Simulation Study on Crankcase Supercharged Four-Stroke Engine for Next Generation Hybrid Drone

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MECWARE

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Introduction

To promote expanding the field of application of drone, extending endurance must be a preferential technical problem, and hybrid drone with range expander system comprised of internal combustion engine and generator may be a practical solution at present.

Most of current hybrid drone has adopted two-stroke engine because of the advantages in power/weight ratio, packaging size, and production cost compared to four-stroke engine. However, exhaust emission regulation with so strict level that two-stroke engines will not be able to accomplish in the near future is expected, as well as the land or marine transportations.

Ex) LEMA regulation scheduled for 2020 is HC+NOx<10g/kWh in 6-Mode test, for portable device engine of which displacement is less than 225cc and power is less than 19kW.

In view of the above considerations, four-stroke engine adoptable to next generation drone with high power, small packaged, and low production cost is awaited.

This report presents a simulation study on crankcase supercharged four-stroke engine as a candidate for the optimal engine for hybrid drone.

Crankcase Supercharged 4-Stroke Engine

Basic Features

1. Apply a crankcase for a reciprocating compressor, inducing air into the crankcase and pressing out to the intake pipe.

2. Providing a valve, such as reed valve or rotary valve, at the inlet and outlet of the crankcase.

3. The usual lubrication system of 4-stroke engines cannot be applied. Instead, lubrication system for 2-stroke engines, such as mixed lubrication by oil-mixed fuel or separated lubrication by oil pump are used.

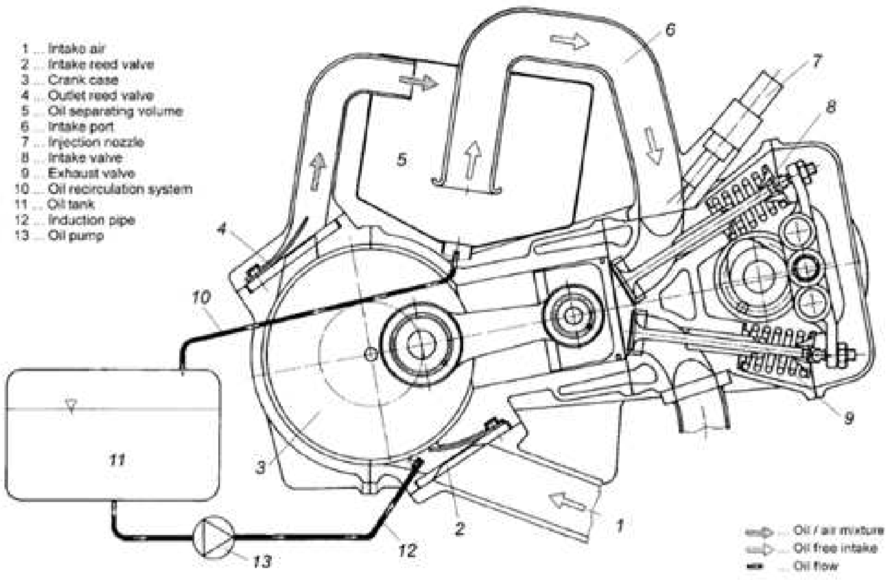


Fig.02: Functional description of a crankcase supercharged four-stroke engine with oil separating system [2]

Technical Knowledge on Performance Determinants by the Past Researches Published

1. Compression Ratio of Crankcase

2. Volume of Chamber in the Downstream of the Crankcase, and Intake Pipe Length.

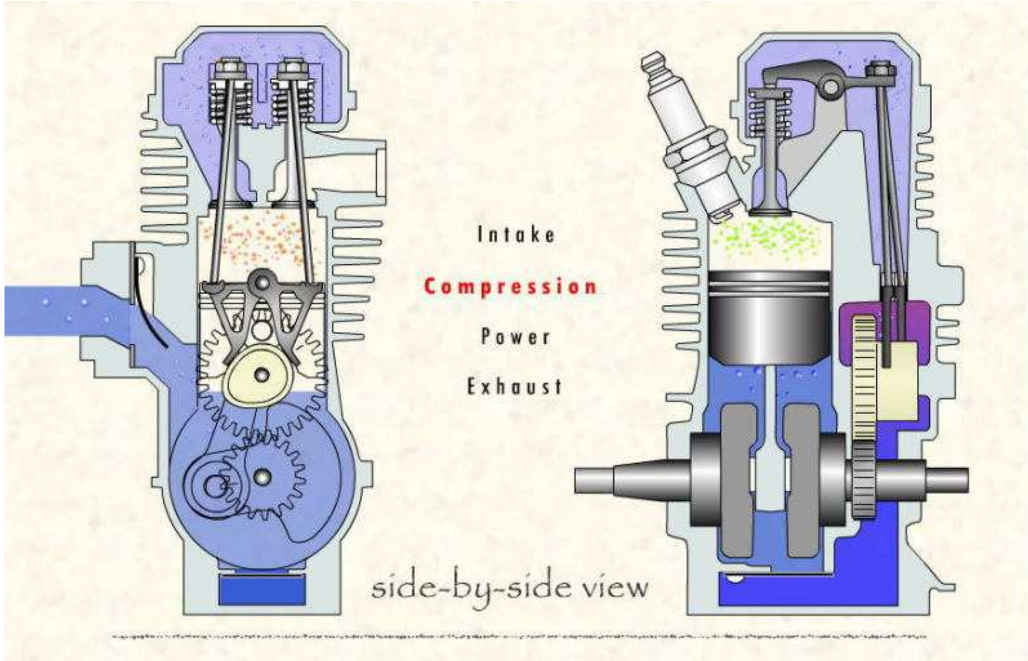
3. Valve Timing or Valve Overlap

Mario Hirz *et al.* **"CRANKCASE SUPERCHARGED FOUR STROKE ENGINE WITH SEPARATING SYSTEM", SAE Paper 2004-01-2105**

Examples of the Crankcase Supercharged 4-Stroke Engine

1) Land Engine

C4 Engine by YAMABIKO(Shin-Daiwa Brand) Co., ltd in Japan



http://www.shindaiwa.co.jp/download/

■Cylinder Layout
Single Cylinder

■Crankcase Valve
Reed Valve x 2

■Valve Train
OHV 2-Valve

■Lubrication
Oil-mixed Fuel 25:1～50:1

■Fuel Supply System
Diaphragm Carburetor

■Throttle
Inlet of the crankcase

◆Advantages
・Lower emission than conventional 2-stroke engine
・More postage free in portable use than conventional 4-stroke engine

2) RC Air-Plane

YS Engine by Yamada Mfg. Co., ltd in Japan

YS Engines 115FZ-WS 4-Stroke Glow Airplane Engine (Warbird Special)

https://www.amainhobbies.com/ys-engines-115fzws-4stroke-glow-airplane-engine-warbird-special-yse0031/p259222

■Cylinder Layout
Single Cylinder

■Crankcase Valve
Rotary Disk Valve
Two ports for inlet and outlet in one disk

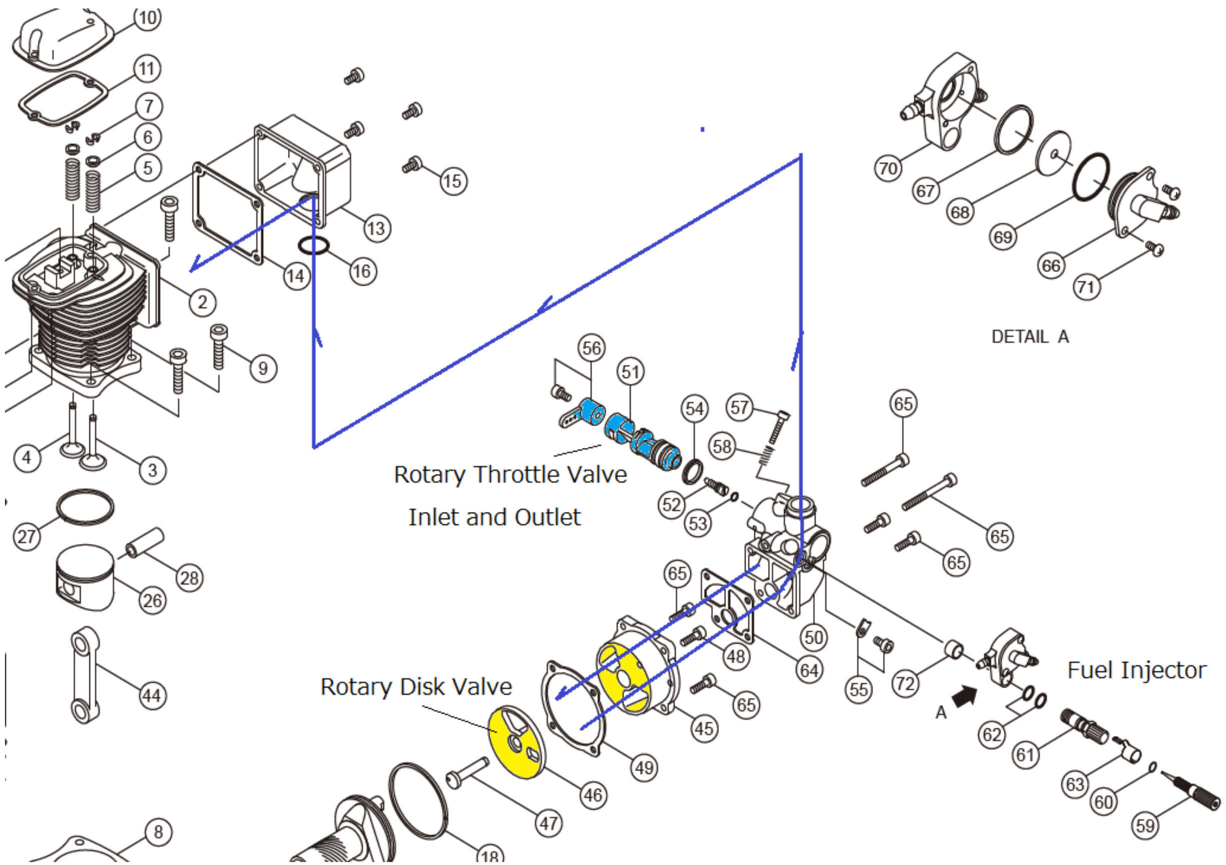
■Valve Train
OHV 2-Valve

■Lubrication
Oil-mixed Fuel
Base: Methanol
Additive: Nitro-Methane(15～30%) with lubricant oil(10～25%)

■Ignition
Glow Plug

■Fuel Supply System
Original fuel system for fuel injection by high pressure in the crankcase.

■Throttle
Throttling Inlet and Outlet Port by Rotary Barrel



http://www.yspower.co.jp/en/data/pdf/fz115s.pdf

Opposed Twin Cylinder Engine for UAV

2-Stroke Engine

1) HIRTH 4201 by HIRTH co. ltd in Germany

Technical data

(Subject to technical changes)

Type:	Two cylinder two stroke (opposed)
Displacement:	183 cm^3 (11.5 cu in)
Stroke:	40 mm (1.57 in)
Bore	54mm (2.13 in)
Max. performance: According to DIN 70020	11 kW (15 HP) at 6500 rpm
Control:	Integrated Throttle servo (Fa. Volz)
Mixture formation:	Fuel injecton (see seperate data sheet)
Ignition System:	CDI controlled by the ECU
Cooling:	Air cooled
Weight:	5700g (12.5 lb) with exhaust system, sensors and wirring harness 600g (1.33 lb) subcomponents (ECU, igni tion system, fuel supply)
Weight reduction drive:	1200g (2.65 lb) (option)
Weight generator option:	800g (1.76 lb) 1kW generator 600g (1.33 lb) 0,5kW/28V starter/regulator box 400g (0.88 lb) 0,5kW/28V regulator box
Length:	145 mm (5.7 in)
Width:	240 mm (9.45 in)
Running direction:	Clockwise, view to output shaft
Speed range:	1800-6500 rpm
Fuel mixture :	Mixture 1:80 2-stroke-oil API TC or BLUEMAX MOGAS o. AVGAS fuel min. 95 octane (RON)

http://uavpropulsiontech.com/wp-content/uploads/2013/07/4201_JAN-2016.pdf

2) OS GT120THU by Ogawa Seiki co. ltd in Japan

http://www.os-engines.co.jp/OS_professional/gt120thu/index_e.html

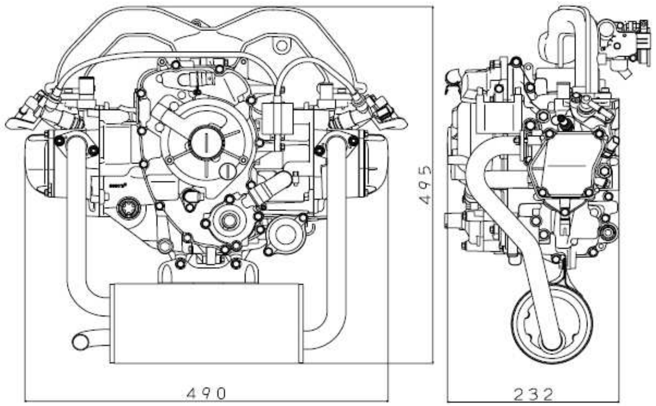
GT120THU SPECIFICATION

Model	GT120THU
Type	air-cooled, 2-stroke, holizontally opposed two-cylinder engine
Displacement	119.82cc
Bore x Stroke	44mm×39.4mm
Max. Output	7.4kW (10ps)/7,500r.p.m.
Practical rpm range	1,500~8,000r.p.m.
Weight	5,200g (engine) / 580g (silencer)
Fuel	Mixed gasoline with 2-stroke oil
Carburetor	Diaphragm type, Warblo WJ
Ignition	CDI
Ignition Plug	M10mm SPARK PLUG (CM-6)
Lubrication	by mixed gasoline
Fuel Consumption	100cc/min/7,000r.p.m.

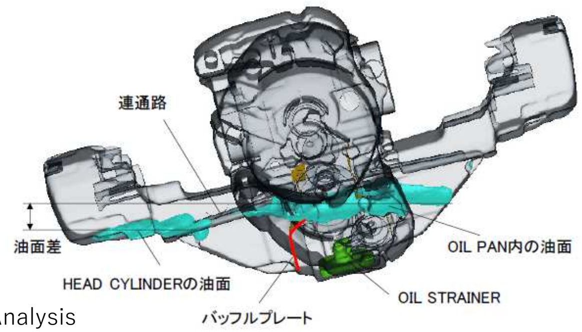
http://www.os-engines.co.jp/OS_professional/gt120thu/spec_e.html

4-Stroke Engine

YAMAHA Unmanned Helicopter FAZER



Specifications	
Engine Type	Water-Cooled 4-Stroke OHV 2 Valve
Cylinder Layout	Opposed Twin
Displacement	390cc
Bore x Stroke	66.0 x 57.0mm
Compression Ratio	10.1:1
Power	19.1kW /6000rpm
Fuel Supply	Fuel Injection
Lubrication	Wet Sump



Oil Motion Analysis

Titanium Alloy Muffler

“Development of a 4-stroke engine for the FAZER industrial-use unmanned helicopter”, YAMAHA Technical Review

Simulation of the Crankcase Supercharged Engine

Supposed Configurations of the Vehicle

◇Power System: Hybrid System that Motors Drive Propellers, and Engine Drives Generator to Provide Electric Power for Motors or Battery.
◇ Rotors: Hexa-Drone with 6-Rotors
◇ Weight: 36kg
◇ Max. Payload: 18kg
◇ Max. Power of Motor: 1.5kW
◇ Total Efficiency for Power Consumption: 0.9 (in Inverter) x (in Motor)
◇Total Efficiency for Power Generation: 0.85 (in Inverter) x (in Generator)

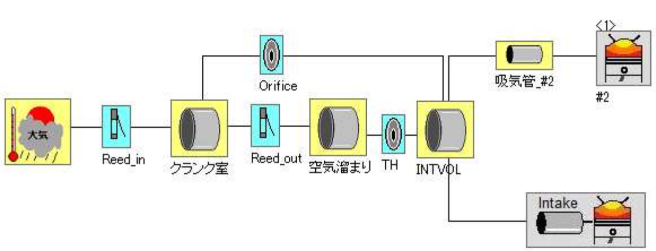
Consideration of the Engine Specifications

◇Demand Rated Power for Engine: 11.7kW(1.5kWx6/0.9/0.85)/6000rpm
◇Engine Type: Air cooled 4-Stroke OHV 2 valve
◇Cylinder Layout: Opposed twin 360deg phase
◇Displacement: 183cc Portable Engine Category (I) of LEMA as HIRTH 4201, opposed twin 2-Stroke for UAV
◇Exhaust System: Muffler with 3-steps expansion chamber for low noise as YAMAHA Helicopter FAZER

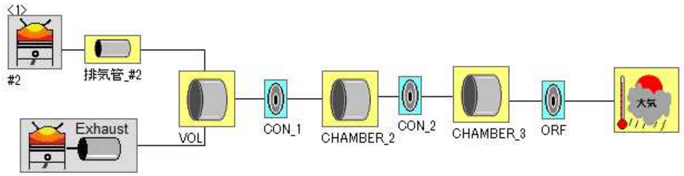
Simulation Codes Used for the Study

・**Main Code: EGSIM** 1-D thermo-dynamic engine simulation code.

Intake System Modeling

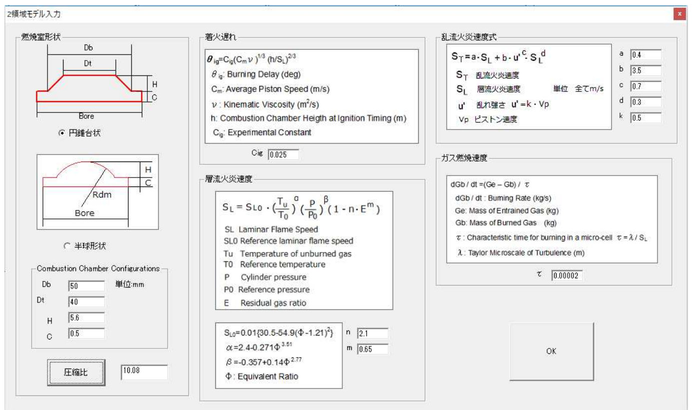


Exhaust System Modeling



Sub code for combustion simulation was used secondarily because the standard version of EGSIM applies one-zone combustion model, cannot predict exhaust emissions.

・**Sub Code: Two-Zone EGSIM** advanced simulation code with two-zone predictive combustion model
Prediction heat release ratio and exhaust emission of NOx based on Zeldovich mechanism.



Combustion Parameters for Two-zone Model

Details of the Engine Model

■Base Specs.

◇Displacement : 183cc

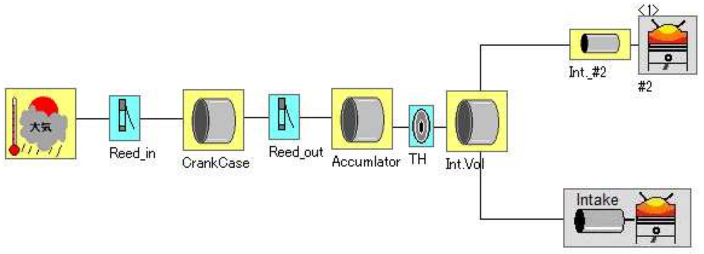
◇Bore x Stroke: 54mm x 40mm (Short Stroke for Low Vibration)

◇Valve Train: OHV 2-Valve

◇Compression Ratio: 10.1:1

◇Valve Dia. and Lift: Non-disclosure

◇Valve Timing: Non-disclosure optimized design parameter



Crankcase Supercharged 4-Stroke Opposed Twin Cylinder Engine Model by 1-D Dynamics Engine Simulation Code EGSIM

■Crankcase Supercharger Specs.

◇Crankcase Compression Ratio: 1.57:1(320cc at BDC)

◇Crankcase Valve: Reed Valve x2set Specs. Non-disclosure optimized design parameter

◇Throttle Valve: Bore 24mm provided after the outlet reed valve

◇Fuel(Gasoline) Supply: Supposed that fuel is injected in an intake volume after the throttle valve

◇Chamber Volume: 200cc optimized design parameter, within reasonable packaging size

◇Intake Pipe Length and Dia.: Non-disclosure optimized design parameter

■Lubrication System

◇Oil-mixture fuel is injected in the intake chamber only, therefore an idea for special configuration for recirculation oil-mixture fuel to the crankcase, valve train from cam shaft to rocker-arms is provided. Non-disclosure

■Exhaust System

◇2-into-1 exhaust pipes, and a muffler with 3 expansion chambers and 2 orifices between the chambers and at open end

■Control Parameters

◇Throttle 100% Open

◇AFR: 13.3:1(Φ=0.9) Φ：Equivalent Ratio

Air-to-fuel ration was determined in consideration of both fuel consumption and exhaust emissions of NOx.

◇Ignition Timing:

Ignition timing was determined to attain the target of NOx emission, retarding from MBT, in constant AFR 13.3.

Target Performances

■Summary of Target Configurations for Drone Engine

1. Higher Specific Power in Lower Speed than 2-Stroke

To promote replacement of 2-stroke engine with 4-stroke engine, it is demanded that the specific power is higher than 2-stroke, and moreover, in lower speed for the lower noise in flight.

2. Lower BSFC than 2-Stroke, compatible with conventional 4-Stroke

In general, BSFC of 2-stroke engine at full load and maximum torque speed is 350～400g/kWh, that is 20～30% higher than 4-stroke, caused of 20% or more loss of fuel in short-circuiting mixture during scavenging period.
If the engine is replaced with 4-stroke engine, fuel consumption is decreased for 20% or more, then endurance of drone is expected to extended for 20% or more.

3. Low emission to meet LEMA 2020 regulation without after-treatment

After-treatment system using catalyst can lower exhaust emission, and many of recent 2-stroke land engines are equipped with oxidation catalyst. However, emission levels of the catalyst engine remains approximately half that without catalyst, because more purification rate leads to over-heating of exhaust pipe or muffler, with possibility of catalyst carrier melting or accident of firing combustible materials around the machine even after engine is stopped.

Furthermore, in case of UAV, cooling of exhaust pipe in hovering state is a big problem, because of the poor wind around the exhaust pipe, even if an engine cooling fan is working to cool the engine cylinder or cylinder head. To solve this problem, YAMAHA helicopter engine applies a titanium alloy muffler, for example.

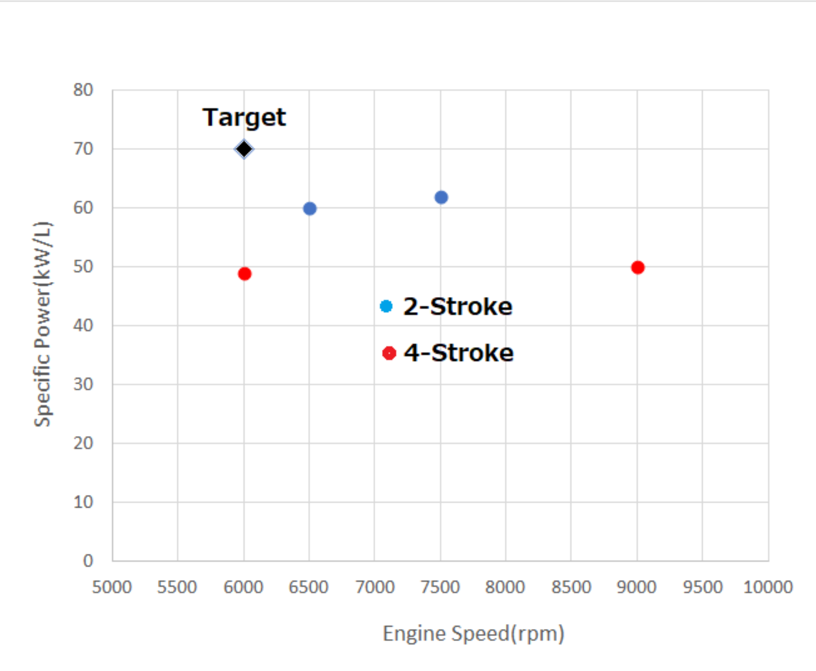
As mentioned above, low emission system for UAV is required not to apply catalyst.

Target Performances

■Rated Speed: 6000rpm

■Specific Power at Rated Speed: 70kW/L → 12.8kW

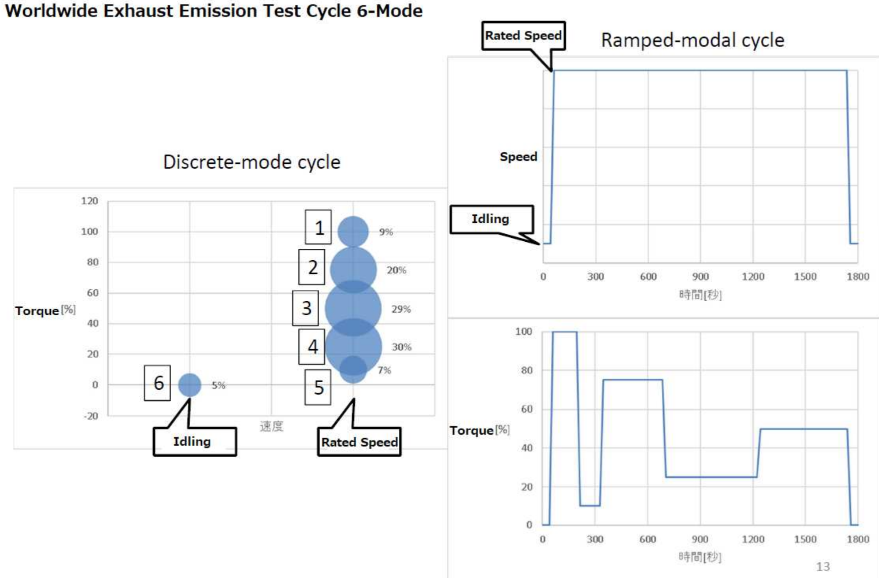
■BSFC at Rated Speed: 270g/kWh



■Exhaust Emissions: LEMA 6-MODE Regulation 2020 HC+NOx<10g/kWh

Point #	Load(%)	Weight(%)	Target NOx(g/kWh)	Target THC(g/kWh)
1	100	9	9	6
2	75	20	5	6
3	50	29	4	2
4	25	30	3	2
5	10	7	2	2
6	Idling	5	2	8
Estimated 6-MODE Emission			4.11(g/kWh)	4.10(g/kWh)

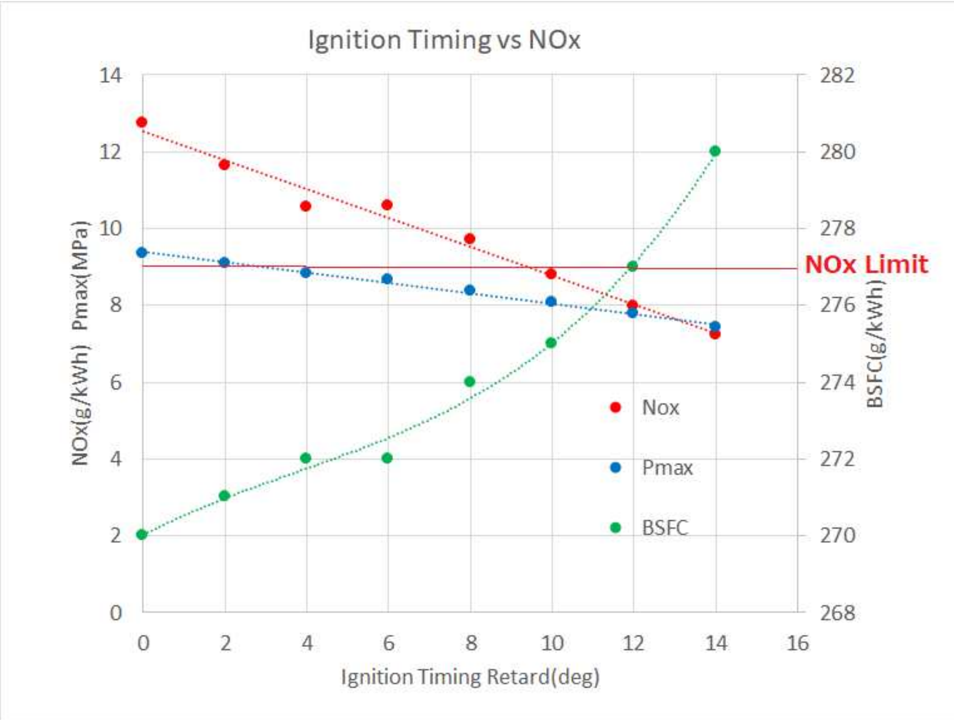
Worldwide Exhaust Emission Test Cycle 6-Mode



https://www.env.go.jp/council/07air-noise/y072-60/ref02_r.pdf

Simulation Results

Pre-Analysis to Determine the Ignition Timing Using Two-zone Predictive Combustion Model



■Engine: Single Cylinder NA

■Specs.

The specs. are same as opposed twin crankcase supercharged engine

◇Displacement : 91.5cc
◇Bore x Stroke: 54mm x 40mm
◇Valve Train: OHV 2-Valve
◇Compression Ratio: 10.1:1
◇Valve Dia. And Lift: Non-disclosure
◇Valve Timing: Same as 'SC VOL53deg' in the next slide

■Operation Conditions:

◇Engine Speed: 6000rpm
◇Cylinder P,T @ IC: P=0.17596MPa(0.17603) T=381K(389)
The ambient pressure and temperature are compensated so that pressure and temperature in cylinder at intake close are same as crankcase supercharged engine.
◇Volumetric Efficiency: 1.25(1.25) ( ) In case of 'SC VOL53deg' in the next slide
◇AFR : 13.3:1
◇Ignition Timing Search: 0～16deg Retard from Base Timing

The figure shows that NOx level is below the target, 9g/kWh when the timing retard is 10deg or more, and then Pmax is below 8Mpa.

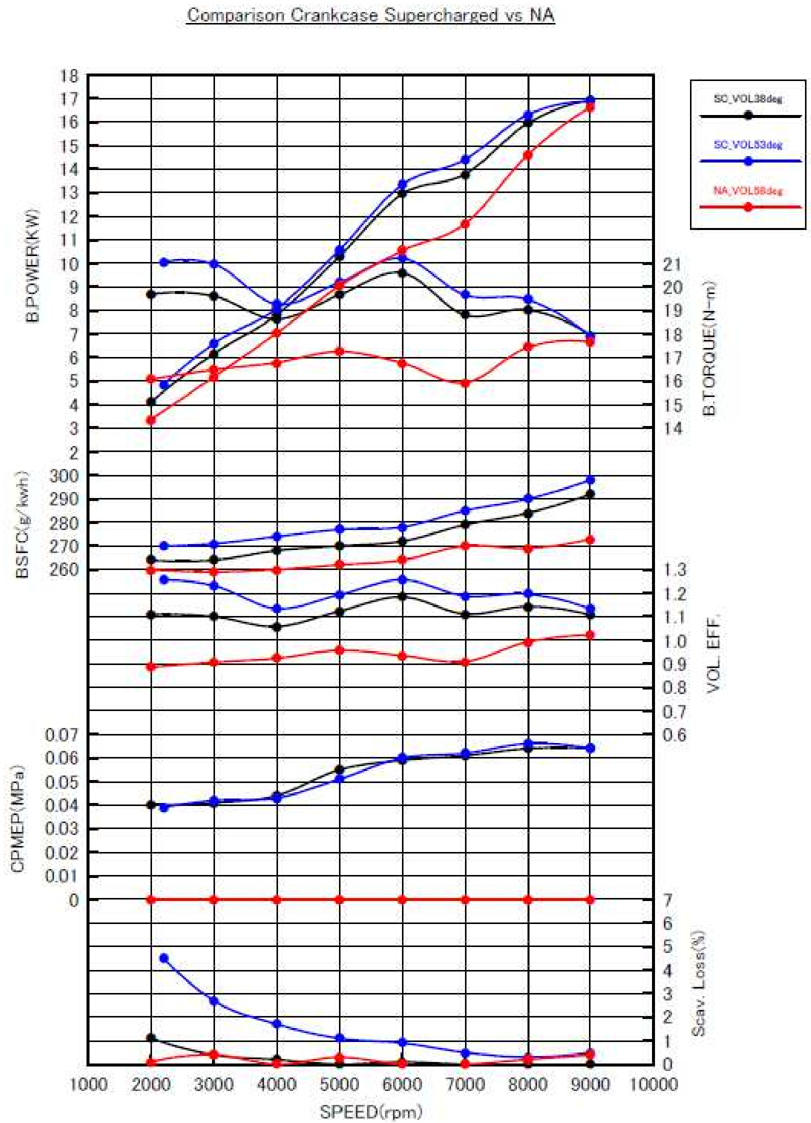
In the simulation of crankcase supercharged opposed twin cylinder engine, ignition timing was determined according to the criterion above.

Performance of the Optimized Engines

Performances		NA VOL58deg	SC VOL53deg	SC VOL38deg
Performance at Rated Speed	Power	10.5kW	13.3	12.9
	Torque	16.8Nm	21.2	20.6
	BSFC	264g/kWh	278	272
	Pmax	6.89MPa(IgT25)	7.39(IgT17)	7.65(IgT20)
	SL	0%	0.9	0.1
Maximum Power		16.6kW	16.9	16.9

Rated Speed:6000rpm Maximum Speed:9000rpm VOL: Valve Overlap
NA: Natural Aspirated SC: Crankcase Supercharged IgT: Ignition Timing BTDC
SL: Scavenging Loss=(1-TrappingEfficiency)x100

Ignition timing were determined so that Pmax is lower than 8MPa to control NOx emission to be lower than 9g/kWh.



Conclusions

◇Crankcase supercharged engine, SC VOL38deg model, attained 12.9kW and BSFC 272g/kWh, against the target power 12.8kW, 270g/kWh respectively, meeting the exhaust emission regulation LEMA 2020, HC+NOx<10g/kWh.
It is the best and practical solution in the simulation study performed in this report.

◇SC VOL53deg model has the highest power, 13.3kW that is over 72.6kW/L. However, increasing of SL in low speed range is a big problem of this model. SL represents an amount of short-circuiting of mixture proportional to HC emission, and if BSFC is 280g/kWh, 1% of SL corresponds 2.8g/kWh of HC emission increasing. It is suggesting inability of correspondence with possible emission regulation for hybrid drone(1), implemented someday in the future.

It is seen that width of valve overlap has large impacts on both power and HC emission of SC engine, such as wide overlap increase power, but leads to arising HC emission concurrently.

◇The SC models have disadvantage in fuel consumption compared with NA because of additional pumping loss of crankcase(CPMEP), particularly in high speed range.
Crankcase supercharged engine is to be used in relatively low speed to take its advantage of 'high torque in low speed' characteristics.

◇Increasing of mass compared with 2-stroke engine

▽Additional components

Valve train, such as camshafts, push-rods, valves and valve springs
One reed valve set, if the 2-stroke engine uses one set of reed valve

▽Mass increasing components

Bigger and heavier cylinder head than 2-stroke
Crankcase assembly, if the intake chamber is formed on the case

Appendix for Footnote (1)

◇Comparison of Engine Operating Point in Case of Drone with that of Fixed Wing UAV(Air-Plane)

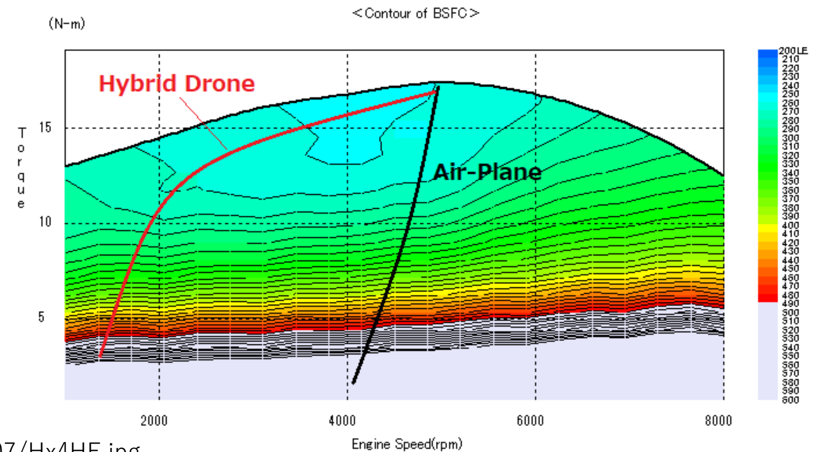
Engine for air-planes or helicopters drives propeller directly, and propeller speed varies depending on propeller load and engine torque(throttle opening). Therefore, the engine speed is not an independent controllable parameter, if fixed pitch propeller applied.

On the other hand, engine for hybrid drone drives only generator, and electric motors drive propellers. So, the engine speed can be controlled so that engine working point is always on the best fuel consumption point so called 'Sweet Spot', independent on propeller load or speed.

◇Reasonable Test Mode of Exhaust Emission for Hybrid Drone

To reflect the actual working point to a test mode for hybrid drone, the working points should be placed dispersed in the control line, unlike current LEMA 6-Mode which has the evaluation points in the rated speed in constant.

https://www.harrisaerial.com/wp-content/uploads/2018/07/Hx4HE.jpg



http://www.aeroexpo.online/prod/erap-korea-co-ltd/product-169721-992.html