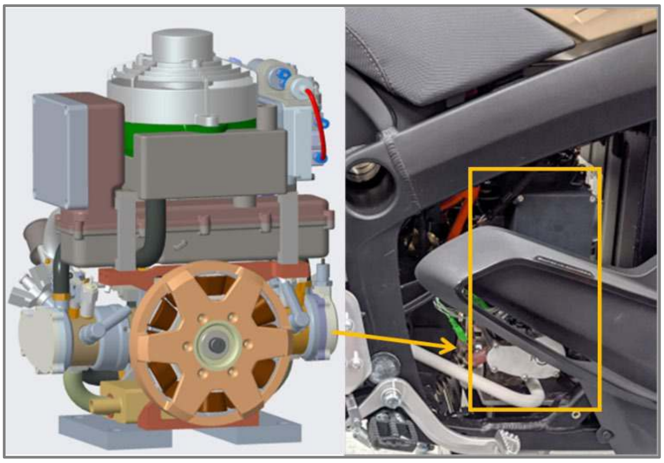

Figure 14. DF70 2 kW hybrid module installed an electric motorcycle.

CK1 GENERAL PURPOSE ENGINE

The general purpose CK1 is engine shown in Figure 15 with specification in Table 2. CK1 was developed on a brushcutter platform but configured to allow application to a wide range of products. CK1 features:

- 25cc single cylinder air cooled rotary valve 4-stroke
- Multi position operation with fuel/oil mix lubrication
- High power to weight and sustained power to 12,000 rpm
- Compliance with EU and US Exhaust emissions regulations

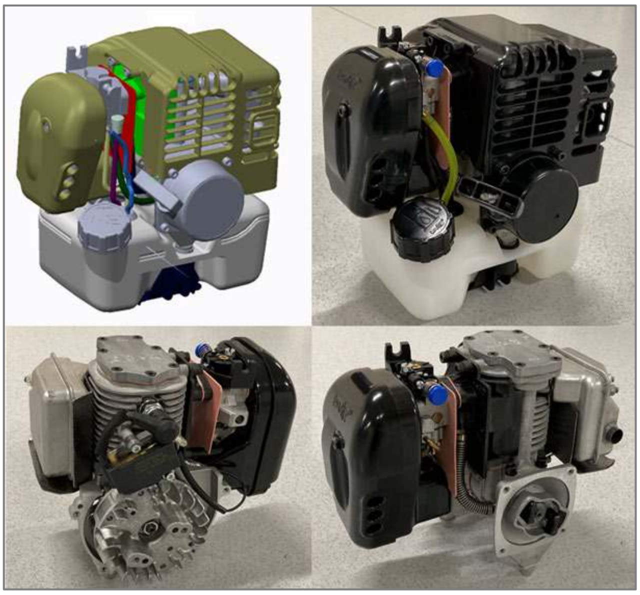

Figure 15. CK1 engine – external views.

Table 2: CK1 engine specifications.

Model	CK1
Engine type	Rotary valve 4-stroke
Cooling	Force air-cooled
Bore x stroke	34 x 26 mm
Displacement	25.2 cm^3
Valve diameter	18 mm
Maximum power	1.25 kW at 9500 rpm
Maximum torque	1.37 Nm at 8000 rpm
Fuel type	Gasoline with oil (50:1)
Start system	Recoil starter
Ignition system	Electronic magneto
Fueling system	Diaphragm carburetor
Fuel tank volume	900 cm^3
Dry weight	3.45 Kg

The CK1 engine features a similar rotary valve arrangement to the DF engine with a gear driven vertical valve. The port layout is adjusted to allow packaging of carburettor/airbox on one side of the engine with exhaust muffler on the opposite side, Figure 16. This layout achieves conventional brushcutter carburettor and exhaust muffler packaging, by use of an angled flange on the exhaust muffler. On the inlet side, the airbox includes a tuning pipe that enhances the power curve, Figure 17.

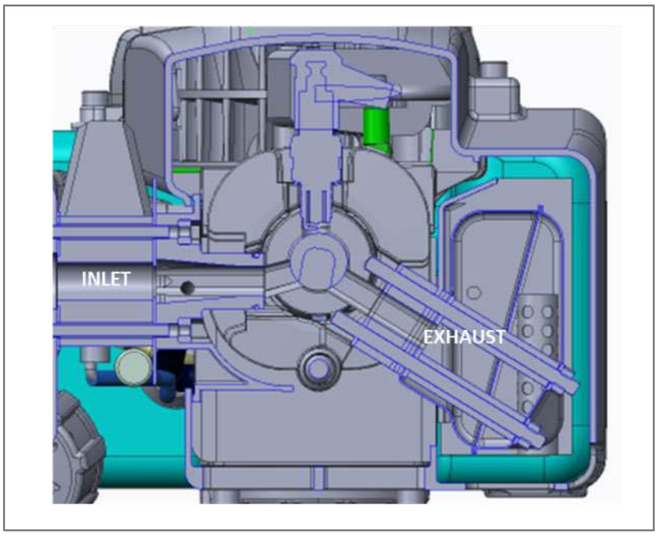

Figure 16. Section through the ports of the CK1 engine.

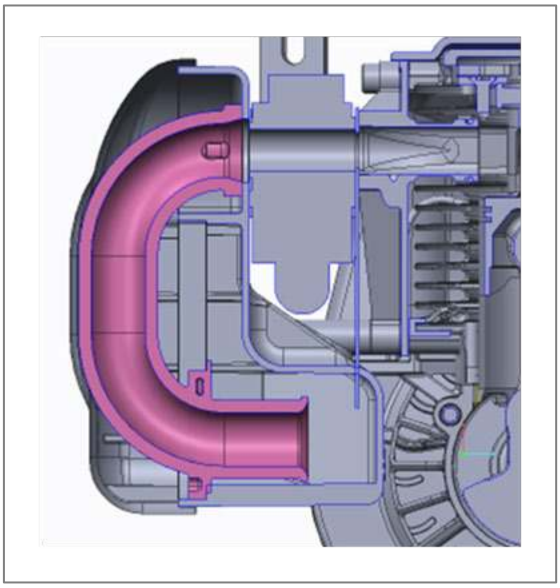

Figure 17. Section through the CK1 airbox.

During development special attention was required to the cooling system as the fan outlet is on the inlet side of the engine while the hot exhaust outlet is diametrically opposite. A deflector is used to encourage airflow to the exhaust side and balance the temperature distribution around the valve outer section. With the high level of power generated by the engine, a double-sided fan is used with CFD optimised engine cover and heat shields. The example in Figure 18 of a section below the ports, shows airflow around the cylinder and the effectiveness of the flow deflector.

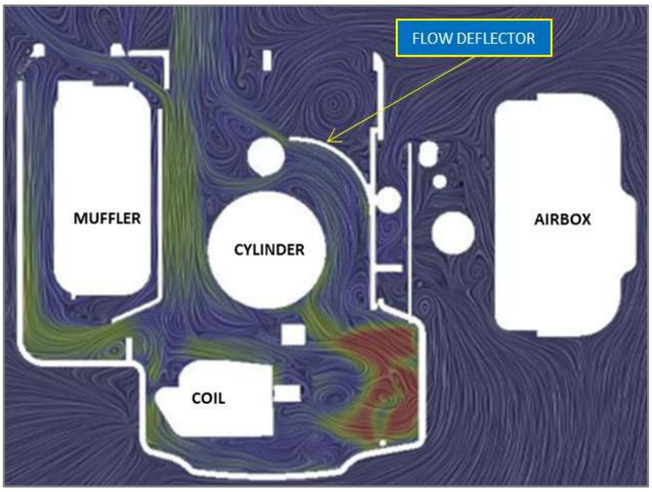

Figure 18. CFD example from CK1 engine cooling system development.

From a manufacturing perspective most of the components on the CK1 engine are conventional and produced using industry standard practice. The cylinder and valve are different, so a manufacturing approach had to be developed consistent with volume production requirements of quality and cost. The valve is a forged component and size graded after machining. The cylinder is diecast in ADC12 with Nickel Silicon Carbide coating on both the cylinder bore and valve bore, Figure 19. Specific techniques have been developed to clean up the ports and spark plug bore following practices used on 2-stroke cylinders.

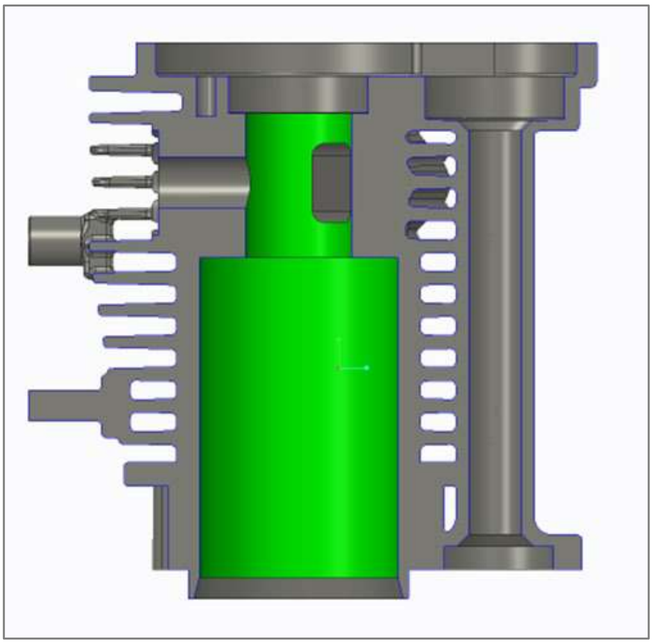

Figure 19. Section through the CK1 cylinder with plated surfaces shown in green.

In terms of overall size, CK1 has similar external dimensions to other mini-4-stroke engines on the market, Table 3, and Figure 20. CK1 even uses a deeper 0.9 litre fuel tank than a more usual 0.6 litre tank to extended use for professional operators between refueling.

Table 3. Comparison of general-purpose engine dimensions and power to weight.

Engine Type	L mm	W mm	H mm	Power/Weight kW/Kg
CK1 25cc	191	233	239	0.35
4-stroke 25 cc	192	221	230	0.27
4-stroke 35cc	204	234	230	0.30
2-stroke 26cc	153	235	236	0.30

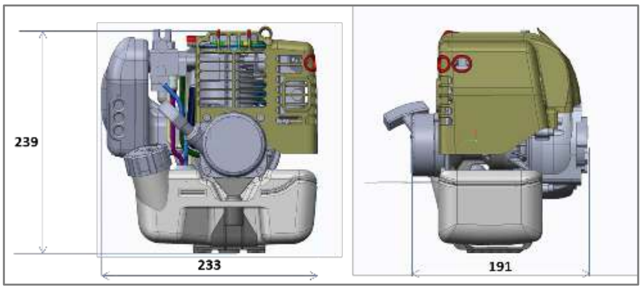

Figure 20. CK1 engine - main dimensions.

The weight of a typical 25cc 4-stroke is in the range of 2.7 to 3.3 Kg. CK1 is 3.45 Kg but produces 60% more power at over 1.2 kW. CK1 has significantly better power to weight, even considering additional weight associated with extra cooling capability and larger diameter heavy duty output clutch necessary to limit clutch slip.

Regarding power and speed, CK1 significantly exceeds that of current 4-stroke general-purpose engines, with high power sustained between 8000 rpm and 11500 rpm, Figure 21. Fuel consumption levels are comparable with other 4-stroke engines under similar test conditions. Exhaust emissions as tested independently for EU homologation are well below legislative limits, Table 4.

Table 4. CK1 exhaust emissions compared to current EU and EPA limits

Exhaust Emissions	CO g/kW.h	HC + NOx g/kW.h
CK1	118.0	20.8
EU 2016/1628 Stage V	805	50
EPA Phase 3		

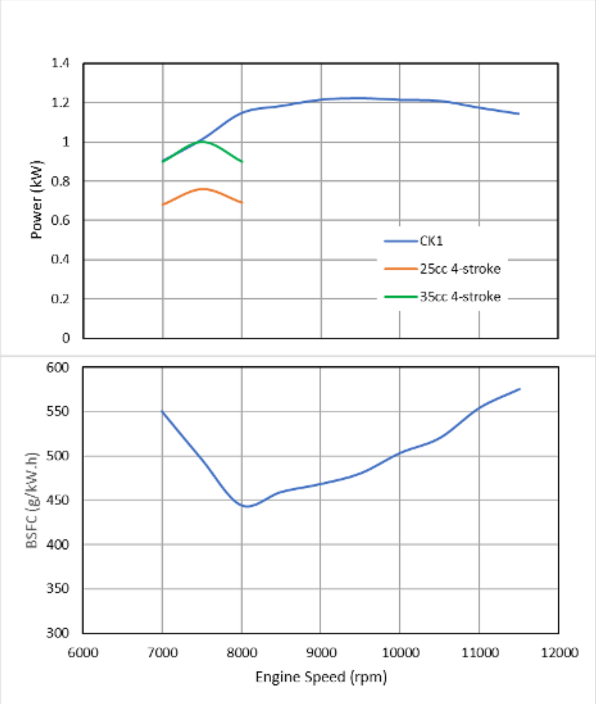

Figure 21. CK1 power and BSFC with catalogue power levels for 25cc and 35cc 4-strokes.

To explore potential for an engine range, a larger capacity 50cc version has been developed as a prototype. Compared to existing engine brushcutter engine types, Figure 22, the CK1 and larger derivative offer a power benefit. The 50cc version shows that it would be quite feasible to offer a full range given sufficient demand in the future.

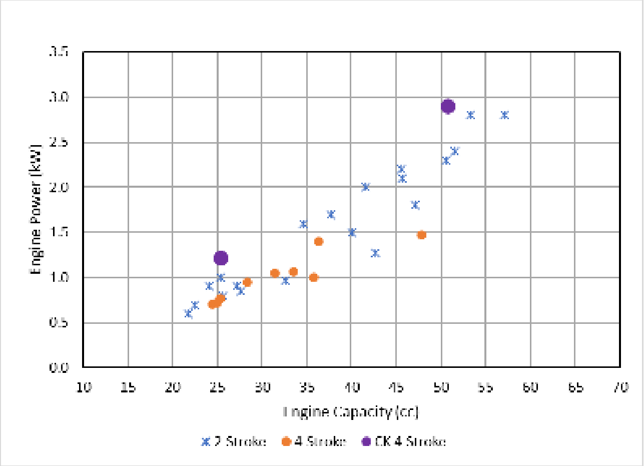

Figure 22. CK 4-stroke compared to manufacturers catalogue power data for 2-stroke and 4-stroke brushcutter engines.

In terms of durability, CK1 has been extensively tested over a 400-hour idle/full load test cycle throughout the various development phases into pre-production. As with other fuel/oil mix 4-strokes on the market, there is some sensitivity to oil type in terms of internal carbon build up on the piston and crankshaft components. With a suitable ash-free oil, carbon build up is minimised. In addition to laboratory-based testing, pre-production samples have been extensively field tested in various countries in Asia, Australia, Europe and South America, Figure 23.

Figure 23. CK1 field testing in South Korea.

SUMMARY

Considering the future small engine attributes identified; how does a RCV rotary valve 4-stroke perform, and which aspects require further development?

Low tailpipe exhaust emissions including particulates from unburnt oil: The CK engine demonstrates low HC and NOx emissions without any exhaust aftertreatment. As both DF and CK engines currently operate on fuel/mix lubrication, a development activity is in progress for separate oil lubrication to minimise particulate emissions and make fuel handling easier for the operator.

Sufficient power to weight for the application to be viable: both the DF and CK engines demonstrate strong power and power to weight. Products using small engines with RCV rotary valve combustion system should still provide sufficient performance even if compromises are necessary for fuel economy, fuel type and/or fuel consumption.

Capable of operating on a range of fuels including net-zero carbon synthetic fuels: the DF engine is already multi-fuel capable and has demonstrated an ability to operate on net-zero carbon synthetic aviation fuel. Operation on hydrogen is considered feasible. Even with an associated fuel related power drop, such an engine would still produce a useful level of power.

Low cost through volume production: the CK1 engine has been developed for volume production. Although the multi-fuel DF engines are specialist relatively high-cost units, with suitable demand, the technology is suitable for more cost sensitive hybrid and portable power applications.

CONCLUSIONS

The RCV rotary valve combustion system demonstrates benefits through ICE product applications for UAVs and small general-purpose engines.

The multi-fuel DF engine range is established as an ICE option for UAVs and unmanned systems with increased use in hybrid applications.

The CK1 engine shows strong power, sustained at high engine speeds with 4-stroke emissions and fuel economy.

The combination of the DF multi-fuel combustion system with volume production technology for the CK1 engine demonstrates that RCV rotary valve technology is a viable candidate for future small engines.

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DEFINITIONS/ABBREVIATIONS

ADC12	Specification for the most commonly used die casting alloy also known as A383
BE	Battery/electric
BSFC	Brake specific fuel consumption
CARB	California air resources board
CK	General purpose engine produced by KAAZ Corporation incorporating RCV technology
DBL	Detonation borderline, the ignition advance where detonation or knock starts
DF	Multi-fuel UAV engine produced by RCV Engines Limited
ECU	Engine control unit
HF	Heavy fuel: JP8, Jet A1, JP5
ICE	Internal combustion engine
Jet A1	Principal kerosene-based aviation fuel used in jets or gas turbines
JP5	Jet propellant 5 – US military jet fuel for use on carrier-based aircraft
JP8	Jet propellant 8 – US military jet fuel
MBT	Minimum amount of ignition advance required to achieve best torque
RCV	RCV Engines Limited
RDE	Real driving emissions
SORE	Small off-road engine (terminology used by CARB)
UAV	Unmanned air vehicle