PARAMETRIC PERFORMANCE AND OPERATIONAL CHARACTERISTICS OF MOTOR GASOLINE FUEL USING LYCOMING O-320 AVIATION ENGINE

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I dedicate this thesis to;
my grandparents;
Mr. Andy & Mrs. Letchumy; Mr. Veerappen & Mrs. Pachaammal
my parents;
Mr. Kumar & Mrs. Saraswathy
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ABSTRACT

Federal Aviation Administration (FAA) is actively conducting research and development for unleaded aviation gasoline (AVGAS) transition for almost 20 years. Recent research with 200 unleaded blends and full-scale engine tests on 45 high-octane unleaded blends has not found a “drop-in” replacement for AVGAS. In this study, analysis of compatibility via optimisation of Lycoming O-320 engine fuelled with blends of RON 97, RON 98, RON 100 and AVGAS was carried out. This is to determine the compatibility, usability and safety of motor gasoline fuel to be used as aviation fuels using the response surface methodology (RSM). Vapor lock (VL) and carburettor icing (CI) analyses were conducted using principal component analysis (PCA). ASTM D7826 was used as a guideline in the evaluation process. The engine was run under varied engine speed of 2000-2700 RPM. Brake horsepower (BHP), brake thermal efficiency (BTHE), brake specific fuel consumption (BSFC), exhaust gas temperature (EGT), relative knock index (RKI), carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbon (UHC) and nitrogen oxide (NO_x) were recorded during the experiments. Response surface equations were developed to predict the values of output parameters. Analysis of variance was carried out to observe the most significant parameters affecting the responses. Optimisation was performed using the RSM optimisation of desirability. The next objective of the study was to measure the VL and CI tendencies of selected fuels by the application of factor analysis known as PCA. Study considered sixteen variables for VL and CI assessments each, using the selected and calculated fuel properties. Twenty-three aviation fuels’ data from literatures were collected. Model equations explaining the VL and CI tendencies of the aviation fuels were derived, and their respective factor scores were calculated. The model was applied to the 14 fuels in this study and their respective factor scores were calculated. All the fuels were ranked using the factor score from the best to worst. RSM results indicated that when the engine was run with a speed of 2300 rpm, RON 98 fuel gave optimum solution. The corresponding values of BHP, BTHE, BSFC, EGT, RKI, CO_2, CO, UHC and NO_x were 146.37 Hp, 28.1%, 0.2792 kg/kW-hr, 375.58 °C, 58.26%, 7.34%, 7.12%, 233.66 ppm and 51.83 ppm respectively. The desirability of 0.717 for RSM optimisation was obtained. Factor analysis results showed that PCA indicated cumulative variance of 86.77% and 86.78% for VL and CI respectively. Best VL and CI tendencies was shown by RON 98 with factor score of -0.64278 and -0.1982 respectively. The findings showed that motor gasolines (MOGAS) RON 97, RON 98 and RON 100 were able to outperform the commercial AVGAS in terms of VL and CI. The study concluded that MOGAS has a great ability to outperform AVGAS in terms of performance, detonation, emission, vapor lock and carburettor icing.

ABSTRAK

Federal Aviation Administration (FAA) melaksanakan penyelidikan dan pembangunan secara aktif selama 20 tahun untuk peralihan gasolin penerbangan (AVGAS) tanpa plumbum. Penyelidikan terbaru dengan 200 campuran tanpa plumbum dan ujian enjin berskala penuh pada 45 campuran tanpa plumbum tinggi tidak menemui penggantian "*drop-in*" untuk AVGAS. Dalam kajian ini, analisis keserasian melalui pengoptimuman enjin Lycoming O-320 telah dikendalikan menggunakan campuran bahan api RON 97, RON 98, RON 100 dan AVGAS. Ini adalah untuk menentukan keserasian, kebolehgunaan dan keselamatan bahan bakar petrol motor untuk digunakan sebagai bahan api penerbangan menggunakan kaedah sambutan permukaan (RSM). Analisa pengunci wap (VL) dan pengaisan karburetor (CI) dilaksanakan menggunakan analisa komponen utama (PCA). ASTM D7826 digunakan sebagai garis panduan dalam proses penilaian. Enjin dikendalikan di bawah kelajuan berbeza dari 2000-2700 RPM. Kuasa brek enjin (BHP), kecekapan terma brek (BTHE), penggunaan bahan api khusus brek (BSFC), suhu gas ekzos (EGT), indeks relatif ketukan (RKI), karbon dioksida (CO_2), karbon monoksida (CO), hidrokarbon tidak terbakar (UHC) dan nitrogen oksida (NO_x) direkodkan semasa eksperimen. Persamaan sambutan permukaan telah dihasilkan untuk meramalkan nilai parameter pengeluaran. Analisa varians telah dijalankan untuk melihat parameter yang paling ketara yang memberi kesan kepada respon. Pengoptimuman dilakukan berdasarkan kecenderungan pengoptimuman RSM. Objektif kajian seterusnya adalah untuk mengukur kecenderungan VL dan CI bahan api terpilih menggunakan analisis faktor dikenali sebagai PCA. Kajian menilai enam belas pemboleh ubah untuk penilaian VL dan CI, menggunakan sifat-sifat bahan api yang dipilih dan dikira. Dua puluh tiga data bahan api penerbangan dari literatur telah dikumpulkan. Persamaan model yang menjelaskan kecenderungan VL dan CI dari bahan api penerbangan diperoleh, dan skor faktor masing-masing telah dikira. Model ini digunakan untuk 14 bahan api dalam kajian ini dan skor faktor telah dikira. Semua bahan api disenaraikan dengan menggunakan skor faktor dari yang terbaik hingga terburuk. Keputusan RSM menunjukkan bahawa apabila enjin dijalankan dengan kelajuan 2300 rpm, bahan api RON 98 memberikan penyelesaian yang optimum. Nilai-nilai sepadan BHP, BTHE, BSFC, EGT, RKI, CO_2, CO, HC dan NO_x didapati masing-masing 146.37 hp, 28.1%, 0.2792 g/kW-hr, 375.58 ℃, 58.26%, 7.34%, 7.12%, 233.66 ppm dan 51.83 ppm. Kecendurangan 0.717 untuk pengoptimuman RSM telah diperolehi. Keputusan analisis faktor menunjukkan bahawa PCA menerangkan 86.77% dan 86.78% daripada varians terkumpul masing-masing untuk VL dan CI. Kecenderungan VL dan CI terbaik ditunjukkan oleh RON 98 dengan skor faktor masing-masing -0.64278 and -0.1982. Penemuan menunjukkan bahawa RON 97, RON 98 dan RON 100 mampu mengatasi AVGAS komersial dari segi VL dan CI. Kajian ini menyimpulkan MOGAS mempunyai keupayaan besar untuk mengatasi prestasi AVGAS dari segi persembahan, ketukan, emisi, pengunci wap dan pengaisan karburetor.

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LIST OF ABBREVIATIONS

100 LL	-	100 “Low-Lead”
102 UL	-	102 Unleaded
80/87 UL	-	80/87 Unleaded
82 UL	-	82 Unleaded
91/96 UL	-	91/96 Unleaded
94 UL	-	94 Unleaded
ACRP	-	Airport Cooperative Research Program
ADI	-	Anti-Detonation Injection
AFTO	-	Approved Flight Training Organizations
AGE85	-	Aviation Grade Ethanol 85
AKI	-	Anti-Knock Index
ALR	-	Aviation Lean Rating
ANOVA	-	Analysis of Variance
AOPA	-	Aircraft Owners and Pilots Association
ARMA	-	Auto Regressive Moving Average
ASTM	-	American Society for Testing Materials
AT	-	Air Taxi
ATAA	-	Air Transport Association of America
ATF	-	Aviation Turbine Fuel
AUTOGAS	-	Automotive Gasoline/Automobile gasoline
AVGAS	-	Aviation Gasoline
BHP	-	Brake Horsepower
BSFC	-	Brake Specific Fuel Consumption
BTHE	-	Brake Thermal Efficiency
C/H	-	Carbon to Hydrogen Ratio
CAA	-	Clean Air Act
CAAM	-	Aviation Authority of Malaysia

CDC - The Centres for Disease Control
CFT - Capillary Flow Technology
CHT - Cylinder Head Temperatures
CI - Carburettor Icing
CLEO - Calculus Luchtvaart Emissies Onder
(Calculus Aviation Emissions Below)
CO - Carbon Monoxide
CO_2 - Carbon Dioxide
CR - Compression Ratio
CRC - Coordinating Research Council
CV - Coefficient of Variation
DAH - Design Approval Holder
DCA - Department of Civil Aviation
DOE - Design of Experiment
DOE - Department of Energy
EAA - Experimental Aircraft Association
EASA - European Aviation Safety Agency
EDB - Ethylene Dibromide
EGT - Exhaust Gas Temperature
EIA - Energy Information Administration
EMS - Emission Analyser
EPA - Environmental Protection Agency
ETBE - Ethyl Tert-Butyl Ether
FAA - Federal Aviation Administration
FBP - Final Boiling Point
FCEE - Faculty of Chemical and Energy Engineering
FF - Fuel Flow
FFP - Fit for Purpose
FOE - Friends of the Earth
FT - Full Throttle
G100UL - GAMI 100 Unleaded
GA - General Aviation
GAMI - General Aviation Manufacturer Incorporation

GC - Gas Chromatographic
GC-FID - Gas Chromatography Flame Ion Detector
GC-MS - Gas Chromatography Mass Spectrometry
GHG - Green House Gas
UHC - Unburned Hydrocarbon (UHC)
LES - Large Eddy Simulation
LOF - Lack of Fit
MOGAS - Motor Gasoline
MON - Motor Octane Number
MSA - Kaiser’s Measure of Sampling Adequacy
MSD - Mass Spectrometry Detector
NAAQS - National Ambient Air Quality Standards
NO_x - Nitrogen Oxides
ONR - Octane Requirement
ORI - Octane Requirement Increase
PAFI - Piston Aviation Fuels Initiative
PCA - Principal Component Analysis
PCM - Pressure Control Module
PN - Performance Number
RFP - Request for Proposals (s)
RKI - Relative Knock Index
RON - Research Octane Number
RPM - Revolutions Per Minute
RSM - Response Surface Methodology
RVP - Reid Vapor Pressure
SAIB - Special Airworthiness Information Bulletin
SF100 - Swift Fuel 100
SI - Spark Ignition/Spark Ignited
SIAB - Special Airworthiness Information Bulletin
SIR - Screening Information Request
SPSS - Statistical Package for the Social Sciences
SR - Supercharged Rich

STC	-	Supplemental Type Certificate
TBD	-	To Be Defined
TC	-	Type Certificate
TCDS	-	Type Certificate Data Sheet
TEL	-	Tetraethyl Lead
TML	-	Tetramethyl Lead
$T_{V/L=20}$	-	Temperature at which the vapor to liquid volume ratio is 20
UAE	-	United Arab Emirates
UAT ARC	-	Unleaded Aviation Transition Aviation Rule Making Committee
UK	-	United Kingdom
UL	-	Unleaded
V/L	-	Vapour to Liquid Ratio
VL	-	Vapor Lock
VLL	-	Very Low Lead
WHO	-	World Health Organization

LIST OF SYMBOLS

N_s - Engine Speed

λi - Eigen Value

kPa - Kilo Pascal

ppm - Part Per Million

R^2 - Regression Squared

α - Reliability of Data

°C - Celsius

% - Percentage

°F - Fahrenheit

g - Grams

gal - Gallon

µg - Micro-Grams

L - Litre

V - Volume

P - Pressure

mL/L - Millitre Per Litre

MJ/Kg - Megajoules Per Kilogram

kg/m^3 - Kilogram Per Meter Cubed

g/L - Grams Per litre

kJ/mol - Joule Per Mole

kW-hour - Kilo Watt Hour

(+) - Plus/Positive Sign

(-) - Minus/Negative Sign

(*) - Multiplication Sign

(/) - Division Sign

Tg - Tetra Grams

µm - Micro Meter

ΔH_{vap}	-	Heat of Vaporisation
ΔHc	-	Heat of Combustion
P_v	-	Vapour Pressure

CHAPTER 1

INTRODUCTION

Approximately 230,000 piston-powered aircrafts worldwide rely on 100 low lead (100LL) Aviation Gasoline (AVGAS) for safe operation (Unleaded AVGAS Transition Aviation Rulemaking Committee, 2012a, 2012b). AVGAS is a specially blended grade of gasoline for use in aircraft engines of the piston type with distillation range normally within 30°C to 200°C (Energy Commission, 2015). But, in reality AVGAS has high levels of Tetraethyl Lead (TEL) (ASTM International, 2017b; Esch, Funke, and Roosen, 2010; Jonathon, 2011; M. Thom and Atwood, 2011). TEL is an additive which is added in aviation fuels to assist on anti-knocking (Atwood and Rodgers, 2014; Energy Commission, 2015; M. Thom and Atwood, 2011). Aircraft engines operate at higher power settings and temperatures and are prone to engines knock and this is the main reason why the TEL continuation as an additive in AVGAS (Jabiru Aircraft Pty Ltd, 2015). Introduction of 100 “low-lead” (100LL) AVGAS, which had the maximum allowable lead content reduced from 4.22 to 2.11 grams of lead per gallon has reduced the emissions of TEL (Lyons et al., 2016).

TEL additive in AVGAS, mainly for octane boosting and valve recession avoidance, can cause serious health impacts, including neurological effects in children that prompt behavioural issues, learning deficiencies and lowered IQ (Centre for Disease Control and Prevention, 2017). Lead content in the blood, bone, and tissues, if it is not promptly discharged, influences the kidneys, liver, sensory system, and blood-forming organs (Lyons et al., 2016). Lead is viewed as a human cancer-causing agent. Human introduction to lead happens fundamentally through breathing which leads to serious health problems. Lead concentrations of 10 µg per decilitre or more has been identified as a “level of concern” to human health by the

The Centres for Disease Control (CDC) and the World Health Organization (WHO) and has not been changed since 1991 (Gerberding, Falk, Rabb, and Brown, 2004). Specialists now utilize the term “a reference level” instead of the term “level of concern” of 5 µg for each decilitre to recognize youngsters with blood lead levels that are much higher than most children’s levels. This new level is based on the U.S. population of children ages 1-5 years who are in the highest 2.5% of children when tested for lead in their blood (Centre for Disease Control and Prevention, 2017).

Friends of the Earth (FOE) filed a "Petition for Rulemaking Seeking the Regulation of Lead Emissions From General Aviation Aircraft Under Clean Air Act (CAA)"(Friends of the Earth, 2016) to make a finding that lead discharged from piston-powered aircrafts using AVGAS jeopardizes the health of humans. FOE suggested the standard evaluation for lead emission from piston-powered aircrafts using AVGAS should be carried out. FOE said if the chairman of Environmental Protection Agency (EPA) trusts that incompetent data exists to make such a finding, start a research to study natural effects of lead discharge, including effects to people, creatures and environments under the CAA and issue a public report about the discoveries of the investigation and research (Environmental Protection Agency, 2010a). Consequently, in October 2010, EPA announced a revised lead National Air Ambient Quality Standard (NAAQS) to 0.15 µg (Environmental Protection Agency, 2010a). Figure 1.1 depicts the AVGAS grade in the general aviation market and the corresponding TEL content.

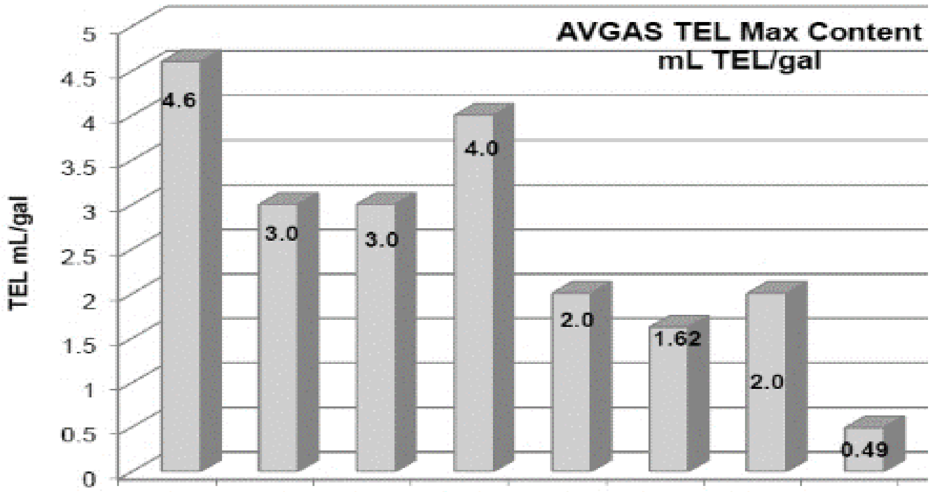

Figure 1.1 AVGAS grade and TEL content (Unleaded AVGAS Transition Aviation Rulemaking Committee, 2012a)

In December 2014, EPA issued a proposed rulemaking in which it reaffirmed its function to give expanded health security to kids and other people prone to the hazard against a variety of unfavourable health impacts, neurological impacts in kids, including neurocognitive and neurobehavioral impacts related to lead (Environmental Protection Agency, 2017a). The EPA currently is serious about issuing a proposed finding on the rulemaking and related materials on lead emissions from aircraft engines using leaded AVGAS. This proposed finding will then undergo public notice and comment. After evaluating comments on the proposal, final determination will be issued in 2019 (Esler, 2015).

Responding to the urgent concerns by the FOE, EPA and general aviation groups, Unleaded AVGAS Transition Aviation Rulemaking Committee (UAT ARC) was sanctioned on January 31, 2011, by the Federal Aviation Administration (FAA) to research and organize the move to an unleaded AVGAS (Unleaded AVGAS Transition Aviation Rulemaking Committee, 2012a, 2012b). Research concentrated on the advancement of unleaded AVGAS has been going for a considerable length of time. Right now, the FAA is proceeding with an assessment program to recognize an appropriate unleaded substitution for AVGAS 100LL (Esler, 2015).

UAT ARC (Unleaded AVGAS Transition Aviation Rulemaking Committee, 2012a, 2012b) in its final report of unleaded AVGAS findings and recommendations identified the following problems that must be addressed in any effort for the transition of the piston-powered aviation sector to an unleaded AVGAS;

a) Unleaded fuel replacement that addresses the issues and meets the mandatory requirements of piston aviation engines does not exist at present.
b) No program exists that can organize and encourage the assessment, certification, deployment and effect of a piston aviation engine fuel substitution of AVGAS.
c) No market driven reason exists to move to a substitution fuel because of the constrained size of the AVGAS market, decreasing interest, special nature of

AVGAS, safety, risk, and the cost required in an endorsement and approval process.

d) No FAA strategy or test methodology exists to empower piston aviation engine evaluation and approval of an unleaded replacement fuel.
e) There is no institutionalized technique for conveying to the business and end-clients the effects postured by a proposed fuel.

Several recommendations were outlined by UAT ARC (Unleaded AVGAS Transition Aviation Rulemaking Committee, 2012a, 2012b) ;

a) Assessment of the suitability of selected unleaded fuels on the aviation engine, performance, emissions and economic evaluations.
b) Centralized testing of possible unleaded fuels at the FAA William J. Hughes Technical Centre.
c) Include a FAA audit board with the specialized personnel from general aviation industry.
d) An industry-government collaboration referred to as the Piston Aviation Fuels Initiative (PAFI).

In response to the recommendations set by the UAT ARC (Unleaded AVGAS Transition Aviation Rulemaking Committee, 2012a, 2012b), FAA formed Piston Aviation Fuels Initiative (PAFI) (Unleaded AVGAS Transition Aviation Rulemaking Committee, 2012b). PAFI with direct supervision from Coordinating Research Council (CRC) of FAA evaluated 245 fuels, selecting 45 of the best evaluated fuels and by further evaluating the 45 fuels in a full-scale engine testing. Surprisingly, none of the fuels could match all the performance regulations of 100LL AVGAS (Unleaded AVGAS Transition Aviation Rulemaking Committee, 2012a, 2012b). Various periods of airplane testing were proposed, and 2019 is the time estimated for distribution of American Society for Testing Materials (ASTM) details for the unleaded substitution fuel. In spite of the fact that there are determinations for a 100 octane "very low lead" (VLL) AVGAS (ASTM, 2017) that brings down the lead content by around 20% with respect to AVGAS 100LL, it gives the idea that AVGAS 100LL will be the most commonly used fuel. This situation will continue to exist until detailed assessment on the unleaded AVGAS can be financially accessible and commercially safe and successful (Lyons et al., 2016).

1.1 Problem Statement

One possible technique for eliminating the effect of TEL emissions caused by general aviation was recognized; which is to make unleaded Motor Gasoline (MOGAS) accessible as another option to leaded AVGAS. In any case, unleaded MOGAS is a current, appropriate substitute for AVGAS. Piston aviation engines can work on a lower octane evaluated fuel, given that the aircraft is approved to run on MOGAS (Lycoming, 2018; Whittaker, 2001). To date 70,000 Supplemental Type Certificates (STC)s have been issued for aircraft modification for the usage of MOGAS and the results have shown that MOGAS is “better for internal engine parts and fuel systems as compared to AVGAS 100LL” (Cloche, 2010). When MOGAS is used in lower rated octane engines, it was seen that fewer spark-plug fouling issues occur with less valve sticking as compared to when these engines are pumped with AVGAS 100LL. According to EAA test reports, “engines running on MOGAS have better extended life and more time between overhauls” (Cloche, 2010). Not only is MOGAS is an efficient and unleaded fuel which when used in a modified engine like Continental O-200 ensures safe and smooth flights, but it’s also cost effective and cheaper than AVGAS 100LL. In the long run, as the production of MOGAS exceeds that of AVGAS 100LL, it will be readily available for its usage in aircrafts, powering almost 70-80% of general aviation fleet (Cloche, 2010).

While there are no safety issues related with using a higher-octane rating, utilization of a fuel with very low octane rating gives safety risk issue. FAA (Federal Aviation Administration, 2006), European Aviation Safety Agency (EASA) (Esch et al., 2010) and Cessna Textron Aviation (Cessna Textron Aviation, 2010) raised serious concerns on the use of MOGAS in aviation. Material incompatibility of the fuel system, danger of phase separation, vapor lock due to increased vapour pressure, carburettor icing due to raised enthalpy of evaporation, reduced energy content and alcohol in MOGAS red-flagged the issue. Apart from engine compatibility issues on the usage of MOGAS in aviation, emissions profile of MOGAS when used in aviation engines raise concerns. Emissions from aircraft piston engines are not considered as a significant problem in comparison to the total emissions. Globally there have not been any efforts to consider emission certification for piston engine aircrafts because data about piston engine aircraft emissions performance is almost non-existent (Rindlisbacher, 2007a; Yacovitch et al., 2016).

Despite the issues on MOGAS usage in aviation, the aviation community has accepted MOGAS to be a sustainable solution for “low compression low octane rated piston powered aircraft engine”. It has to be convinced that MOGAS in aviation is already happening as around 10% of piston aviation fuel usage is MOGAS (Lyons et al., 2016). In the long run, as the production of MOGAS exceeds that of AVGAS 100LL, it will be readily available for its usage in aircrafts, powering almost 70-80% of general aviation fleet (Cloche, 2010). Information that the Experimental Aircraft Association (EAA) produced from their Cessna 150 flights (Jonathon, 2011) and FAA (Gallagher, 1998) comprehensively tested has demonstrated that MOGAS is able to give satisfactory operational safety in their piston-engine. To support this, Australia, Bangladesh, Canada, New Zealand, Holland, Ireland, Malta, United Arab Emirates (UAE) and United Kingdom (UK) via civil aviation authority, allow the use of MOGAS (Beard, 1984; Canada, 1993; Canteenwalla, Imray, Earle, and Chishty, 2017; Civil Aviation Authority United Kingdom, 2016; Civil Aviation Safety Authority Australia, 2007; European Aviation Safety Agency, 2007; Irish Aviation Authorithy, 2014; Jack Stanton, 2007; Light Aircraft Association, 2015; Majlis, 1999; Transport Malta, 2009).

The Civil Aviation Authority of Malaysia (CAAM), previously known as the Department of Civil Aviation of Malaysia (DCAM) in its airworthiness notice dated 01 April 1987, made nine points on MOGAS usage in piston-powered aircrafts in Malaysia and conclusively said that, “taking all the facts into consideration the CAAM decided that applications for the utilization of MOGAS in aviation engines will not be evaluated or mandated in Malaysia unless supported by the aircraft manufacturer or a research organisation who will be required to present appropriate technical data” (Civil Aviation Authority of Malaysia, 1987). Realizing the huge potential of unleaded MOGAS in aviation engines in terms of economy and environment, necessity of providing complete data in terms of performance, detonation, emissions, vapor lock and carburettor icing characteristics within the climatic envelope of Malaysia (Civil Aviation Authority of Malaysia, 1987) is vital and extremely beneficial to the country.

1.2 Objectives

This study aims to determine the compatibility of using locally made motor gasoline fuels in aviation engine which specifically focused on the following objectives:

a. To characterise the physical and chemical composition of tested fuels in this work to be compared to the base reference fuel and to develop a parametric optimisation modelling of each tested fuel on the performance, detonation and emissions responses by employing Response Surface Methodology (RSM).
b. To determine vapour lock and carburettor icing tendencies of the tested fuels by employing Factor Analysis of the Principal Component Analysis (PCA) with comparative analysis from experimental data.

1.3 Scopes of Research

The research is subjected to several scopes and limitations due to wide area of research in fuel analysis, optimisation analysis and Principal Component Analysis. In order to achieve the objectives, a few scopes and limitations haven been identified in this research as listed:

a. Selection of fuel was limited to RON 97 as the lowest octane rated fuel with Octane Requirement Increase (ORI) of the engine was taken into consideration.
b. Gas Chromatography Mass Spectrometry (GCMS) is used to categorise the chemical composition of each tested fuels based on type of hydrocarbon.
c. Standard laboratory analysis is used to determine the physical and chemical properties of the fuel blends.
d. Dynamometer and exhaust gas analyser equipped with dedicated sensors are used to collect experimental data on the performance, detonation, emission, vapor lock and carburettor icing.
e. Experimental vapor lock data is collected by means of temperature measurement using a dedicated thermocouple installed at location of the fuel as it approaches carburettor of the test engine.
f. Experimental carburettor icing data measurement is done based on the brake specific fuel consumption (BSFC) data collected.
g. Engine speed was limited to 2000-2700 RPM as this is the crucial speed concerned to the descending, cruising, climbing and take-off speeds.
h. Optimisation analysis on the effects of RPM and fuel types on the performance, detonation and emissions responses is done using Response Surface Methodology (RSM).
i. Design of Expert version 10.0.1 is used to implement the Response Surface Methodology (RSM).
j. Factor analysis in Principal Component Analysis (PCA) is used to study the behaviour based on Factor Scores and the model was applied to the tested fuels of the study.
k. Factor Score ranking of the fuels is compared with experimental rank of the fuels to study the relationship between statistical and experimental methods for vapour lock and carburettor icing evaluation.
l. Only Principal Component (PC) which had highest score for vapor lock and carburettor icing were chosen for model prediction instead of all the PCs with eigenvalues more than 1.

1.4 Significance of the Study

To the best of the author's knowledge and based on literature, the last conducted test by the FAA on a similar research was in the late 1980, MOGAS in General Aviation Aircraft by FAA Technical Centre in March 1987. As years developed, MOGAS qualities have changed drastically according to current world needs. As quoted by CAAM (1987) about lead in MOGAS and MTBE content in MOGAS, present MOGAS available in Malaysia are all unleaded and without MTBE content and this indicates a serious amendment of the current stand of the CAAM and it would be best with full operational data.

CAAM (1987) mentions that it is aware of the high cost of AVGAS and that certain foreign regulatory authorities are approving the use of MOGAS in some types of light piston engine aircraft, but CAAM does not consider that these approvals can be directly read across to the use of such a fuel in Malaysia. All such approvals are related to a specific climatic envelope and the use of fuels produced within defined specification limits (Civil Aviation Authority of Malaysia, 1987). This research adopted the climatic envelope of Malaysia (research conducted in Universiti Teknologi Malaysia – UTM, Johor Bahru, Johor) and the results of the study are expected to change the stand of the CAAM on the possible usage of MOGAS in aviation in Malaysia and countries with similar climatic envelope with Malaysia.

CAAM (1987) also mentioned that it is important to realise that mogas differs from AVGAS in being produced to much wider specifications allowing for considerable variability in chemical composition and physical properties. It follows that mogas marketed in Malaysia can show significant variation in characteristics related to the refineries from which it was supplied. This research addresses all these issues using current MOGAS in Malaysia market which is expected to make a breakthrough of MOGAS usage in aviation.

The vapour pressure (P_v) of AVGAS is required to lie in the range 38 – 48 kPa and engine and aircraft fuel systems are designed, tested and certificated on that basis (Civil Aviation Authority of Malaysia, 1987). CAAM (1987) says it has no data on the P_v of locally available MOGAS, but it is probable that the top end of the range is considerably higher than that specified for AVGAS. This research provides full chemical and physical property data including the vapor pressure data of the local AVGAS, local MOGAS and the blends to address the concern raised by the CAAM.

CAAM (1987) further mentioned that the difference in volatility and vapour pressure between AVGAS and MOGAS can be highly significant in relation to the risk of vapour lock. Aircraft fuel systems are not designed to cope with large volumes of vapour and may be especially susceptible to this problem when climbing to altitude with warm mogas in the fuel tanks (Civil Aviation Authority of Malaysia, 1987). This research has evaluated the vapor lock tendency of AVGAS, MOGAS and the blends extensively based on experimental results and Principal Component Analysis (PCA).

Apart from that no such tests have been initiated or done as far as Malaysia’s general aviation market is concerned. This research will eventually give an updated study of the locally available MOGAS and their performance characteristics on spark ignited (SI) aviation engine. Since no unleaded fuel replacement that addresses the issues and meets the mandatory requirements of SI aviation engines exist, this study will give an option for general aviation operators globally using SI aviation engines to consider a transition to an unleaded fuel. This study will also be an eye opener for the environmental agencies in Malaysia and South East Asia to enhance further research on TEL emissions from aircrafts using AVGAS.

A technically viable program will be organized to encourage the assessment of MOGAS or unleaded fuel effects on a SI aviation engine with a setup of proper engine testing laboratory and test methodologies as currently no FAA strategy or test methodology exists to empower SI aviation engine evaluation and approval of an unleaded replacement fuel.

Apart from that, no optimisation studies have been undertaken on aviation fuel research worldwide and this research initiated optimisation analysis of aviation fuels and motor gasoline fuels in an aviation engine based on Response Surface Methodology (RSM).

This study will give an empirical model of assessment for performance, detonation and emissions parameters of leaded and unleaded fuels for piston engine fuel development initiative. Optimisation of fuel blends and base fuels in this study gives a clearer picture of possible unleaded transition towards the efforts of TEL elimination from AVGAS. Empirical model created to assess the vapor lock and carburettor icing tendencies of the fuels intended to be used in aviation before it could be used for future experimental runs, will eventually save cost. Best candidate fuels can be evaluated statistically before can be selected for laboratory testing.

MOGAS adaptation in aviation industry in Malaysia will significantly give economic importance as MOGAS is far cheaper than AVGAS which will benefit greatly Approved Flight Training Organizations (AFTO) and other general aviation operators who operate with piston powered aircrafts in Malaysia.

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