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Turbocharging of Spark Ignited Wankel engine for High Altitude Application Using 1-D Simulation Approach

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Abstract

Wankel engines are increasingly finding their application in unmanned aerial vehicles, especially where high power-to-weight ratio is of utmost importance. This advantage makes the Wankel engines outperform the reciprocating engines despite several shortfalls. 1-D simulation model of the Wankel engine has been constructed from commercially available software for reciprocating piston engines. This model was then used to study the matching of turbocharger for the required application and the effect of charging the engine. The developmental methodology of a turbocharged wankel engine based on 1-D simulation approach is described. The behavior of the engine and turbocharger at various altitude conditions were studied with a validated model. The simulation model was then used to study the intake and exhaust manifolds and also to design the wastegate opening strategy & ECU correction factors for various altitude conditions. The model has been validated with the test results from prototype engine with the selected turbocharger at sea level operating conditions.

Keywords: *Wankel engine, turbo charging, 1-D modeling, simulation, high altitude*

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INTRODUCTION

Use of 1-D simulation tools in engine development process has proved very effective right from the concept development stages till product realization and improvement. The commercially available tool GT-Power has been used to model the Wankel engine and the model was proved to show satisfactory correlation[1] with the test results. 1-D simulation has been used to optimize the inlet and exhaust manifolds[2] for turbocharged engines. This paper presents a report of use of such a simulation model in the development of turbocharged Wankel engine for high altitude UAV (Unmanned aerial vehicle) engine applications. It describes the application of 1-D simulation from the selection of turbocharger, matching of turbocharger with engine, transient performance of the turbocharger with the engine, validation of the model and use of the model to develop the control strategy for using the turbocharger for altitude compensation.

With the knowledge of the turbocharged engine operation at various altitude conditions, it reduces considerably the need for prototype testing and thus, reduces the overall development process time and cost. 1-D modeling of Wankel engines through the use of software for piston engines is relatively new. In the current work, 1-D simulation model of Wankel engine using pseudo-cylinder methodology to model it as three reciprocating cylinders is presented. The model was validated using practical data from in-house developed wankel engines. The turbocharger unit was added to the base calibrated model and the model was tuned using test bed data from prototype engines.

Selection of suitable turbocharger for this application, design of intake and exhaust manifolds, virtual testing of the engine with turbocharger and development of the control strategy for the turbocharger are the key areas where the 1-D model proved to be a valuable tool.

1-D MODELING OF WANKEL ENGINE

The entire engine is modeled as a collection of ducts and blocks representing the piping and engine cylinders respectively. The 1-D software RICARDO WAVE calculates the details of the flow in the flow network as a solution of quasi-one dimensional compressible flow equations governing the conservation of mass, momentum and energy. The flow network is discretized into a series of small volumes and the governing equations are then solved using finite difference techniques for each of these elementary volumes.

The baseline 1-D engine performance model was prepared using the input data from the Wankel engine. Rotor dimensions are converted to pseudo reciprocating cylinder model which sweeps the same volume as that of the Wankel engine. Due to rotor-crankshaft speed relationship, engine is modeled as a 3-cylinder 6-stroke unit. With pseudo cylinder bore, which corresponds to same surface area as a single rotor face, a nominal stroke is calculated[1].

Ports are modeled as Y-junctions, since a three cylinder model is used to represent the three working chambers. The three outlets converge into a single exhaust port and similarly, the inlet port diverges into three inlets for each of the cylinders. Port timings and areas are adjusted to match the actual engine data. The baseline engine model was run at engine test conditions and the baseline engine model was calibrated for test conditions. The Figure 1 shows the 1-D model of the baseline naturally aspirated Wankel engine.

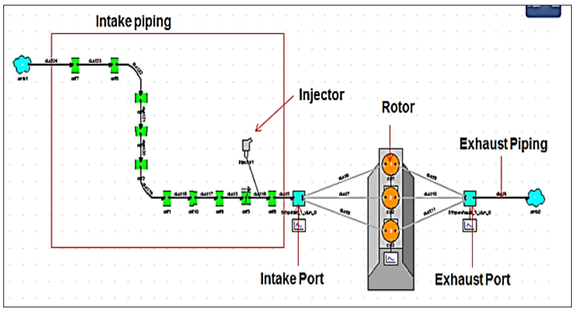

Fig.1: *1-D Model of Naturally Aspirated Wankel Engine.*

The following are the dimensional parameters of the Wankel engine used in model.

Table 1: *FRE-55 Engine Specifications.*

Parameter	**Value**
Chamber width (mm)	75.2
Displacement (cm^3)	324
Rated power, (hp)	55
Rated speed, (RPM)	8000

The above mentioned Wankel engine is replaced with 3-cylinder, 6-stroke reciprocating engine. The cylinders fire in sequence so that at an instant one cylinder delivers power output and other two cylinders are in intake and exhaust phase. Also, the 6-stroke mode makes only each cycle time to be 1080°corresponding to Wankel engine operation and the engine itself will function in four stroke mode of operation.

The default volume calculation based on stroke is overridden with instantaneous piston location *Vs* crank angle data which will amount to wankel chamber volume. The following are the parameters used for the equivalent reciprocating engine 1-D model.

Table 2: *Reciprocating Engine Parameters.*

Parameter	**Value**
No. of cylinder	3
Compression ratio	9.5
Bore (mm)	105
Stroke (mm)	37.62
Crank radius (mm)	18.81

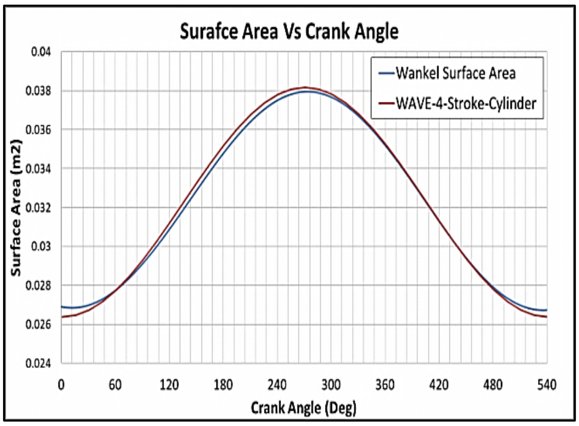

Fig1.1: *Wankel Vs Piston Engine Surface Area Matching.*

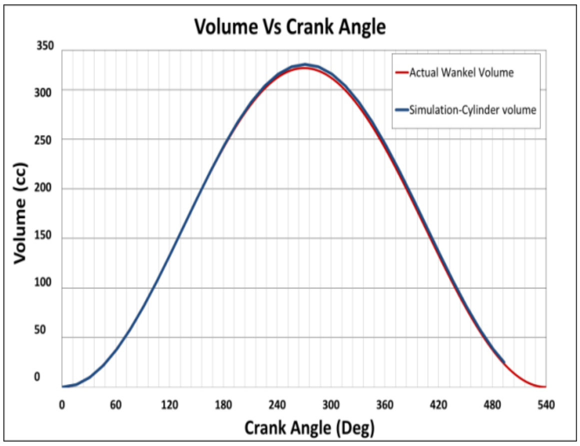

Fig. 1.2: *Wankel Vs Piston Engine Volume Matching.*

The engine was tested on the dynamometer to generate the necessary data for calibrating the 1-D model. Many of the sections in the model are based on test data and without practical data from the engine it is difficult to define the sections, particularly combustion and friction models. The co-efficient based friction model was used to model engine friction and the Wiebe combustion model was used for heat release rate modeling.

The main parameters required *viz*. the air mass flow rate, fuel flow rate, intake & exhaust air pressure and temperature, in cylinder combustion pressure and torque output were measured. Based on the measured in-cylinder pressure data, the combustion model parameters were tuned for the entire speed range of the engine.

The engine was tested both on dynamometer and thrust cradle to acquire sufficient data for model validation. In-cylinder pressure was one of the critical parameters for measurement as well as for model validation. Heat loads were estimated by mass averaged coolant temperatures and from flow rates to correlate the same with the simulation model.

As the HTC (Heat Transfer Coefficient) estimation based on Woschni correlation is not directly applicable for a Wankel engine model[1], appropriate heat transfer multipliers were used. The comparison of test data with simulation results are shown in Figure 2-5.

Fig.2: *Prototype Wankel engine on Test Bed.*

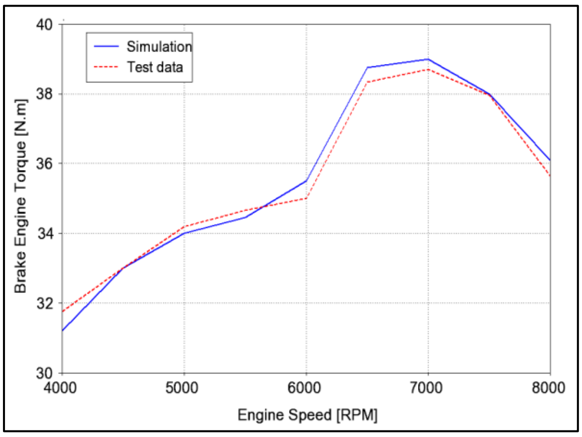

Fig. 3*: Simulation Vs Test Data-Engine Brake Torque.*

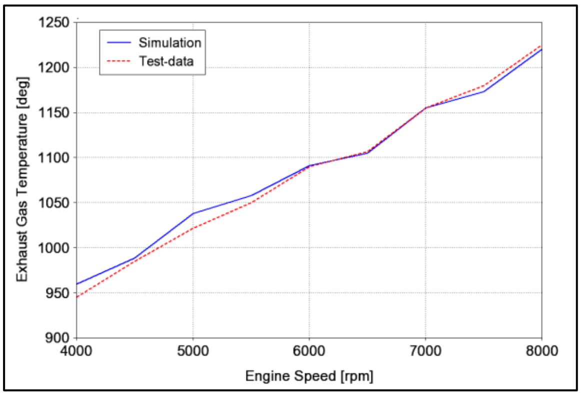

Fig. 4: *Simulation Vs Test data-Exhaust Temperature.*

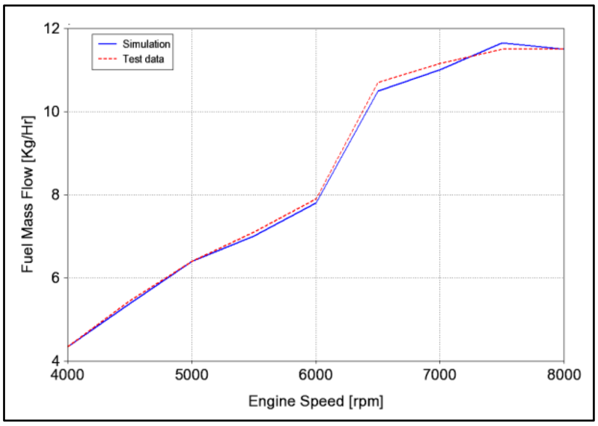

Fig. 5: *Simulation Vs Test Data-Fuel Mass Flow.*

The base model showed good correlation with the test data and proved very useful in many of the development applications. The validated base model was used as a benchmark for carrying out several optimizations and new engine development programs. Turbocharging the Wankel engine for UAV application was one such utility of the 1-D model which is described below.

TURBOCHARGED 1-D ENGINE MODEL

In a turbocharged engine model, in addition to the Wankel engine components, the turbine and compressor are modeled using physics models available within the tool. Various performance maps are required to model compressor and turbine coupled by a shaft. These maps are commonly provided by the manufacturer, measured by the particular turbocharger manufacturer using turbocharger test bench.

Turbocharger maps comprise series of data points explaining the different operating conditions of the compressor/turbine by turbo shaft speed, mass flow rate, pressure ratio, and efficiency. The compressor and turbine performance map in the form of lookup tables experimentally obtained in turbocharger test benches are fed into the 1-D model. The models used in the current process are described below:

Turbine Model

The physics model assumes that the flow in the turbine behaves in a quasi-steady manner and the mass flow and enthalpy rise across the turbine as well as the torque produced by the turbine are calculated using the lookup table data. A map of torque coefficient as a function of pressure ratio and BSR (Blade Speed Ratio*)* is automatically created at the beginning of the simulation. The BSR, mass flow and torques coefficient are defined as follows:

$$BSR^* = \frac{\pi\, D_{ref} N}{60\sqrt{2\, C_p T_i \left(1 - \left(P_i/P_o\right)^{1-\gamma/\gamma}\right)}}$$

$$\dot{m}^* = \frac{\dot{m}\sqrt{RT_i}}{P_i {D_{ref}}^2}$$

$$\tau^* = \sqrt{\frac{1}{8}\frac{\eta_t}{BSR}}$$

At each step, the pressure ratio and blade speed ratio are calculated. These are then used to interpolate the dimensionless mass flow, torque coefficient and efficiency from the map. These results are used to calculate the instantaneous mass flow, the torque, and the enthalpy drop of the turbine. But the calculated turbine power is not well predicted and must be adjusted with efficiency and mass flow multipliers[3]. The approximate values of suitable multipliers to account for the variation from experimental results have to be found out and fed into the model, especially in the closed waste gate region.

Compressor Model

Momentum Source Physics model predicts the surging behavior of a system consisting of a compressor discharging into a plenum. In this model, the compressor has two components, a planar rotor element and an output duct. The duct has a length L, and a cross sectional area A. The acceleration of the fluid in the duct depends only on the pressure at each end of the duct. Validation of this model for a radial compressor with a rotational speed that varies under compressor loading is presented by Fink D.A.[4]. The momentum balance for the compressor from the Greitzer[5] model has been implemented in the solver. The change in mass flow rate due to this momentum is shown in the following equation:

$$\frac{d\dot{m}}{dt} = \frac{A}{L}\,(P_o - P_e) = \frac{A}{L}\,P_i\left(PR - \frac{P_e}{P_i}\right)$$

In the original Greitzer model[5], the duct at the compressor exit consists of the flow passage in the compressor plus any ducting connecting the compressor to the plenum.

In the current model, the compressor discharges into a duct that has a gas-dynamic flow model, therefore, the value of compressor inductance (A/L) that would be used for the model includes only the flow passages internal to the compressor. In order to model a radial compressor, with a geometrically complex volute, a more general definition of the compressor inductance is required. The stage inductance is defined[6] by the following equation:

$$\frac{L}{A} = \int_{0}^{i-l_o} \frac{dl}{A(l)}$$

The value of l includes the flow passage from the impeller entrance to the compressor exit.

Turbocharger-Matching & Selection

The turbocharger selection and sizing is very critical, as a smaller turbocharger can go to very high speeds to produce the required pressure ratios at high altitude and a bigger turbocharger can make the operating points fall in the surge region. Thus, a careful selection of the turbocharger is necessary before going into further developmental activities. The selection procedure adopted is described as follows.

It was cost effective to choose from a commercially available turbocharger to meet the requirement if possible, than to go for a new development. Hence, the available turbochargers in this category have been evaluated and the preliminary matching was carried out.

Pressure ratio of compressor is given by,

$$\frac{P_e}{P_i} = \frac{\rho_e}{\rho_i}\left[1+\frac{1}{\eta_c}\left(\left(\frac{P_e}{P_i}\right)^{\frac{\gamma-1}{\gamma}} -1\right)\right]$$

Assuming the compressor efficiency at max power, the required pressure ratio for the desired density ratio can be calculated iteratively by matching the requirement of mass flow rate and pressure ratio on the assumed iso-efficiency line. The calculated points were then plotted on the map to identify the operating points on the turbocharger. This will give a preliminary idea of suitability of using the turbocharger for the required application.

The Figure 6 shows the matching points for the selected turbocharger on the compressor map for engine operation at high altitude. The points were calculated from the pressure ratios corresponding to the required density ratios[7]. Once the turbocharger is selected, the non-dimensional parameters are acquired for the compressor and turbine of the turbocharger; they were fed into the 1-D model. The exhaust and inlet manifolds are also modelled as in the test bed and the test results were compared with simulation data. Figure 7

The model was provided with sensors, which record the required data such as instantaneous pressure, temperature and mass flow rate which are for validating the simulation output with the test results.

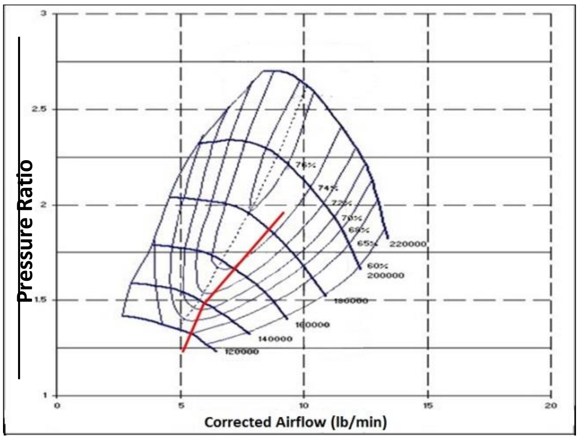

Fig.6: *Preliminary Matching Points on the Compressor Map.*

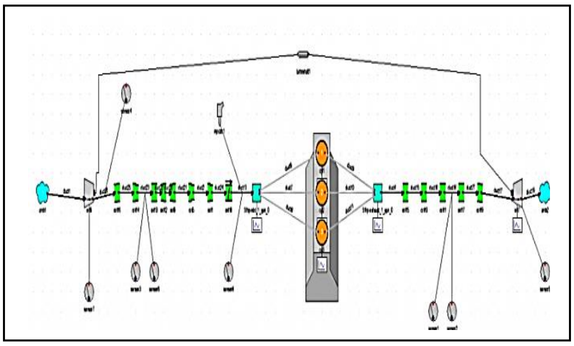

Fig. 7: *Turbocharged Wankel Engine Model.*

The main data of concern was the compressor outlet temperature & pressure and the turbine inlet temperature & pressure. The locations of the sensors in the model were kept same as that in the actual test bed engine sensors for comparison.

Turbocharger Integration & Testing

The selected turbocharger was integrated on the engine with Electronic Fuel Injection system and modified intake and exhaust manifolds. The main problem with turbocharging Wankel engine is that the exhaust temperatures are very high when compared to reciprocating engines and its sensitivity to exhaust back pressure. Based on initial calculations, it was decided that an intercooler may not be necessary in this application as the desired pressure ratios are less and also the application is already at higher altitudes where the temperatures are lesser. The oil cooling and water cooling requirements of the turbocharger were met by external systems for initial tests.

Throttle body fuel injection system was used on the engine with turbocharger. The ECU (Electronic Control Unit*)* had to be mapped for the increased air flow rate with the turbocharger. The maximum turbine inlet temperature for the selected turbocharger is 1050°C. The exhaust temperature with the turbocharger was kept below the limit by adjusting the Air-Fuel ratio.

The maximum turbine inlet temperature was kept below 950°C for most of the operating region. The cooling system was also modified to accommodate the additional loads[8]. The inbuilt waste gate actuator provided in the turbocharger was set to a boost limit of 7 psi (~0.5 Bar) which is undesirable for the current application. Hence, the waste gate actuator was replaced by a custom turbo control unit for initial testing of the turbocharger with engine.

The tests were carried out both on thrust cradle and dynamometer with turbocharger and fuel injection system at ground level. The application had serious space constraints for accommodating the turbocharger which proved critical to exhaust and intake manifold design. Although, the back pressure ground level is slightly higher for the selected turbocharger, it produces lesser back pressures at desired altitude of continuous engine operation. The conditions for fully closed wastegate operation are simulated at two different operating altitudes. The simulated turbocharger match[8] with the final integration design in propeller load is shown in the Figure 8.

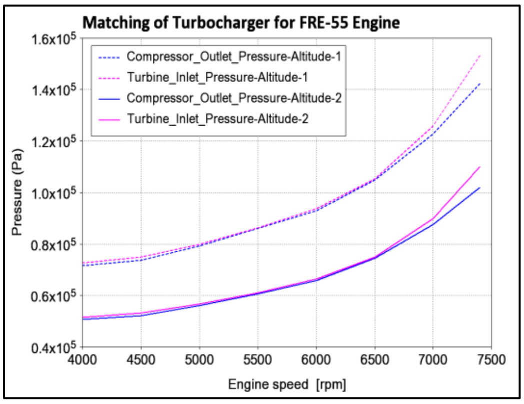

***Fig. 8:** Turbocharged Engine Model.*

The maximum exhaust back pressures, which will be produced at fully closed WGO (Waste gate opening), are sufficiently lesser. Thus, the selected turbocharger is a good match for producing full compensation in continuous engine operation region. The actual engine operating points will produce lesser back pressures as the WGO will be more than 0% above altitude1 for 6000 RPM and higher speeds.

VALIDATION OF 1-D MODEL

Comparison with Ground Level Test Data

Practical tests were carried out in propeller loaded engine to generate data for tuning and validating the 1-D turbocharged engine model. The model was initially fed with the lookup tables for compressor and turbine. To match more accurately with the experimental data, the mass flow and efficiency multipliers had to be added. This provided more accurate predictions of turbocharger performance at different waste gate openings[9,10]. The cycle based pressures at intake & exhaust manifolds were recorded against crank angle. The time and mass averaged pressure and temperature data at several locations were also used for the model tuning and validation.

The exhaust pressure against eccentric shaft angle from test bed and simulation at two different engine operating points are shown in Figures 9 and 10. The model shows good correlation with less than 6% variation from the test data.

The model predicted accurately the variation in pressures and turbocharger response with different manifold lengths and geometries. This helped greatly in deciding the appropriate manifold for the required turbocharger location and control strategy design for various operating points. Turbocharger response with Wankel engine behaves more like 4-stroke piston engines. The turbocharger in this current application had to be located at a considerable distance from exhaust port for packing purpose which reduced the pulsations at turbine inlet.

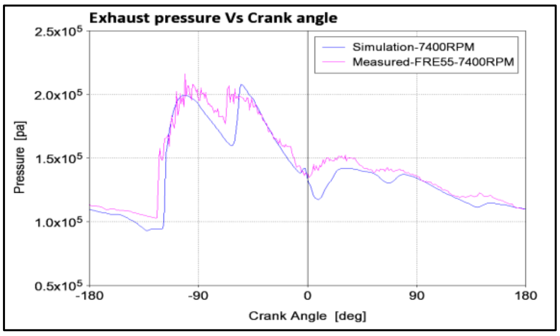

***Fig. 9:** Simulation Vs Test data-Turbine Inlet Pressure-7400 RPM.*

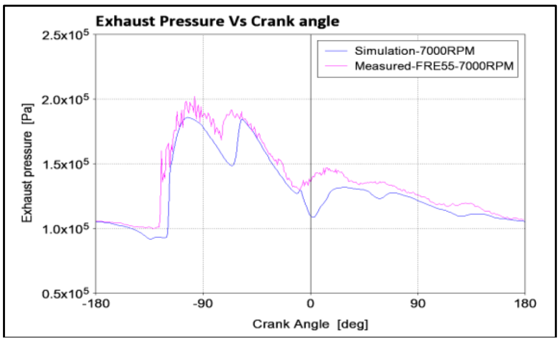

***Fig. 10**: Simulation Vs Test data-Turbine Inlet Pressure-7000 RPM.*

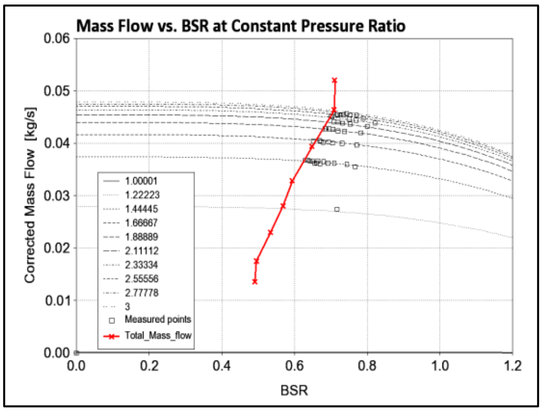

Fig. 11: *Turbine BSR Vs Total Corrected Mass Flow.*

This, along with the temperature predictions before and after turbine proved that the model was able to predict the turbine performance accurately and the turbine was a good match for the engine as predicted. The turbine mass flow against the blade speed ratio is also plotted in Figure 11 for various operating points with propeller operation.

The maximum efficiency of the turbine occurs in the BSR was around 0.7 and hence, it is desirable to select a turbine which operates in this region. The Figure 11 shows that the turbine operates in the maximum efficiency region for most of the engine operating envelope. This shows that the selected turbine is a good match for the engine in the desired operating region[3,11].

Similarly the compressor outlet pressure is measured against eccentric shaft angle and compared with simulation results. The Figures 12 and 13 show the measured and simulated data. This also shows correlation with measured data except for the instantaneous peak values being marginally higher. This can be attributed to the mismatch of excitation from piston which does not occur in case of practical Wankel engine test data. But, the variation is still below 4.5% which is a sufficiently accurate prediction. The port flow coefficient values which were assumed from available literature may also contribute to the variations from practical data.

The data plotted is for (–180° to +180°) 360° of eccentric shaft angle which corresponds to one-third of rotor revolution or one combustion cycle of the Wankel engine.

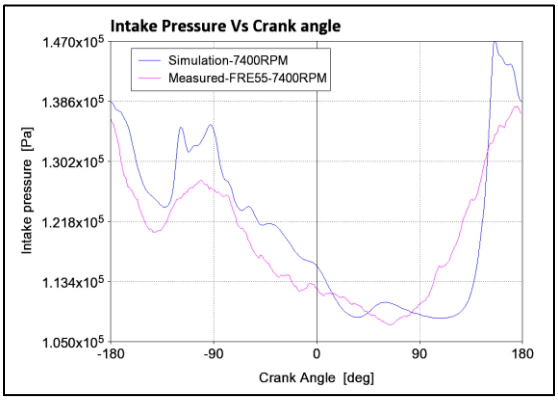

Fig. 12: *Simulation Vs Test data-Engine intake pressure-7400 RPM.*

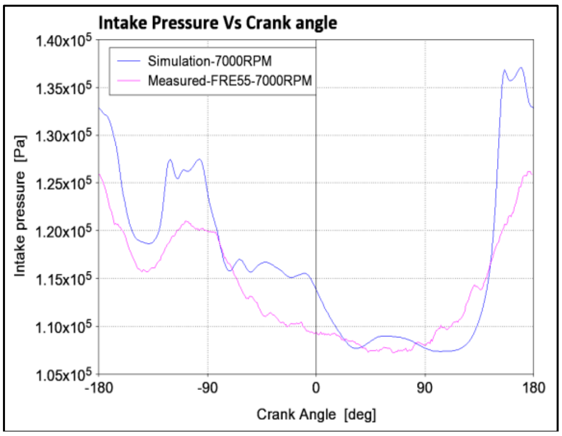

Fig. 13: *Simulation Vs Test data-Engine intake pressure-7400 RPM.*

The time averaged pressures at different locations and mass averaged temperatures were also used to validate the 1-D turbocharged Wankel engine model. Figure 7. The model showed excellent correlation[12] with steady state data with less than 3% variation from the test results, as shown in Figures 14, 15 and 16.

The model showed sufficient correlation with test results and was further used to optimize the exhaust manifold, ECU tuning and waste gate control.

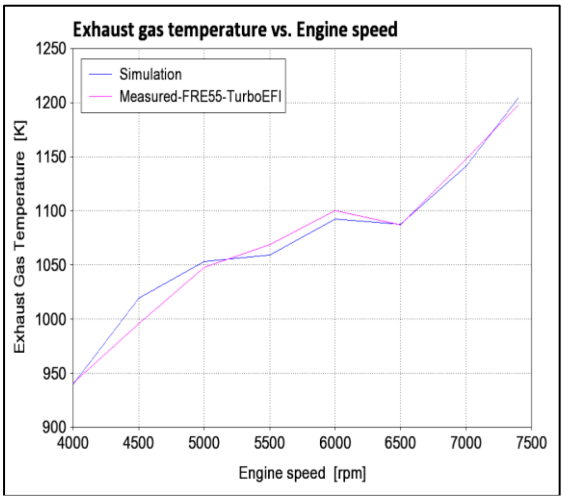

Fig. 14: *Simulation Vs Test data-Exhaust Gas Temperature.*

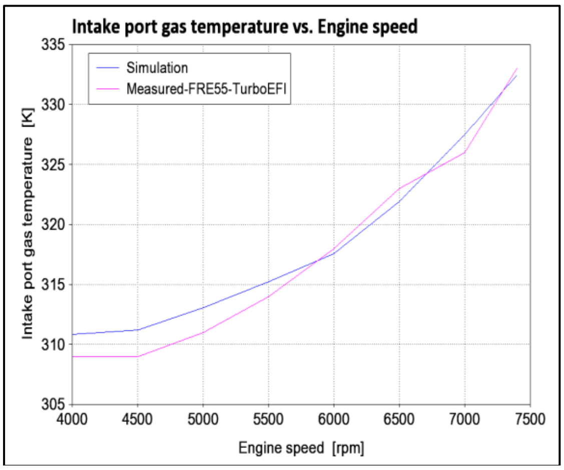

Fig. 15: *Simulation Vs Test data-Compressor Outlet Temperature.*

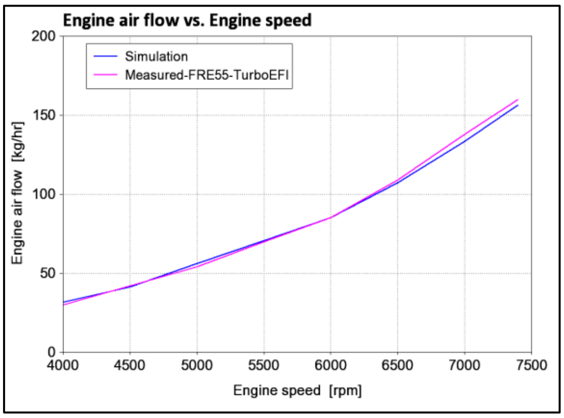

Fig.16: *Simulation Vs Test data-Engine Air Mass Flow.*

One of the major advantages of such a well correlated model is the ability to simulate the performance of the engine at high altitudes since the engine in context is used for UAV propulsion. With the completion of the ground trials of the turbocharged engine, the model served as a backbone for arriving at the operating limits, control parameters and performance of the engine at various altitude conditions.

STEADY MATCHING PREDICTION

Ground Level Matching Points

The calculation of steady matching could be performed by starting from changing the waste gate opening and finding those satisfying the equilibrium in both mass flow rate and pressure ratio[3].

The Figure 17 shows the operating points over the speed range plotted on the compressor map at various Waste gate openings for ground level engine operation. At 100% WGO, it can be seen that compressor is operating in low efficiency region. Although this is undesirable, the required pressure ratio at ground level is less and hence the turbocharger produces the required boost for the engine. As the waste gate is closed further, the pressure ratio at output increases and this will produce an excessive boost which is not required. Initially, the compressor operates in low efficiency region but continuous engine operation will be above altitude-1 and this is where the turbocharger operation is desired.

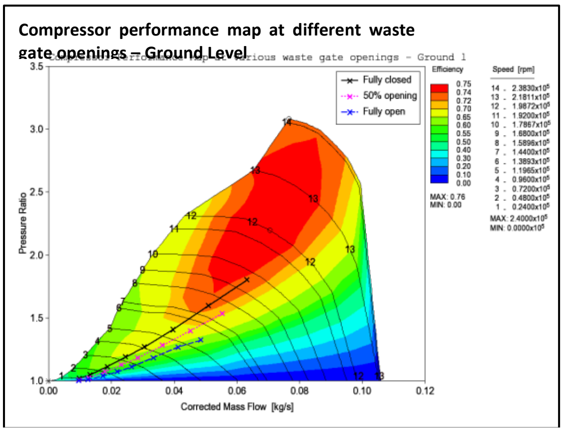

Fig. 17: *Predicted Compressor Match at Ground Level.*

The boost pressure produced with this turbocharger will meet all the requirements at ground level for the necessary power increase and maintain temperature limits. The simulated operating points as plotted on the compressor map for ground level operation has been validated with test data.

Matching Points for Altitude-1

The Figure 18 shows the operating points over the speed range plotted on the compressor map at various waste gate openings for engine operation at altitude-1. At 0% WGO, it can be seen that compressor is operating in the maximum efficiency region of 75% at max speed and with the waste gate further opened, the compressor operating efficiency falls to 70% land with pressure ratio of 1.5 which still meets the performance requirement. Hence, it was concluded that this compressor will meet all the requirements at this operating region. The operating range for the turbocharger from ground level to altitude-1 will be within the 100% WGO to 50% opening where the required pressure ratios are met with high compressor and turbine efficiency. The operating area within this can be predicted accurately and fed as an input for the turbo control unit over the range of altitudes and loads of engine operation with propeller.

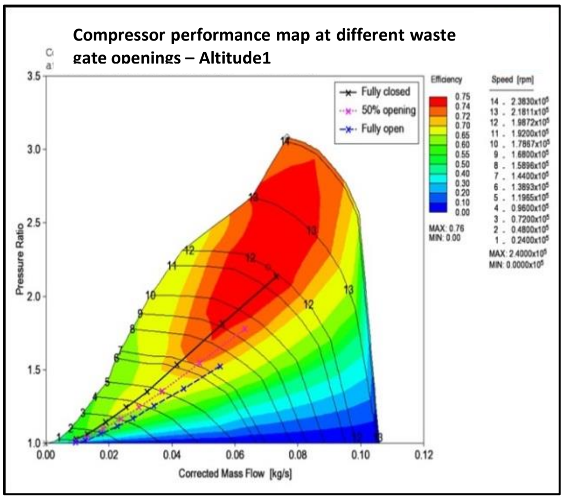

***Fig. 18**: Predicted Compressor Match at Altitude-1.*

Matching Points for Altitude-2

The turbocharger speed is a critical parameter in enhancing turbo life and hence, it must be within limits at all conditions. Reaching the limiting speed is one of the main failure causes for turbochargers. Especially in a high altitude application, where the turbine side pressure ratio is continuously increasing, the chances of reaching the limiting speed are very high. The simulation model is here used to predict the operational limit in terms of engine speed as well as load for the turbocharger. Figure 19

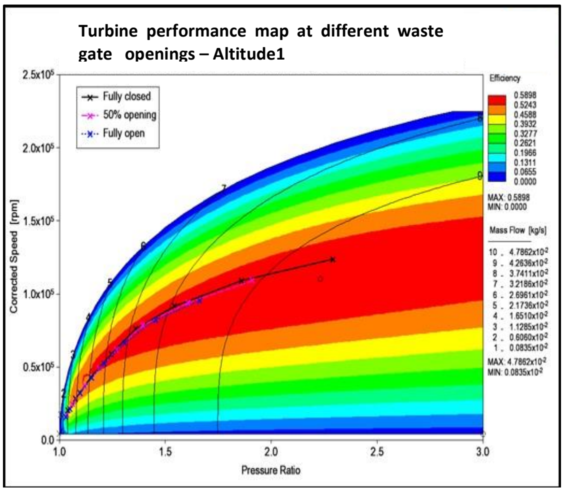

***Fig.19:** Predicted Turbine Match at Altitude-2.*

The operating points over the speed range were studied with compressor map data at different waste gate openings for engine operation at altitude-2. A margin of 10% for the limiting speed for turbocharger was considered while designing the operational limit for the engine. The limiting speed of the turbocharger limits the operational altitude of the UAV.

But the power requirement at higher altitude also reduces which in turn reduces the output reqsuirement from the engine and turbocharger.

The selected turbocharger operates mostly in the high efficiency land over the operational range of the engine which is in-between altitude 1 and 2. Also, it operates with little margin for surge which needs to be addressed further. Thus, from the simulations at altitude-2 it can be concluded that the selected turbocharger is matching the engine requirement for the application.

SUMMARY AND CONCLUSION

Commercially available piston engine 1-D software has been used to develop a turbocharged Wankel engine model. Standard models available within the software were used to model the engine with use of multipliers wherever necessary. Fixed radial turbine with map data was modeled using standard physics and fixed centrifugal compressor with map data was modelled using the momentum source physics model.

The results of the model were well correlated with test data of prototype turbocharged engine. The developed simulation approach has been validated using the prototype FRE (Flight Rotary Engine)-55 turbocharged engine.

The simulated turbine inlet pressure and compressor outlet pressure have been validated with test bed data. The model has also been validated with air mass flow rate, fuel flow rate, exhaust temperature, heat loads, and intake gas temperature and cylinder pressure at various engine operating points. The model was found to show satisfactory correlation with practical data.

The model proved its utility in turbocharger selection, design of high temperature manifolds, performance tuning, high altitude correction factors prediction, turbo control unit design and full engine performance prediction at different operating points. Different turbochargers were tested virtually on the model to identify the performance match with Wankel engine for selection of suitable turbocharger for high altitude application

NOMENCLATURE

N	Rotational speed
D_{ref}	Reference diameter
R	Universal gas constant
m	Mass flow rate
Ti	Inlet temperature
Pi	Inlet pressure
h_t	Turbine efficiency
Po	Pressure at rotor outlet
Pe	Pressure at compressor exit
Pi	Pressure at rotor inlet
l	Meridional distance along the flow passage in the compressor
ρ_e	Compressor outlet density
ρ_i	Compressor inlet density
η_c	Compressor efficiency
η_t	Turbine efficiency

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