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ANTI-KNOCKING CHARACTERISTICS OF MOTOR GASOLINE FUEL IN RECIPROCATING LYCOMING O-320 ENGINE IN COMPARISON TO AVIATION GASOLINE FUEL

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ABSTRACT

Aircraft engines worldwide rely on 100 low lead (100LL) aviation gasoline (AVGAS) for its safe operation. AVGAS basically contains high levels of tetraethyl lead (TEL) which boost its octane ring and assist in anti-knocking. Knock or detonation refers to the rapid explosion of the fuel instead of burning smoothly within the engine cylinders which can cause serious damage to the engine. The 100LL AVGAS is mainly utilized in aircraft engines in order to minimize the occurrence of this event. However, the leaded AVGAS is one of the major reasons for lead emission into the atmosphere. It contributes to serious health impacts among humans. The only solution for this problem is to make unleaded motor gasoline (MOGAS) as the substitute for leaded AVGAS for the use in reciprocating aviation engines as MOGAS is capable of giving a comparable performance to the AVGAS. However, the unleaded MOGAS has relatively lower octane rating compared to leaded AVGAS. This increases the tendency of the gasoline to ignite instantaneously during combustion stroke of the engine which increases the probability for the occurrence of engine detonation. Therefore, a research is carried out to study on the anti-knocking characteristics of these fuels. In this study, the full-scale engine detonation performance of the locally available unleaded MOGAS fuels are determined and compared to typical leaded AVGAS fuel. This is done by performing a full-scale Lycoming O-320-B2A reciprocating engine performance test to obtain comprehensive data on engine detonation. The fuels tested in this study are 100LL AVGAS, RON100 MOGAS, RON97 MOGAS and RON95 MOGAS. Each of these fuels is tested at a time in the Lycoming O-320-B2A engine and the knock data are recorded. From the experiment conducted, it can be concluded that the 100LL AVGAS has the best anti-knocking characteristics followed by RON100 MOGAS, RON97 MOGAS and lastly RON95 MOGAS.

KEYWORDS

Engine detonation, engine knocking, aviation gasoline (AVGAS), motor gasoline (MOGAS).

1. INTRODUCTION

Based on a study, approximately 230,000 piston-powered aircrafts worldwide rely on 100 low lead (100LL) AVGAS for safe operation [1]. AVGAS contains high levels of tetraethyl lead (TEL) in it. TEL is an additive which is added into the aviation gasoline fuels to boost the octane ring and assist in anti-knocking, in which it helps to suppress knock. TEL is really crucial because aircraft engine is prone to detonation as it operates at higher power settings and temperatures. Detonation or also known as knocking occurs when the temperature and pressure of the compressed mixture in the combustion chamber reach levels sufficient to cause instantaneous explosion of the fuel-air mixture. Excess temperatures and pressures can result from numerous engine parameters, including high inlet-air temperature, insufficient ignition timing, excessively lean air-fuel mixture, and high compression ratio.

A major cause of detonation is when an engine operates with either a fuel having a lower octane rating for the engine or a high-combustion-rate fuel. Fuel with higher octane rating withstands higher temperature and pressure before igniting than the one with a lower octane rating. This is why TEL is added. As the detonation occurs, the air-fuel mixture may burn properly for a portion of its combustion and then explode as the pressure and temperature in the cylinder increase beyond their normal limits [2]. Because of detonation, there is further increase in piston and cylinder temperatures, and this may melt the head of a piston. Generally, detonation causes a serious loss of power. The piston gets a very short high-pressure push, similar to the head of the piston being hit with a hammer. The high- pressure push is very sudden to be absorbed by the piston, which results in power loss.

The utilization of AVGAS in aircraft engines has limited the occurrence of engine detonation. According to research approximately 190 million gallons of 100LL is burnt annually by more than 200,000 general aviation aircraft [3]. This causes a huge amount of lead to be released into the atmosphere and contributes to 45% of the total lead emissions in the air over the United States. The Environmental Protection Agency (EPA) estimates that the combustion of AVGAS has released 34,000 tons of lead into the atmosphere from 1970 until 2007 which affects three million children who attend school near aviation facilities [4]. It is clear that the usage of AVGAS contributes to serious health impacts among humans. Responding to the expanding health concerns, the usage of unleaded MOGAS replacing the leaded AVGAS has already started in aviation industry.

The amount of horse power of a high-performance aircraft engine is directly proportional to the octane level it requires to operate safely. Based on a study, Motor Octane Number (MON) values of fuels must satisfy the minimum octane performance required by a given full-scale engine to ensure safe operation [5]. An unleaded fuel possessing the same MON as a leaded fuel may not provide a full-scale engine the octane performance it requires. It is solved by making the unleaded fuel to meet a MON value higher than the minimum octane value the engine was originally certified on to ensure equivalent full-scale engine performance. These higher-octane values for unleaded fuels may result in the use of greater amounts of specialty chemicals, impacting other properties that may move the fuel out of specification. Besides, use of mixtures of high octane components may result in significant antagonistic and synergistic effects of octane response. Therefore, majority of MOGAS blends have lower octane ratings than AVGAS blends.

There is no safety issues related with aircraft engines utilizing fuel with a higher octane rating such as the leaded AVGAS. The problem only comes in when a fuel with too low of an octane rating such as unleaded MOGAS is utilized. This is because it leads to security risk due to engine detonation or knocking. TEL is a compound of lead that improves octane rating of the gasoline. High octane rating reduces the tendency of the gasoline to ignite suddenly and instantaneously from compression, during the combustion stroke of the engine. Therefore, the leaded AVGAS reduces the probability for the occurrence of engine detonation. While the utilization of the unleaded MOGAS which has a relatively lower octane rating in comparison to the leaded AVGAS, will have a greater safety risk as the engine detonation will be more common in this situation. Sustained detonation may lead to catastrophic failure of the engine.

This study is conducted in order to determine the anti-knocking characteristics of the locally available unleaded MOGAS fuels in comparison to aviation gasoline fuel. This is to evaluate the compatibility of MOGAS in terms of detonation protection in a full-scale engine. The scope of this study is to perform a full-scale Lycoming O-320-B2A reciprocating engine performance test to obtain comprehensive data on engine detonation. This research will eventually give an updated study on the locally available MOGAS and their engine detonation performance characteristics in a reciprocating aviation engine in comparison to the leaded AVGAS.

2. EXPERIMENTAL

2.1 Test Engine Set-up

The test engine used for this experiment is the Lycoming O-320-B2A reciprocating engine. It is a four cylinder, horizontally opposed, direct drive, air cooled engine. Figure 1 shows the front view of the Lycoming O-320-B2A reciprocating engine.

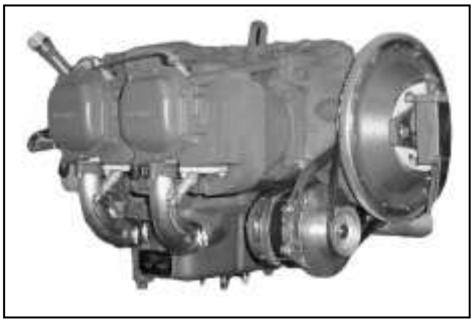

Figure 1: Right front view of Lycoming O-320-B2A engine

The test engine is set-up in the engine testing room of the laboratory located in UTM-MPRC in order to conduct the engine detonation testing. This is to demonstrate fuel detonation performance in a full-scale engine and obtain supporting laboratory data. The test engine is mounted on the dynamometer located in the engine testing room. Dynamometer is a device that is used to measure the operating parameters of an engine. DYNOmite dynamometer is the type of dynamometer used for this experiment. It is very crucial to connect the test engine to the DYNOmite dynamometer as it ensures easier monitoring of the engine parameters such as the engine speed (RPM), brake horsepower (BHP), fuel flow, engine shaft torque and many more. Other necessary sensors such as knock sensor, exhaust measuring system, pressure transducers and thermocouples are also connected to the test engine in order to monitor every single parameter of the engine for smooth operation. Figure 2 shows the test engine connected to the dynamometer and sensors.

Figure 2: Test engine set-up from (a) right side view, (b) left side view, (c) front view and (d) back view

The test engine and all the sensors connected externally to it are connected to the DYNOmite dynamometer through cables and pipes. This is to enable the dynamometer to measure and monitor the engine's parameters. The dynamometer is later on connected to the pro console placed in the observation room. The pro console is equipped with a PC and a high-resolution LCD monitor, and various controls installed in it to provide a professional dynamometer operating station. This makes the test engine, dynamometer and pro console to be interconnected with each other. This combination makes the engine detonation testing more organized. The pro console allows full remote operation of the test engine from the observation room as it can control the test engine's speed, torque, fuel flow and others. The operating parameters of the test engine is then measured by the dynamometer and transferred to the pro console to be displayed on its monitor.

2.2 Selection of Fuels for Testing

There are a total of four fuels tested for this study. Table 1 shows the type of fuels that are chosen for the engine detonation testing. The 100LL AVGAS is the chosen type of AVGAS for this study. This is because it is the most common AVGAS fuel used in the aviation industry as it gives the best performance for an aircraft engine. The 100LL AVGAS is bought through a supplier as it is not commonly available in the petrol stations. 100LL AVGAS is used as the reference fuel for this experiment to which the anti-knocking characteristics of the MOGAS are compared to. The types of MOGAS chosen are RON100, RON97 and RON95. These are the common unleaded fuels available in Malaysia. The MOGAS is obtained from a single company so that the quality of the fuels used will be the same throughout the experiment. Only certain companies in Malaysia provide RON100 MOGAS. Petron is one of the companies that has many outlets offering RON100 MOGAS. Therefore, the MOGAS are obtained from the Petron outlet.

Table 1: List of fuels tested

Fuel	Lead content	Source
100LL AVGAS	Leaded	Supplier
RON100 MOGAS	Unleaded	Petron Blaze 100 Euro 4M
RON97 MOGAS	Unleaded	Petron Blaze 97 Euro 4M
RON95 MOGAS	Unleaded	Petron Blaze 95

2.3 Engine Detonation Testing

The selected MOGAS and AVGAS fuels are tested in the Lycoming O-320-B2A reciprocating engine to study on their anti-knocking characteristics. The testing methodology is based on the ASTM D6424. Each of the fuels is tested at a time. All of the MOGAS are tested first before the AVGAS. This is because the lead deposits from the AVGAS could affect the accuracy of the results. The important data that should be obtained from this experiment are the engine speed (RPM), brake horsepower (BHP), fuel mass flow and the knock intensity. During the testing, the engine speed is varied from the minimum engine speed to the maximum achievable engine speed. All the engine parameters, especially the knock intensity corresponding to the engine speeds are recorded. The experiment is stopped if heavy knocking occurs as it can damage the engine [6]. The testing is repeated for three times for each of the fuels to get more accurate results on the anti-knocking characteristic of the fuels.

3. RESULTS AND DISCUSSION

The engine detonation testing is performed under extreme conditions which could promote detonation. All the testing was done under sea level-hot and dry day condition. According to research, the engine detonation testing is greatly influenced by the air humidity [7]. This is because it is found that the higher inlet air humidity results in a reduced engine detonation. The dry day condition ensures that the air humidity stays as lowest as possible. For an aircraft engine operating at a higher altitude from the sea level, as the altitude increases, the engine intake air temperature decreases while the output power reduces proportionally to the outside air pressure. This higher altitude causes the engine inlet air to be colder while colder air also flows into the cowling for engine cooling. Study showed both of these situations provide the aircraft engine with a lower internal working temperature that only decreases the probability of engine detonation [8]. This is why sea level-hot and dry day condition is said to be extreme condition for an aircraft engine to be operating. The probability for engine detonation is the highest at this condition. The engine detonation testing is conducted under this extreme condition in order to study the anti-knocking performance of the fuels and also to see whether these fuels could withstand this critical condition.
The four fuels that are tested during the engine detonation testing are 100LL AVGAS, RON100 MOGAS, RON97 MOGAS and RON95 MOGAS. The testing is carried out with Lycoming O-320-B2A reciprocating engine which is connected to a dynamometer. Two of the readings that are mainly used for the analysis of anti-knocking characteristics of the fuels are the engine speed and knock intensity. The dynamometer measures the engine speed in terms of RPM while the universal knock sensor measures the knock intensity in terms of percentage. Each of these fuels was tested three times under sea level-hot and dry day condition. The knock data of engine detonation testing for all the fuels are shown in Tables 2 through 5. Graphs of knock intensity versus engine speed are also plotted for each fuel as shown in Figure 3.

Table 2: Knock data of engine detonation testing for 100LL AVGAS

Fuel	Run 1		Run 2		Run 3	
	Engine speed (RPM)	Knock intensity (%)	Engine speed (RPM)	Knock intensity (%)	Engine speed (RPM)	Knock intensity (%)
100LL AVGAS	1000	8.633	1000	8.884	1000	8.629
	1100	9.388	1100	9.565	1100	10.03
	1200	9.902	1200	10.68	1200	10.23
	1300	10.41	1300	11.58	1300	11.24
	1400	11.34	1400	11.92	1400	12.12
	1500	14.96	1500	13.90	1500	14.27
	1600	18.74	1600	17.46	1600	17.75
	1700	22.01	1700	20.28	1700	20.30
	1800	24.77	1800	23.33	1800	23.58
	1900	32.29	1900	29.19	1900	30.82
	2000	36.77	2000	36.43	2000	40.26
	2100	42.06	2100	44.04	2100	45.35
	2200	45.73	2200	50.49	2200	50.71
	2300	54.22	2300	57.61	2300	53.48
	2400	64.47	2400	64.47	2400	63.49
	2500	81.55	2500	74.35	2500	69.58

Table 3: Knock data of engine detonation testing for RON100 MOGAS

Fuel	Run 1		Run 2		Run 3	
	Engine speed (RPM)	Knock intensity (%)	Engine speed (RPM)	Knock intensity (%)	Engine speed (RPM)	Knock intensity (%)
RON100 MOGAS	1000	7.963	1000	8.759	1000	6.766
	1100	8.731	1100	8.716	1100	9.562
	1200	9.537	1200	11.19	1200	9.756
	1300	10.96	1300	12.32	1300	10.80
	1400	12.35	1400	13.73	1400	12.60
	1500	14.61	1500	15.95	1500	14.98
	1600	17.40	1600	18.70	1600	18.15
	1700	21.12	1700	21.70	1700	22.10
	1800	25.62	1800	25.74	1800	26.92
	1900	32.60	1900	31.88	1900	32.30
	2000	36.43	2000	37.39	2000	37.87
	2100	42.25	2100	44.57	2100	44.08
	2200	50.43	2200	52.02	2200	52.44
	2300	55.38	2300	59.20	2300	59.28
	2400	64.13	2400	67.42	2400	68.76
	2500	68.81	2500	77.33	2500	81.40

Table 4: Knock data of engine detonation testing for RON97 MOGAS

Fuel	Run 1		Run 2		Run 3	
	Engine speed (RPM)	Knock intensity (%)	Engine speed (RPM)	Knock intensity (%)	Engine speed (RPM)	Knock intensity (%)
RON97 MOGAS	1000	9.427	1000	8.920	1000	8.601
	1100	9.355	1100	9.214	1100	9.048
	1200	9.422	1200	10.29	1200	10.86
	1300	10.28	1300	11.22	1300	12.53
	1400	12.36	1400	13.42	1400	14.47
	1500	16.92	1500	17.46	1500	17.19
	1600	22.40	1600	22.20	1600	20.88
	1700	26.40	1700	25.38	1700	23.14
	1800	30.90	1800	27.55	1800	25.33
	1900	38.82	1900	31.98	1900	29.96
	2000	39.29	2000	38.05	2000	36.58
	2100	43.68	2100	43.49	2100	41.67
	2200	52.27	2200	53.97	2200	54.72
	2300	58.34	2300	54.38	2300	63.61
	2400	66.60	2400	68.32	2400	71.89
	2500	76.12	2500	76.92	2500	78.89

Table 5: Knock data of engine detonation testing for RON95 MOGAS

Fuel	Run 1		Run 2		Run 3	
	Engine speed (RPM)	Knock intensity (%)	Engine speed (RPM)	Knock intensity (%)	Engine speed (RPM)	Knock intensity (%)
RON95 MOGAS	1000	7.330	1000	9.714	1000	9.179
	1100	8.707	1100	9.818	1100	10.43
	1200	9.214	1200	11.03	1200	11.77
	1300	11.66	1300	13.76	1300	13.29
	1400	15.06	1400	16.55	1400	15.25
	1500	19.45	1500	21.12	1500	18.85
	1600	24.14	1600	27.65	1600	23.48
	1700	29.71	1700	28.85	1700	26.97
	1800	30.89	1800	30.34	1800	29.39
	1900	41.71	1900	36.70	1900	33.56
	2000	43.56	2000	42.71	2000	38.52
	2100	43.05	2100	45.51	2100	42.50
	2200	52.76	2200	53.44	2200	56.45
	2300	61.59	2300	61.14	2300	62.09
	2400	69.98	2400	73.70	2400	70.80
	2500	81.52	2500	80.86	2500	79.69

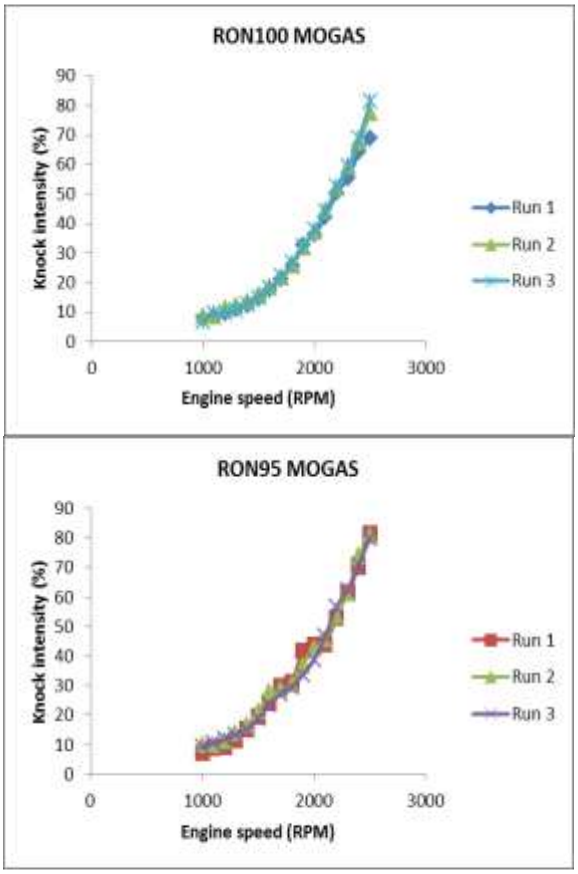

Figure 3: Knock data for all fuels under sea level-hot and dry day condition

From Figure 3, we can see that all the four graphs show the same trend, which is as the engine speed increases, the knock intensity also increases. This is true according to the theory. When the speed of an aircraft engine increases, the piston and crankshaft tend to move faster to produce the necessary power corresponding to the engine speed. The faster movement of the engine components at higher speed produces heat which directly increases the internal temperature and pressure of an engine. The fuels can only withstand a certain temperature and pressure limit before detonation or knocking takes place. Beyond that point, only the knock intensity increases with the temperature and pressure of the internal space of the engine. Therefore, the faster the speed of the engine, the higher the knock intensity produced by the engine. The average knock data of each fuel is shown in Table 6. The same data is plotted in a graph of knock intensity versus engine speed to compare the anti-knocking characteristic of each fuel as shown in Figure 4.

Table 6: Average knock data of each fuel

100LL AVGAS		RON100 MOGAS		RON97 MOGAS		RON95 MOGAS	
Engine speed (RPM)	Knock intensity (%)	Engine speed (RPM)	Knock intensity (%)	Engine speed (RPM)	Knock intensity (%)	Engine speed (RPM)	Knock intensity (%)
1000	8.7150	1000	7.8290	1000	8.9830	1000	8.7410
1100	9.6610	1100	9.0030	1100	9.2060	1100	9.6520
1200	10.271	1200	10.161	1200	10.191	1200	10.671
1300	11.077	1300	11.360	1300	11.343	1300	12.903
1400	11.793	1400	12.893	1400	13.417	1400	15.620
1500	14.377	1500	15.180	1500	17.190	1500	19.807
1600	17.983	1600	18.083	1600	21.827	1600	25.090
1700	20.863	1700	21.640	1700	24.973	1700	28.510
1800	23.893	1800	26.093	1800	27.927	1800	30.207
1900	30.767	1900	32.260	1900	33.587	1900	37.323
2000	37.820	2000	37.230	2000	37.973	2000	41.597
2100	43.817	2100	43.633	2100	42.947	2100	45.353
2200	48.977	2200	51.630	2200	53.653	2200	54.217
2300	55.103	2300	57.953	2300	58.777	2300	61.607
2400	64.143	2400	66.770	2400	68.937	2400	71.493
2500	75.160	2500	75.847	2500	77.310	2500	80.690

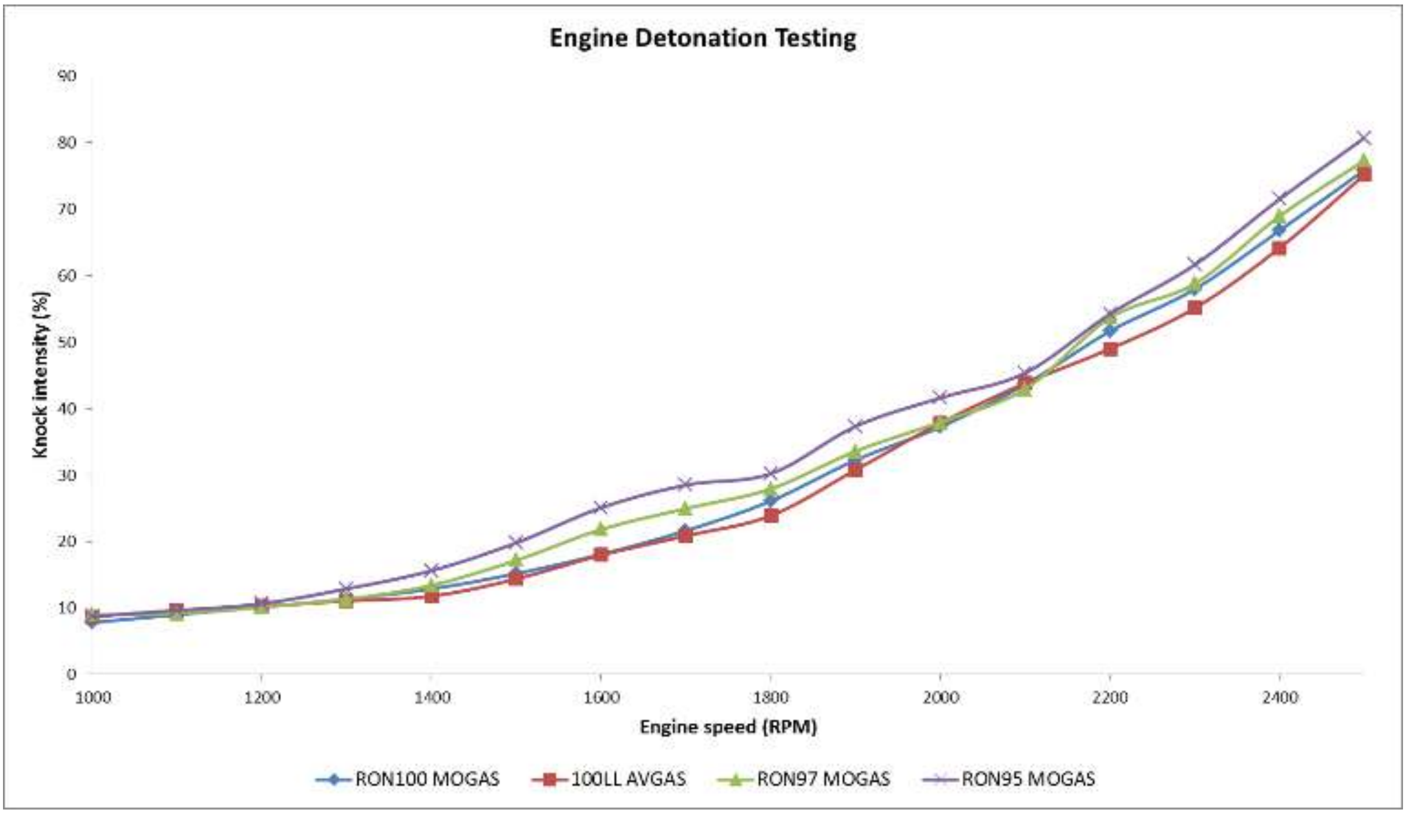

Figure 4: Average knock data of each fuel under sea level-hot and dry day condition

From Figure 4, it is clear that under the sea level-hot and dry day condition, 100LL AVGAS exhibited the best anti-knocking performance. The line representing 100LL AVGAS in Figure 4 is mostly found at the bottom of the other three lines. This shows that 100LL AVGAS mostly exhibited the lowest knock intensity corresponding to the engine speed throughout the testing compared to other fuels. Whereas, RON95 MOGAS showed the worst anti-knocking performance as it mostly exhibited highest knock intensity compared to other fuels. The line representing RON95 MOGAS in Figure 4 is mostly seen at the top most and clearly separated from the other three lines. 100LL AVGAS is followed by RON100 MOGAS and then RON97 MOGAS in terms of better anti-knocking performance. Both of these fuels' lines are mostly seen in between the lines of 100LL AVGAS and RON95 MOGAS in the graph of Figure 4. At the lower engine speeds, all the fuels exhibited similar knock intensity. Their anti-knocking characteristics could not be differentiated from each other. This is mainly because the temperature and pressure inside the engine is not that high due to low speed and all of the fuels are able to withstand this temperature and pressure with similar knock intensity. However, this is not the case for higher engine speeds. At higher engine speeds, the temperature and pressure within the engine tend to increase exponentially. At these higher temperatures and pressures, the actual anti-knocking performance of the fuels can be clearly seen through Figure 4 as the fuels have different resistance towards knock.

Based on a study, the 100LL AVGAS has the best anti-knocking characteristic compared to all the other MOGAS tested. This is mainly because it contains TEL, which is a lead additive added to assist in anti-knocking [9]. 100LL AVGAS able to exhibit lower knock intensity due to the help from TEL. The 100LL AVGAS is followed by RON100 MOGAS, RON97 MOGAS and RON 95 MOGAS in terms of better anti-knocking characteristics. This is mainly because of the octane rating of the MOGAS. The octane rating of MOGAS characterizes its resistance towards knocking [10]. The resistance of the MOGAS towards knocking increases as the fuel's octane rating increases. This is why RON100 MOGAS mostly exhibited lower knock intensity compared to RON97 MOGAS and RON95 MOGAS.

The knock intensity ranging from 0% to 100% is actually categorized as light knocking and moderate knocking. An aircraft engine can actually withstand these categories of knocking without any extensive damage to the engine. However, the knock intensity above 100% is categorized as heavy knocking. Only this type of knocking results in great damage to the engine. Study showed prolonged heavy knocking can even lead to catastrophic failure of the engine [11]. According to Figure 4, all the tested fuels exhibited knock intensity values lower than 100% with the highest knock intensity recorded by RON95 MOGAS which reaches around 80%. This shows that RON100 MOGAS, RON97 MOGAS and RON95 MOGAS are compatible with aircraft engine and provides a reasonable detonation protection to the engine.

4. CONCLUSIONS

The engine detonation testing was successfully performed using the Lycoming O-320-B2A reciprocating engine, which is connected to the dynamometer and necessary sensors. All the selected fuels were tested under the sea level-hot and dry day condition. None of the MOGAS performed better than 100LL AVGAS in the engine detonation test. This is because the 100LL AVGAS contains TEL, which boosts its octane rating and assist in anti-knocking. Among the other MOGAS tested, RON100 MOGAS showed the best anti-knocking performance while RON95 MOGAS showed the worst performance. This is because the higher the octane rating of MOGAS, the higher its resistance towards knocking. Therefore, 100LL AVGAS has the best anti-knocking characteristics followed by RON100 MOGAS, RON97 MOGAS and lastly RON95 MOGAS. However, all the fuels performed exceptionally well in terms of knock intensity. Even the highest knock intensity recorded by each MOGAS during the testing were within an acceptable range. This makes the RON100 MOGAS, RON97 MOGAS and RON95 MOGAS to be compatible with aircraft engines as their detonation performance are within a safe range.

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REFERENCES

[1] Unleaded AVGAS Transition Aviation Rulemaking Committee. 2012. FAA UAT ARC Final Report Part I. Federal Aviation Administration.

[2] Michael, J.K., Thomas, W.W. 1995. Aircraft powerplants. 7th Edition. New York, Glencoe and McGraw-Hill.

[3] Schaufele, R.D. 2008. FAA Aerospace Forecast. Washington, D.C., United States Department of Transportation.

[4] Environmental Protection Agency. 2010. Advance notice of proposed rulemaking on lead emissions from piston-engine aircraft using leaded aviation gasoline, Regulatory announcement.

[5] Warrendale, P.A. 1983. Coordinating Research Council. Handbook of aviation fuel properties. Society of Automotive Engineers.

[6] Atwood, D. 2009. Full-scale engine detonation and power performance evaluation of swift enterprises 702 fuel. Washington, D. C., United States Department of Transportation.

[7] Atwood, D., Rodgers, M. and Huang, C. 2015. Anti-knock performance of unleaded 94 aviation gasoline in high-octane demand full-scale engines. Washington, D. C., United States Department of Transportation.

[8] Atwood, D., Rodgers, M. 2014. Anti-knock performance of reduced lead aviation gasoline in a full-scale engine. Washington, D.C., United States Department of Transportation.

[9] DeMik, R., Keleher, J., Kasak, N., Keller, J., Mazza, A. and Raess, J. 2012. Lead memory in general aviation aircraft engine emissions. Journal of Aviation Technology and Engineering, 1 (2), 74-78.

[10] Duncan Seddon and Associates Pty Ltd. 2000. Octane enhancing petrol additives and products, Literature review and analysis. Victoria, Duncan Seddon and Associates Pty Ltd.

[11] Wang, Z., Liu, H., Reitz, R.D. 2017. Knocking combustion in spark-ignition engines. Progress in Energy and Combustion Science, 61, 78-112.