Effect of Flight Altitude on the Knock Tendency of SI Reciprocating Turbocharged Engines

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Abstract

This paper provides an analysis of the effect of a flight altitude on knock occurrence in reciprocating SI turbocharged engines. It presents results of the computational study aimed at investigating reasons leading to knock occurrence and methods of alleviating the knock tendency of small aircraft engines. Turbochargers are frequently used to improve the performance of aviation platforms at high altitudes. Although a turbocharger provides the benefits of increased power, improved BSFC and a downsized engine, it can result in engine knock because of increasing the intake air temperature, due to a rise in the compression ratios as the air density drops. Aerial platforms experience environmental conditions that can change drastically in a matter of a few minutes. Therefore, it is important to be aware of the combined effects of altitude, initial ground temperature, humidity, flight velocity and fuel octane numbers on the emergence of knock following takeoff. A novel approach was suggested for assessing the joint influence of various ambient and operating parameters on knock appearance in a turbocharged aircraft engine that can be used for knock risk and severity evaluation prior to takeoff, during a flight and for taking measures to prevent knock at real-time operation. Conditions that may provoke knock during certain flight circumstances were identified and analyzed. Possible methods of in-flight knock prevention, such as water injection, retarded ignition, EGR, intercooling etc. were analyzed.

Introduction

Knock phenomenon has been extensively studied over the years, and has been an influencing factor on the development of SI engines. Knock (or detonation) is an abnormal combustion in the cylinder of SI ICE, caused by an undesired flame front or auto ignited pockets formed inside the cylinder in addition to the flame initiated from the spark plug. Knock is a result of self-ignition of end-gas heated above the auto-ignition point when the time available before flame-front arrival is longer than the auto-ignition delay time (induction time). This phenomenon can lead to decrease in power output, reduction in engine's energy efficiency, increase in the pollutants emission and even lead to a total destruction of an engine in the worst case [1], [2], [3], [4].

To address the problem, it is necessary to identify knock while happening and to understand the main factors influencing its occurrence. There are many methods available to detect engine knock: Cylinder pressure analysis - Direct measurement of the in-cylinder pressure by an intrusive pressure sensor inside the cylinder head [3], Engine block vibration analysis [5], Exhaust gas temperature measurements [6], Intermediate radicals and species analysis [3], Heat release analysis [7], etc.

The end-gas temperature and the time available before flame arrival are the two fundamental variables that determine whether or not knock will occur [3], [4], [8], [9]. As a result, the methods developed to treat and prevent this phenomenon are manifested in affecting those parameters directly or indirectly. One of the most influential parameters is the end-gas temperature, and therefore, most of the knock treatment methods address this direction. For existing engines, optimization and improvement of the cooling system [10], [3] can be an effective method of knock prevention. Retarded ignition is a simple and efficient knock mitigation method widely applied in the automotive industry [11]. Also decrease in compression ratio [3], introducing inert gases [12], including EGR [13], water injection [14], etc. are used sometimes. Other methods address the combustion time through affecting the fuel octane number [2], the lubricants reactivity [15], in-cylinder turbulence [10] or using DI of second fuel [16], [17], [18].

Altitude effect on fuel's octane requirements and knock tendency have been studied in [19], [20] and the responses of various engine control parameters were measured at an altitude of 1500 meters [21]. In naturally aspirated engine, the altitude effect on knock tendency is positive, but comes on expense of power output. The air density decreases at higher altitudes. The latter results in a respective reduction in amount of the injected fuel, thus leading to lower temperatures and pressures inside the combustion chamber and less knock [21]. In aviation, the altitude differences lead to a relatively large difference in ambient pressure in comparison to automotive applications and the power output drops drastically. One of the most common used methods of engine power keeping at high flight altitude is turbocharging. The latter compensates for the air density losses and expands the ability of the aerial platform to operate at high altitudes and also to improve the BSFC. The disadvantage of this method is the raise in sensitivity to knock occurrence due to higher temperatures after the compressor. This problem exacerbates with the altitude increase, because the decrease in air density results in higher compressor pressure ratios. In addition, the aerial platforms experience environmental conditions that can change drastically in a matter of a few minutes in terms of temperature, air density, humidity, and air flow. The range of the possible change in those parameters is wider than in automotive application and therefore, the chance of encountering a combination of parameters that will provoke knock is higher. Although aerial SI engines can benefit and improve from the research on knock on the automotive engines, many mitigation methods cannot be implemented on aerial platforms due to different operating conditions and requirements. This study was performed to identify and classify the various parameters and their combinations critical to appearance of knock in SI turbocharged engines of aerial platforms, and to suggest an approach that will allow assessing joint influence of those parameters on knock appearance in the aircraft engine prior to takeoff and during a flight for knock risk evaluation and taking measures to prevent knock. Consequently, an additional goal was to analyze knock-prevention solutions that can be suitable for an existing aerial platform in terms of their cost, weight and complexity, in order to be implemented as the aforementioned measures for knock mitigation.

Methodology

A computer model of the engine was built using the GT-SUITE software (Figure 1). The engine that was used as a base for this study is a 4-cylinder SI four-stroke turbocharged engine Rotax 914 (see Table 1), which is in wide use in aerial platforms. The Rotax 914 has 2 spark plugs per cylinder and the cylinder head is water- and air-cooled. The ignition in Rotax 914 is carried out using two spark plugs per cylinder (40 mm vertical distance between each other). The first of the two plugs ignites at this operating mode at 26° BTDC. We assumed in these simulations that both spark plugs were fired simultaneously.

Table 1. Rotax 914 specifications.

Displaced volume	1211 cm^3
Stroke	61 mm
Bore	79.5 mm
Connecting Rod	105.5 mm
Compression ratio	9:1
Number of Valves	2
Maximum power (5 minutes)	115 HP/84.5 kW @ 5800
Rated power (sustained)	100 HP/73.5 kW @ 5500
Maximum torque	106 ft-lb / 144 N · m@ 4900
Lambda	0.79-0.85
Spark timing	26^o BTDC
Boost target	1.21 bar (1.35 @ 5800)

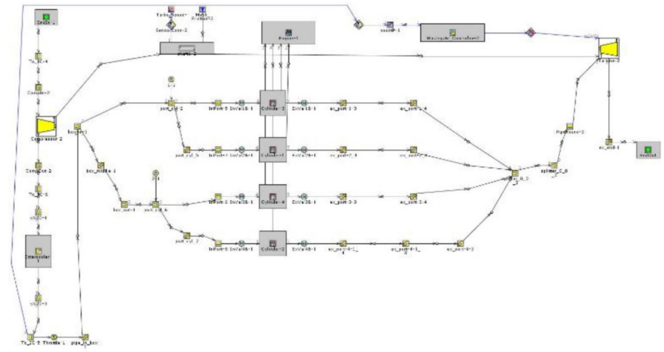

Figure 1. Rotax 914's model in GT-SUITE.

The engine's manifolds geometry was modeled using 3D models of the manifolds that were converted to a block diagram with GEM3D feature of GT-SUITE. Compressor and turbine maps were introduced to the model based on the real-used turbocharger of Rotax 914. The most important feature in the model for knock analysis is the combustion profile inside the cylinder, which is utilized to predict combustion and heat release behavior in various conditions as similar as possible to the real behavior of the engine. Burn rate profiles were calculated using the available experimentally measured indicatory diagrams kindly provided by Israel Aerospace Industries (IAI) that were inserted into the model. These burn rate profiles were used for calculating initial conditions in the combustion chamber (tumble, swirl, turbulence strength and turbulent length scale). After having all those parameters, they were inserted to a simplified one-cylinder model and a DOE (design of experiment) method was used in order to find the 4 combustion variables (flame kernel growth multiplier, turbulent flame speed multiplier, Taylor length scale multiplier, dilution exponent multiplier) that will yield the smallest error between the experimental and the calculated indicatory diagrams.

For knock prediction, the auto-ignition delay time was calculated, and the model was calibrated using data on the recorded knock events from dedicated experiments conducted by IAI for the purpose of this research. As known, the autoignition delay time is the time for which a homogeneous mixture must be maintained at temperature, T, and pressure, p, before it auto-ignites. When the temperature and pressure are continually changing, as they are in the end-gas of SI engine, the Livengood-Wu integral [9] is frequently used to assess likelihood of auto-ignition occurrence during a time t:

$$I(t) = \int_0^t \frac{1}{\tau} dt \quad (\tau - autoignition\, delay\, time) \tag{1}$$

Here: τ is the induction time at the instantaneous temperature and pressure of the mixture; t is the elapsed time from the start of the end-gas compression process to the auto-ignition time. Knock is predicted to occur at the crank angle when the integral (for any end-gas zone) attains a value of "1". Several correlations for induction time of specific hydrocarbons and blended fuels have been developed. Usually these relations have the form of equation (2) [8]:

$$\tau = Ap^{-n}\left(\frac{B}{T}\right) \tag{2}$$

where:

A, B - Fitted parameters per fuel.

The accuracy of these types of equations to predict the onset of knock has not been conclusively proven. The most extensively tested correlation is the one proposed by Douaud and Eyzat [8]:

$$\tau = 17.68\left(\frac{ON}{100}\right)^{3.402} p^{-1.7} \exp\left(\frac{3800}{T}\right) \tag{3}$$

Where: τ is induction time in milliseconds, P is absolute pressure of the end-gas in atm, and T is end-gas temperature in deg. Kelvin. ON is the fuel's octane number. If the temperature and pressure time history of the end-gas during a cycle are known, equations (1) and (3) can be used to determine whether knock occurs before the propagating flame consumes the entire volume of the combustion chamber.

For knock intensity analysis we used the knock index (KI) expression suggested in [22] (eq. 4), as well as examination of the maximum peak pressure created due to the combustion of the rest of the unburned fuel in the first time step after knock onset. KI is calculated according to the equation:

$$KI = 10000u\frac{V_{TDC}}{V}\exp\left(\frac{-6000}{T}\right)\max(0,1-(1-\phi)^2)\frac{I_{avg}}{I_{K-corr}} \tag{4}$$

Where: KI - Knock index; u- Percentage of cylinder mass unburned; V_{TDC} - Cylinder volume at top dead center; V - Cylinder volume; T - Bulk unburned gas temperature (K); ϕ - Equivalence ratio in the unburned zone; I_{avg} - Induction time integral, averaged over all end-gas zones; $I_{K\text{-}corr}$ - Induction time integral correlation factor. The KI value, which was used as a basis for the comparison, was the value received on simulation at the same conditions (power and ambient conditions) and was recorded as destructive to the real engine (resulted in engine failure) - ≈ 91.

As in real measurements, also in the model predictions cylinder 1 was found to be the first for knock onset. This result is explained by the intake manifold's shape that allows higher amount of AF mixture to enter this cylinder. Hence, the subsequent analysis was performed for this cylinder.

Knock onset and engine performance were studied at various engine speeds. At each RPM case the model's target was set to achieving a specific air box pressure obtained previously in ground experiments. The accuracy of the model was validated by comparing the predicted main performance parameters of the engine to those measured in laboratory experiments. As shown in Table 2, the difference between the model predictions and the real engine experiments was less than 3%.

Table 2. Model validation results.

Experiment / Model prediction				
RPM	5800	5500	5000	4500
P [kW]	80.9 / 80.9	68.85 / 68.9	63.9 / 64.0	55.8 / 55.9
BSFC g/kWh	300.2 / 306.4	297.6 / 301.5	296.6 / 299.9	322.1 / 319.0
Air flow kg/h	297.1 / 298.5	255.35 / 256.0	232.7 / 233.8	207.1 / 204.3

The engine tendency to knock was studied at various combinations of initial temperatures at sea level, altitudes (affecting ambient pressure and temperature), relative humidity and fuel octane numbers (see table 3).

The altitude effect on ambient pressure and temperature was calculated as shown in eq. (5) and (6) [22]:

$$T = T_0 - 0.0065 \cdot \Delta Z \tag{5}$$

$$P = P_0 \cdot \left(\frac{T_0 - 0.0065 \cdot \Delta Z}{T_0}\right)^{\left(\frac{g}{0.005R}\right)} \tag{6}$$

Where:

T, P - Corrected temperature / pressure [K] / [bar];

T_0, P_0 - Initial temperature / pressure [K] / [bar] at the sea level

ΔZ - Altitude - reference altitude [m]

g - Acceleration due to gravity [m/sec^2]

R- Gas constant [J/kg]

The simulations were performed using the DOE (design of experiments) method, in which influence of the entire possible combinations of the defined parameters (Table 3) on knock appearance and engine performance were analyzed. In this study, the response functions that were investigated are brake power and KI of cylinder 1. For both response functions, the chosen surface fitting method was Ordinary Least Square (OLS) (with quartic resolution), that uses a least square polynomial fit.

Table 3. Base input parameters for DOE.

Input Parameter	Range	Steps
Octane number	90-95 RON	4
Humidity	0-0.8 @sea level	4
Altitude	0-15000 feet (4572 m)	6
Initial ground temperature	240-320 K	6

Results and Discussion

Parameters' Combinations Effect on Knock

In order to get a general idea about the effect of each parameter, the other three parameters were set to their mean value (ON - 92.5, humidity - 0.4, altitude - 7500 feet, initial ground temperature - 280K), and the effect was examined changing the values of studied parameter from minimum to maximum as defined at table 3. The results are shown in Figure 2.

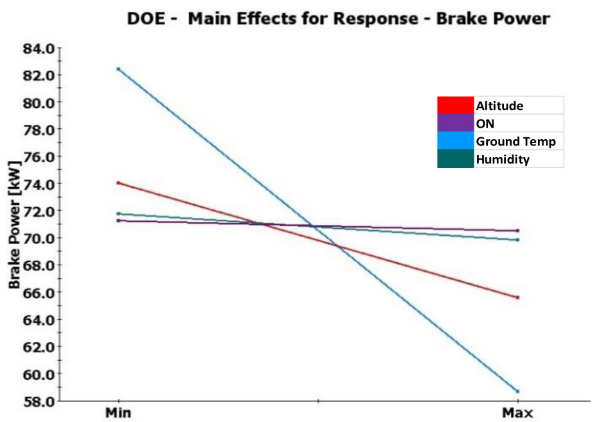

Figure 2. Parameter's effects on engine's brake power.

The most influencing parameter on the power output is the ambient temperature at sea level (see Figure 2). The ground temperature influences the AF mixture's temperature at the cylinders' entrance directly and higher temperatures mean less dense air and less oxygen, and as a result, reduced power output. In addition, the higher temperatures have a crucial role in knock occurrence and intensity that deteriorate power output. The second most influencing parameter from those checked is flight altitude. It is not significant as ground temperature. Engine power drops from 74 kW to 65.5 kW with the flight altitude increase from sea level to 15000 feet respectively, because the turbocharger compensates for the lost air density by compressing the air to a constant pressure of 1.21 bar (121 kPa) inside the air box. As expected, humidity slightly decreases the power output (~2 kW) by displacing oxygen from the air. ON almost do not change the power output because the compression ratio is the same through the entire simulation.

Regarding KI (Figure 3), all four studied parameters show significant influence. The initial ground temperature and platform's altitude are provoking knock when rising. The effect of ambient temperature is straightforward - increasing the intake air temperature at start of combustion, and the altitude's effect are eventually the same, but through a different mechanism. The turbocharger increases the intake air temperature, due to a rise in the compressor pressure ratio as the air density drops with altitude increase. The effect of higher temperatures on the probability of knock appearance and in turn on KI can be seen also from equations (3) and (4), where the mixture temperature can be found inside the exponent expression. From the other side, increased humidity and ON can decrease the KI and even completely eliminate knock. Higher humidity decreases knock intensity by cooling the mixture. Higher ON of a fuel usually correlates with higher activation energy required to initiate auto-ignition and thus improves the fuel-air mixture resistance to knock combustion.

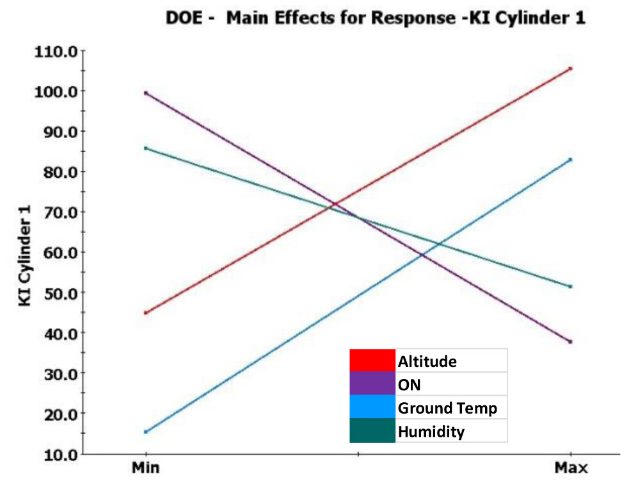

Figure 3. Parameter's effects on KI in cylinder 1.

When applying the surface fit mentioned before at 5500 RPM (maximum speed of engine continues operating) the following polynomial equation, which describes the KI response surface is obtained:

$$\begin{aligned} KI &= 65.27+62.0788\cdot W+38.8053\cdot X-17.7505\cdot Y-30.8715\cdot Z+ \\ &+24.812\cdot W*X-29.318\cdot W\cdot Y-14.8442\cdot W\cdot Z+ \\ &+3.9465\cdot X\cdot Y-10.3989\cdot X\cdot Z+3.9962\cdot Y\cdot Z- \\ &-3.6938\cdot W^2+7.8628\cdot X^2+3.2122\cdot Y^2+3.2076\cdot Z^2-28.329\cdot W^3- \\ &-8.5049\cdot X^3+0.5554\cdot Y^3+0.1221\cdot Z^3-12.5565\cdot W^4+2.0141\cdot X^4 \end{aligned} \tag{7}$$

Where: W - Ground temperature; X - Altitude; Y - Relative humidity; Z - ON. When W, X, Y, Z are normalized to the range of -1 to 1 as can be seen in eq. (8):

$$i_{Norm}=\frac{i-i_{Mean}}{i_{Max}-i_{Mean}} \tag{8}$$

In the same way, the polynomial equation, which describes the power output response surface is as follow:

$$\begin{aligned} P &= 70.8611-9.5966\cdot W-2.9888\cdot X-0.9785\cdot Y-0.3955\cdot Z+ \\ &+3.6374\cdot W*X-1.5921\cdot W\cdot Y+0.0186\cdot W\cdot Z+ \\ &+0.6899\cdot X\cdot Y+0.0282\cdot X\cdot Z-0.0186\cdot Y\cdot Z+ \\ &+0.03\cdot W^2-1.6254\cdot X^2-0.073\cdot Y^2+0.0154\cdot Z^2-2.2539\cdot W^3- \\ &-1.2378\cdot X^3+0.0166\cdot Y^3+0.0213\cdot Z^3-0.349\cdot W^4+0.5514\cdot X^4 \end{aligned} \tag{9}$$

From eq. (7) one can evaluate the chance of appearing destructive knock at maximum continuous engine operating speed for the considered engine example. The suggested approach can be applied to assess joint influence of various ambient and operating parameters on knock appearance in the aircraft engine. Such equations can be used for knock risk evaluation as well as for understanding the chances of reaching destructive knock limit prior to takeoff, during a flight and for taking measures to prevent knock at real-time operation. Below we provide an example of using this approach for analysis of knock appearance at various combinations of influencing parameters.

By placing standard values of 0.5 relative humidity and 290 at sea level eq. (7) yields the following altitudes as the conditions where destructive knock will start occurring:

- @90 ON: 4700 ft. (brake power - 69.04 kW)
- @93 ON 11400 ft. (brake power - 66.44 kW)
- @95 ON: out of danger.

When applying the same humidity and 310 the results are as follow:

- @90 ON: 2860 ft. (brake power - 62.28 kW)
- @93 ON 9450 ft. (brake power - 61.85 kW)
- @95 ON: 14250 ft. (brake power - 59.81 kW)

In the above examples the higher temperature results in higher altitudes in which knock is predicted to occur. The power output is decreasing also with the temperature rise, because the higher temperatures means less dense air and less power output as a result.

In case the flight altitude is known in advance, one can check the basic ground temperature above it destructive knock is likely to occur. E.g. at relative humidity of 0.2 and flight altitude of 5000 feet:

- @90 ON: ground temperature of 277
- @93 ON ground temperature of 309
- @95 ON: out of danger

Figure 4 describes the effect of initial ground temperature and altitude on KI. The results are shown for the most unfavorable case of dry air (relative humidity of 0) and fuel octane number 93. The values where destructive knock is occurring can be spotted according to the black horizontal line that indicates the threshold of destructive knock intensity.

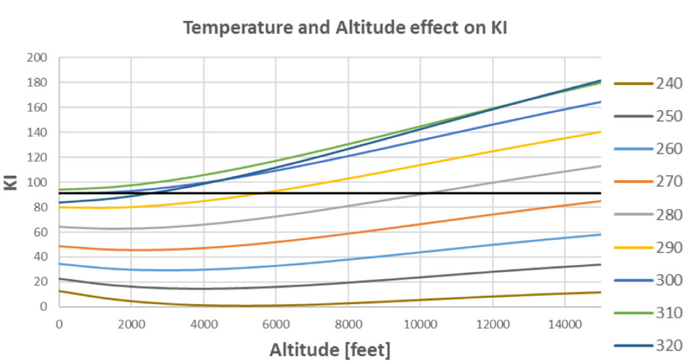

Figure 4. Altitude and Ground Temperature effect on KI.

In case of the initial ground temperature does not exceeding 270° K there is no knock danger. At 280° K knock becomes destructive in the range of 10000-12000 feet and at 290° K in 6000 feet. Above 300° K the knock phenomenon is a limiting factor from the start (at sea level).

Possible Methods of Knock Prevention

Based on the DOE analysis and the finding of the most influential factors affecting the knock phenomenon in aviation platforms, methods of in-flight knock prevention were selected and checked from a wide range of possible treatments. The emphasis was on simplicity, cost and low weight solutions suitable for existing aviation platforms. All considerations provided below were made based on the computational analysis described beforehand. The following possible methods of knock prevention were selected and subsequently analyzed:

- Optimization of the cooling system (intercooler)
- EGR
- Spark timing
- Water injection

Intercooling

Experiments with a plate-fin, cross flow, dual pass 20X20X8.5 intercooler, typical for aviation platforms, were carried out on the engine and their results (as shown in Table 4) were introduced into the computational model.

Table 4. Intercooler's experimental data. (Received from Israel Aerospace Industries - IAI)

RPM	5800	5500	4500	3500	2500
Inlet temp [^oC]	73.32	62.15	59.81	50.98	39.03
Outlet temp [^oC]	41.28	39.05	38.31	39.55	40.53

A comparison of the KI of cylinder 1 was made between the intercooled engine and the same engine without the intercooler (Figure 5) at standard atmospheric conditions (298° K at sea level and 0 relative humidity). It can be easily seen that the KI without intercooler is higher in the entire range of altitudes, and the gap is constantly growing. KI value is lower and almost stable for the intercooled engine, so there is no concern of sudden increase in KI value with altitude change. The similar behavior (stable KI) is observed with changing other ambient and operating parameters. As can be seen from Figure 6, the intercooled engine allows achieving higher power output throughout the entire operating altitudes range without a destructive knock. At the altitude of 15000 feet the maximum gain - more than 8 kW is achieved with the intercooler.

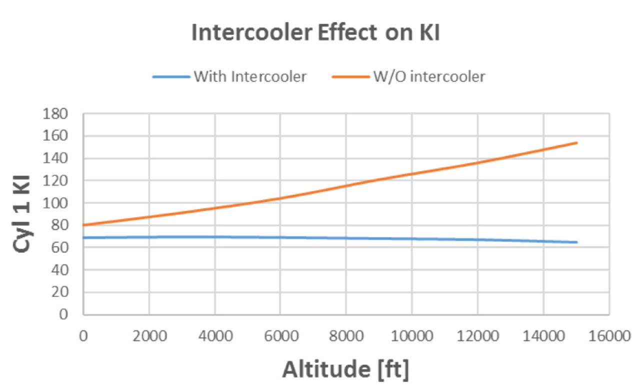

Figure 5. Comparison of the effect of intercooler on knock intensity.

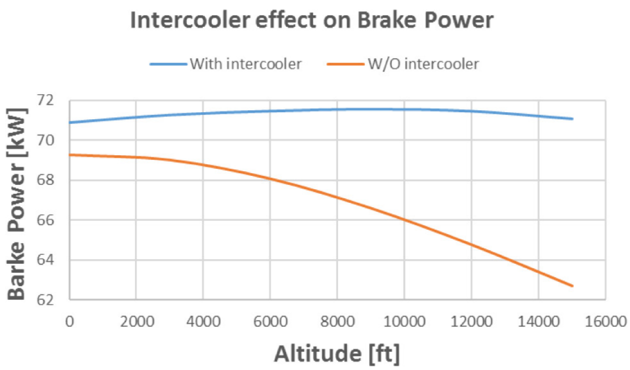

Figure 6. Comparison of the effect of intercooler on brake power.

EGR

The induction time (see eq. 3) has no direct dependency on AFR or EGR fraction, even though knock is influenced by those two parameters. When applying EGR in significant amounts or non-typical AFR while using knock model depending on eq. 3, a multiplier is needed to be modified according to experimental setup in order to calibrate the model. In the absence of such experimental data, the multiplier was not changed and therefore the predicted values of KI in this case are overestimated. In Figure 7, simulation of different EGR rates at 6 different altitudes is presented and the results show substantial reduction in KI at altitudes up to 9000 feet already at 5% of EGR. At the flight altitude above 9000 feet, only at EGR levels of 15-20% the method become effective, i.e. enables reduction of KI below 90. At all operating modes significant reduction of brake power was observed with applying exhaust gas recirculation. The reason for this is the fact that the considered aircraft engine operates with a fixed intake air box pressure. Hence, the exhaust gas introduced into the intake manifold replaces the fresh air and the compressor doesn't compensate for the loss. The possible solution for this issue can be a different control method, targeting brake power or AFR [23]. In addition, because of the constant air box pressure and the reduction in exhaust pressure with altitude rise, one can see decrease of the EGR effect at the highest studied altitudes. A possible reason of this finding is in reduction of the pressure difference between the engine exhaust manifold (the turbine inlet) and the air box (compressor outlet), which may result in inability to achieve the target EGR rate at steady state and in some cases can even lead to a reversed flow. Because of this, the EGR method is less efficient at higher altitudes. These considerations are supported by the brake power behavior depending on EGR rate at various altitudes - Figure 8. As can be seen from Figure 8, the engine power is less influenced by the EGR rate up to high levels of 15-20%.

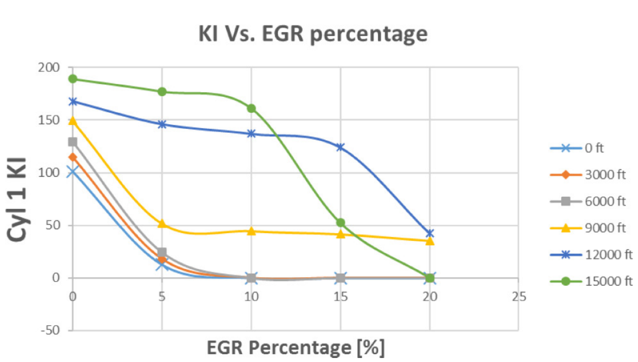

Figure 7. EGR percentage vs KI in cylinder 1.

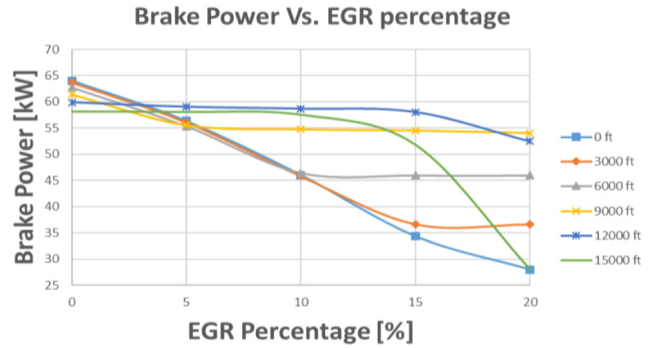

Figure 8. EGR percentage vs brake power in cylinder 1.

Spark Timing

In order to see clearly the effect of spark advance on KI and power output, a single operating regime inside the destructive zone of knock intensity was chosen: 5510 rpm, 1.212 bar (121.2 kPa) inside the intake air box, altitude of 5000 feet and 320° K initial ground temperature. The ignition delay was applied by steps of 0.5° at a time from 27° BTDC to 23° BTDC. The results of this simulation (Figure 9) show constant decrease in KI as spark timing is retarded. At 2° retard, the engine is out of the dangerous knock zone on "expense" of 1.5 [kW] loss in brake power. The biggest advantage of this method is the quick and simple implementation on any existing platform and the quick response in real-time operation with no penalty in a platform's weight. However, as mentioned already, ignition retarding results in a recoverable engine power loss.

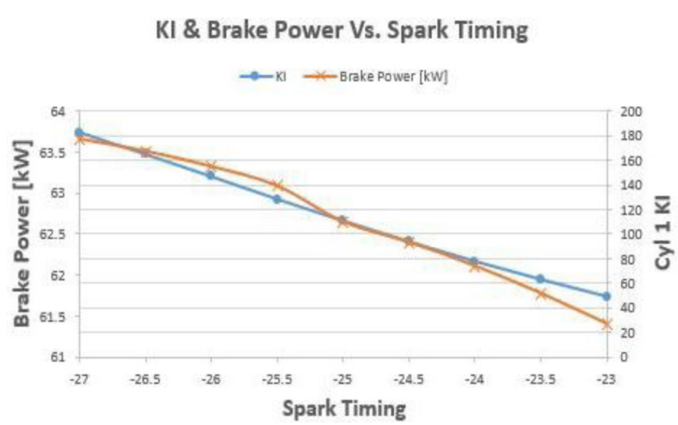

Figure 9. The effect of spark timing on KI and brake power.

Water Injection

Water injection was simulated at amounts of 0-10% of fuel injected mass, for 6 different altitudes (0-15000 feet), ambient temperature 298° K at sea level and 0 relative humidity (Figure 10). At 15000 feet, the reduction of KI is sufficient when 10% of water is injected, but still is right on the border of destructive knock. At 12000 feet the achieved KI reduction allows engine operating inside the safe zone already at 7.5% of water injected, but still not enough to provide a good knock resistance if one considers the cycle-to-cycle variation expected in SI engines at standard engine operation. The important result is a slight increase in brake power at each altitude as injected water's mass increases (Figure 11). This improvement is due to lower knock intensity and the slightly increased mass air flow. The latter is a consequence of the denser air obtained from the cooling effect of the water injection, as compared to the EGR method where temperature reduction is achieved on expense of volumetric efficiency worsening. Combining water injection method with other method, e.g. intercooling, can provide substantial improvement in power output along with significant reduction of knock intensity.

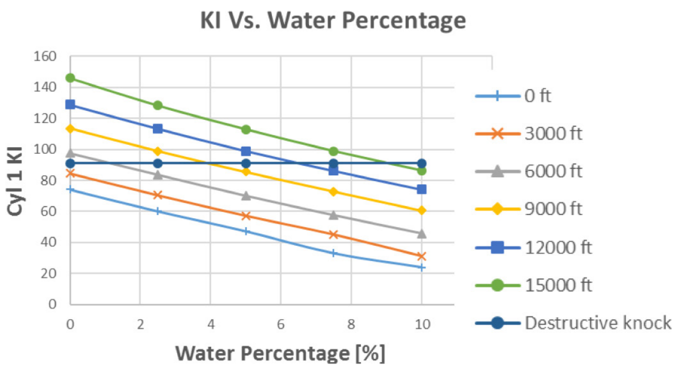

Figure 10. Effect of Water injection to intake manifold on KI.

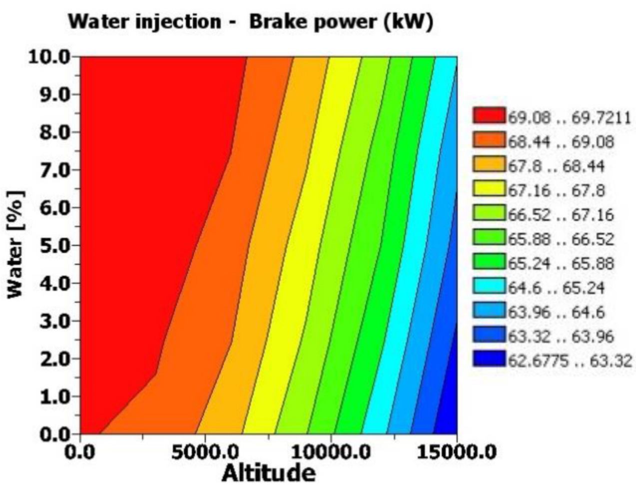

Figure 11. Effect of injected water injection and altitude on brake power.

Summary and Conclusions

A novel approach was suggested for assessing the joint influence of various ambient and operating parameters on knock appearance in a turbocharged aircraft engine that can be used for knock risk and severity evaluation prior to takeoff, during a flight and for taking measures to prevent knock at real-time operation.

Engine knock behavior can change drastically at widely varying ambient conditions experienced by aerial platforms. Computer simulations showed the influence of flight altitude, ON, humidity and initial ground temperature on the knock occurrence and intensity in an aircraft turbocharged engine. The effects of the different possible combinations of these parameters on knock intensity and brake power (or any other related response) can be summarized to one equation at a certain engine speed or load. Such equations can be used for knock risk evaluation and for understanding the chances of reaching destructive knock limit during a flight.

Various knock mitigation methods suitable for possible use in aerial platforms that emphasize simplicity, low cost and low weight were selected and analyzed. Intercooling showed the best results in stabilizing the engine operation and keeping it out of destructive knock intensity while maintaining and even improving brake power output. Spark timing retarding reduced knock intensity by about 60% when ignition was retarded by 3° CA, while losing less than 2kW of brake power. In a turbocharged engine the frequently applied control method of targeting constant intake air box pressure makes EGR not an ideal way of knock mitigation because of the substantial loss of power output. Water injection shows great potential of knock reduction, but not enough for a standalone solution.

Future research should include creating a complete set of knock intensity equations for a specific platform, and implementing it for use in real-time flights. Along with a continuous update of weather forecast, real time calculations of knock tendency by using the fitted equations will allow avoiding certain flight conditions that may provoke knock occurrence.

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Definitions/Abbreviations

AF - Air-fuel

AFR - Air-fuel ratio

BSFC - Brake specific fuel consumption

DI - Direct injection

DOE - Design of Experiments

EGR - Exhaust gas recirculation

ICE - Internal combustion engine

KI - Knock index

ON - Octane number

RPM - Rounds per minute

SI - Spark ignition

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