附件二 WDL 公司氣動力設計及冷卻分析簡報

AA000 Rotary Engine
Design & Analysis Support

Performance Prediction

July 2012

Contents

WDL

- Overview
- Objectives & Scope
- Background Information
- Performance simulation
- Summary
- Conclusions & Recommendations

Objectives & Scope

- Objectives:
  - Build & Run 1D WAVE simulations of the A0000/AA1 engine
  - Evaluate performance improvement possibilities for the AA2 engine
  - Recommendation design & development work for AA2 engine
- Scope:
  - Receive & check ASRD design & test information for A0000/AA1 engines
  - Review performance & design related feature of other rotary engines
  - Build WAVE model of rotary engine
  - Correlate with measured performance
  - Perform simulations to study engine performance improvements

Background Information

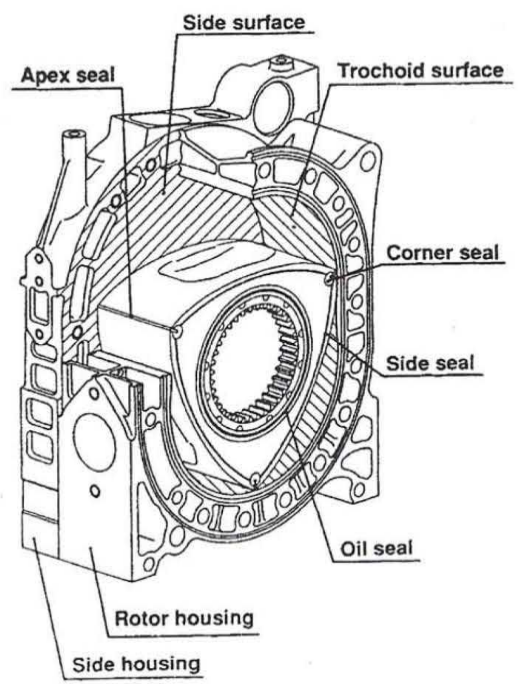
Rotary Characteristics and Considerations

- WDL has reviewed literature on rotary engines to determine typical characteristics, design options and performance trends
- Consider that a rotary engine performs a 4-stroke cycle in 1080° rotation of the output shaft
  - Output shaft torque is 2/3 lower than standard reciprocating 4-stroke
  - Output shaft speed is 3/2 higher
- Most rotary engine development has been on automotive engines where low load/low speed performance is important for emissions and fuel consumption
- The ASRD rotary engine is for a UAV application where the engine operates at high loads/high speeds – some features used on automotive rotary engines AA not relevant
- Also critical for a UAV is maximum take off weight – this influences the amount of payload and/or mission duration, so important characteristics AA:
  - Power to weight
  - Fuel economy

Performance Formula

Vch	Swept volume/chamber		cc
Nrot	Number of rotors		
Vtot	Swept volume	Vch . N rot / 1000	litre
Mo	Output shaft torque		Nm
P	Output power	π . Mo . no /30000	kW
BMEP	Mean working pressure	6 . π . Mo / Vtot / 100	bar
no	Output shaft rpm		rpm
n	Equivalent 4-cycle rpm	no . 2/2	rpm
M	Equivalent 4-cycle torque	To . 3/2	Nm

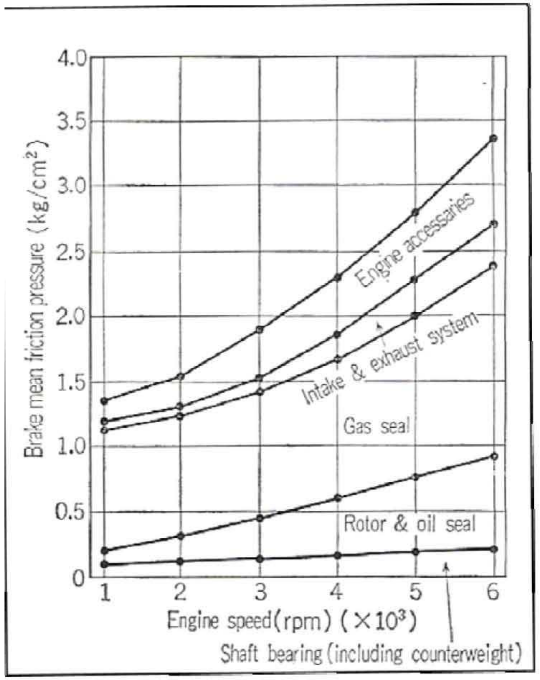
Rotary Engine Seal System

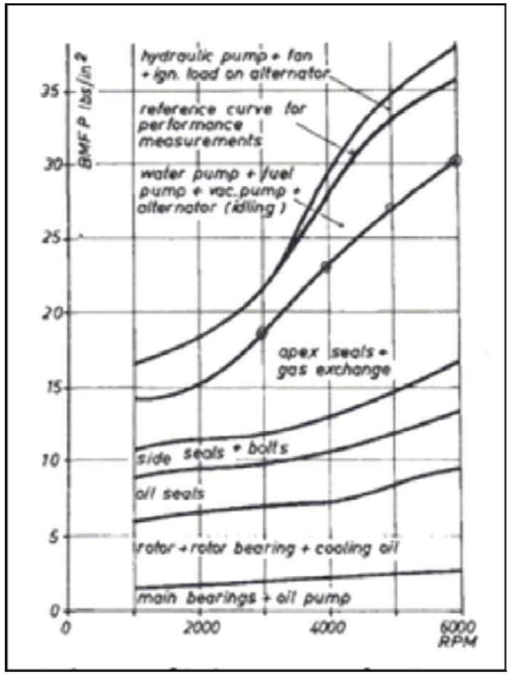


Rotary engines use a seal grid that connects Apex and side seals with corner seals.

If an oil cooled rotor is used – an oil seal is necessary on the rotor sides.

Friction

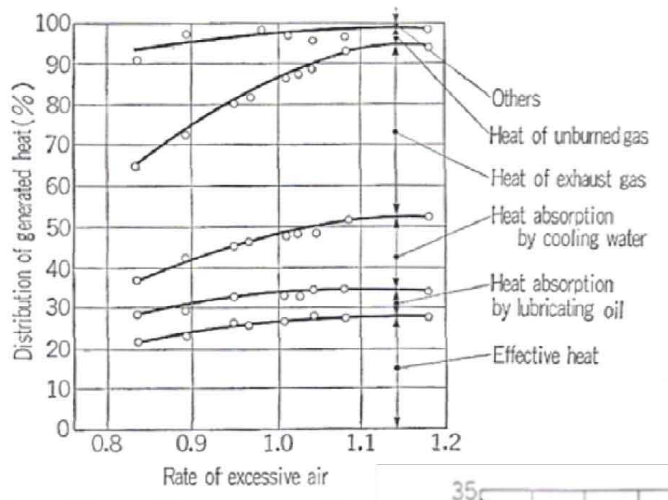


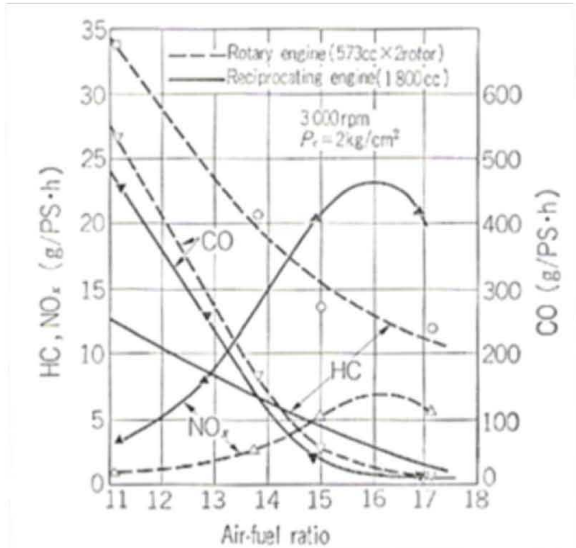


Rotary engines have relatively lower friction than reciprocating engines typically 30%
- No reciprocating mass
- No valve train

The ASRD engine is air cooled so has less mechanical losses

Combustion

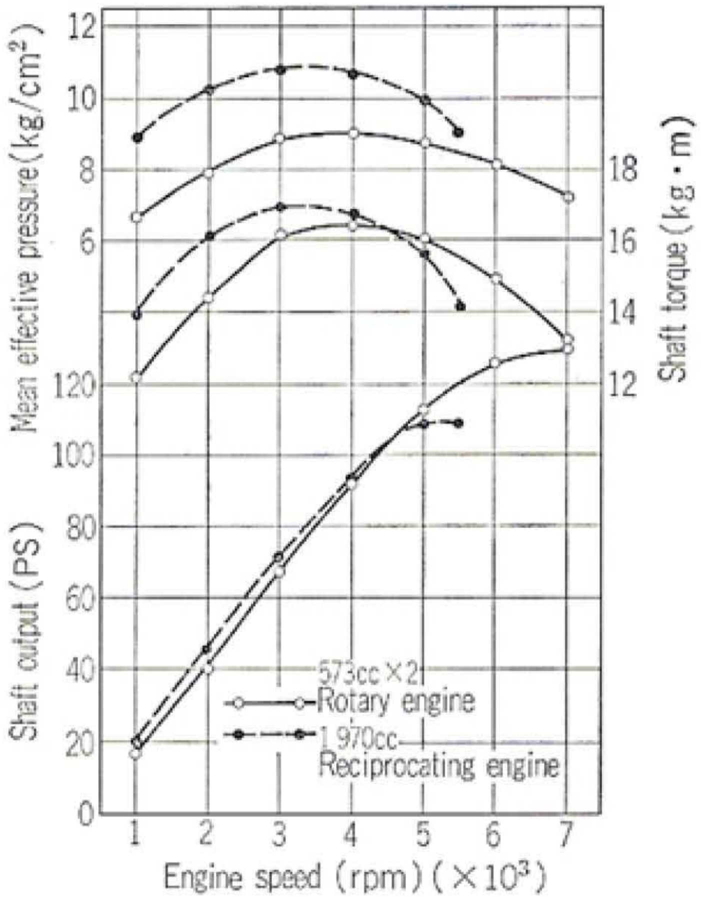




Rotary engines do not have ideal combustion chambers resulting in:

- High fuel consumption.
- High HC emissions.
- Un-burnt fuel .
- Poor combustion

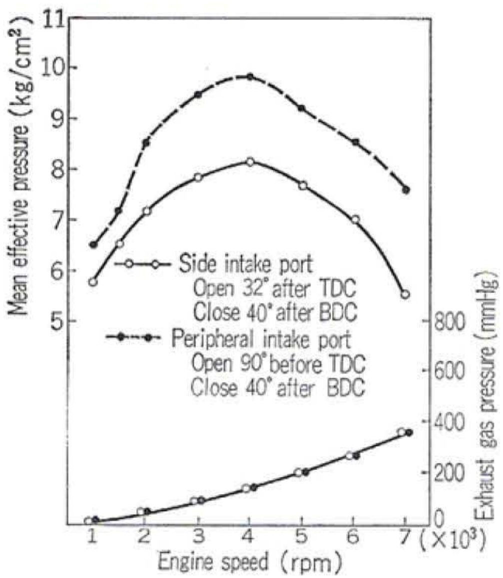
Comparative Performance

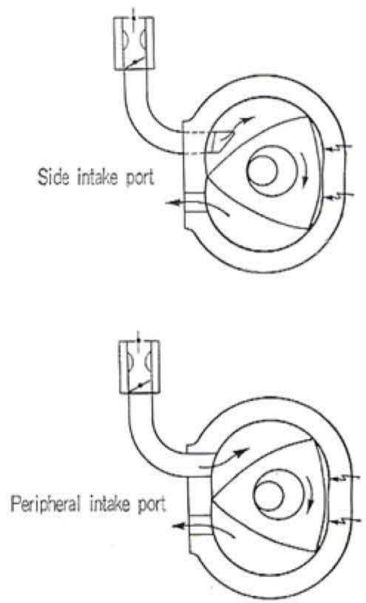


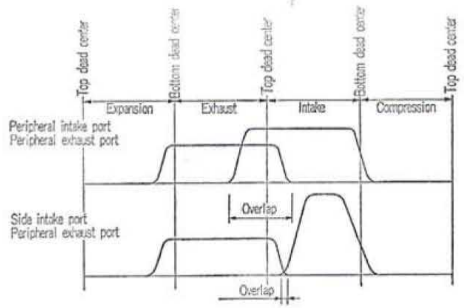
A comparison with a reciprocating engine shows a similar power at low speed with an increase high speed power.

BMEP is lower as this is for a side port rotary engine – which has lower volumetric efficiency.

Port Layout







Automotive engines use side ports to reduce fuel short circuiting and residual dilution at low speed/load conditions.

Performance is reduced due to port flow losses and reduced valve opening duration.

Peripheral ports AA the most suitable for a high power to weight UAV engine.

Design – Dual Spark Plugs

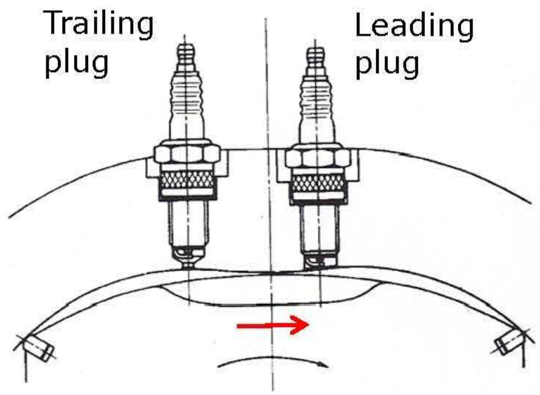


Fig. 10 - Arrangement of dual spark plugs

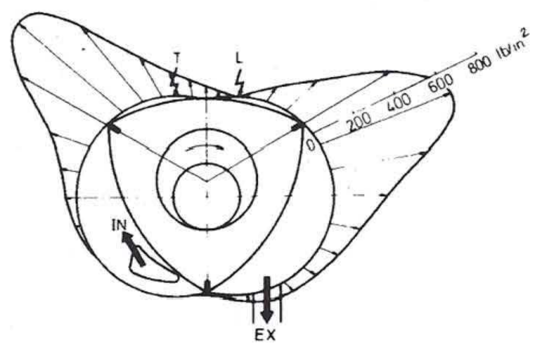


Fig. 11 - Gas pressure difference in the adjacent chambers

The combustion chamber on a rotary engine is flat and thin

-Slow burn rates
-Incomplete combustion

Automotive engines generally use dual spark plugs

-Leading plug with standard plug hole
-Trailing plug – recessed

Dual plugs gives highest power output.

CAA must be taken with the position of the trailing plug as the hole can create apex seal leakage.

Cooling

TABLE 1 – The influence of the cooling system solution on engine performance

Bearing System	Cooling System: Housing	Rotor	Eccentric Shaft	Classification	Shaft performance %
Sleeve (Friction) Bearing	Liquid	Oil	No Cooling	OCR - Oil Cooled Rotor Current Wankel engine concept for heavy duty application; automotive, marine propulsion, etc.	100
	Air	Oil	No Cooling	OCR	80
Anti-Friction Bearing	Liquid	Charge Mixture	Charge Mixture	CCR - Charge Cooled Rotor Current Wankel engines for light duty applications	80
	Liquid	No Cooling	No Cooling	UCR - Uncooled Rotor (No practical application)	65
	Liquid	Charge Mixture	Liquid	LCCR - Liquid and Charge Cooled Rotor	95
	Air	Charge Mixture	Charge Mixture	CCR - light duty application, cost effective production type	65

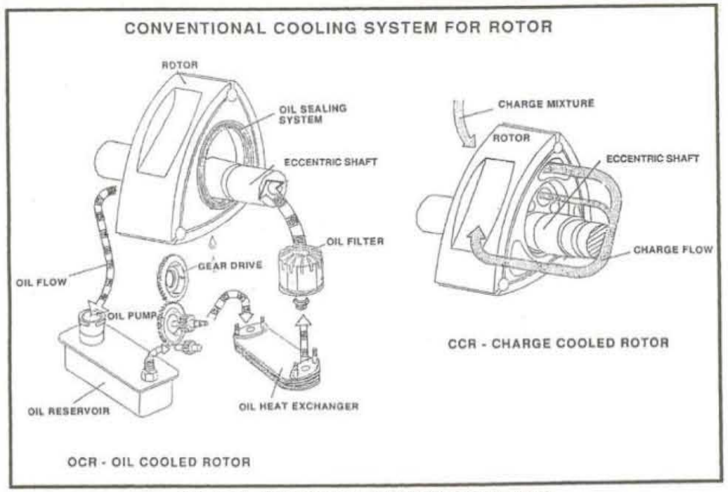


FIGURE 1 - VARIOUS ROTOR COOLING SOLUTIONS

Rotary engines use different cooling strategies depending on the application.

The ASRD engine has an air cooled housing with air cooled rotor.

The ASRD rotor is externally air cooled.

Table 1 does not have the ASRD strategy but is could be around 80% of relative shaft performance

Cooling by charge mixture reduces power due it intake flow losses and charge heating (approx. -15%)

Typical Temperatures

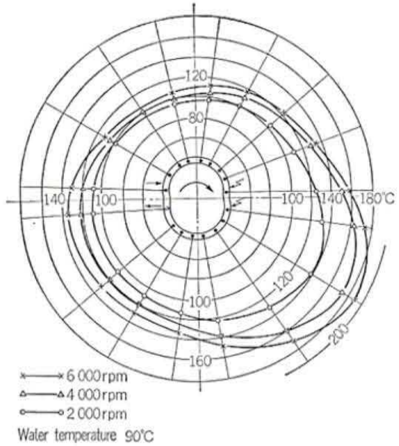


Fig. 3.5 Temperature distribution of inner surface of rotor housing

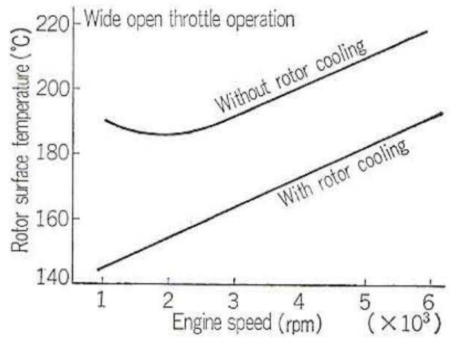


Fig. 3.46 Comparison of temperature of rotor housing

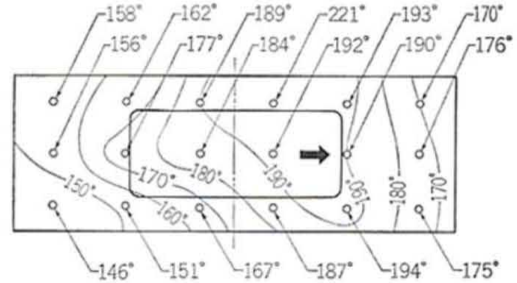


Fig. 3.45 Temperature distribution of rotor surface

These figures show typical temperature distributions. Rotor face temperatures AA @30°C lower with an oil cooled rotor.

The housing is around 100°C on the intake side and close to 200°C on the combustion side

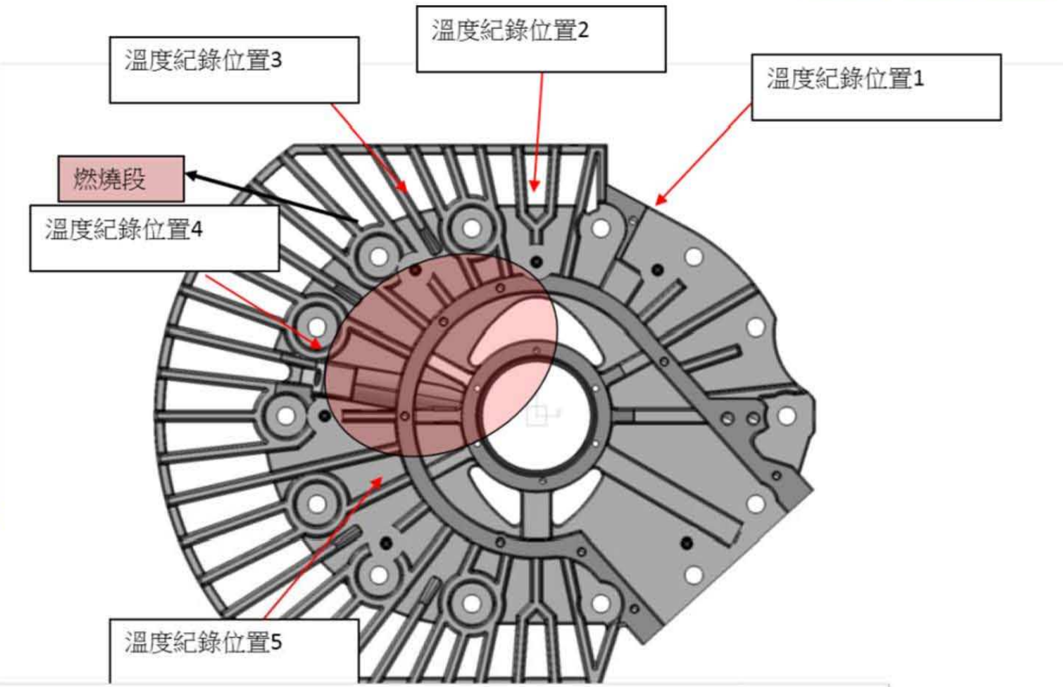
The ASRD engine is air cooled – more suitable for altitude operation

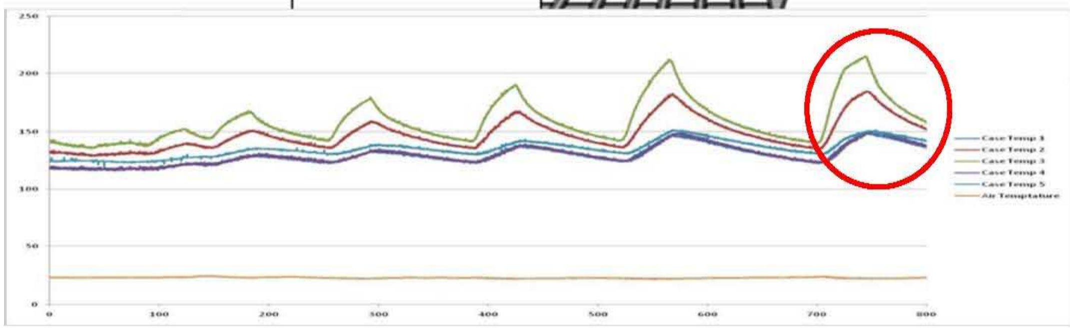
ASRD Measured Temperatures

ASRD tests show unstable temperatures. On the last transient – temperatures reach approx:

T1: ~150°C
T2: ~180°C
T3: ~220°C
T4: ~150°C
T5: ~150°C

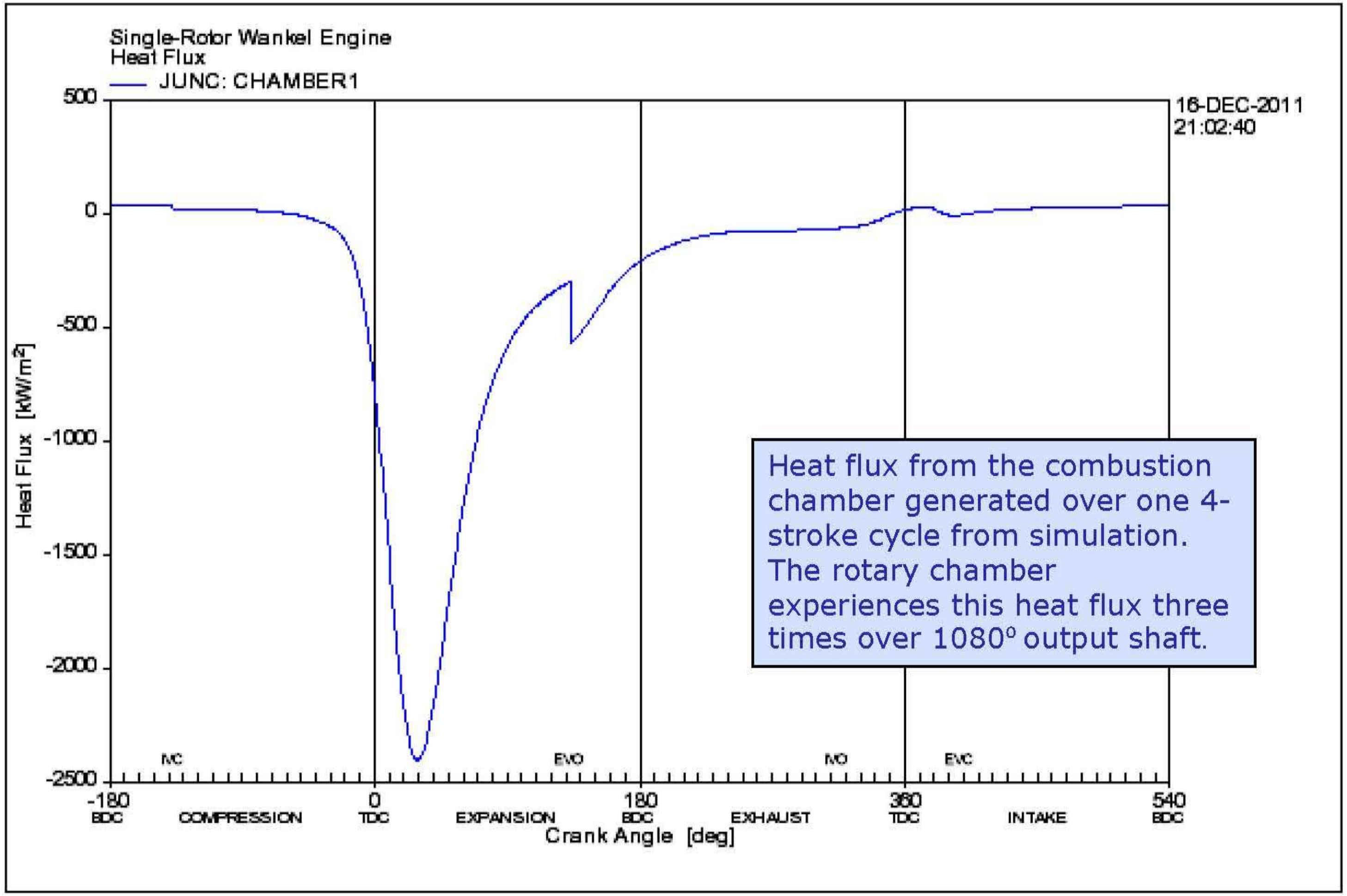
But these AA not temperatures close to the working surfaces of the engine.





BRM

Heat Flux for One Chamber



Design Rotor Recess

A rotor recess closer to the leading side increases burn rate and improves squish flow from the trailing edge

A deeper recess also increase the AAa of the flame front

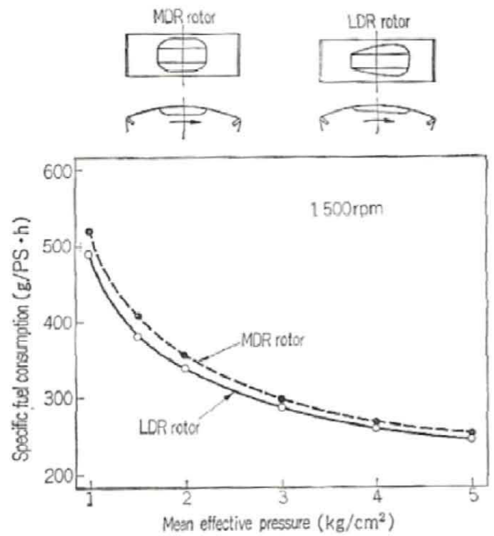


Fig. 4.33 Comparison of specific fuel consumption

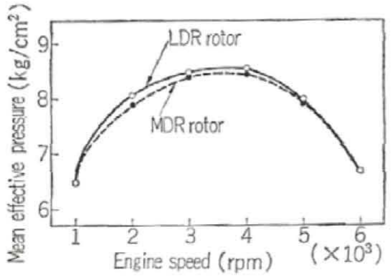


Fig. 4.34 Comparison of W.O.T. performance

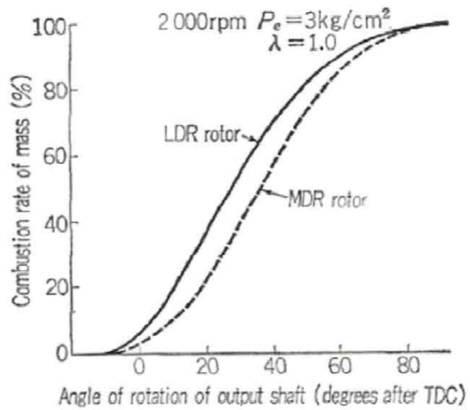


Fig. 4.32 Comparison of combustion speed

	50% Burn	10-90%
Output shaft angle		
LDR	27°	55°
MDR	35°	54°
4-stroke angle		
LDR	18°	37°
MDR	23°	36°

Performance Simulation

Rotary Engine Simulation

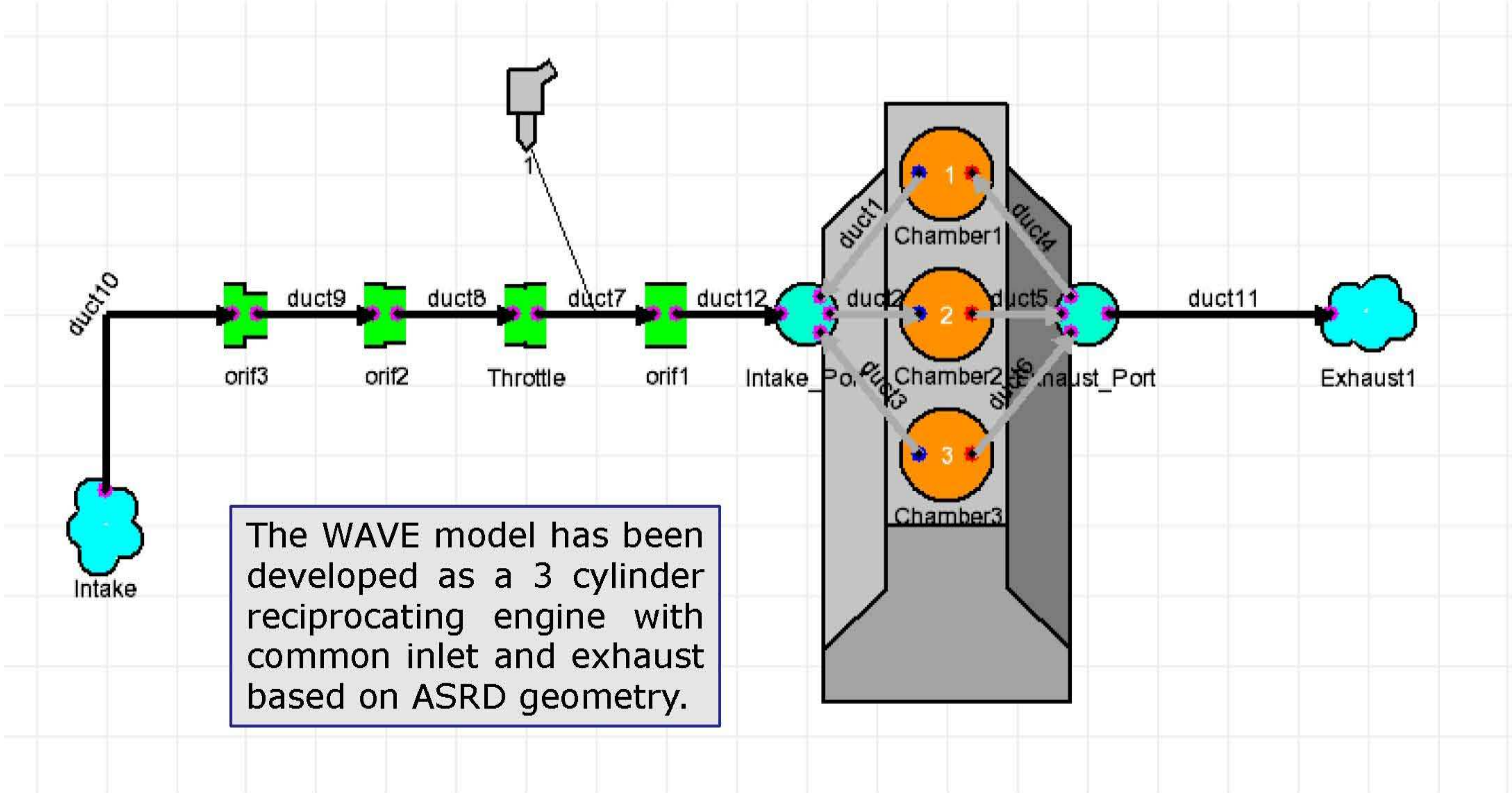
WDL

- A base engine simulation model has been prepAAd to simulate the ASRD engine using the Ricardo 1-D simulation code WAVE
- The model has two purposes
  - To generate heat flux for thermal analysis
  - To evaluate parameters influencing power to identify changes required to achieve 40hp
- Simulation has been achieved by representing the 208cc displacement rotary engine with a 3 cylinder piston engine with 72Ø bore and 51 stroke
- Thermal losses have been adjusted to match the surface AAas for heat transfer in a rotary engine where the rotor surface represents the piston
- Compression ratio has been calculated from CAD data supplied by ASRD by the AAa data supplied by ASRD
- There is no published use of such simulation on rotary engines. To perform this task reference to published characteristics of rotary engines has been used to balance the simulation
- Without detailed test data the model has been used to assess sensitivity to a number of parameters as a guide to development

ASRD Specification

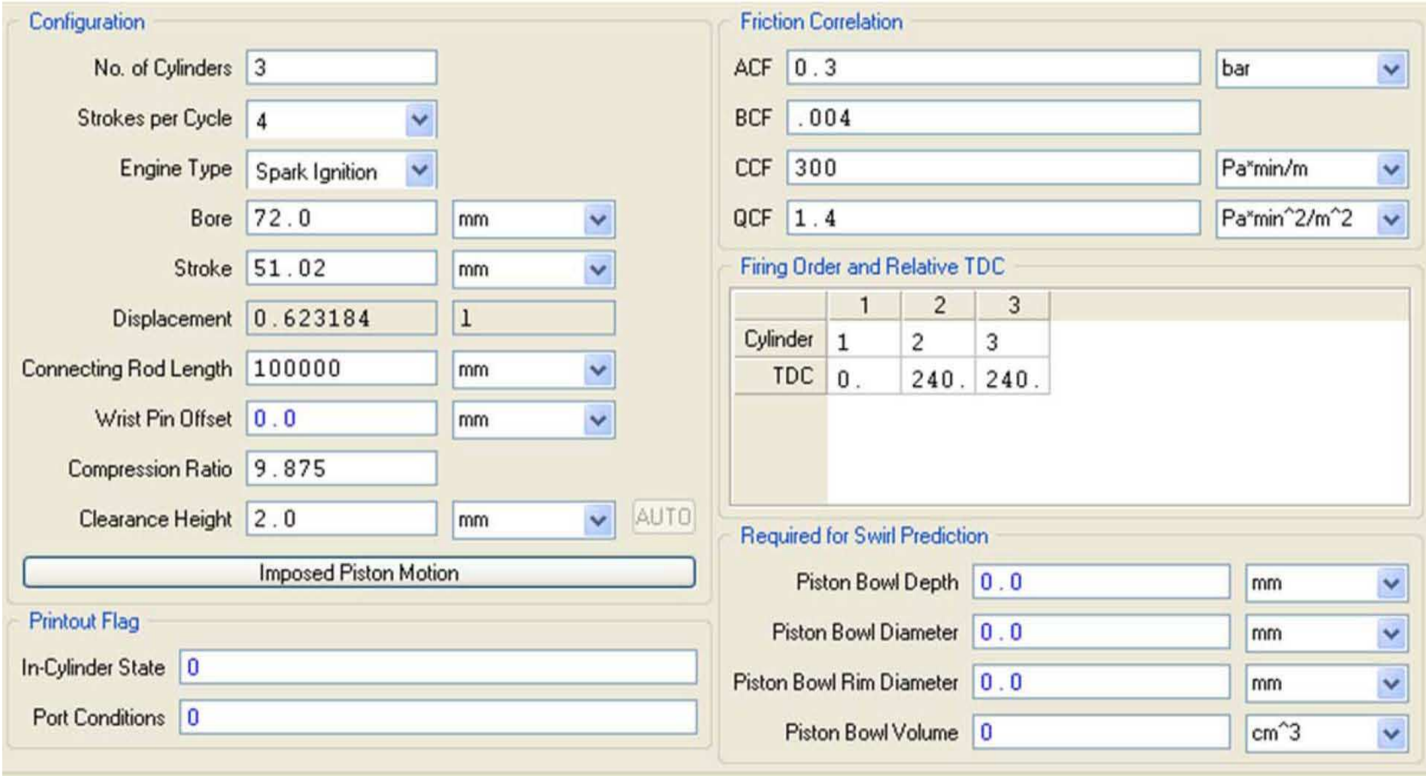
- Single rotor
- Air cooled housing and rotor
- Chamber swept volume = 208 cc
- Rotary key dimensions:
  - Radius, R = 71.5
  - Eccentricity, e = 11.6
  - Width, w = 48
- Compression Ratio = 9.87

Basic Model



The WAVE model has been developed as a 3 cylinder reciprocating engine with common inlet and exhaust based on ASRD geometry.

Engine Geometry



To achieve the swept volume to angle correlation of a rotary the connecting rod length has to be set to a high value

Port Timing

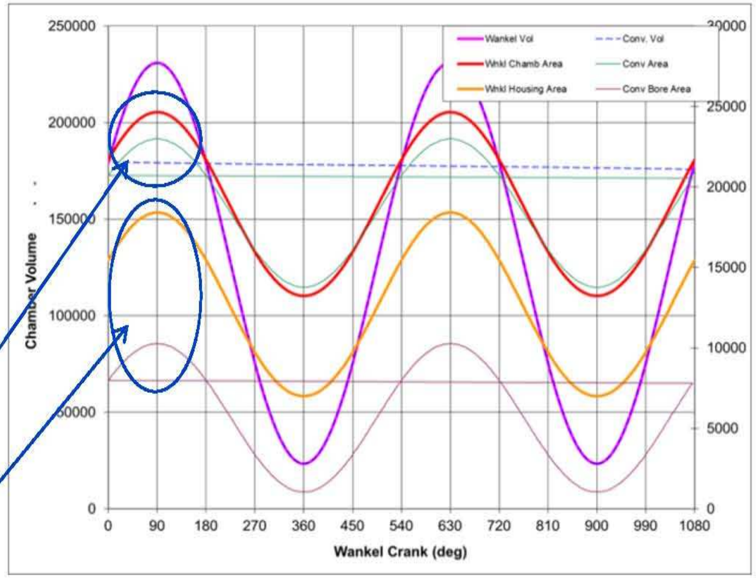
	Main Shaft^0	4-Cycle ^{0}	Timing
EVO	200 - 235	133 – 157	47~23 BBDC
IVO	472 - 513	314 - 342	46~18 BTDC
EVC	560 - 595	373 - 397	13~37 ATDC
IVC	832 - 873	554 - 582	14~42 ABDC

- Rotary Main Shaft has 1080^0 for a 720^0 4-stroke cycle
- WAVE simulation is based on a 4-stroke 720^o cycle
- In 1080^o the rotor turns 360^o
- Timing shown in 4-stroke notation

AAas and Volumes

- To evaluate how to represent the geometry of a rotary engine using a reciprocating engine model – volumes and AAas have been compared:
  - Rotor area to bore area
  - Wankel chamber to Conv(=conventional piston engine) area
  - Wankel housing to Conv bore
- Using the following definitions:
  - Conv bore = Bore swept surface area
  - Conv area = Combustion chamber surface area
  - Wankel chamber = Total chamber surface area
  - Wankel Housing = Wankel chamber – Rotor area
- In WAVE it is possible to increase the convective area specifically for the cylinder head and piston – these parameters have been adjusted to match up the areas

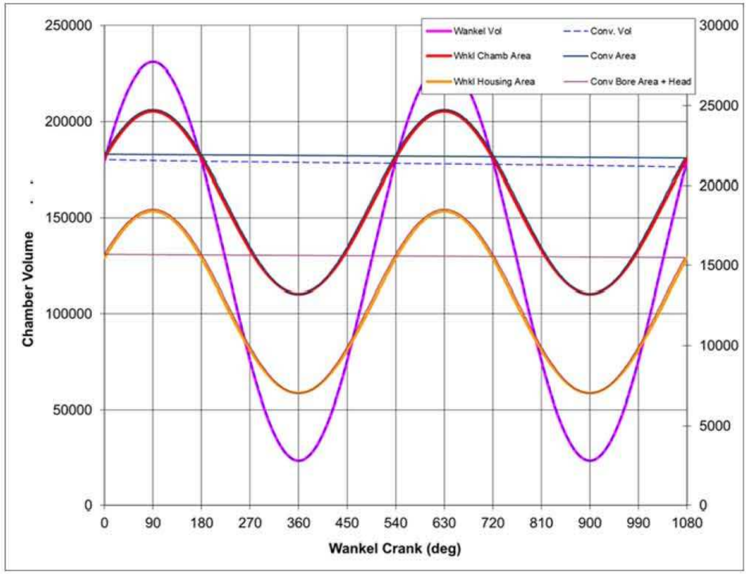
Match Bore and Rotor area



Swept volume matched by using a long connecting rod

With Bore set to 89.1Ø equivalent to the rotor area
- there is a reasonable match for total chamber area
- the housing AAa and bore swept AAa do not match

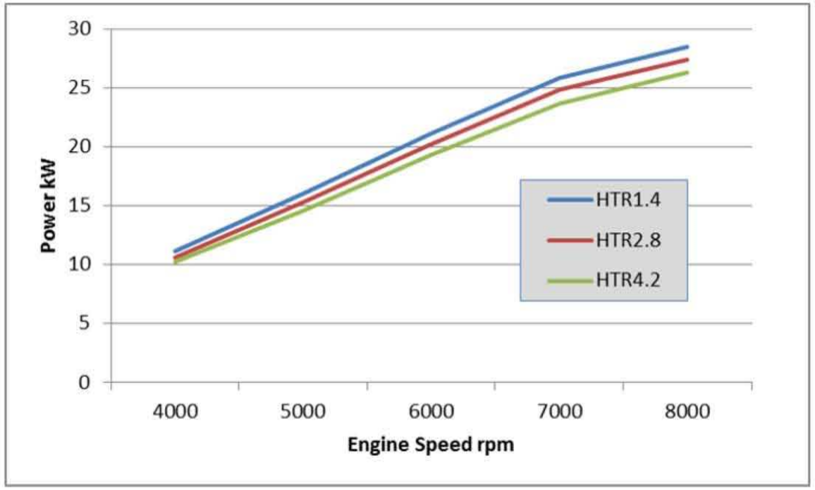
Correlating Volumes and AAas

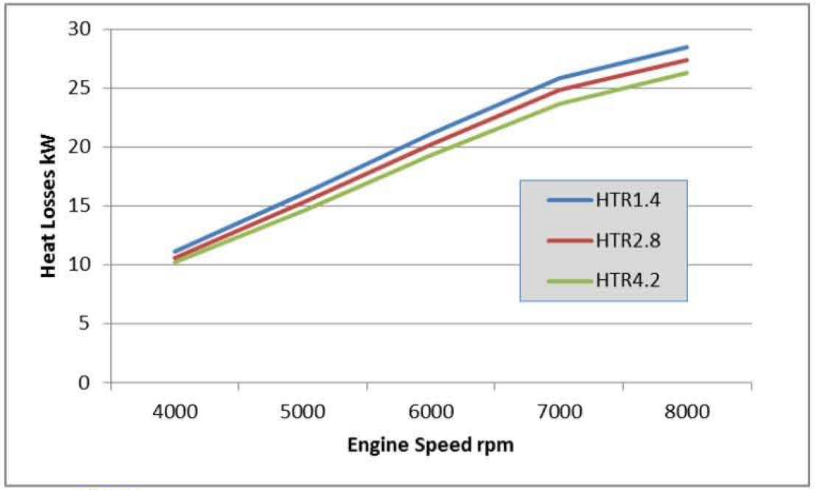


With adjustments to the equivalent convective areas of the “piston” and “head” good correlation can better correlation can be achieved:

- Equivalent Bore x Stroke = 72Ø x 51
- Conv. bore AAa to include surface including the ”head”
- Heat transfer AAa factors used:
  - 1.53 on 72Ø bore piston
  - 1.4 on “head AAa”

Chamber Heat Losses

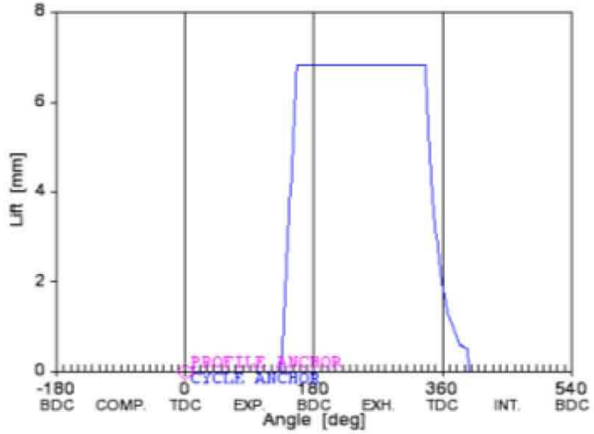




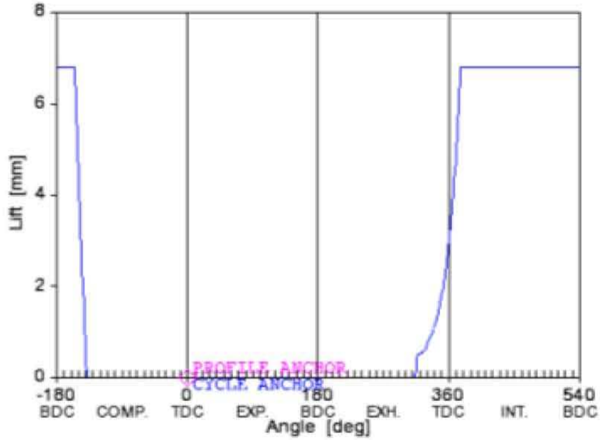
- The WAVE simulation is for an engine with 3 cylinders where as a rotary engine effectively has 3 pistons (rotor faces) in a single cylinder
- To investigate the sensitivity to this the factor used to apply heat transfer to the "head" has been adjusted
- The results show the sensitivity to chamber heat losses. Although this reduces power in the simulation has minimal effect on volumetric efficiency

Port Flow Modelling

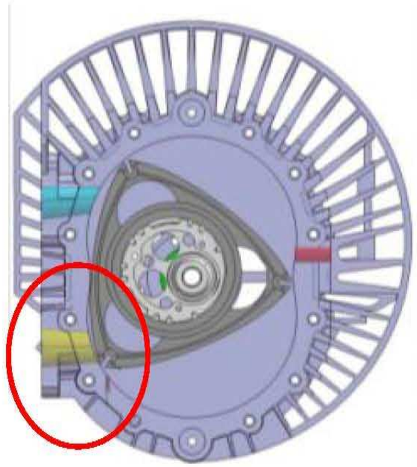
Exhaust



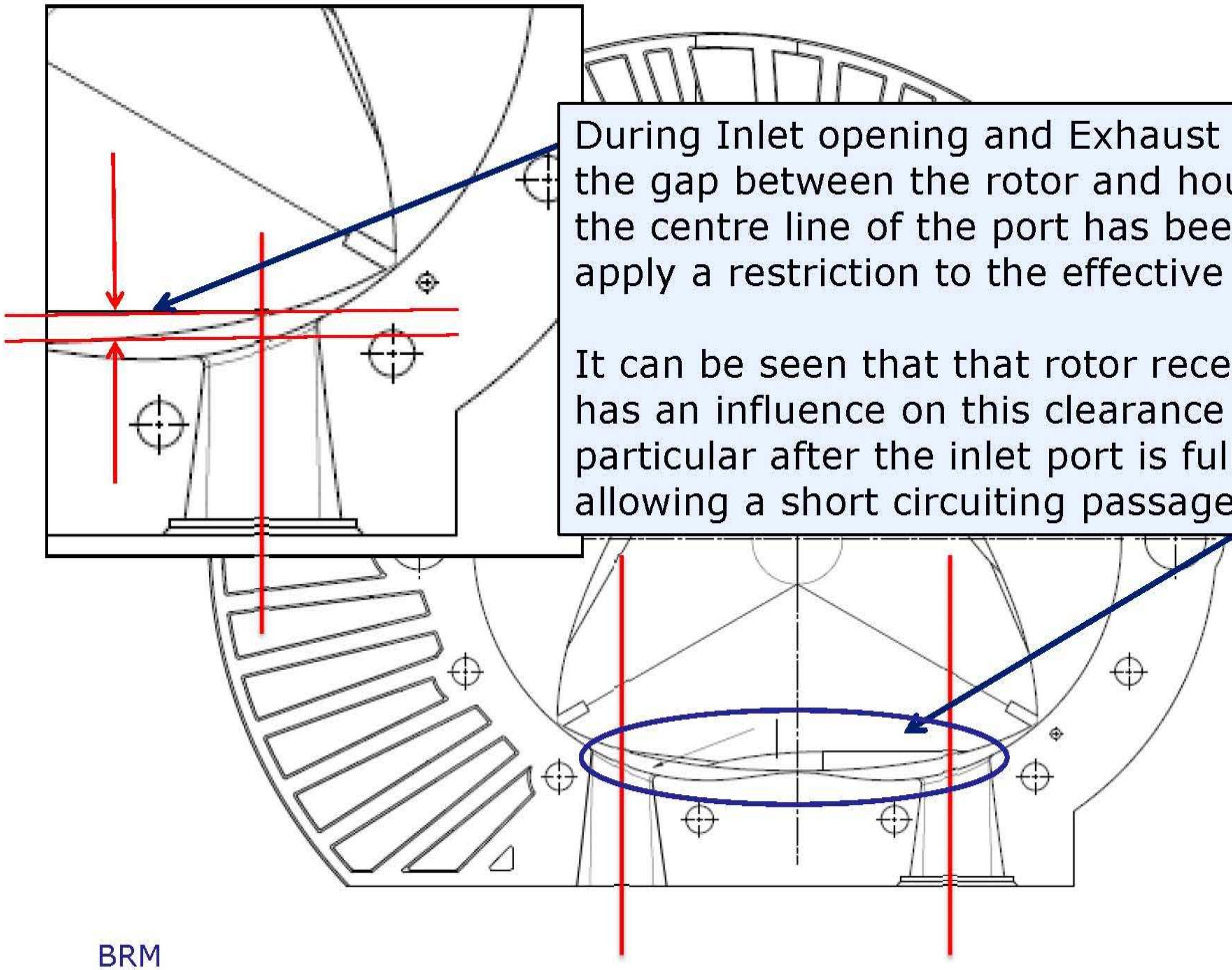
Inlet



- Port flow is based on effective AAa
- The rotor effectively blocks the ports during overlap. After the distance between the rotor and port exceeds the curtain AAa then the port is unrestricted
- CF of the open port initially set at 0.95 then adjusted according to literature on 2-stroke engines



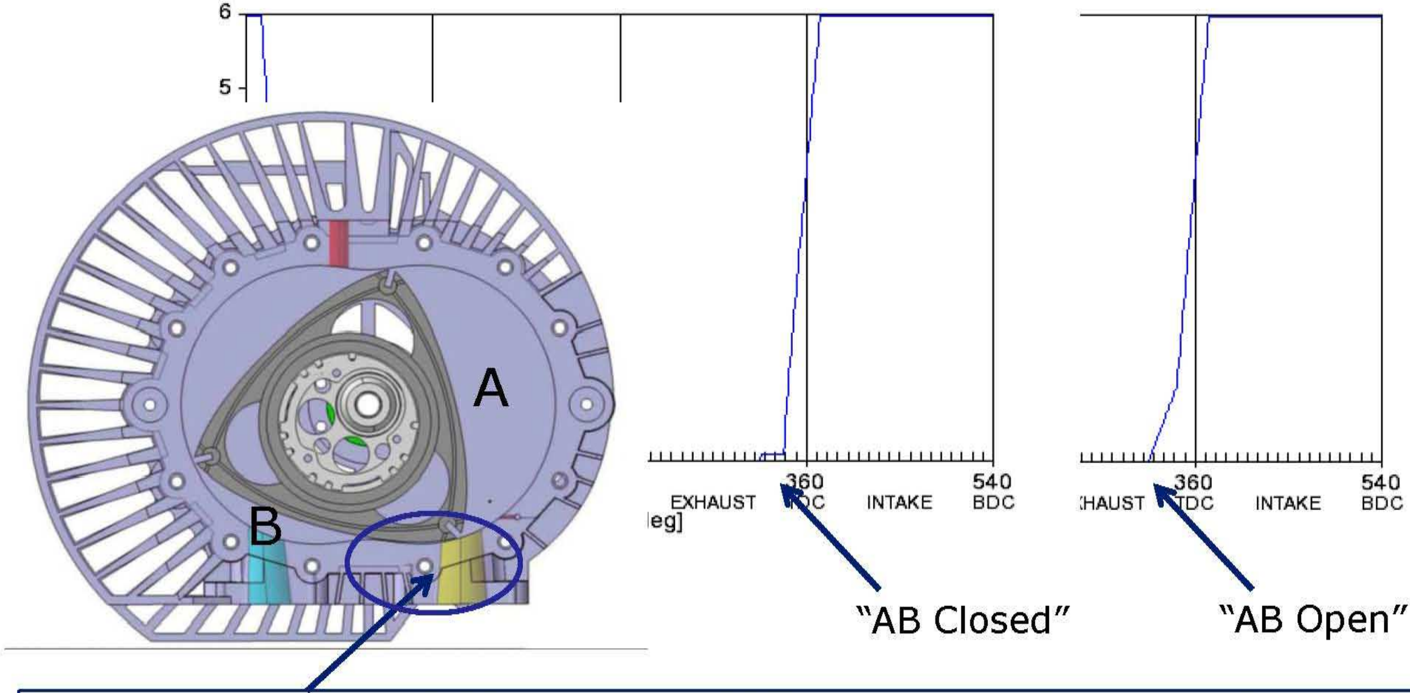
Port Dimensions



During Inlet opening and Exhaust closing the gap between the rotor and housing at the centre line of the port has been used to apply a restriction to the effective AAa.

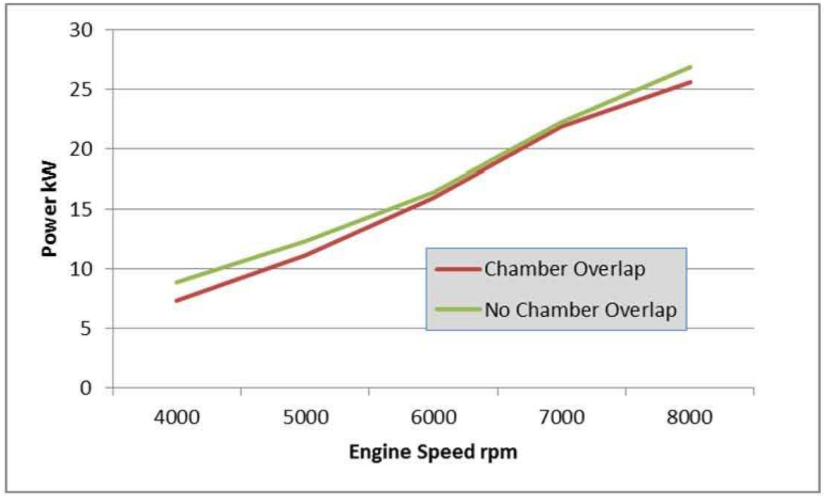
It can be seen that that rotor recess also has an influence on this clearance in particular after the inlet port is fully open allowing a short circuiting passage.

Rotor Chamber Overlap



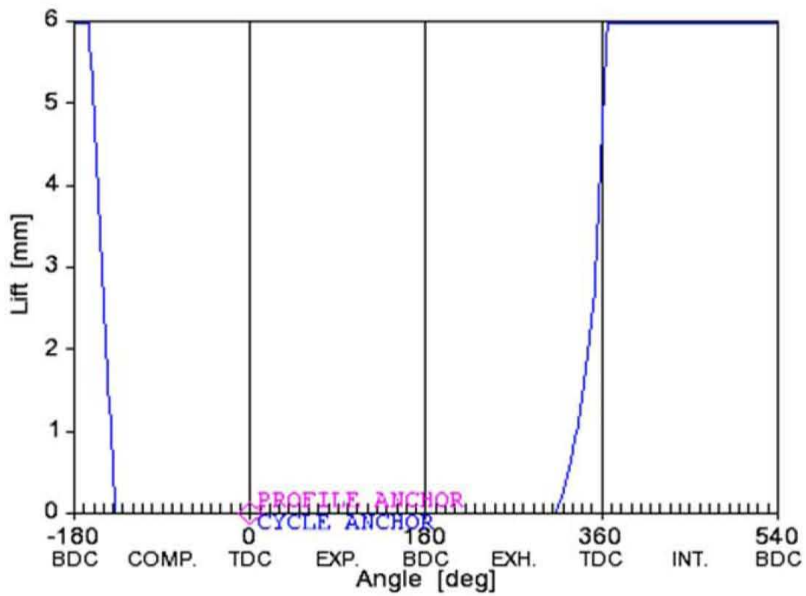
The inlet port opens for chamber "B" as chamber "A" is closing.
- The influence on simulation has been investigated with "AB Closed" and "AB Open" set with the "effective valve lift" .

Rotor Chamber Overlap



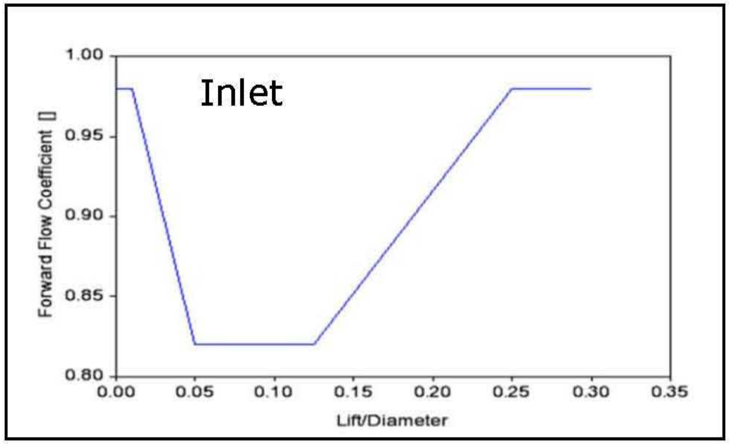
- Shows a comparison of
  - "AB Open" – Chamber Overlap
  - "AB Closed" – No Chamber Overlap
- The difference in performance is a result of differences in
  - Volumetric efficiency
  - Exhaust residuals
- This difference is 20% at low rpm and 5% at high rpm

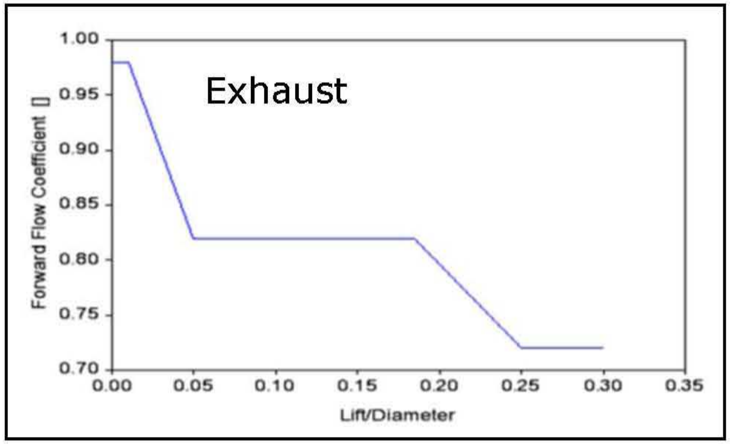
Clearance Data



- Clearance data requested and supplied by ASRD has been used for simulation
- For improved representation the curtain AAa between the port aperture and rotor might give better correlation between test and simulation

Port Flow





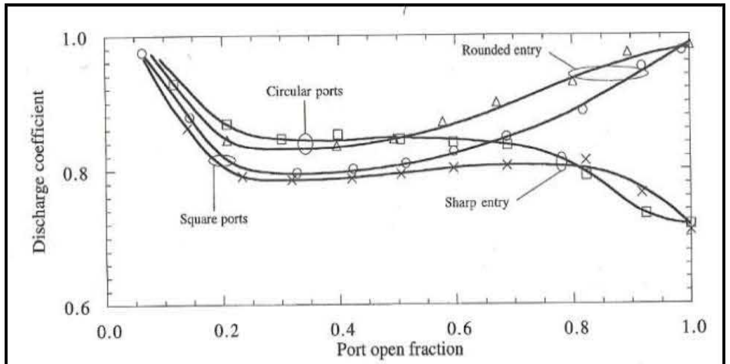
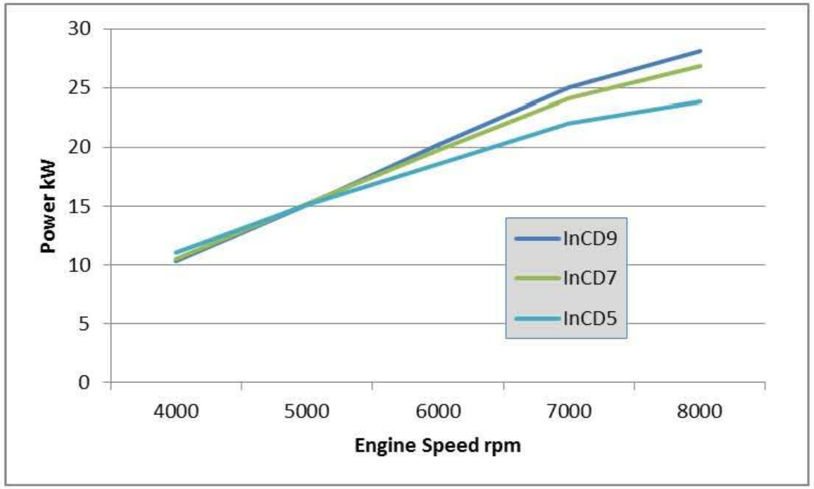
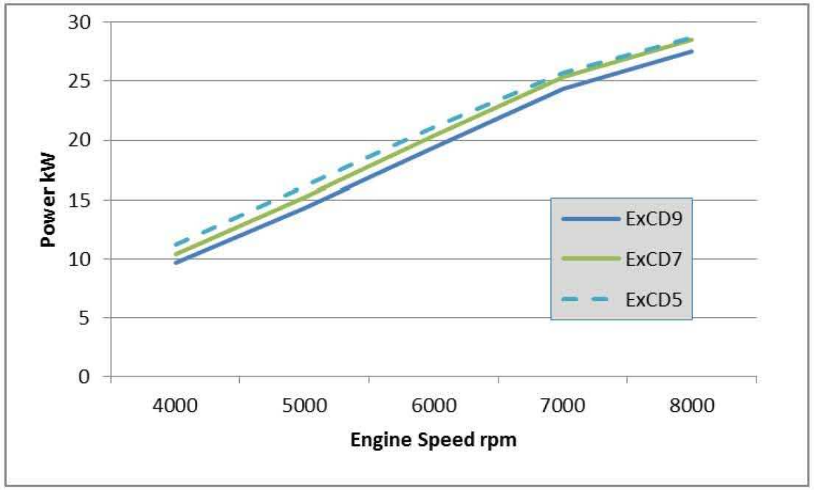


Figure 5-21 Steady-state discharge coefficient of square and circular radial scavenge ports as a function of port open fraction.[14,31,32] Reproduced with permission of The McGraw-Hill Companies.

- The closest similarity to a rotary engine port is the port on a 2-stroke engine
- Although test data has not been available a best estimate has been used based on typical 2-stoke ports
- In addition sensitivity to port discharge coefficient has been investigated to check sensitivity on performance

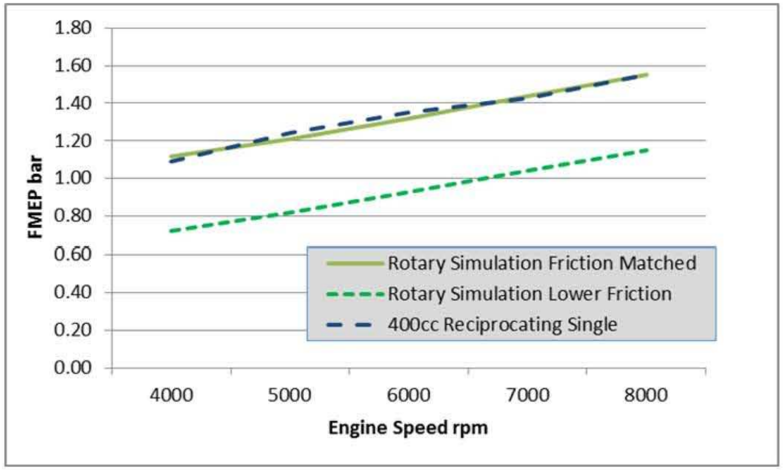
Sensitivity to Discharge Coefficient

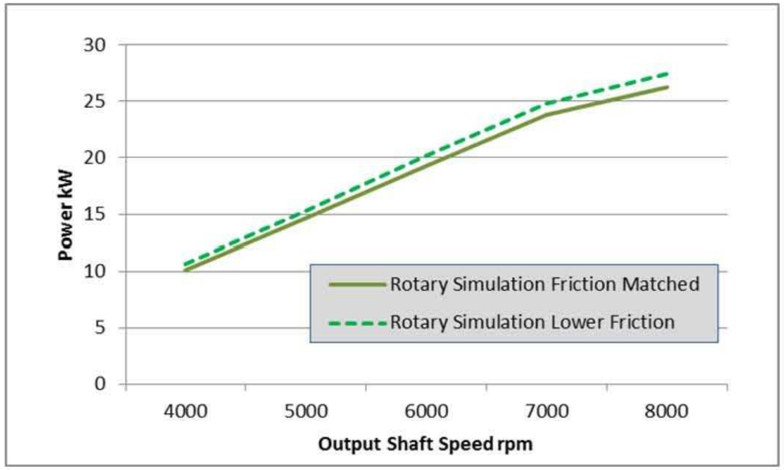




- Simulation runs at constant CD have been used to assess the influence of port discharge coefficient on performance
- In WAVE the discharge coefficient is applied to the effective port area
- The inlet port has the most effect in performance and care should be taken with the design
- The exhaust appears to respond positively with a less effective port – however this could be that the model is not representing the chamber/port overlap event
- It is recommended to flow test the ports

Friction



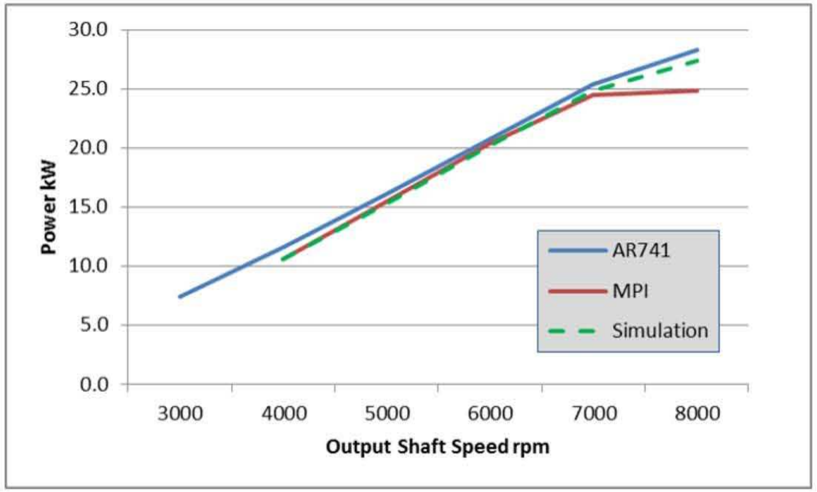


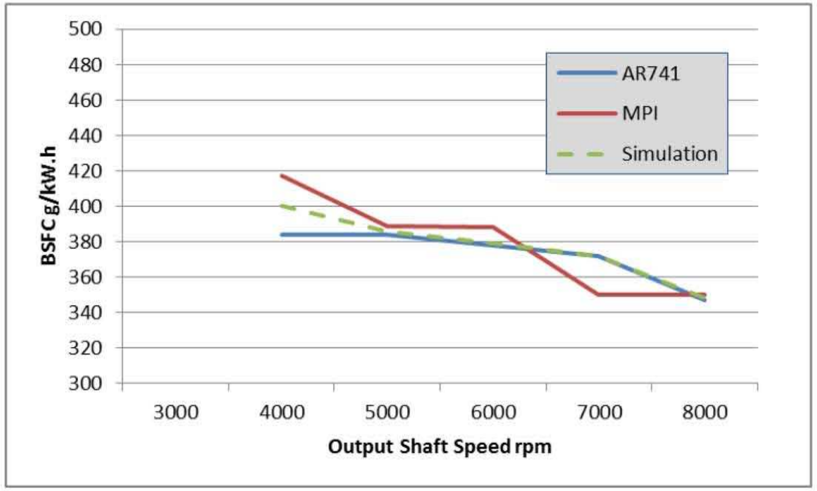
- The simulation uses a Chen-Flyn correlation for friction

  FMEP = acf + bcf (Pmax) + ccf (rpm x stroke) + qcf $(\text{rpm x stroke}/2)^2$

- Parameters acf, bcf, ccf and qcf AA specified to generally match test and predicted friction levels
- Parameters were chosen and compAAd to a modern 400cc single cylinder motorcycle engine – considering that the ASRD engine has no water pump or other ancillaries, a lower level might be applicable
- Friction requires confirmation from test data

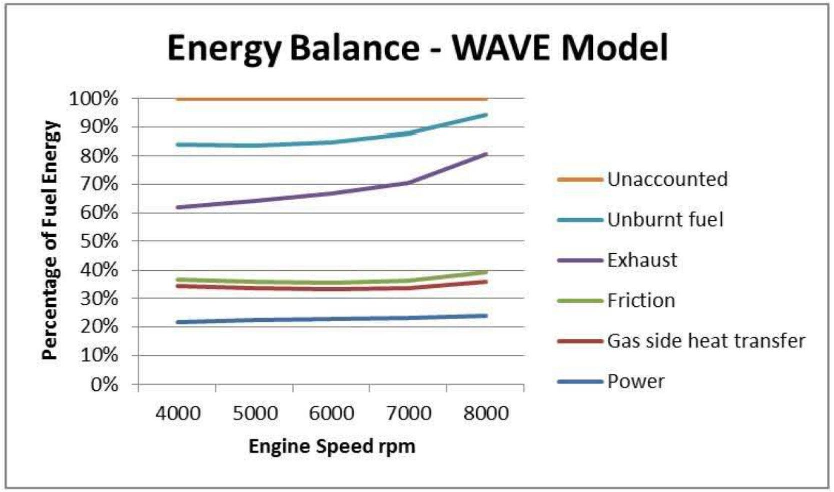
Correlation of Simulation

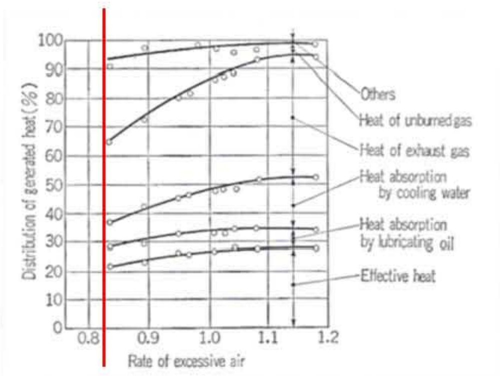




- Correlation approach has been based on:
  - representative geometry
  - specification of engine temperatures and heat transfer surface AAas
  - specification of friction parameters acf, bcf, ccf and qcf
  - specification of port flow characteristics
  - implementation of rotor shrouding of port during overlap
  - specification of 10 to 90% burn rate and position of 50% burn
- Adjustment of combustion and AFR to match power/fuel consumption

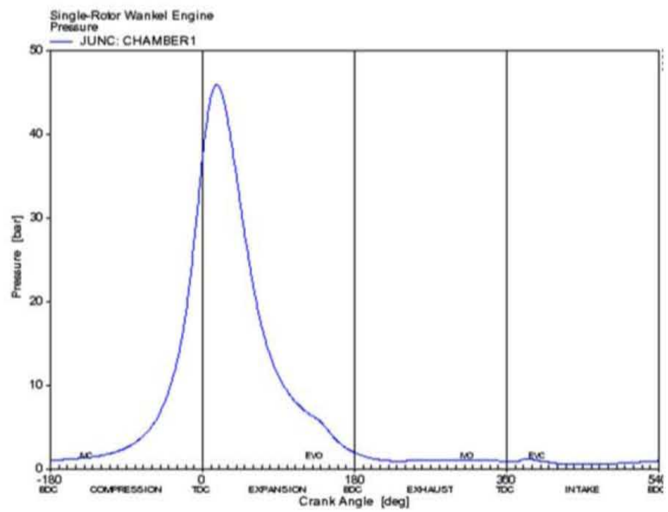
WAVE Energy Balance

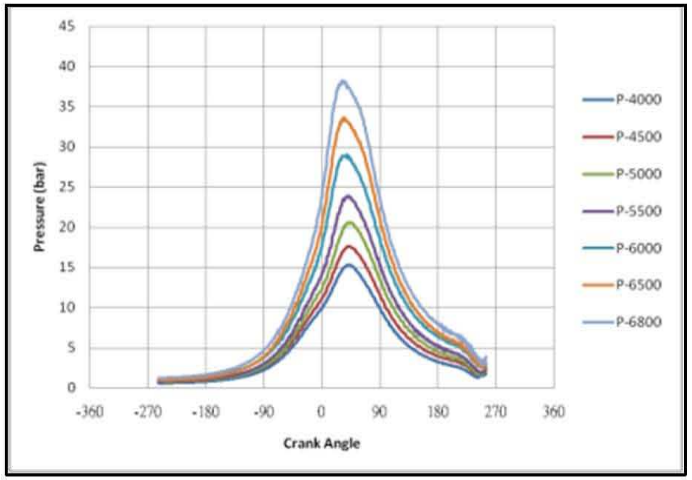




- Energy balance determined from simulation output
- As the ASRD engine has a high BSFC the actual AFR is rich as a result of unburnt fuel – this has been estimated but is similar to literature findings
- Accountable losses AA around 70% of the fuel energy equivalent to @Lambda 0.83 on the literature balance
- In addition the % due to friction looks low but needs to be confirmed by engine tests

Comparison of Cylinder Pressure

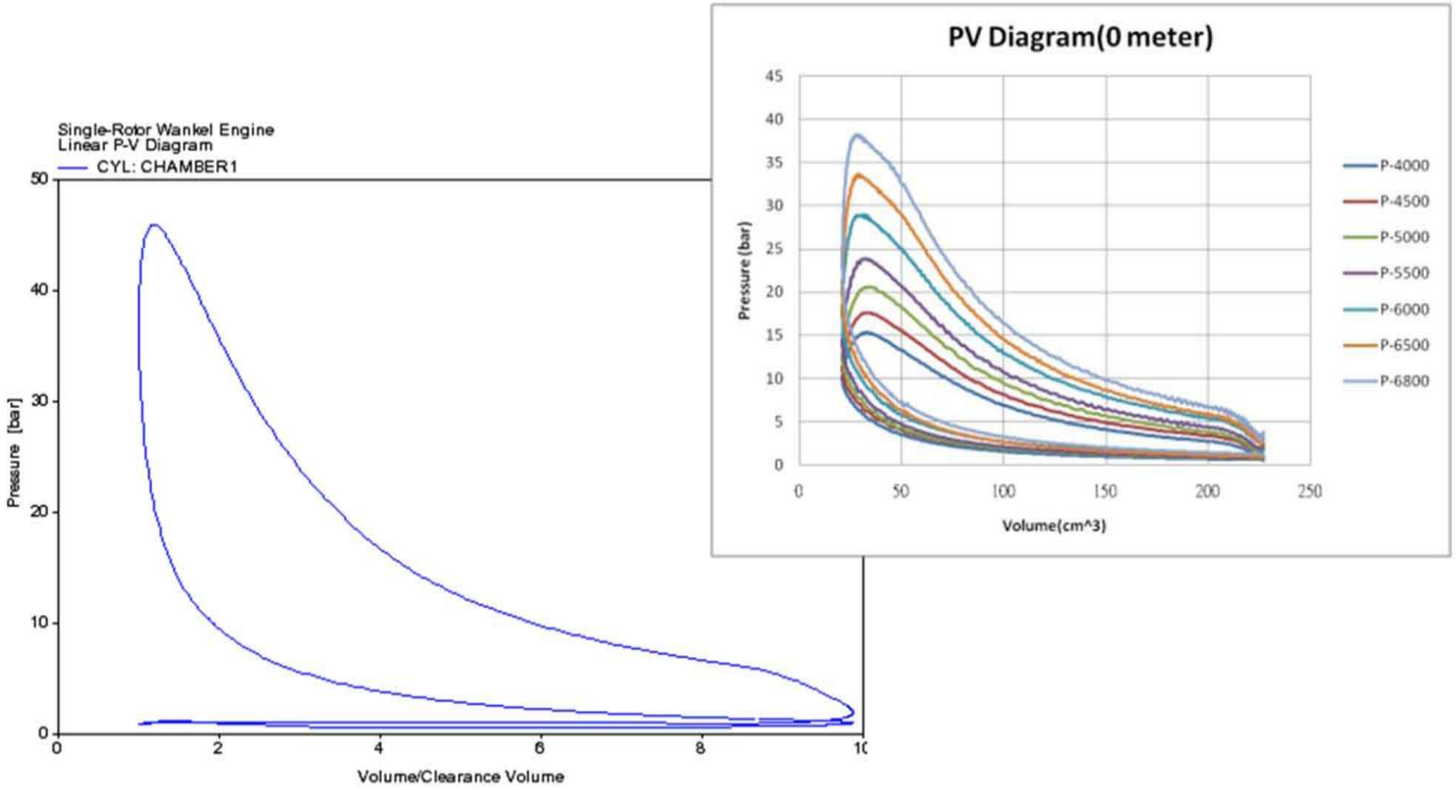




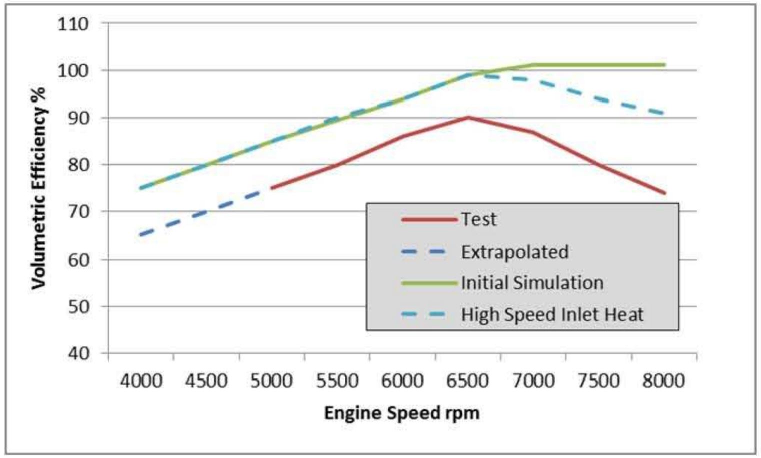
- Max cylinder pressure (Pmax) “predicted” ranges from 38bar to 46bar.
- ASRD measured at 6800rpm is @38bar
- Simulation at 7000rpm is @45bar
- In a reciprocating engine Pmax is typically 70bar
- To approximate the combustion in a rotary engine
  - 50% burn point set around 18° (4-cycle)
  - 10% to 90% burn duration between 30° and 56° (4-cycle)
  - AFR and completion of combustion adjusted to match BSFC

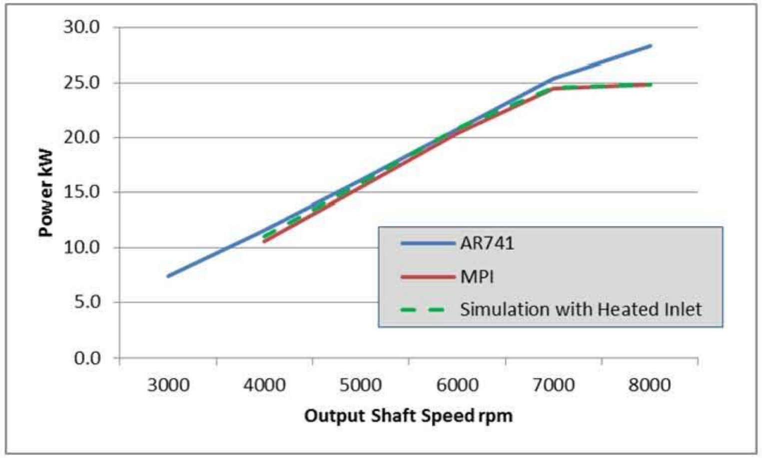
38

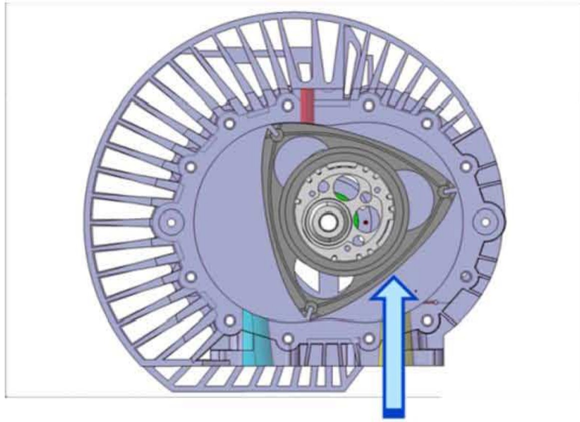
Comparison of P-V Diagrams



Volumetric Efficiency



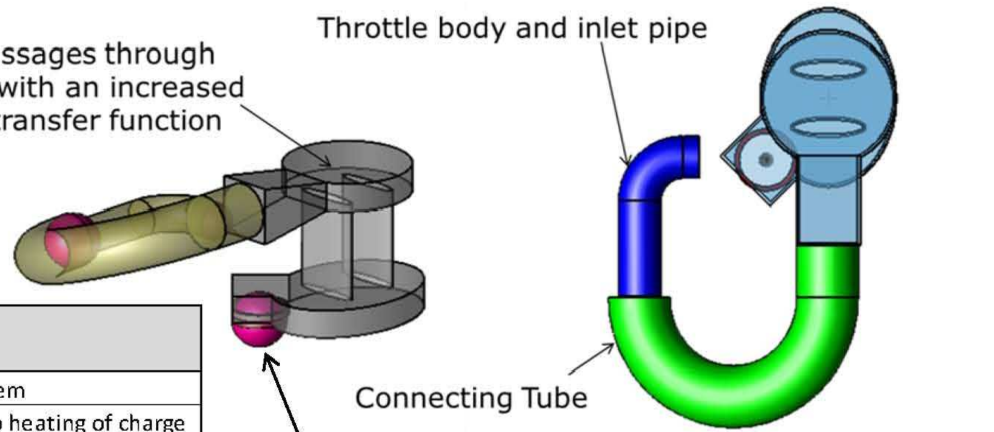




Inlet flow impinges on the rotor face

- Test volumetric efficiency provided shows a difference with simulation
- To match the test data results in too much power reduction
- Heating imposed on the inlet pipe has been used to simulate the effect of inlet heating and match the ASRD power curve
- It is as if on the ASRD test there is not enough rotor cooling air to control temperatures

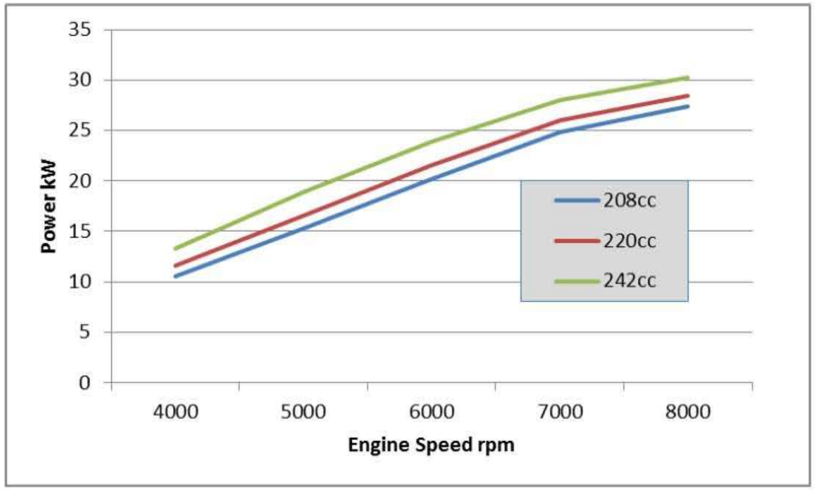
Rotor Cooling by Induction Air

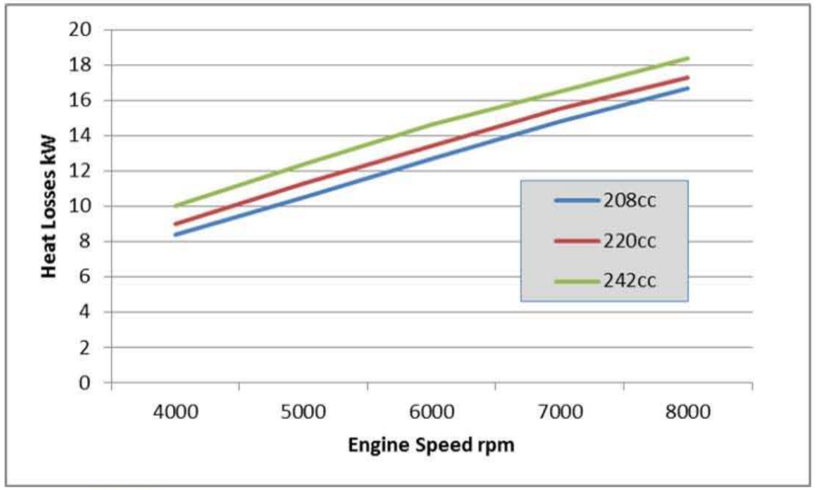


Build	Power kW	Rotor kW	Δ Temp °C	Note
Base	28.2	0	3	Std inlet system
Rotor Cooling 1	27.1	0	3	Rotor inlet no heating of charge
Rotor Cooling 2	24.7	-1.2	31	Charge heating +30°
Rotor Cooling 3	22.8	-2.1	54	Charge heating +50°

- To cool the rotor with inlet charge has two effects on volumetric efficiency
  - Air heating reducing charge density
  - Flow resistance due to additional pipes, bends and AAa changes
- Using WAVE Build3D a simplified representation of a possible system has been put together with the heat transfer factor increased through the rotor passages to increase charge heating/rotor cooling
- The results indicate
  - A power loss of 1 kW due to the ducting system
  - A significant power reduction @6kW for @2kW of heat removal

Increased Rotor Width

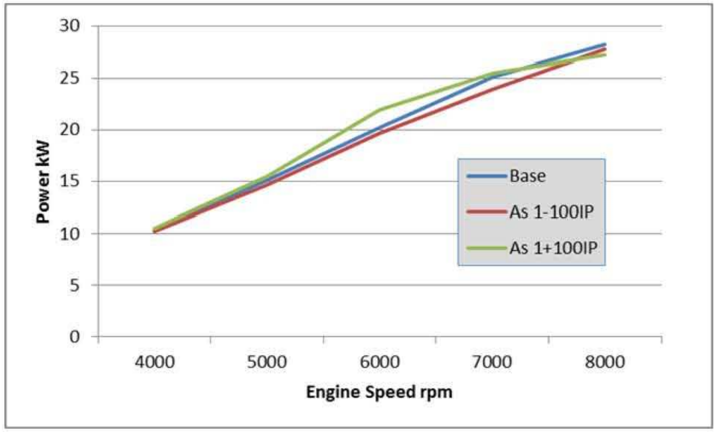


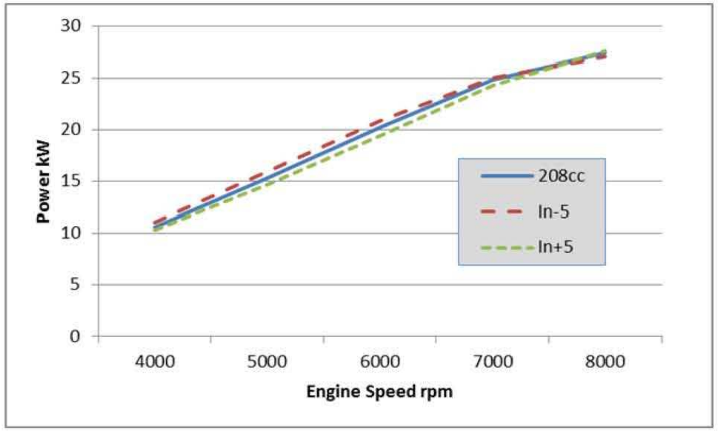


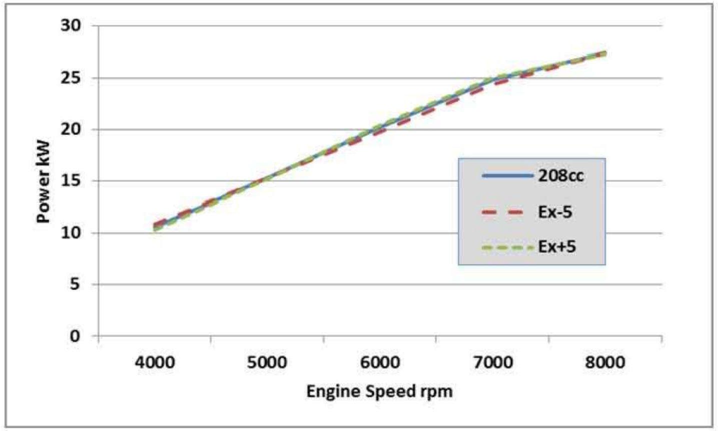
- Rotor width
  - 48.2mm = 208cc
  - 51.2mm = 220cc
  - 56.2mm = 242cc
- With the current A0000 build specification the engine can achieve 30.2kW (41hp) at 242cc but with an increase in chamber heat transfer of 1.7kW
- ASRD testing indicates that the engine is thermally limited at it's current rating – without cooling improvements a larger engine would not achieve the power target

BRM

General Tuning







- In general engine parameters such as port timing, AAas and inlet pipe length the engine appears to be well optimised.
- To increased performance will come from improved cooling and combustion

Summary

- Simulation of a rotary engine using WAVE has been a challenge. An ideal situation would be to develop the model at the same time as testing.
- Simulation of the ASRD rotary engine has been used to look at sensitivity to key parameters and to consider areas for improvement.
- For better correlation it would help to have:
  - port flow data, friction data and accurate AFR data.
- AFR measured with a Lambda sensor is misleading in engines where there AA high levels of unburnt fuel, 2-stroke test methods can be used.
- ASRD tests do not match the A0000 at high rpm – this could be due to insufficient rotor cooling in that rotor temperatures become unstable above 7000 rpm.
- The use of rotor cooling results in too much power loss due to flow losses and charge heating and is not recommended
- The base engine is well optimised in terms of tuning – to increase performance will require:
  1. Improved combustion – trailing spark plug
  2. Improved cooling – rotor and housing
  3. Increase engine capacity – might not be necessary if (1) and (2) can be resolved

Conclusions (1)

- A WAVE model of the A0000/AA1 engine has been built & correlated with the available data
- The correlation was acceptable, except above 7000 rpm, where the predicted power is higher than the measured data supplied. The measured performance is also below the published performance of the UEL (A0000) engine
- The model was used to investigate sensitivities to:
  - Heat losses
  - Volumetric efficiency
  - Port timing
  - Use of rotor cooling by charge air
  - Increased rotor width
  - Combustion
- Improve correlation could be achieved if ASRD can supply:
  - Port flow data
  - Friction data
  - Engine airflow & accurate AFR data

Conclusions (2)

- The modelling indicate that the intake air temperature may become too high due to poor rotor & housing cooling
- High surface temperatures will heat the intake air & reduce performance
- Changes that can be applied to improve the engine performance are:
  - Improved cooling
  - Optimised ignition timing
  - Dual-spark plug system to improve combustion
  - Optimised intake port area & timing
  - Increase engine capacity (wider rotor)
- Charge (=combustion) air rotor cooling reduces engine performance