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PRESSED

NATURAL GAS BI-FUEL ENGINE

by

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PHD**

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LIST OF ABBREVIATIONS

AFR	Air Fuel Ratio	ROHR	Rate of Heat Release
AMM	Agilent Measurement Manager	NGV	Natural Gas Vehicle
BDC	Bottom Dead Centre	RH	Relative Humidity
BSFC	Brake Specific Fuel Consumption	SI	Spark Ignition
CA	Crank Angle	TDC	Top Dead Centre
CFD	Computational Fluid Dynamics	TKE	Turbulent Kinetic Energy
CNG	Compressed Natural Gas	RPM	Revolution Per Minute
CO	Carbon monoxide	SN	Swirl Number
COV	Coefficient of Variation	SULEV	Super Ultra-Low Emission Vehicle
CSV	Comma-Separated Values	V	Voltage
DAQ	Data Acquisition Unit		
DVL	Dissimilar Valve Lift		
ECU	Engine Control Unit		
EDC	Eddy-Dissipation Concept		
EV	Exhaust Valves		
EVC	Exhaust Valves Close		
EVO	Exhaust Valves Open		
EXPT	Experimental		
HC	Hydrocarbon		
ICE	Internal Combustion Engine		
IV	Intake Valves		
IVC	Intake Valves Close		
IVO	Intake Valves Open		
LHV	Lower Heating Value		

LIST OF SYMBOLS

$^{\circ}\text{C}$	Degree Celsius	a	crankshaft linkage
$^{\circ}\text{CA}$	Degree crank angle	V	cylinder volume
R	Gas constant	ε	geometric ratio
p	Pressure	E	total energy of the system
γ	Specific heat ratio	ϕ	equivalence ratio
T	Temperature	R	Gas Constant
η_v	Volumetric efficiency	\bar{Q}_{LHV}	rate of lower heating value
\dot{m}_a	Mass of air flowrate	A	combustion area
V_d	Engine displacement	p	cylinder pressure
Re_T	Turbulent Reynolds number	R_b	base circle
ε	Viscous dissipation	R_A	radius curvature for point A
Q_{ch}	Cumulative net heat release	CP	combustion pressure
C_s	the swirl coefficient	T	Torque
ω_p	is the paddle wheel angular velocity	\dot{m}_f	fuel consumption
x_b	Mass fraction burn	η	engine efficiency
$\Delta\theta_d$	Flame-development angle	Q_{lhv}	lower heating value of fuel
S_m	Mass added	\bar{C}_{ip}	specific heat at constant pressure of species i
R_s	Swirl number	ρ	is the density
ω_s	Angular velocity	n	number of cells within the cylinder
s	Stroke length		
l	connecting rod		
m_i	mass within each cell		

ABSTRACT

The development of advanced technology for medical and biological diagnostician is significantly increased. Electrochemical biosensors become more desirable since it offered an attractive replacement for the bulky and expensive analytical instruments. The design and fabrication of a novel electrochemical biosensor using microfluidic chip are the aims of this research. Additionally, the effects of the design parameters including the microchannel size and electrode size are to be investigated. The designed biosensor is consisting of two chips; a microfluidic chip which was made of PMMA (polymethyl methacrylate) where the microchannel is created. The second chip is made of glass, where the three electrodes cell was fabricated. This design offered more flexible testing and multi diagnostician at the same chip. The performance of such biosensor is then examined using the electrokinetic and cyclic voltammetry techniques in order to ensure the quality of the biosensor. The effect of the microchannel size on the performance of the sensor was then investigated by conducting cyclic voltammetry testing for four different sizes of the fabricated channels at electrode size of $100\mu\text{m}$. Likewise, similar channels sizes were investigated at $200\mu\text{m}$ electrode size. The fabricated chips morphology showed the smoothness on the surface in both the microchannel chip and the electrode chip. No defects on the fabricated chips were reported. The electrokinetic properties of the microchannel were found to be affected by the size of both the microchannel and the electrode. The highest sensitivity of the sensor was reported at microchannel size of 700 and electrode size of $200\mu\text{m}$. High accuracy and fast responding electrochemical biosensor are expected to be produced through the optimization of the microchannel size and the electrode surface area.

ABSTRAK

Perkembangan teknologi maju untuk diagnostik perubatan dan biologi meningkat dengan ketara. Biosensor elektrokimia menjadi lebih wajar kerana ia ditawarkan pengganti yang menarik bagi instrumen analisis besar dan mahal. Reka bentuk dan fabrikasi yang biosensor elektrokimia novel menggunakan cip microfluidic adalah Tujuan kajian ini. Selain itu, kesan parameter reka bentuk termasuk saiz saluran mikro dan saiz elektrod yang akan disiasat. The biosensor direka adalah terdiri daripada dua cip; cip microfluidic yang diperbuat daripada PMMA (polymethyl metakrilat) di mana saluran mikro yang dicipta. Cip kedua diperbuat daripada kaca, di mana sel tiga elektrod telah dipalsukan. Reka bentuk ini ditawarkan ujian yang lebih fleksibel dan pelbagai diagnostik pada cip yang sama. Prestasi biosensor itu kemudiannya diperiksa menggunakan teknik voltammetri elektrokinetik dan kitaran untuk memastikan kualiti biosensor ini. Kesan saiz saluran mikro ke atas prestasi sensor kemudiannya disiasat dengan menjalankan ujian voltammetri berkitar selama empat saiz yang berbeza daripada saluran yang direka pada saiz elektrod $100\mu\text{m}$. Begitu juga, saluran sama saiz telah disiasat pada saiz elektrod $200\mu\text{m}$. Yang direka morfologi cip menunjukkan kelancaran di permukaan di kedua-dua cip saluran mikro dan cip elektrod. Tiada kecacatan pada cip direka dilaporkan. Sifat-sifat elektrokinetik daripada saluran mikro yang didapati dipengaruhi oleh saiz kedua-dua saluran mikro dan elektrod. Kepakaan tertinggi sensor dilaporkan pada saiz saluran mikro 700 dan saiz elektrod $200\mu\text{m}$. Ketepatan yang tinggi dan cepat bertindak balas biosensor elektrokimia dijangka akan dihasilkan melalui pengoptimuman saiz saluran mikro dan kawasan permukaan elektrod.

REFERENCES

- Abianeh O.S., Mirsalim M., OMMI F. (2009). Combustion Development Of A Bi-Fuel Engine. *International Journal of Automotive Technology*, 10(1), 17-25. doi:10.1007/s12239
- Agilent Technologies. (2012). Agilent U2500A Series USB Simultaneous Sampling Multifunction Data Acquisition Devices Service Guide.
- Ali, R. (2011). Modeling Of Turbulent Flame Velocity For Spark Ignition Engines. *International Journal of Engineering Science and Technology (IJEST)*, 3(4), 2648-2658.
- Alkidas, A. C. (2007). Combustion advancements in gasoline engines. *Energy Conversion and Management*, 48, 2751-2761. doi:10.1016/j.enconman.2007.07.027
- Amr Ibrahim, Saiful Bari. (2008). Optimization of a natural gas SI engine employing EGR strategy using a two-zone combustion model. *Fuel*, 87(10-11), 1824-1834. doi:10.1016/j.fuel.2007.10.004
- Aslam, M. U., Masjuki, H. H., Kalam, M. A., & Amalina, M. A. (2005). A Comparative Evaluation of the Performance and Emissions of a Retrofitted Spark Ignition Car Engine, 4, 97-110.
- Aslam M.U., Masjuki H.H., Kalam M.A., Abdesselam H., Mahlia T.M.I., Amalina M.A. (2006). An experimental investigation of CNG as an alternative fuel for a retrofitted gasoline vehicle. *Fuel*, 85(5-6), 717-724. doi:10.1016/j.fuel.2005.09.004
- Astbury, G. R. (2008). A review of the properties and hazards of some alternative fuels. *Process Safety and Environmental Protection*, 86(6), 397-414. doi:10.1016/j.psep.2008.05.001
- Badr, O., Alsayed, N., & Manaf, M. (1998). A parametric study on the lean misfiring and knocking limits of gas-fueled spark ignition engines. *Applied Thermal Engineering*, 18(7), 579-594. doi:10.1016/S1359-4311(97)00029-X
- Begg, S. M., Hindle, M. P., Cowell, T., & Heikal, M. R. (2009). Low intake valve lift in a port fuel-injected engine. *Energy*, 34(12), 2042-2050. Elsevier Ltd. doi:10.1016/j.energy.2008.08.026

- Bourn, G. D., Phillips, F. A., & Harris, R. E. (2005). *Technologies To Enhance The Operation Of Existing Natural Gas Compression Infrastructure - Manifold Design For Controlling Engine Air Balance* (p. 26). Morgantown University.
- Brown, B. R. (2001). Combustion Data Acquisition and Analysis. Loughborough University.
- Byung Hyouk Min, Jin Taek Chung, Ho Young Kim, Simsoo Park. (2002). Effects of Gas Composition on the Performance and Emissions of Compressed Natural Gas Engines. *KSME International Journal*, 16(2), 219-226.
- C.L. Myung, K.H. Choi, I.G. Hwang, K.H. Lee, & S. Park. (2009). Effects Of Valve Timing And Intake Flow Motion Control On Combustion And Time-Resolved Hc & Nox Formation Characteristics. *International Journal of Automotive Technology*, 10(2), 161-166.
- Carlucci, a. P., de Risi, a., Laforgia, D., & Naccarato, F. (2008). Experimental investigation and combustion analysis of a direct injection dual-fuel diesel-natural gas engine. *Energy*, 33(2), 256-263. doi:10.1016/j.energy.2007.06.005
- Ceviz M.A. (2007). Intake Plenum Volume And Its Influence On The Engine Performance, Cyclic Variability And Emissions. *Energy Conversion and Management*, 48(3), 961-966. Yurkey: Elsevier Ltd.
- Cheung, H. (1993). A Practical Burn Rate Analysis for Use in Engine Development and Design. PHD Thesis. *Massachusetts Institute of Technology*.
- Chiru, A., & Buzea, D. (2012). The Influence Of Variable Valve Timing System Over Internal Combustion Engine ' S Performances. *International Journal Of Mechanics*, 5(1).
- Cho, H. M., & He, B.-quan. (2009). Combustion and Emission Characteristics of a Natural Gas Engine under Different Operating Conditions, Korean Society of Environmental Engineers, 14(2), 95-101.
- Choi, G. H., Lee, J. C., Kwon, T. Y., Ha, C. U., Lee, J. S., Chung, Y. J., Chang, Y. H., (2009). Combustion characteristics of a swirl chamber type diesel engine †. *Journal of Mechanical Science and Technology*, 23, 3385-3392. doi:10.1007/s12206-009-1011-2
- Clenci, A. C., Iorga-Simăn, V., Deligant, M., Podevin, P., Descombes, G., & Niculescu, R. (2014). A CFD (computational fluid dynamics) study on the effects of operating an engine with low intake valve lift at idle corresponding speed. *Energy*, 71, 202-217. doi:10.1016/j.energy.2014.04.069
- Cosgarea, R., Aleonte, M., & Cofaru, C. (2011). The influence of the valve lift strategies on the combustion characteristics of a homogeneous charge compression ignition engine model, 5(3), 191-201.

- Damrongkijkosol, C. (2006). *An Experiment Study On Influence Of Compression Ratio For Performance And Emission Of Natural Gas Retrofit Engine*. King Mongkut's Institute Of Technology, North Bangkok.
- Daihatsu Motor Company Ltd. (2000). *Service Manual Type K3 Engine* (1st ed., p. 9737). Daihatsu Motor Company Ltd.
- Daihatsu Motor Company Ltd. (2012). *Annual report 2011. EPPO Bulletin* (Vol. 42, pp. 11-43). doi:10.1111/epp.2606
- Das, A, & Watson, H. C. (1997). Development of a natural gas spark ignition engine for optimum performance. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 211(5), 361-378. doi:10.1243/0954407971526506
- DeHong Zhang. (1995). *Turbulent swirling combustion of premixed natural gas and air*. The University Of British Columbia, PHD Thesis.
- Dehong Zhang, Philip G. Hill. (1996). Effect of swirl on combustion in a short cylindrical chamber. *Combustion and Flame*, 106(3), 318-332. doi:[http://dx.doi.org/10.1016/0010-2180\(95\)00256-1](http://dx.doi.org/10.1016/0010-2180(95)00256-1)
- Demirbas, A. (2009). Transportation Fuels. *Biohydrogen* (1st ed., pp. 85-104). London: Springer-Verlag.
- Demirbas, A. (2010). Natural Gas. *Methane Gas Hydrate* (1st ed., Vol. 2003, pp. 57-76). London: Springer-Verlag.
- Dondero, L., & Goldemberg, J. (2005). Environmental implications of converting light gas vehicles: the Brazilian experience. *Energy Policy*, 33(13), 1703-1708. doi:10.1016/j.enpol.2004.02.009
- Duleep, G. (2011). *Comparison of Vehicle Efficiency Technology Attributes and Synergy Estimates Comparison of Vehicle Efficiency Technology Attributes and Synergy Estimates* (p. 7).
- Energy Commision Malaysia. (2008). Statistics of Piped Gas Distribution Industry 2008. *Suruhanjaya Tenaga*.
- Etheridge, J., Mosbach, S., Kraft, M., Wu, H., & Collings, N. (2011). Modelling cycle to cycle variations in an SI engine with detailed chemical kinetics. *Combustion and Flame*, 158(1), 179-188. The Combustion Institute. doi:10.1016/j.combustflame.2010.08.006
- Ewald, J., & Peters, N. (2007). On unsteady premixed turbulent burning velocity prediction in internal combustion engines. *Proceedings of the Combustion Institute*, 31(2), 3051-3058. doi:10.1016/j.proci.2006.07.119
- Flekiewicz Marek. (2009). Ignition Timing Advance In The Bi-Fuel Engine. *Transport Problems*, 4(2), 117.

- Fluke. (2001). 53 & 54 Series II Thermometer Users Manual.
- Focus Applied Technologies. (2009). Dynamometer Controller Model DC2AP.
- Fontana, G., & Galloni, E. (2009). Variable valve timing for fuel economy improvement in a small spark-ignition engine. *Applied Energy*, 86(1), 96-105. doi:10.1016/j.apenergy.2008.04.009
- Fu-Rong Zhang, Kazuhisa Okamoto, Satoshi Morimoto, Fujio Shoji. (1998). Methods of Increasing the BMEP (Power Output) for Natural Gas Spark Ignition Engines, (724).
- Geok, H. H. (2009). Experimental Investigation of Performance and Emission of a Sequential Port Injection Natural Gas Engine. *European Journal of Scientific Research*, 30(2), 204-214.
- Georgios Karavalakis et.al. (2012). Air pollutant emissions of light-duty vehicles operating on various natural gas compositions. *Journal of Natural Gas Science and Engineering*, 4, 8-16. Elsevier B.V. doi:10.1016/j.jngse.2011.08.005
- Gharehghani, a., Mirsalim, M., & Yusaf, T. (2013). Experimental investigation of thermal balance of a turbocharged SI engine operating on natural gas. *Applied Thermal Engineering*, 60(1-2), 200-207. Elsevier Ltd. doi:10.1016/j.applthermaleng.2013.06.029
- Guillaume, D. W., & Larue, J. C. (1995). Combustion enhancement using induced swirl. *Experiments in Fluids*, 20(March), 59-60.
- H.G. Zhang, X.J. Han, B.F. Yao, G.X. Li. (2013). Study on the effect of engine operation parameters on cyclic combustion variations and correlation coefficient between the pressure-related parameters of a CNG engine, 104, 992-1002. doi:10.1016/j.apenergy.2012.11.043
- Heim, D. M., & Ghandhi, J. B. (2011). Investigation of swirl meter performance. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 225(8), 1067-1077. doi:10.1177/0954407011404763
- Heywood J.B. (1988). *Internal Combustion Engine* (Vol. 21, p. 219). New York: McGraw-Hill, Inc.
- Hosseini, V., Checkel, M. D., & Neill, W. S. (2008). Natural gas spark ignition engine efficiency and NO_x emission improvement using extreme exhaust gas recirculation enabled by partial reforming. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 222(12), 2497-2510. doi:10.1243/09544070JAUTO539
- Huang, Z., Liu, B., Zeng, K., Huang, Y., Jiang, D., Wang, X., & Miao, H. (2007). Combustion Characteristics and Heat Release Analysis of a Spark-Ignited Engine Fueled with Natural Gas-Hydrogen Blends. *Energy & Fuels*, 21(5), 2594-2599. doi:10.1021/ef0701586

- J.N. Kim, H.Y. Kim, S.S. Yoon, S.D. SA. (2008). Effect Of Intake Valve Swirl On Fuel-Gas Mixing And Subsequent Combustion In A Cai Engine. *International Journal of Automotive Technology*, 9(6), 649-657. doi:10.1007/s12239
- Joo, S. H., & Chun, K. M. (2000). Swirl Effect on the Flame Propagation at Idle In a Spark Ignition Engine, 14(12), 1412-1420.
- Kahn Ribeiro, S. et al. (2007). Transport and its infrastructure. In *Climate Change 2007: Mitigation* (p. 328).
- Kang, K. Y., & Reitz, R. D. (1999). The effect of intake valve alignment on swirl generation in a DI diesel engine, 20, 94-103.
- Kapadani, K. R., & Navale, S. J. (2014). Investigation Of Performance Of Si Engine With Fuels - Gasoline , Natural Gas And H-Cng5 Gas. *International Journal of Research in Engineering and Technology*, 3(4), 351-359.
- Ke Zeng, Zuohua Huang, Bing Liu, Liangxin Liu, Deming Jiang, Yi Ren, Jinhua Wang. (2006). Combustion characteristics of a direct-injection natural gas engine under various fuel injection timings. *Applied Thermal Engineering*, 26(8-9), 806-813. doi:10.1016/j.applthermaleng.2005.10.011
- Khalid Abdul Rahim, Audrey Liwan. (2012). Oil and gas trends and implications in Malaysia. *Energy Policy*, 50, 262-271.
- Kirkpatrick, C. R. F. and A. T. (2001). *Internal Combustion Engines*. (J. Hayton, Ed.). New York: John Wiley & Sons Inc.
- Klell, M., Eichlseder, H., & Sartory, M. (2012). Mixtures of hydrogen and methane in the internal combustion engine e Synergies , potential and regulations. *International Journal of Hydrogen Energy*, 37(15), 11531-11540. Elsevier Ltd. doi:10.1016/j.ijhydene.2012.03.067
- Kornbluth, K., McCaffrey, Z., & Erickson, P. a. (2009). Incorporating in-cylinder pressure data to predict NOx emissions from spark-ignition engines fueled with landfill gas/hydrogen mixtures. *International Journal of Hydrogen Energy*, 34(22), 9248-9257. Elsevier Ltd. doi:10.1016/j.ijhydene.2009.09.020
- Kuo, P. S. (1996). Cylinder Pressure in a Spark-Ignition Engine : A Computational Model. *Journal of Undergraduate Sciences*, 145(Fall), 141-145.
- Laemmle, C. (2005). *Numerical and Experimental Study of Flame Propagation and Knock in a Compressed Natural Gas Engine*. Swiss Federal Institute Of Technology Zurich.
- Lapidus A.I., Krylov I.F., Tonkonogov B.P. (2005). Natural Gas as Motor Fuel. *Chemistry and Technology of Fuels and Oils*, 41(3), 165-174. doi:10.1007/s10553-005-0041-4

- Lee, K., Bae, C., & Kang, K. (2007). The effects of tumble and swirl flows on flame propagation in a four-valve S.I. engine. *Applied Thermal Engineering*, 27(11-12), 2122-2130. doi:10.1016/j.applthermaleng.2006.11.011
- M. I. Jahirul, H.H. Masjuki, R.Saidur, M.A.Kalam, M.H. Jayed, M.A. Wazed. (2010). Comparative engine performance and emission analysis of CNG and gasoline in a retrofitted car engine. *Applied Thermal Engineering*, 30(14-15), 2219-2226. Elsevier Ltd. doi:10.1016/j.applthermaleng.2010.05.037
- M.I. Jahirul, R. Saidur, M. Hasanuzzaman, H.H. Masjuki, M.A. Kalam. (2007). A Comparison Of The Air Pollution Of Gasoline And Cng Driven Car For Malaysia. *International Journal of Mechanical Engineering (IJMME)*, 2(2), 130-138.
- Malaysian Gas Association. (2013). *Malaysia : Natural Gas Industry Annual Review 2012* (p. 25).
- Maly, R. R. (1994). State Of The Art And Future Needs In S.I. Engine Combustion. *Twenty-Fifth Symposium (International) on Combustion*, 111-124.
- Mamat, R., Abdullah, N. R., Xu, H., Wyszynski, M. L., & Tsolakis, A. (2010). Effect of Air Intake Pressure Drop on Performance and Emissions of a Diesel Engine Operating with Biodiesel and Ultra Low Sulphur Diesel (ULSD). *International Conference on Renewable Energies and Power Quality*.
- Mansha, M., Saleemi, a ., & Ghauri, B. M. (2010). Kinetic models of natural gas combustion in an internal combustion engine. *Journal of Natural Gas Chemistry*, 19(1), 6-14. CAS/DICP. doi:10.1016/S1003-9953(09)60024-4
- Mattarelli, E., Borghi, M., Balestrazzi, D., & Fontanesi, S. (2004). The Influence of Swirl Control Strategies on the Intake Flow in Four Valve HSDI Diesel Engines. *SAE International*, (724).
- Md. Ehsan. (2006). Effect Of Spark Advance On A Gas Run Automotive Spark Ignition Engine. *Journal of Chemical Engineering*, 24(1), 42-49.
- Mendera, K. Z., Spyra, A., & Smereka, M. (2002). Mass Fraction Burned Analysis. *Journal of KONES Internal*, 9(3), 193-201.
- Merker, G. P., Schwarz, C., Stiesch, G., & Otto, F. (2006). *Simulating Combustion* (p. 12). Berlin Heidelberg: Springer-Verlag.
- Meyer, J. (2007). *Engine Modeling of an Internal Combustion Engine*. The Ohio State University.
- Miles, P. C. (2009). *Flow and Combustion in Reciprocating Engines*. (C. Arcoumanis & T. Kamimoto, Eds.). Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-540-68901-0
- Milton, B. E., Behnia, M., & Ellerman, D. M. (2001). Fuel deposition and re-atomisation from fuel / air flows through engine inlet valves, 22, 350-357.

- Moritani, H., & Nozawa, Y. (2004). Oil Degradation in Second-Land Region of Gasoline Engine Pistons. *Review of Toyota CRDL*, 38(3), 36-43.
- Muk, H., & He, B.-quan. (2007). Spark ignition natural gas engines — A review, 48, 608-618. doi:10.1016/j.enconman.2006.05.023
- NGV Communications Group. (2012, October). Asian NGV Communications. *Argentina*, (68), 28. Argentina.
- Nijboer, M. (2010). The Contribution of Natural Gas Vehicles to Sustainable Transport. Paris, France.
- Per Anders Tunestal. (2000). *The Use of Cylinder Pressure for Estimation of the In-Cylinder Air/Fuel Ratio of an Internal Combustion Engine*. University Of California, Berkeley.
- Performance Trends INC. (2011). *Swirl Meter*.
- Persson, H., Johansson, B., & Remón, A. (2007). The Effect of Swirl on Spark Assisted Compression Ignition (SACI). *SAE International, JSAE 20077*(SAE 2007-01-1856), 365-375.
- Pischinger, S., & Umierski, M. (2003). SAE TECHNICAL New CNG Concepts for Passenger Cars : High Torque Engines with Superior Fuel Consumption, (724).
- Pischinger, Stefan. (2004). The future of vehicle propulsion – combustion engines and alternatives, 2004(July), 5-16.
- Pourkhesalian, A. M., Shamekhi, A. H., & Salimi, F. (2010). Alternative fuel and gasoline in an SI engine: A comparative study of performance and emissions characteristics. *Fuel*, 89(5), 1056-1063. Elsevier Ltd. doi:10.1016/j.fuel.2009.11.025
- Production, R., & Trade, P. (2012). BP Statistical Review of World Energy June 2012, (June).
- R. Chandra, V.K. Vijay, P.M.V. Subbarao, T.K. Khura. (2011). Performance evaluation of a constant speed IC engine on CNG , methane enriched biogas and biogas. *Applied Energy*, 88(11), 3969-3977. Elsevier Ltd. doi:10.1016/j.apenergy.2011.04.032
- R.A. Bakar. (1997). *Computational And Experimental Investigation of The Combustion Performance in a Diesel Engine*. Hanyang University, PHD Thesis.
- Rosli Abu Bakar, Mardani Ali Sera, Wong Hong Mun. (2002). Towards The Implementation Of CNG Engine : A Literature Review Approach To Problems And Solutions, BSME-ASME International Conference on Thermal Engineering, Bangladesh.

- Rothbart, H. a., & Klipp, D. L. (2004). *Cam Design Handbook*. (Harold A. Rothbart, Ed.) *Journal of Mechanical Design* (Vol. 126, p. 467). New York: McGraw-Hill, Inc. doi:10.1115/1.1723466
- Roussel, O., & Schneider, K. (2006). Numerical study of thermodiffusive flame structures interacting with adiabatic walls using an adaptive multiresolution scheme. *Combustion Theory and Modelling*, 10(2), 273-288. doi:10.1080/13647830500429222
- S. Maji, Rakesh Ranjan, P. B. S. (2000). Comparison of Emissions and Fuel Consumption from CNG and Gasoline. *SAE Technical Paper*, (2000-01-1432). SAE Technical Paper Number 2000-01-1432.
- SAE J1349. (2004). Surface Vehicle Standard. *SAE Power Test Code Committee*.
- Seang-Wock Lee, Han-Seung Lee, Young-Joon Park, Yong-Seok Cho. (2011). Combustion and emission characteristics of HCNG in a constant volume chamber. *Journal of Mechanical Science and Technology*, 25(2), 489-494. doi:10.1007/s12206-010-1231-5
- Sen, a. K., Litak, G., Yao, B.-F., & Li, G.-X. (2010). Analysis of pressure fluctuations in a natural gas engine under lean burn conditions. *Applied Thermal Engineering*, 30(6-7), 776-779. Elsevier Ltd. doi:10.1016/j.applthermaleng.2009.11.002
- Sera, M. A., Bakar, R. A., & Leong, S. K. (2003). CNG Engine Performance Improvement Strategy Through Advanced Intake System. *SAE Technical Paper*, 2003-01-19, 4.
- Smits, J. J. M. (2006). *Modeling of a fluid flow in an internal combustion engine* (p. 94). Eindhoven.
- Suruhanjaya Tenaga Malaysia. (2011). *Annual Report 2011*.
- T. Korakianitis, A.M. Namasivayam, R.J. Crookes. (2011). Natural-gas fueled spark-ignition (SI) and compression-ignition (CI) engine performance and emissions. *Progress in Energy and Combustion Science*, 37(1), 89-112. Elsevier Ltd. doi:10.1016/j.pecs.2010.04.002
- T.K. Ghosh and M.A. Prelas. (2009). *Natural Gas*. (T.K. Ghosh and M.A. Prelas, Ed.) *Energy Resources and Systems* (1st ed., Vol. 1, pp. 281-381). Columbia: Springer Science + Business Media B.V.
- Taylor, A. M. K. P. (2008). Science review of internal combustion engines. *Energy Policy*, 36(12), 4657-4667. doi:10.1016/j.enpol.2008.09.001
- US EPA. (1995). *Compilation of Air Pollutant Emission Factors* (pp. 1.4-1). North Carolina.
- US Energy Information Administration. (2010). *International Energy Outlook* (Vol. 0484, pp. 250-266). Washington DC.

- Urushihara, T., Nakada, T., Kakuhou, A., & Takagi, Y. (1996). Effects of Swirl / Tumble Motion on In-Cylinder Mixture Formation in a Lean-Burn Engine. *SAE Technical Paper*, 961994(412).
- Verhelst, S., & Sheppard, C. G. W. (2009). Multi-zone thermodynamic modelling of spark-ignition engine combustion – An overview. *Energy Conversion and Management*, 50(5), 1326-1335. Elsevier Ltd. doi:10.1016/j.enconman.2009.01.002
- Wei, L., Ying, W., & Longbao, Z. (2007). Study on improvement of fuel economy and reduction in emissions for stoichiometric gasoline engines. *Applied Thermal Engineering*, 27(17-18), 2919-2923. doi:10.1016/j.applthermaleng.2007.04.005
- Whyatt GA. (2010). *Issues Affecting Adoption of Natural Gas Fuel in Light- and Heavy-Duty Vehicles* (p. 26). Richland, Washington 99352.
- Xu (Stewart) Cheng. (2008). *Modeling Injection And Ignition In Direct Injection*. University of Toronto.
- Yoshida, a., Naito, H., & Mishra, D. P. (2008). Turbulent combustion of preheated natural gas-air mixture. *Fuel*, 87(6), 605-611. doi:10.1016/j.fuel.2007.06.030
- Yu Liu, Jeongkuk Yeom, Seongsik Chung. (2013). A study of spray development and combustion propagation processes of spark-ignited direct injection (SIDI) compressed natural gas (CNG). *Mathematical and Computer Modelling*, 57(1-2), 228-244. Elsevier Ltd. doi:10.1016/j.mcm.2011.06.035
- Zhao, F., Lai, M.-C., & Harrington, D. . (1999). Automotive spark-ignited direct-injection gasoline engines. *Progress in Energy and Combustion Science*, 25(5), 437-562. doi:10.1016/S0360-1285(99)00004-0
- Zuohua Huang, Yong Zhang, ke Zeng, Bing Liu, Qian Wang, Deming Jiang. (2007). Natural Gas-Hydrogen-Air Premixed Mixture Combustion with a Constant Volume Bomb. *Energy & Fuels*, 27(4), 692-698.