INVESTIGATION TO DIRECT ETHANOL INJECTION IN SPARK IGNITION GASOLINE ENGINES

By
Yuan ZHUANG

Thesis submitted as a requirement for the degree of
Doctor of Philosophy

School of Electrical, Mechanical and Mechatronic Systems
Faculty of Engineering and Information Technology

University of Technology, Sydney (UTS)
July, 2014

Declaration of Authorship

I, Yuan ZHUANG, certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signed:

Date:

Acknowledgements

I would like to take this opportunity to express my gratitude to all of the people who have offered me help and support during the past four years of my candidature. First and foremost, I would like to give my sincere thanks to my supervisor A/Prof. Guang Hong for providing the project and for her guidance, inspiration, numerous hours of discussion, and revision of the papers. From her I acquired not only knowledge but also high order research methodology skills which will benefit me throughout my career.

I wish to acknowledge my co-supervisor Dr. Jianguo Wang and visiting scholar Dr. Zhipeng Li who respectively helped me to solve the software problems of our engine control unit. I benefited greatly from their support, and I sincerely appreciated their contribution to the project.

I wish to acknowledge the strong support that I received from staff in Mechanical engineering Laboratories and FEIT workshop at UTS, including Len D'Arcy, Chris Chapman, Holger Roser, Jack Liang, Laurence Stonard, John Funnell, and Ron Smith. Without their excellent technical assistance, the building up, calibration and maintenance of the testing rig system would not have been possible.

Many thanks to the capstone students, Gim Lim Ong, Tin Shea, Kelvin Tran, Fabio Perri, Michael Milledge and Kiel D'Arcy who assisted with the experimental work. I also want to thank Dr. Ding Fei, A/Prof. Bin Zhou, Dr. Cliff Wang and Mr. Yuhan Huang who gave me great assistance in both my studies and daily life.

My deep thanks go to my parents and friends, who have always been proud of my achievements and who have consistently supported and cared for me throughout the years.

I extend my gratitude to the China Scholarship Council who provided the scholarship for my four years of study. I also would like to express my great appreciation for the financial support from the Faculty of Engineering & IT, including my top-up scholarship for four years and the funding for setting up the engine rig. Manildra Group, the supplier of the ethanol fuel is also gratefully acknowledged.

Finally, I would like to thank Shale Preston for proofreading my thesis.

Publications

Journal Papers:

Yuan Zhuang and Guang Hong. "Primary investigation to leveraging effect of using ethanol fuel on reducing gasoline fuel consumption." Fuel 105 (2013): 425-431.

Yuan Zhuang and Guang Hong. " Effects of direct injection timing of ethanol fuel on engine knock and lean burn in a port injection gasoline engine." Fuel 135 (2014) 27–37.

Conference Papers:

Yuan Zhuang and Guang Hong. "Investigation to Leveraging Effect of Ethanol Direct Injection (EDI) in a Gasoline Port Injection (GPI) Engine." SAE Technical Paper 2013-04-08, 2013, doi: 10.4271/2013-01-1322.

Yuan Zhuang and Guang Hong. The Effect of Direct Injection Timing and Pressure on Engine Performance in an Ethanol Direct Injection Plus Gasoline Port Injection (EDI+ GPI) SI Engine. SAE Technical Paper 2013-01-0892, 2013, doi:10.4271/2013-01-0892.

Yuan Zhuang, Guang Hong, and Jianguo Wang. "Preliminary investigation to combustion in a SI engine with direct ethanol injection and port gasoline injection (EDI+ GPI)." (2012), 18th Australasian Fluid Mechanics Conference, Launceston, Australia.

Yuan Zhuang, Jianguo Wang, and Guang Hong. "A single cylinder research engine for investigating combustion of direct ethanol injection and port gasoline injection." (2012), 18th Australasian Fluid Mechanics Conference, Launceston, Australia.

Papers Submitted for Publications:

Yuan Zhuang and Guang Hong. "Effects of spark timing on the performance of an ethanol direct injection plus gasoline port injection (EDI+GPI) engine" Submitted to Applied Energy, in review.

Abstract

Ethanol is a promising alternative fuel in terms of addressing future energy and environmental problems. The existing method of using ethanol fuel by blending gasoline and ethanol fuel does not fully exploit ethanol's advantages. The dual-fuel injection strategy, ethanol direct injection plus gasoline port injection (EDI+GPI), offers a potentially new way to make use of ethanol fuel more effectively and efficiently. The effect of EDI+GPI on engine performance has been experimentally investigated on a 249cc, 4 stroke, air cooled single cylinder engine which was modified by adding an ethanol fuel direct injection system. The research purpose was focused on efficiency improvement (leveraging effect) and emissions reduction. Engine performance at original engine spark timing setting (15 CAD BTDC), knock margin and lean conditions was carried out to assess EDI+GPI's effectiveness. The impacts of EDI+GPI on engine control parameters, such as start of injection (SOI) timing and spark timing, were also evaluated in order to best match this new fuelling system to conventional SI engines.

When the engine was operating at the original engine spark timing setting (15 CAD BTDC), less energy input was required in a SI engine equipped with EDI+GPI to achieve comparable engine power output. Thus, the total fuel consumption could be reduced by leveraging the use of ethanol fuel. At engine speed of 3500rpm, when the ethanol energy ratio (EER) was less than 42.4% at light load and 36.3% at medium load, the EDI+GPI showed a positive impact in relation to combustion with reduced combustion duration and advanced central combustion phasing. However, with further increase of EER, the combustion duration prolonged and central combustion phasing retarded. This may be caused by over cooling due to increased ethanol fuel directly injected.

EDI+GPI effectively mitigated engine knock and permitted more advanced spark timing and higher inlet air pressure. At three tested engine loads of indicated mean effective pressure (IMEP), 7.2 Bar, 7.8 Bar and 8.5 Bar, every 2% or 3% increment of EER permitted about 2 CAD advance of knock limited spark advance (KLSA) when the EER was in the range from 15% to 35%. The highest load achieved in this investigation was 10.5 Bar IMEP at inlet (compressed) air pressure of 1.4 Bar. The EER level at this condition was 36.9%.

Early ethanol direct injection (EEDI) was more suitable to the EDI+GPI engine since the IMEP in EEDI conditions was greater than that in later ethanol direct injection (LEDI) conditions due to improved volumetric efficiency and combustion. LEDI was less effective on increasing IMEP

because its major combustion duration was longer than that in the EEDI condition. In lean burn, EEDI was more effective on extending the lean burn limit than LEDI. The maximum lean burn limit (λ) achieved by EEDI was 1.29. LEDI only slightly increased the lean burn limit which was just over the stoichiometric air-fuel ratio (AFR).

When the EER varied, spark timing required corresponding changes to achieve the best efficiency. At IMEP of around 4.0 Bar, spark timing of 25 CAD BTDC resulted in the highest indicated thermal efficiency when the EER was less than 29%, whilst when the EER was greater than 39%, the maximum indicated thermal efficiency was at spark timing of 30 CAD BTDC.

Contents

List of Tables

List of Figures

Acronyms and Abbreviations

HE: Heating energy

HC: Hydrocarbon

ATDC: After top dead center

BTDC: Before top dead center

CI: Compression ignition

CO: Carbon monoxide

DI: Direct fuel injection

ECU: Electronic control unit

EDI: Ethanol fuel direct injection

EEDI: Early ethanol direct injection

EGDI: Early gasoline direct injection

ERR: Ethanol/gasoline energy ratio

FFV: Fuel flexible vehicle

GDI: Gasoline direct injection

GPI: Gasoline port injection

HC: Hydrocarbon

IMEP: Indicated mean effective pressure

ISCO: Indicated specific carbon monoxide

ISHC: Indicated specific hydrocarbon

ISNO: Indicated specific nitric oxide

KLSA: Knock limited spark advance

LEDI: Late ethanol direct injection

LGDI: Late gasoline direct injection

MBT: Maximum advanced for best torque

NO_x: Nitric oxygen

PFI: Port fuel injection

SIDI: Spark ignition direct injection

SOI: Start of injection

ST: Spark timing

SI: Spark ignition

TDC: Top dead center

RPM: Revolutions per minute

Variables

CA0-5%: Combustion initiation duration (degree)

CA50: Crank angle position where the accumulated heat release reaches 50% of the total released heat (degree)

CA5-50%: Early combustion duration (degree)

CA5-90%: Major combustion duration (degree)

CAD: Crank angle degree (degree)

HE: Heating energy (kW)

Lambda (λ): Air/fuel equivalence ratio (dimensional)

MBF: Mass burnt fraction (dimensional)