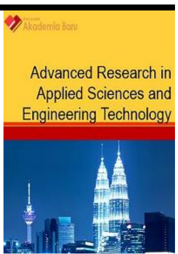
Journal of Advanced Research in Applied Sciences and Engineering Technology 23, Issue 1 (2021) 18-25

Penerbit Akademia Baru

Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage: www.akademiabaru.com/araset.html
ISSN: 2462-1943



Altitude Performance and Fuel Consumption Modelling of Aircraft Piston Engine Rotax 912 S/ULS

Murat Otkur[1,*]

[1] Mechanical Engineering Department, College of Engineering and Technology, American University of the Middle East, Kuwait

ABSTRACT

Rotax 912 spark-ignition (SI) naturally aspirated aircraft piston engine is one of the most popular prime movers for the ultra-light weight aircrafts used for short and moderate range flights. SI engines operate at stoichiometric combustion and at high altitude conditions atmospheric pressure is lower than sea level reducing mass of air intake to the engine. At these conditions engine power degrades significantly from sea level, affecting flight parameters such as range and endurance. In order to optimize these parameters, engine power modelling is of vital importance. Within the scope of this study, a thermodynamic SI engine model with performance parameters (break torque and power) and fuel consumption estimation developed in MATLAB/Simulink software. Model tuning is realised using data extracted from Rotax engine operating manual at sea level and high altitude conditions. Model inputs are set as altitude, throttle lever and engine speed. Pressure drop at the intake port is modelled as a function of mass air flow using engine operating manual pressure data at various engine speed points. Mass air flow is determined via employing a volumetric efficiency map based on intake port pressure and engine speed inputs, calibrated using engine operating manual fuel data considering stoichiometric combustion. Compression and expansion strokes area modelled as isentropic events and combustion is modelled as constant volume heat input at top dead centre (TDC). However a combustion efficiency map based on engine speed and fuel flow is employed for the heat input in order to tune the work output of the engine and heat loss to the coolant and exhaust. Pumping loss is calculated based on friction mean effective pressure data. Introduced approach provides high accuracy performance and fuel consumption modelling based on engine operating manual data and can be used for flight parameters optimization studies.

Keywords:
Fuel Consumption; Rotax 912 spark-ignition; aircraft piston engine

Received: 28 July 2020 **Revised: 8 October 2020** **Accepted: 2 February 2021** **Published: 31 May 2021**

1. Introduction

Rotax aircraft engines is the most used internal combustion engine (ICE) for ultra-light aircrafts with over 175000 units sold since 1975 and 40000 of them are still in active use. One of the two models of current production portfolio is Rotax 912 engine family that started production in 1989 and more than 50000 engines were sold as of 2012 [1]. Rotax 912 ULS/S is the best-selling four-stroke aircraft engine offering best power to weight ratio in its class and a time between overhauls of 2000 hrs. [2]. It is an opposed four cylinder liquid/air cooled engine generating 128 Nm max torque at 5000 rpm and 73.5 kW power at rated speed of 5800 rpm.

---

[*] *Corresponding author.*
E-mail address: Murat.Otkur@aum.edu.kw

https://doi.org/10.37934/araset.23.1.1825

Performance modelling of ICEs is of vital importance considering engine selection of aircrafts to obtain the optimum performance parameters. As a result, various researchers modelled and investigated performance of ICEs. Luongo *et al* performed a 1-D simulation with six different engine configurations in order to find the highest power to weight ratio with the least voluminous configuration [3]. Using AVL Boost software, Grabowski *et al* developed a 1-D engine model with simulation capabilities of air flow through the air intake system components as inlet pipes, carburetors, intake manifold and valves and as well as combustion simulation. Laboratory bench testing established using the actual engine in order to find the engine parameters that are not listed in the Rotax engine catalogue. Authors have successfully simulated engine performance parameters: torque, power and fuel consumption for various testing points [4]. Similarly, Donateo *et al* developed a 1-D engine model using AVL Boost software in order to investigate the performance of a turbocharged 2 stroke diesel engine that is matched with a medium-altitude, medium-endurance unmanned aerial vehicle (UAV). Simulations were performed at various engine speed, air fuel ratio and flight altitude values [5].

Environmental pressure drop at elevated altitude conditions significantly effects engine performance due to reduced intake air mass, which results significant derated engine power output with respect to sea level. This phenomenon degrades endurance and range flight parameters of the plane calculated with engine performance specifications at sea level condition. As a result, it is very important to model the performance of the engines for high altitude conditions considering it is one of the state-of-the-art research topics for aeronautical and mechanical engineer. Ommi and Mansouri generated a 1-D model in GT-Power software for the Rotax 914 turbocharged engine and investigated the performance of the aircraft at the climb phase of flight [6]. The model contains engine and air intake system components such as air intake manifold, inlet and outlet valves, piston, cylinder, crankshaft, exhaust manifold and turbocharger. Carlucci *et al* developed 0/1-D engine model in AVL Boost software for a 6-cylinder 2-staged turbocharged engine with two intercoolers and analyzed altitude capability with an optimization study related with the charging system for aircraft propulsion performance [7]. Kreyer *et al* built an engine model with altitude simulation capability employing a map based algorithm in order to determine fuel consumption with respect to flight altitude [8]. In GT-Suite software authors developed a 1-D engine model that is capable of analyzing the gas exchange and combustion processes taking into consideration friction and heat losses for various altitude scenarios. Fuel consumption simulation results from the GT-Suite were used to generate fuel consumption maps for different engine configurations.

2. Thermodynamic engine modelling

ICEs convert chemical energy generated from combustion of the fuel to mechanical energy via continuous rotation of the crankshaft. Considering aviation practices torque and fuel consumption estimation is of vital importance for range and performance calculations. Ultra-light weight aircrafts are generally equipped with ICEs using gasoline fuel. Gasoline engines rely on “Otto cycle” (Figure 1) and due to emissions considerations generally operated with stoichiometric combustion where excess air ratio is equal to 1. In an ideal cycle representation for a four-stroke gasoline engine, it is assumed that the homogeneous air fuel mixture is combusted at an instant with the activation of the spark plug at TDC therefore heat input is considered to be at constant volume. In a similar manner heat output is assumed to be realized at constant volume when the piston is at bottom dead center (BDC) with the assumption that at the instant of the exhaust valve opening all the exhaust is deported from the combustion chamber. Both expansion and compression events are considered as adiabatic assuming no heat transfer.

For the compression stroke until start of combustion process, in cylinder temperature and pressure curves are calculated based on the polytrophic compression equations 1 and 2 using reference volume and pressure values at the end of the intake stroke.

$$V^{(k-1)}\,T = {V_1}^{(k-1)}\,T_1 \tag{1}$$

$$P\,V^k = P_1\,{V_1}^k \tag{2}$$

where k is defined as the specific heat coefficients ratio (c_p/c_v).

For AVGAS 100LL airplane fuel with lower heating value of 44000 kJ/kg, heat input is calculated using equation 3 and heat loss to exhaust and coolant is estimated employing a combustion efficiency map similar to the reference study as shown in figure 2.

$$Q = m_{fuel}\,H_u\,\eta_{combustion\_eff} \tag{3}$$

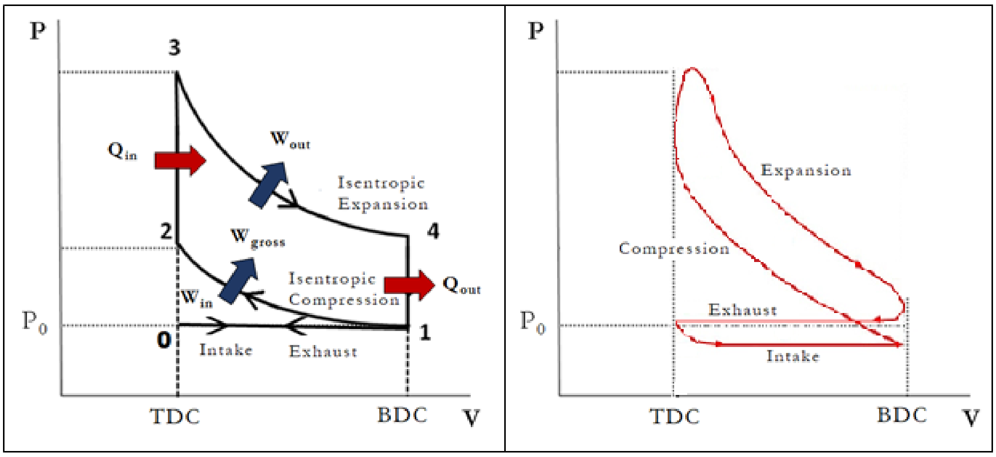


Fig. 1. Ideal (left) and actual (right) Otto cycles pressure – volume (PV) representation

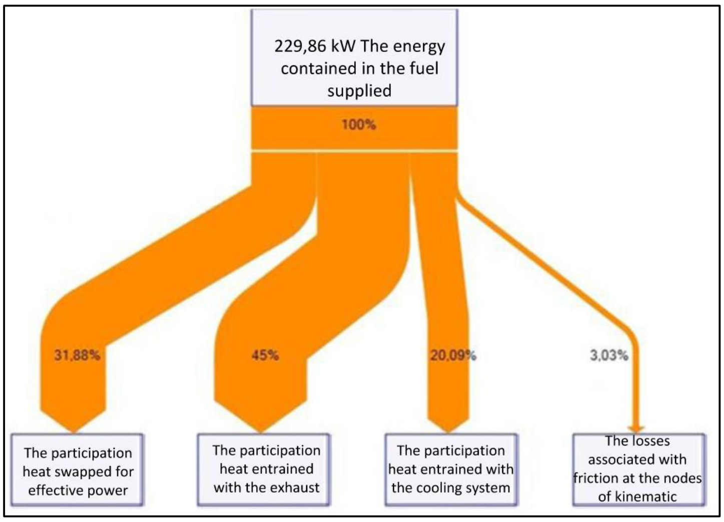


Fig. 2. Sankey diagram for Rotax 912S engine showing the total energy loss to exhaust and cooling system for a specific flight simulation [9]

Temperature rise during combustion phase is calculated using equation 4 and thermodynamics 1st law ($\Delta U = Q - W$) and assuming zero work at constant volume combustion as there is no volume change.

$$\Delta U = Q = m_{air}\,c_v\,\Delta T \tag{4}$$

Pressure at the end of the combustion process is calculated using ideal gas equation (*P V = m R T*) and isentropic equation 2 is used to calculate pressure values during the expansion stroke employing reference pressure and volume values at TDC after the combustion process.

As the combustion and exhaust events are assumed to be realized at constant volume, for calculating the gross work of the gasoline cycle, compression and expansion stroke pressure values are integrated with respect to engine volume as shown in equation 5.

$$W_{gross} = \int_{\theta=-\pi}^{\theta=\pi} P(\theta)\, dV(\theta) \tag{5}$$

Pumping loss work is calculated using pressure difference between intake and exhaust ports employing equations 6, 7 and 8.

$$P_{in} = P_{atm} - P_{inlet\_depression} \tag{6}$$

$$P_{exh} = P_{atm} + P_{exhaust\_back\_pressure} \tag{7}$$

where $P_{inlet\_depression}$ *and* $P_{exhaust\_back\_pressure}$ are determined based on air and exhaust flow pressure losses respectively as shown in figure 3.

$$W_{pump\_loss} = (P_{exh} - P_{in})\, V_d/(2\,\pi\, i) \tag{8}$$

where V_d is the cylinder displacement volume and *i* is set as 2 for 4-stroke engines considering the number of revolutions per cycle.

Engine net work and indicated torque values are calculated using equations 9 and 10 respectively.

$$W_{net} = W_{gross} - W_{pumping\_loss} \tag{9}$$

$$T_{in} = W_{new}\,\frac{n_c}{4\pi} \tag{10}$$

where n_c is the total cylinder number.

Engine brake torque is calculated as subtracting the friction torque from the indicated torque using equation 11.

$$T_{br} = T_{in} - T_{fr} \tag{11}$$

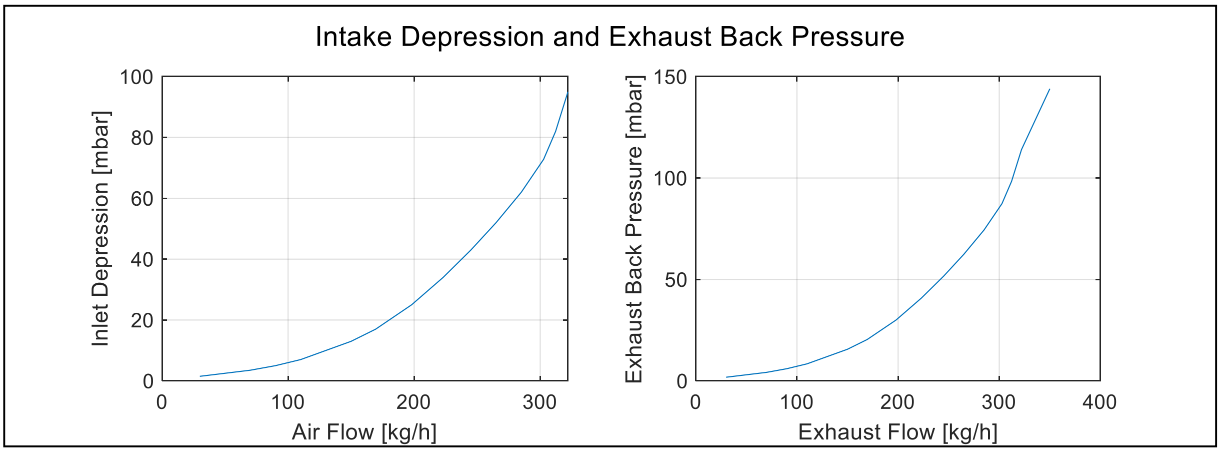


Fig. 3. Intake air pressure loss (left) and exhaust back pressure (right) curves

3. MATLAB/Simulink engine modelling and results

MATLAB/Simulink program is used to develop an analytical engine model with performance and fuel consumption estimation capability as shown in figure 4. Inputs to the model are flight altitude, lever position and engine speed. Ambient air pressure and temperature values are calculated employing look-up tables based on the values shown in figure 5. Engine friction torque data is inherited from the study of Grabowski *et al*. as shown in figure 6 [4]. Power, torque and fuel consumption values are calculated as model outputs based on analytical equations 1-11.

Rotax 912 series operator's manual data is used to determine the parameters used in the MATLAB/Simulink model as shown in table 1 [2].

Table 1
Technical combustion parameters data of the Rotax 912 S/ULS

Parameter	Value
Bore	84 mm
Stroke	61 mm
Displacement	1352 cm^3
Compression Ratio	11:1

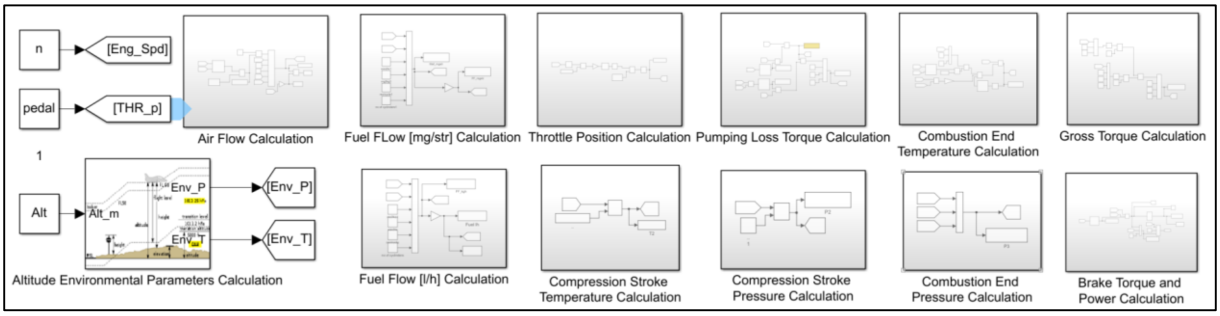


Fig. 4. Matlab/Simulink engine model

Two 2-D look up tables are employed in the Simulink model to tune the mass air flow for the volumetric efficiency and the generated combustion process heat output. Using operating manuals sea level and high-altitude full load data, a volumetric efficiency map with intake port pressure and engine speed input parameters is developed as shown on the surface plot at figure 7. Mass airflow of the engine is calculated based on this volumetric efficiency map. It can be clearly seen from the surface plot that the volumetric efficiency decreases with increasing engine speed and decreasing intake air pressure decreases in accordance with physical law expectations. Using the same engine data from operating manual, a combustion efficiency map with fuel flow and engine speed inputs is developed to determine the net heat generated subtracting heat loss to exhaust and coolant as shown on figure 7. Combustion end pressures and temperatures are calculated based on net heat generated using the combustion efficiency map equation 4 and ideal gas equation.

Developed engine model is capable of predicting sea level engine performance and fuel consumption values with high accuracy (Figures 8 and 9). Furthermore, developed model works considerably well for high altitude conditions. Model simulations are shown with respected to engine performance data in figure 10 for both sea level and high-altitude conditions and it can be clearly seen that engine model predictions are well matched with the operating manuals data.

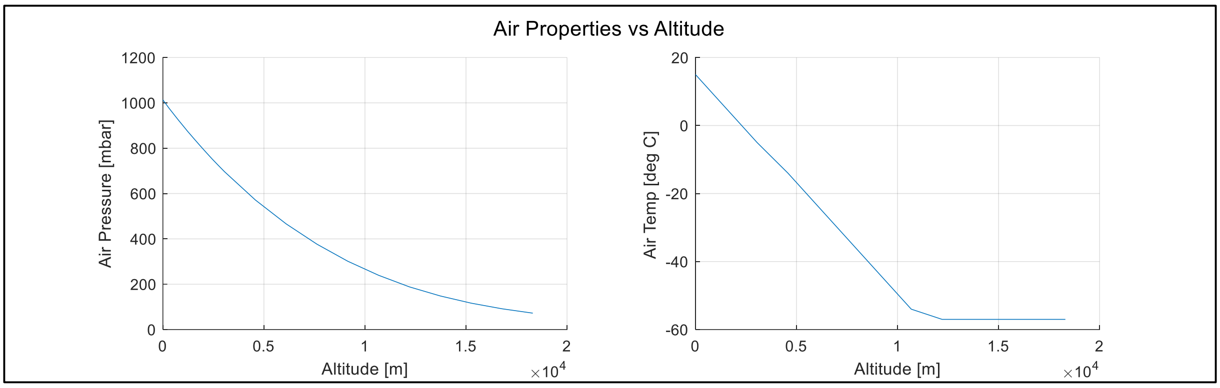


Fig. 5. Ambient air properties with respect to altitude

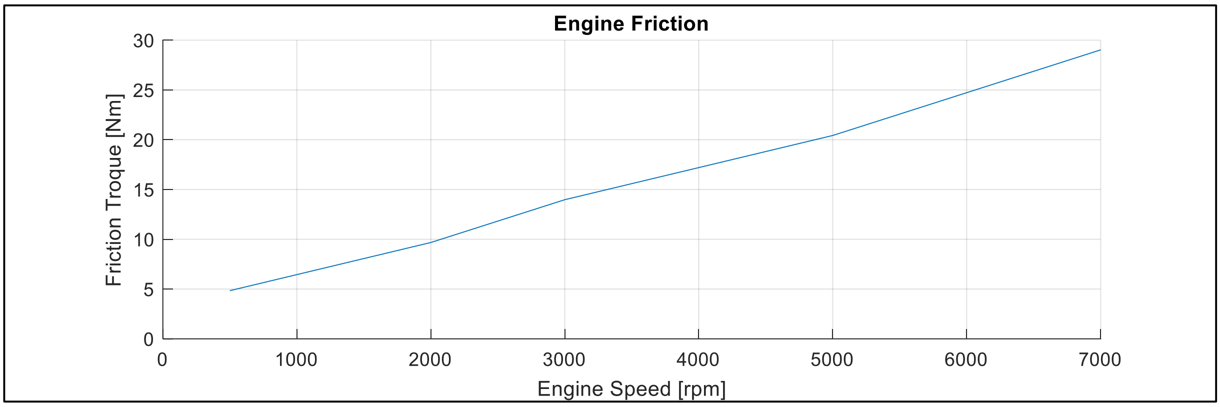


Fig. 6. Rotax 912 engine friction torque [4]

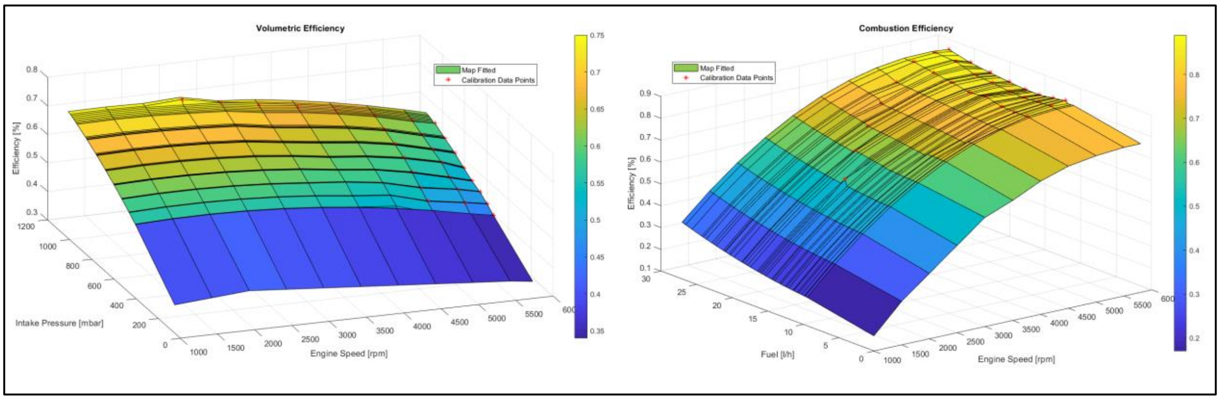


Fig. 7. Volumetric efficiency and combustion efficiency tuning maps fitted based on provided data from operating manual

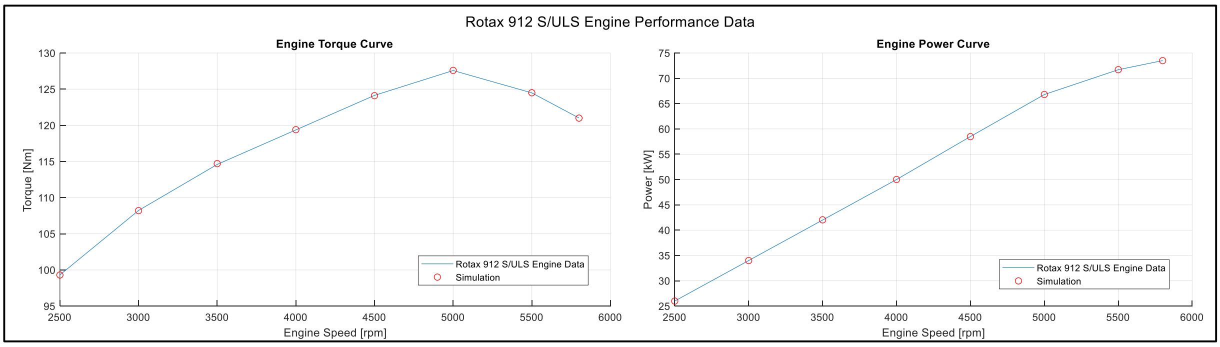


Fig. 8. Full load performance data at sea level

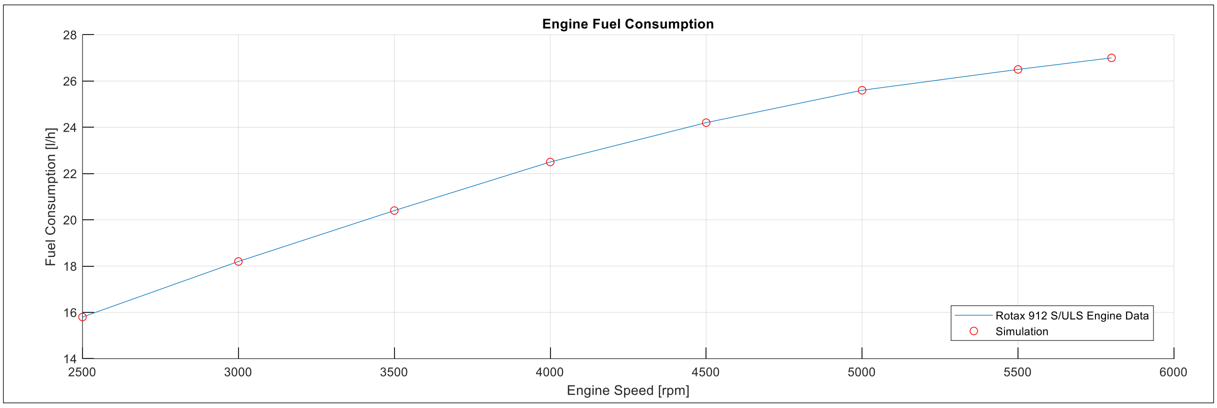


Fig. 9. Sea level full load fuel consumption

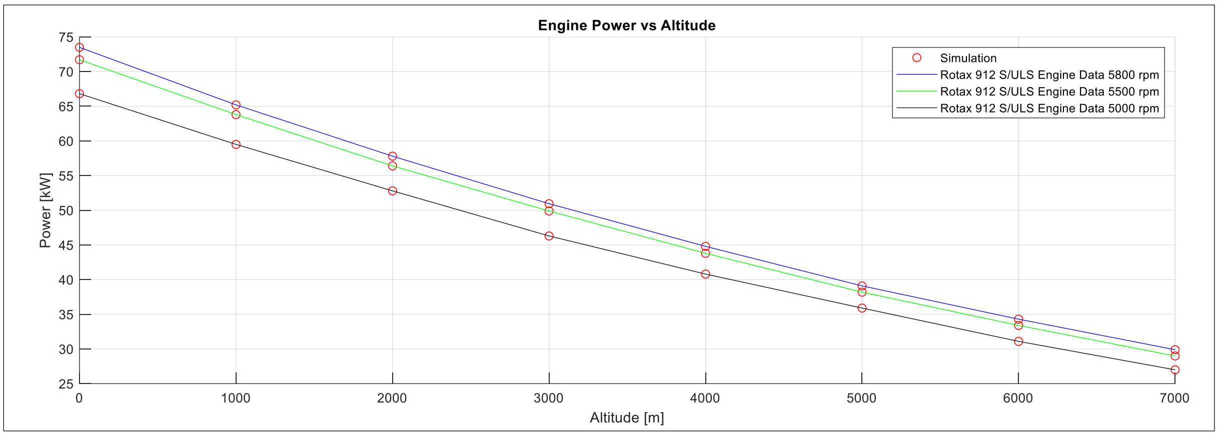


Fig. 10. Up to 7000 m altitude full load rated power

4. Conclusion

An analytical thermodynamic combustion model is developed in MATLAB/Simulink for simulating generated torque and power values, and fuel consumption with altitude capability for Rotax 912 S/ULS engine. Analytical model uses two 2-D calibration maps: Combustion efficiency and volumetric efficiency with engine speed as the common axis for both maps and fuel consumption and intake pressure are the remaining axes respectively. Rotax engine operating manual provided by manufacturer is used to extract the engine performance values for full load conditions between 2500 - 5800 rpm engine speed range at sea level and up to 7000 m altitude for every 1000 m interval for engine speed values of 5000, 5500 and 5800 rpm in order to calibrate the stated maps. Developed MATLAB/Simulink model is rather simple and capable of predicting engine performance data and fuel consumption values with high accuracy and low computational load.

5. Future work

Developed MATLAB/Simulink model will be used as power source for ultra-light weight aircraft for flight parameters optimization such as endurance and range using genetic algorithm. Additionally, model capability will be improved with the addition of turbocharger that will allow simulating the engine performance and fuel consumption for Rotax 914 UL/F engine.

References

[1] Dopona, Michael, Nigel Foxhall, and Christoph Dutzler. *912iS fuel injected aircraft engine*. No. 2012-32-0049. SAE

Technical Paper, 2012. https://doi.org/10.4271/2012-32-0049

[2] ROTAX 912 ULS/S Engine specifications,viewed 31 July 2020, https://www.flyrotax.com/pr-odukte /detail/rotax-912-uls-s.html

[3] Luongo, Andrea, Patrizio Nuccio, and Marcello Vignoli. *Optimization of a light aircraft spark-ignition engine*. No. 2006-01-2420. SAE Technical Paper, 2006. https://doi.org/10.4271/2006-01-2420

[4] Grabowski L, Siadkowska K and Skiba K 2019 *MATEC Web of Conferences* 252:05007. https://doi.org/10.1051/matecconf/201925205007

[5] Donateo, Teresa, Luigi Spedicato, Gianluca Trullo, A. Paolo Carlucci, and Antonio Ficarella. "Sizing and Simulation of a Piston-prop UAV." *Energy Procedia* 82 (2015): 119-124. https://doi.org/10.1016/j.egypro.2015.12.003

[6] Mansouri, Hossein, and Fatholah Ommi. "Performance prediction of aircraft gasoline turbocharged engine at high-altitudes." *Applied Thermal Engineering* 156 (2019): 587-596. https://doi.org/10.1016/j.applthermaleng.2019.04.116

[7] Carlucci, Antonio Paolo, Antonio Ficarella, and Gianluca Trullo. "Performance optimization of a Two-Stroke supercharged diesel engine for aircraft propulsion." *Energy Conversion and Management* 122 (2016): 279-289. https://doi.org/10.1016/j.enconman.2016.05.077

[8] Kreyer, J. O., M. Müller, and Thomas Esch. *A map-based model for the determination of fuel consumption for internal combustion engines as a function of flight altitude*. Deutsche Gesellschaft für Luft-und Raumfahrt-Lilienthal-Oberth eV, 2020.

[9] Grabowski, Lukasz, Zbigniew Czyz, and Krzysztof Kruszczynski. *Numerical analysis of cooling effects of a cylinders in aircraft SI engine*. No. 2014-01-2883. SAE Technical Paper, 2014. ttps://doi.org/10.4271/2014-01-2883