THERMOPHYSICAL AND OPTIMIZATION OF PERFORMANCE AND EMISSION OF TURBOCHARGED SI ENGINE USING GASOLINE, ETHANOL AND FUSEL OIL BLENDS

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SUPERVISOR'S DECLARATION

We hereby declare that we have checked this thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Doctor of Philosophy.

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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ABSTRAK

Akhir-akhir ini, penggunaan bahan api alternatif menjadi pilihan untuk enjin gasolin. Tambahan pula, penggunaan bahan api fosil untuk menghasilkan tenaga menyebabkan pelepasan ekzos gas yang memudaratkan dan membawa kepada pencemaran udara. Minyak fusel merupakan dihasilkan dari bahan sisa (by-product) melalui penapaian gula atau kanji. Objektif kajian ini adalah untuk menyiasat prestasi enjin, pencemaran, kualiti pembakaran, dan kestabilan pembakaran di dalam enjin silinder. Semua data akan dioptimis menggunakan perisian Design of Expert. Pengukuran sifat bahan api dilakukan terhadap bahan api asas dan bahan tambah (etanol dan minyak fusel) termasuk ketumpatan, nisbah bahan api-udara, nilai tenaga dan kadar alir. Enjin diuji dengan tujuh bahan api dengan berlainan campuran. Keputusan menunjukkan setiap peratus peningkatan pendikit menunjukkan kuasa brek, kecekapan termal brek dan suhu gas ekzos menurun apabila minyak fusel dan etanol digunakan sebanyak 5%, 3.8% dan 4.7% dibandingkan dengan gasolin. Kecekapan bahan api tentu etanol dan minyak fusel didapati meningkat sekata sebanyak 5% dibandingkan bahan api gasolin. Manakala, pencemaran ekzos terhadap NOx, HC dan CO menunjukkan penurunan sebanyak 13%, 3.4% dan 11.5% apabila etanol dan minyak fusel dicampur dengan gasolin. Kadar haba dibekalkan, kadar peningkatan tekanan dan pembakaran sisa jisim menurun sekata sebanyak 3.7%, 2% 3.7% dan 2% untuk campuran etanol dan minyak fusel dibandingkan gasolin. Manakala, kestabilan enjin telah diuji dengan Pekali Variasi masing-masing menunjukkan pada 2.16%, 2.20%, 2.36%, 2.46%, 2.5%, 2.8% untuk F10, F20, F30, E10, E20, E30. Pekali variasi gasolin adalah 2.03%. Manakala pekali variasi untuk E10, E20, E30 F10, F20 dan F30 adalah 2.16%, 2.20%, 2.36%, 2.46%, 2.5% and 2.8%. Pengoptimuman data menggunakan RSM menunjukkan campuran minyak fusel 30%, 3000 rpm dan beban enjin pada 40% adalah signifikan. Ianya dijelaskan dengan keinginan 0.833% dan R kuasa dua (R^2) yang sangat hampir kepada 1 menggunakan perisian komputer. Sebagai kesimpulan, walaupun minyak fusel adalah produk buangan, apabila diproses semula, ia mempunyai nilai tenaga yang setara jika dibandingkan dengan etanol yang merupakan bahan yang dihasilkan khusus untuk digunakan sebagai bahan bakar alternatif.

ABSTRACT

Recently, the use of renewable fuels as substitute of fossil fuel in gasoline engine is increased significantly. Moreover, the use of fossil fuel for energy conversion produces exhaust gases that lead to air pollution. Ethanol is a well-known source of alternative fuel, however, fusel oil which is one of the by-products have also become one of the potential energy resources. It is waste product after ethanol process. An objective of the study is to investigate the engine performance, exhaust emission, combustion quality and combustion stability in the engine cylinder using gasoline, ethanol and fusel oil blends. Then all data of fuel blends were analyse using Response Surface Methodology (RSM) to optimize result for engine testing. The experiment was conducted on a commercial four-cylinder turbocharged gasoline engine. The gasoline fuel and blends with ethanol and fusel oil physicochemical properties were measured. This includes density, air-fuel ratio, heating value and viscosity. The results show brake power, brake thermal efficiency, exhaust gas temperature reduced dramatically when percentage of fuel blends increased by 5%, 3.8% and 4.7% respectively, compared to gasoline. The brake specific fuel consumption significantly increases when fuel blends increased by 5% compared to gasoline. Meanwhile, the NOx, HC and CO emission show improvements when used fuel blends by 13%, 3.4% and 11.5% respectively, compared to gasoline. The in-cylinder pressure shows correlation as cylinder temperature, rate of heat release, rate of pressure rise and mass fraction burn. They were significantly reduced by 3.7%, 2%, 3.7% and 2% respectively, compared to gasoline. Although the engine stability showed a significant increase of the coefficient of variation by 2.16%, 2.20%, 2.36%, 2.46%, 2.5%, 2.8% for F10, F20, F30, E10, E20, E30 respectively. Coefficient of variation for mean effective pressure using gasoline is 2.03%. While coefficient of variation of fuel blends increase such as E10, E20, E30 F10, F20 and F30 by 2.16%, 2.20%, 2.36%, 2.46%, 2.5% and 2.8% respectively. Optimization using RSM was showed the model was significant at 3000 rpm, 40% engine throttle and using fusel oil 30%. In addition, the R-squared was close to 1 and desirability was 0.833%. As a conclusion, although fusel oil is considered a by-product of ethanol production, it has comparable performance with gasoline and ethanol itself.

TABLE OF CONTENT

REFERENCES

Abdullah, N. R., Masjuki, H. H., Ali, O. M., Najafi, G., Abdullah, N. R., Masjuki, H. H., Ali, O. M., Najafi, G., & Yusaf, T. (2018). *Evaluation on physicochemical properties of iso-butanol additives in ethanol-gasoline blend on performance and emission characteristics of a spark-ignition engine*. *144*(June), 960–971. https://doi.org/10.1016/j.applthermaleng.2018.08.057

Agarwal, A. K., Singh, A. P., Maurya, R. K., Chandra Shukla, P., Dhar, A., & Srivastava, D. K. (2018). Combustion characteristics of a common rail direct injection engine using different fuel injection strategies. *International Journal of Thermal Sciences*, *134*(April 2017), 475–484. https://doi.org/10.1016/j.ijthermalsci.2018.07.001

Al-Hasan, M. (2003). Effect of ethanol–unleaded gasoline blends on engine performance and exhaust emission. *Energy Conversion and Management*, *44*(9), 1547–1561. https://doi.org/10.1016/S0196-8904(02)00166-8

Alahmer, A., & Aladayleh, W. (2016). Effect two grades of octane numbers on the performance, exhaust and acoustic emissions of spark ignition engine. *Fuel*, *180*, 80–89. https://doi.org/10.1016/j.fuel.2016.04.025

Alptekin, E. (2017). Evaluation of ethanol and isopropanol as additives with diesel fuel in a CRDI diesel engine. *Fuel*, *205*, 161–172. https://doi.org/10.1016/j.fuel.2017.05.076

Alvarez, C. E. C., Couto, G. E., Roso, V. R., Thiriet, A. B., & Valle, R. M. (2018). A review of prechamber ignition systems as lean combustion technology for SI engines. *Applied Thermal Engineering*, *128*, 107–120. https://doi.org/10.1016/j.applthermaleng.2017.08.118

Arroyo, J., Moreno, F., Muñoz, M., & Monné, C. (2015). Experimental study of ignition timing and supercharging effects on a gasoline engine fueled with synthetic gases extracted from biogas. *Energy Conversion and Management*, *97*, 196–211. https://doi.org/10.1016/j.enconman.2015.03.061

Augustus De Melo, C., De Martino Jannuzzi, G., & De Mello Santana, P. H. (2018). Why should Brazil to implement mandatory fuel economy standards for the light vehicle fleet? *Renewable and Sustainable Energy Reviews*, *81*(April 2016), 1166–1174. https://doi.org/10.1016/j.rser.2017.08.054

Awad, O. I., Ali, O. M., Mamat, R., Abdullah, A. A., Naja, G., Kamarulzaman, M. K., Yusri, I. M., & Noor, M. M. (2017). *Using fusel oil as a blend in gasoline to*

improve SI engine e ffi ciencies : A comprehensive review. *69*(October 2015), 1232–1242. https://doi.org/10.1016/j.rser.2016.11.244

Awad, O. I., Mamat, R. Bin, Ali, O. M., & Yusri, I. M. (2016). *Effect of fuel oil - gasoline fusel blends on the performance and emission characteristics of spark ignition engine : A review*. *3*(5), 31–36.

Awad, O. I., Mamat, R., Ali, O. M., Sidik, N. A. C., Yusaf, T., Kadirgama, K., & Kettner, M. (2017). Alcohol and ether as alternative fuels in spark ignition engine: A review. *Renewable and Sustainable Energy Reviews*, *82*(January 2017), 2586–2605. https://doi.org/10.1016/j.rser.2017.09.074

Awad, O. I., Mamat, R., Ali, O. M., Yusri, I. M., Abdullah, A. A., Yusop, A. F., & Noor, M. M. (2016). The effect of adding fusel oil to diesel on the performance and the emissions characteristics in a single cylinder CI engine. *Journal of the Energy Institute*. https://doi.org/10.1016/j.joei.2016.04.004

Awad, O. I., Mamat, R., Ibrahim, T. K., Ali, O. M., Kadirgama, K., & Leman, A. M. (2017). Performance and combustion characteristics of an SI engine fueled with fusel oil-gasoline at different water content. *Applied Thermal Engineering*, *123*, 1374–1385. https://doi.org/10.1016/j.applthermaleng.2017.05.132

Awad, O. I., Mamat, R., Ibrahim, T. K., Hagos, F. Y., Noor, M. M., Yusri, I. M., & Leman, A. M. (2017). Calorific value enhancement of fusel oil by moisture removal and its effect on the performance and combustion of a spark ignition engine. *Energy Conversion and Management*, *137*, 86–96. https://doi.org/10.1016/j.enconman.2017.01.009

Baêta, J. G. C., Pontoppidan, M., & Silva, T. R. V. (2015). Exploring the limits of a down-sized ethanol direct injection spark ignited engine in different configurations in order to replace high-displacement gasoline engines. *Energy Conversion and Management*, *105*, 858–871. https://doi.org/10.1016/j.enconman.2015.08.041

Bekhet, H. A., & Othman, N. S. (2017). Impact of urbanization growth on Malaysia CO2emissions: Evidence from the dynamic relationship. *Journal of Cleaner Production*, *154*, 374–388. https://doi.org/10.1016/j.jclepro.2017.03.174

Belgiorno, G., Di Blasio, G., Shamun, S., Beatrice, C., Tunestål, P., & Tunér, M. (2018). Performance and emissions of diesel-gasoline-ethanol blends in a light duty compression ignition engine. *Fuel*, *217*(December 2017), 78–90. https://doi.org/10.1016/j.fuel.2017.12.090

Benajes, J., Molina, S., Garcia, A., & Monsalve-Serrano, J. (2015). Effects of direct

injection timing and blending ratio on RCCI combustion with different low reactivity fuels. *Energy Conversion and Management*, *99*, 193–209.

Bergthorson, J. M., & Thomson, M. J. (2015). A review of the combustion and emissions properties of advanced transportation biofuels and their impact on existing and future engines. *Renewable and Sustainable Energy Reviews*, *42*, 1393–1417. https://doi.org/10.1016/j.rser.2014.10.034

Binjuwair, S., & Alkudsi, A. (2016). The effects of varying spark timing on the performance and emission characteristics of a gasoline engine: A study on Saudi Arabian RON91 and RON95. *Fuel*, *180*, 558–564. https://doi.org/10.1016/j.fuel.2016.04.071

Buchspies, B., & Kaltschmitt, M. (2018). A consequential assessment of changes in greenhouse gas emissions due to the introduction of wheat straw ethanol in the context of European legislation. *Applied Energy*, *211*(October 2017), 368–381. https://doi.org/10.1016/j.apenergy.2017.10.105

Calam, A. (2020). Effects of the fusel oil usage in HCCI engine on combustion, performance and emission. *Fuel*, *262*(October 2019), 116503. https://doi.org/10.1016/j.fuel.2019.116503

Calam, A., Içingür, Y., Solmaz, H., & Yamk, H. (2015). A comparison of engine performance and the emission of fusel oil and gasoline mixtures at different ignition timings. *International Journal of Green Energy*, *12*(8), 767–772. https://doi.org/10.1080/15435075.2013.849256

Calam, A., Solmaz, H., Uyumaz, A., Yilmaz, E., & Içingür, Y. (2015). *Investigation of usability of the fusel oil in a single cylinder spark ignition engine*. *88*, 258–265. https://doi.org/10.1016/j.joei.2014.09.005

Canakci, M., Ozsezen, A. N., Alptekin, E., & Eyidogan, M. (2013). Impact of alcohol–gasoline fuel blends on the exhaust emission of an SI engine. *Renewable Energy*, *52*, 111–117. https://doi.org/10.1016/j.renene.2012.09.062

Chen, Z., Yang, F., Xue, S., Wu, Z., & Liu, J. (2015). Impact of higher n-butanol addition on combustion and performance of GDI engine in stoichiometric combustion. *Energy Conversion and Management*, *106*, 385–392. https://doi.org/10.1016/j.enconman.2015.09.051

Costa, R. C., & Sodré, J. R. (2011). Compression ratio effects on an ethanol/gasoline fuelled engine performance. *Applied Thermal Engineering*, *31*(2–3), 278–283. https://doi.org/10.1016/j.applthermaleng.2010.09.007

Demirbas, A. (2002). Relationships between Heating Value and Lignin, Moisture, Ash and Extractive Contents of Biomass Fuels. *Energy Exploration & Exploitation*, *20*(1), 105–111. https://doi.org/10.1260/014459802760170420

Deng, X., Chen, Z., Wang, X., Zhen, H., & Xie, R. (2018). Exhaust noise, performance and emission characteristics of spark ignition engine fuelled with pure gasoline and hydrous ethanol gasoline blends. *Case Studies in Thermal Engineering*, *12*(February), 55–63. https://doi.org/10.1016/j.csite.2018.02.004

Duan, X., Liu, J., Tan, Y., Luo, B., Guo, G., Wu, Z., Liu, W., & Li, Y. (2018). Influence of single injection and two-stagnation injection strategy on thermodynamic process and performance of a turbocharged direct-injection spark-ignition engine fuelled with ethanol and gasoline blend. *Applied Energy*, *228*(June), 942–953. https://doi.org/10.1016/j.apenergy.2018.06.090

Elfasakhany, A. (2015). Investigations on the effects of ethanol–methanol–gasoline blends in a spark-ignition engine: Performance and emissions analysis. *Engineering Science and Technology, an International Journal*, *18*(4), 713–719. https://doi.org/10.1016/j.jestch.2015.05.003

European Comission. (2015). *Climate Action Progress Report 2015*. *525*, 1–64. http://ec.europa.eu/clima/policies/strategies/progress/docs/progress_report_2015_en.pdf

Fagundez, J. L. S., Sari, R. L., Mayer, F. D., Martins, M. E. S., & Salau, N. P. G. (2017). Determination of optimal wet ethanol composition as a fuel in spark ignition engine. *Applied Thermal Engineering*, *112*, 317–325. https://doi.org/10.1016/j.applthermaleng.2016.10.099

Folkson, R. (2014). *Alternative fuels and advanced vehicle tecnologies for improved environment performance*. 736–760. https://doi.org/10.1016/B978-0-85709-522-0.50027-3

Fu, J., Liu, J., Wang, Y., Deng, B., Yang, Y., Feng, R., & Yang, J. (2014). A comparative study on various turbocharging approaches based on IC engine exhaust gas energy recovery. *Applied Energy*, *113*, 248–257. https://doi.org/10.1016/j.apenergy.2013.07.023

Galloni, E., Fontana, G., & Palmaccio, R. (2013). Effects of exhaust gas recycle in a downsized gasoline engine. *Applied Energy*, *105*, 99–107. https://doi.org/10.1016/j.apenergy.2012.12.046

Hagos, F. Y., Aziz, A. R. A., Sulaiman, S. A., Firmansyah, & Mamat, R. (2017). Effect

of fuel injection timing of hydrogen rich syngas augmented with methane in direct-injection spark-ignition engine. *International Journal of Hydrogen Energy*, *42*(37), 23846–23855. https://doi.org/10.1016/j.ijhydene.2017.03.091

He, B. Q., Chen, X., Lin, C. L., & Zhao, H. (2016). Combustion characteristics of a gasoline engine with independent intake port injection and direct injection systems for n-butanol and gasoline. *Energy Conversion and Management*, *124*, 556–565. https://doi.org/10.1016/j.enconman.2016.07.053

Heywood, J. B. (1988). Internal combustion engine. In *McGraw-Hill,Inc* (Vol. 11, Issue 5). https://doi.org/10.1016/0160-4120(85)90256-9

Hsieh, W. D., Chen, R. H., Wu, T. L., & Lin, T. H. (2002). Engine performance and pollutant emission of an SI engine using ethanol-gasoline blended fuels. *Atmospheric Environment*, *36*(3), 403–410. https://doi.org/10.1016/S1352-2310(01)00508-8

Hu, Y., Chen, H., Wang, P., Chen, H., & Ren, L. (2018). Nonlinear model predictive controller design based on learning model for turbocharged gasoline engine of passenger vehicle. *Mechanical Systems and Signal Processing*, *109*(61703177), 74–88. https://doi.org/10.1016/j.ymssp.2018.02.012

Hunicz, J. (2014). An experimental study of negative valve overlap injection effects and their impact on combustion in a gasoline HCCI engine. *Fuel*, *117*, 236–250. https://doi.org/10.1016/j.fuel.2013.09.079

Igliński, H., & Babiak, M. (2017). Analysis of the Potential of Autonomous Vehicles in Reducing the Emissions of Greenhouse Gases in Road Transport. *Procedia Engineering*, *192*, 353–358. https://doi.org/10.1016/j.proeng.2017.06.061

İlhak, M. İ., Doğan, R., Akansu, S. O., & Kahraman, N. (2020). Experimental study on an SI engine fueled by gasoline, ethanol and acetylene at partial loads. *Fuel*, *261*(October 2019). https://doi.org/10.1016/j.fuel.2019.116148

Imran, A., Varman, M., Masjuki, H. H., & Kalam, M. A. (2013). Review on alcohol fumigation on diesel engine: A viable alternative dual fuel technology for satisfactory engine performance and reduction of environment concerning emission. *Renewable and Sustainable Energy Reviews*, *26*, 739–751. https://doi.org/10.1016/j.rser.2013.05.070

Iodice, P., Senatore, A., Langella, G., & Amoresano, A. (2016). Effect of ethanol–gasoline blends on CO and HC emissions in last generation SI engines within the cold-start transient: An experimental investigation. *Applied Energy*, *179*, 182–190.

https://doi.org/10.1016/j.apenergy.2016.06.144

Jamrozik, A. (2017). The effect of the alcohol content in the fuel mixture on the performance and emissions of a direct injection diesel engine fueled with diesel-methanol and diesel-ethanol blends. *Energy Conversion and Management*, *148*, 461–476. https://doi.org/10.1016/j.enconman.2017.06.030

Jesu Godwin, D., Edwin Geo, V., Thiyagarajan, S., Leenus Jesu Martin, M., Maiyalagan, T., Saravanan, C. G., & Aloui, F. (2019). Effect of hydroxyl (OH) group position in alcohol on performance, emission and combustion characteristics of SI engine. *Energy Conversion and Management*, *189*(November 2018), 195–201. https://doi.org/10.1016/j.enconman.2019.03.063

Jiang, C., Li, Z., Qian, Y., Wang, X., Zhang, Y., & Lu, X. (2018). Influences of fuel injection strategies on combustion performance and regular/irregular emissions in a turbocharged gasoline direct injection engine: Commercial gasoline versus multi-components gasoline surrogates. *Energy*, *157*, 173–187. https://doi.org/10.1016/j.energy.2018.05.160

Jindal, S., Nandwana, B. P., Rathore, N. S., & Vashistha, V. (2010). Experimental investigation of the effect of compression ratio and injection pressure in a direct injection diesel engine running on Jatropha methyl ester. *Applied Thermal Engineering*, *30*(5), 442–448. https://doi.org/10.1016/j.applthermaleng.2009.10.004

Kalghatgi, G. T. (2014). Developments in internal combustion engines and implications for combustion science and future transport fuels. *Proceedings of the Combustion Institute*. https://doi.org/10.1016/j.proci.2014.08.031

Karabektas, M., & Hosoz, M. (2009). Performance and emission characteristics of a diesel engine using isobutanol-diesel fuel blends. *Renewable Energy*, *34*(6), 1554–1559. https://doi.org/10.1016/j.renene.2008.11.003

Karagöz, Y., Yüksek, L., Sandalcı, T., & Dalkılıç, A. S. (2014). An experimental investigation on the performance characteristics of a hydroxygen enriched gasoline engine with water injection. *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2014.11.013

Karavalakis, G., Durbin, T. D., Shrivastava, M., Zheng, Z., Villela, M., & Jung, H. (2012). Impacts of ethanol fuel level on emissions of regulated and unregulated pollutants from a fleet of gasoline light-duty vehicles. *Fuel*, *93*, 549–558. https://doi.org/10.1016/j.fuel.2011.09.021

Lanzanova, T. D. M., Dalla Nora, M., & Zhao, H. (2016). Performance and economic analysis of a direct injection spark ignition engine fueled with wet ethanol. *Applied Energy*, *169*, 230–239. https://doi.org/10.1016/j.apenergy.2016.02.016

Lary Altose. (2000). *Health Effects from Automobile Emissions*. 2.

Li, T., Gao, Y., Wang, J., & Chen, Z. (2014). The Miller cycle effects on improvement of fuel economy in a highly boosted, high compression ratio, direct-injection gasoline engine: EIVC vs. LIVC. *Energy Conversion and Management*, *79*, 59–65. https://doi.org/10.1016/j.enconman.2013.12.022

Li, Yu, Gong, J., Deng, Y., Yuan, W., Fu, J., & Zhang, B. (2017). Experimental comparative study on combustion, performance and emissions characteristics of methanol, ethanol and butanol in a spark ignition engine. *Applied Thermal Engineering*, *115*, 53–63. https://doi.org/10.1016/j.applthermaleng.2016.12.037

Li, Yuanxu, Nithyanandan, K., Meng, X., Lee, T. H., Li, Y., Lee, C. fon F., & Ning, Z. (2017). Experimental study on combustion and emission performance of a spark-ignition engine fueled with water containing acetone-gasoline blends. *Fuel*, *210*(x), 133–144. https://doi.org/10.1016/j.fuel.2017.07.058

Li, Yuqiang, Chen, Y., Wu, G., & Liu, J. (2018). Experimental evaluation of water-containing isopropanol-n-butanol-ethanol and gasoline blend as a fuel candidate in spark-ignition engine. *Applied Energy*, *219*(October 2017), 42–52. https://doi.org/10.1016/j.apenergy.2018.03.051

Li, Yuqiang, Meng, L., Nithyanandan, K., Lee, T. H., Lin, Y., Lee, C. fon F., & Liao, S. (2016). Combustion, performance and emissions characteristics of a spark-ignition engine fueled with isopropanol-n-butanol-ethanol and gasoline blends. *Fuel*, *184*, 864–872. https://doi.org/10.1016/j.fuel.2016.07.063

Liu, H., Wang, Z., & Wang, J. (2014). Methanol-gasoline DFSI (dual-fuel spark ignition) combustion with dual-injection for engine knock suppression. *Energy*, *73*, 686–693. https://doi.org/10.1016/j.energy.2014.06.072

Liu, W., & Qin, Y. (2017). A quantitative approach to evaluate risks of spontaneous combustion in longwall gobs based on CO emissions at upper corner. *Fuel*, *210*(May), 359–370. https://doi.org/10.1016/j.fuel.2017.08.083

Luo, Y., Zhu, L., Fang, J., Zhuang, Z., Guan, C., Xia, C., Xie, X., & Huang, Z. (2015). Size distribution, chemical composition and oxidation reactivity of particulate matter from gasoline direct injection (GDI) engine fueled with ethanol-gasoline fuel. *Applied Thermal Engineering*, *89*, 647–655.

https://doi.org/10.1016/j.applthermaleng.2015.06.060

Manzetti, S., & Andersen, O. (2015). A review of emission products from bioethanol and its blends with gasoline. Background for new guidelines for emission control. *Fuel*, *140*, 293–301. https://doi.org/10.1016/j.fuel.2014.09.101

Masum, B. M., Masjuki, H. H., Kalam, M. A., Palash, S. M., & Habibullah, M. (2015). Effect of alcohol–gasoline blends optimization on fuel properties, performance and emissions of a SI engine. *Journal of Cleaner Production*, *86*, 230–237. https://doi.org/10.1016/j.jclepro.2014.08.032

Masum, B. M., Masjuki, H. H., Kalam, M. A., Rizwanul Fattah, I. M., Palash, S. M., & Abedin, M. J. (2013). Effect of ethanol–gasoline blend on NOx emission in SI engine. *Renewable and Sustainable Energy Reviews*, *24*, 209–222. https://doi.org/10.1016/j.rser.2013.03.046

Mayer, F. D., Feris, L. A., Marcilio, N. R., Staudt, P. B., Hoffmann, R., & Baldo, V. (2015). influence of fusel oil components on the distallation of hydrous ethanol fuel (HEF) in a bench column. *Brazilian Journal of Chemical Engineering*, *32*(2), 585–593. https://doi.org/10.1590/0104-6632.20150322s00003215

Mayer, Flávio Dias, Feris, L. A., Marcilio, N. R., & Hoffmann, R. (2015). Why small-scale fuel ethanol production in Brazil does not take off? *Renewable and Sustainable Energy Reviews*, *43*, 687–701. https://doi.org/10.1016/j.rser.2014.11.076

Mello, P., Wildner, F., Souza, G., & Catalun, R. (2014). *Combustion time of the oxygenated and non-oxygenated fuels in an Otto cycle engine*. 403–410. https://doi.org/10.1007/s40430-013-0094-y

Mingrui, W., Thanh Sa, N., Turkson, R. F., Jinping, L., & Guanlun, G. (2017). Water injection for higher engine performance and lower emissions. *Journal of the Energy Institute*, *90*(2), 285–299. https://doi.org/10.1016/j.joei.2015.12.003

Mlay, H., Katima, J. H. Y., & Minja, R. J. A. (2015). *Plant Oil / Fusel Oil Blends as Alternative Fuels in Low- and Medium Speed Diesel Engines*. *2*(2), 9–16.

Mohammad, S., Ardebili, S., Solmaz, H., Calam, A., & Ipci, D. (2021). *Modelling of performance , emission , and combustion of an HCCI engine fueled with fusel oil-diethylether fuel blends as a renewable fuel*. *290*(November 2020). https://doi.org/10.1016/j.fuel.2020.120017

Mohd, C. he W. (2018). *Experimental And Prediction Model On Low Compression*

Marine Diesel Engine Fuelled With Palm Biodiesel- Diesel Blends.

Najafi, G., Ghobadian, B., Moosavian, A., Yusaf, T., Mamat, R., Kettner, M., & Azmi, W. H. (2016). SVM and ANFIS for prediction of performance and exhaust emissions of a SI engine with gasoline-ethanol blended fuels. *Applied Thermal Engineering*, *95*, 186–203. https://doi.org/10.1016/j.applthermaleng.2015.11.009

Najafi, Gholamhassan, Ghobadian, B., Yusaf, T., Ardebili, S. M. S., & Mamat, R. (2015). Optimization of performance and exhaust emission parameters of a SI (spark ignition) engine with gasolineeethanol blended fuels using response surface methodology. *Energy*, *90*, 1815–1829. https://doi.org/10.1016/j.energy.2015.07.004

Nanthagopal, K., Kishna, R. S., Atabani, A. E., Al-Muhtaseb, A. H., Kumar, G., & Ashok, B. (2020). A compressive review on the effects of alcohols and nanoparticles as an oxygenated enhancer in compression ignition engine. *Energy Conversion and Management*, *203*(November 2019), 112244. https://doi.org/10.1016/j.enconman.2019.112244

Navarro, E., Leo, T. J., & Corral, R. (2013). CO2 emissions from a spark ignition engine operating on natural gas–hydrogen blends (HCNG). *Applied Energy*, *101*, 112–120. https://doi.org/10.1016/j.apenergy.2012.02.046

Pan, M., Qian, W., Wei, H., Feng, D., & Pan, J. (2020). Effects on performance and emissions of gasoline compression ignition engine over a wide range of internal exhaust gas recirculation rates under lean conditions. *Fuel*, *265*(November 2019), 116881. https://doi.org/10.1016/j.fuel.2019.116881

Park, C., Choi, Y., Kim, C., Oh, S., Lim, G., & Moriyoshi, Y. (2010). Performance and exhaust emission characteristics of a spark ignition engine using ethanol and ethanol-reformed gas. *Fuel*, *89*(8), 2118–2125. https://doi.org/10.1016/j.fuel.2010.03.018

Peters, C. a. (2001). Statistics for Analysis of Experimental Data Princeton University Statistics for Analysis of Experimental Data. *Environmental Engineering Processes Laboratory Manual*, 1–25. https://doi.org/10.1145/2901739.2901780

Pulkrabek, W. W. (1997). Engineering fundamentals of the internal combustion engine. In *Prentice Hall* (Vol. 126). https://doi.org/10.1115/1.1669459

Qian, Y., Liu, G., Guo, J., Zhang, Y., Zhu, L., & Lu, X. (2019). Engine performance and octane on demand studies of a dual fuel spark ignition engine with ethanol/gasoline surrogates as fuel. *Energy Conversion and Management*,

183(January), 296–306. https://doi.org/10.1016/j.enconman.2019.01.011

Qian, Y., Zhu, L., Wang, Y., & Lu, X. (2015). Recent progress in the development of biofuel 2,5-dimethylfuran. *Renewable and Sustainable Energy Reviews*, *41*, 633–646. https://doi.org/10.1016/j.rser.2014.08.085

Rajesh Kumar, B., Saravanan, S., Rana, D., & Nagendran, A. (2016). Combined effect of injection timing and exhaust gas recirculation (EGR) on performance and emissions of a DI diesel engine fuelled with next-generation advanced biofuel – diesel blends using response surface methodology. *Energy Conversion and Management*, *123*, 470–486. https://doi.org/10.1016/j.enconman.2016.06.064

Reddy, S. S. K., Pandurangadu, V., & Hussain, S. P. A. (2013). Effect of Turbo charging On Volumetric Efficiency in an Insulated Di Diesel Engine For Improved Performance. *International Journal of Modern Engineering Research (IJMER)*, *3*(2), 674–677.

Rizwanul Fattah, I. M., Masjuki, H. H., Kalam, M. A., Mofijur, M., & Abedin, M. J. (2014). Effect of antioxidant on the performance and emission characteristics of a diesel engine fueled with palm biodiesel blends. *Energy Conversion and Management*, *79*, 265–272. https://doi.org/10.1016/j.enconman.2013.12.024

Rosdia, S. M., Mamata, R., Azri, A., Sudhakar, K., & Yusri, I. M. (2019). Evaluation of properties on performance and emission to turbocharged SI engine using fusel oil blend with gasoline. *IOP Conference Series: Materials Science and Engineering*, *469*(1). https://doi.org/10.1088/1757-899X/469/1/012113

Rothamer, D. A., & Jennings, J. H. (2012). Study of the knocking propensity of 2,5-dimethylfuran–gasoline and ethanol–gasoline blends. *Fuel*, *98*, 203–212. https://doi.org/10.1016/j.fuel.2012.03.049

Safieddin Ardebili, S. M., Solmaz, H., & Mostafaei, M. (2019). Optimization of fusel oil – Gasoline blend ratio to enhance the performance and reduce emissions. *Applied Thermal Engineering*, *148*(December 2018), 1334–1345. https://doi.org/10.1016/j.applthermaleng.2018.12.005

Sakthivel, P., Subramanian, K. A., & Mathai, R. (2018). Indian scenario of ethanol fuel and its utilization in automotive transportation sector. *Resources, Conservation and Recycling*, *132*(September 2017), 102–120. https://doi.org/10.1016/j.resconrec.2018.01.012

Sakthivel, P., Subramanian, K. A., & Mathai, R. (2019). Comparative studies on combustion, performance and emission characteristics of a two-wheeler with

gasoline and 30% ethanol-gasoline blend using chassis dynamometer. *Applied Thermal Engineering*, *146*, 726–737. https://doi.org/10.1016/j.applthermaleng.2018.10.035

Sen, A. K., Ash, S. K., Huang, B., & Huang, Z. (2011). Effect of exhaust gas recirculation on the cycle-to-cycle variations in a natural gas spark ignition engine. *Applied Thermal Engineering*, *31*(14–15), 2247–2253. https://doi.org/10.1016/j.applthermaleng.2011.03.018

Shameer, P. M., & Ramesh, K. (2017). Experimental evaluation on performance, combustion behavior and influence of in-cylinder temperature on NOx emission in a D.I diesel engine using thermal imager for various alternate fuel blends. *Energy*, *118*, 1334–1344. https://doi.org/10.1016/j.energy.2016.11.017

Sharma, N., Patel, C., Tiwari, N., & Agarwal, A. K. (2019). Experimental Investigations of Noise and Vibration Characteristics of Gasoline/ Methanol Blend Fuelled Gasoline Direct Injection Engine and Their Relationship with Combustion Characteristics. *Applied Thermal Engineering*, 113754. https://doi.org/10.1016/j.applthermaleng.2019.113754

Sharudin, H., Abdullah, N. R., Najafi, G., Mamat, R., & Masjuki, H. H. (2017). Investigation of the effects of iso-butanol additives on spark ignition engine fuelled with methanol-gasoline blends. *Applied Thermal Engineering*, *114*, 593–600. https://doi.org/10.1016/j.applthermaleng.2016.12.017

Shehata, M. S. (2010). Cylinder pressure, performance parameters, heat release, specific heats ratio and duration of combustion for spark ignition engine. *Energy*, *35*(12), 4710–4725. https://doi.org/10.1016/j.energy.2010.09.027

Shirazi, S. A., Abdollahipoor, B., Windom, B., Reardon, K. F., & Foust, T. D. (2020). Effects of blending C3-C4 alcohols on motor gasoline properties and performance of spark ignition engines: A review. *Fuel Processing Technology*, *197*(August 2019), 106194. https://doi.org/10.1016/j.fuproc.2019.106194

Shuba, E. S., & Kifle, D. (2018). Microalgae to biofuels: 'Promising' alternative and renewable energy, review. *Renewable and Sustainable Energy Reviews*, *81*(May 2017), 743–755. https://doi.org/10.1016/j.rser.2017.08.042

Simsek, S., & Ozdalyan, B. (2018). Improvements to the Composition of Fusel Oil and Analysis of the Effects of Fusel Oil–Gasoline Blends on a Spark-Ignited (SI) Engine's Performance and Emissions. *Energies*, *11*(3), 625. https://doi.org/10.3390/en11030625

Siwale, L., Kristóf, L., Adam, T., Bereczky, A., Mbarawa, M., Penninger, A., & Kolesnikov, A. (2013). Combustion and emission characteristics of n-butanol/diesel fuel blend in a turbo-charged compression ignition engine. *Fuel*, *107*, 409–418. https://doi.org/10.1016/j.fuel.2012.11.083

Solmaz, H. (2015). *Combustion , performance and emission characteristics of fusel oil in a spark ignition engine*. *133*, 20–28. https://doi.org/10.1016/j.fuproc.2015.01.010

Szwaja, S., & Naber, J. D. (2010). Combustion of n-butanol in a spark-ignition IC engine. *Fuel*, *89*(7), 1573–1582. https://doi.org/10.1016/j.fuel.2009.08.043

Taylor, P., Karaosmanoğlu, Fi., Işiğigür, A., & Aksoy, H. A. (2007). *Methanol-Unleaded Gasoline Blends Containing Fusel Oil Fraction as Spark Ignition Engine Fuel Methanol-Unleaded Gasoline Blends Containing Fuse1 Oil Fraction as Spark Ignition Engine Fuel*. *July 2012*, 37–41.

Thangavel, V., Momula, S. Y., Gosala, D. B., & Asvathanarayanan, R. (2016). Experimental studies on simultaneous injection of ethanol-gasoline and n-butanol-gasoline in the intake port of a four stroke SI engine. *Renewable Energy*, *91*, 347–360. https://doi.org/10.1016/j.renene.2016.01.074

Thangavelu, S. K., Ahmed, A. S., & Ani, F. N. (2016). Review on bioethanol as alternative fuel for spark ignition engines. *Renewable and Sustainable Energy Reviews*, *56*, 820–835. https://doi.org/10.1016/j.rser.2015.11.089

Topg, T., Ycesu, Hseyin Serdar inar, C., & Koca, A. (2006). The effects of ethanol-unleaded gasoline blends and ignition timing on engine performance and exhaust emissions. *Renewable Energy*, *31*(15), 2534–2542. https://doi.org/10.1016/j.renene.2006.01.004

Turner, J. W. G., Popplewell, A., Patel, R., Johnson, T. R., Darnton, N. J., Richardson, S., Rover, J. L., Tudor, R. J., Bithell, C. I., Jackson, R., Global, S., Uk, S., Fernandes, J. X., Lewis, A. G. J., Akehurst, S., Brace, C. J., & Copeland, C. (2018). *Ultra Boost for Economy : Extending the Limits of Extreme Engine Downsizing*. https://doi.org/10.4271/2014-01-1185

U.S. EPA. (2018). *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. https://www.epa.gov/sites/production/files/2018-01/documents/2018_complete_report.pdf

Vilnis, & Maris. (2011). *effect of ignition timing on emission of spark ignition engine using e85 fuel*. *1*, 1–7.

Wan Ghazali, W. N. M., Mamat, R., Masjuki, H. H., & Najafi, G. (2015). Effects of biodiesel from different feedstocks on engine performance and emissions: A review. *Renewable and Sustainable Energy Reviews*, *51*, 585–602. https://doi.org/10.1016/j.rser.2015.06.031

Wang, C., Janssen, A., Prakash, A., Cracknell, R., & Xu, H. (2017). Splash blended ethanol in a spark ignition engine – Effect of RON, octane sensitivity and charge cooling. *Fuel*, *196*, 21–31. https://doi.org/10.1016/j.fuel.2017.01.075

Wang, S., Ji, C., Zhang, B., Cong, X., & Liu, X. (2016). Effect of CO2 dilution on combustion and emissions characteristics of the hydrogen-enriched gasoline engine. *Energy*, *96*, 118–126. https://doi.org/10.1016/j.energy.2015.12.017

Wang, S., Ji, C., Zhang, M., & Zhang, B. (2010). Reducing the idle speed of a spark-ignited gasoline engine with hydrogen addition. *International Journal of Hydrogen Energy*, *35*(19), 10580–10588. https://doi.org/10.1016/j.ijhydene.2010.08.002

Wang, X., Chen, Z., Ni, J., Liu, S., & Zhou, H. (2015). The effects of hydrous ethanol gasoline on combustion and emission characteristics of a port injection gasoline engine. *Case Studies in Thermal Engineering*, *6*, 147–154. https://doi.org/10.1016/j.csite.2015.09.007

Wang, Z., Liu, H., Long, Y., Wang, J., & He, X. (2015). Comparative study on alcohols–gasoline and gasoline–alcohols dual-fuel spark ignition (DFSI) combustion for high load extension and high fuel efficiency. *Energy*, *82*, 395–405. https://doi.org/10.1016/j.energy.2015.01.049

Wang, Z., Liu, H., & Reitz, R. D. (2017). Knocking combustion in spark-ignition engines. *Progress in Energy and Combustion Science*, *61*, 78–112. https://doi.org/10.1016/j.pecs.2017.03.004

Wei, H., Feng, D., Pan, M., Pan, J., Rao, X., & Gao, D. (2016). Experimental investigation on the knocking combustion characteristics of n-butanol gasoline blends in a DISI engine. *Applied Energy*, *175*, 346–355. https://doi.org/10.1016/j.apenergy.2016.05.029

Wei, H., Feng, D., Shu, G., Pan, M., Guo, Y., Gao, D., & Li, W. (2014). Experimental investigation on the combustion and emissions characteristics of 2-methylfuran gasoline blend fuel in spark-ignition engine. *Applied Energy*, *132*, 317–324. https://doi.org/10.1016/j.apenergy.2014.07.009

Wilson, T., Baker, R., Ricketts, M., Roe, S., Wilson, C., & Koehler, N. (2016). 2 0 16 e t h a n o l i n d u s t r y o u t l o o k. *Renewable Fuels Association*.

Yahoo, M., & Othman, J. (2017). Employing a CGE model in analysing the environmental and economy-wide impacts of CO2emission abatement policies in Malaysia. *Science of the Total Environment*, *584–585*, 234–243. https://doi.org/10.1016/j.scitotenv.2017.01.164

Yasin, M. H. M., Mamat, R., Yusop, A. F., Rahim, R., Aziz, A., & Shah, L. A. (2013). Fuel physical characteristics of biodiesel blend fuels with alcohol as additives. *Procedia Engineering*, *53*, 701–706. https://doi.org/10.1016/j.proeng.2013.02.091

Yusri, I. M., Mamat, R., Azmi, W. H., Najafi, G., Sidik, N. A. C., & Awad, O. I. (2016). Experimental investigation of combustion, emissions and thermal balance of secondary butyl alcohol-gasoline blends in a spark ignition engine. *Energy Conversion and Management*, *123*, 1–14. https://doi.org/10.1016/j.enconman.2016.05.082

Zabed, H., Sahu, J. N., Suely, A., Boyce, A. N., & Faruq, G. (2017). Bioethanol production from renewable sources: Current perspectives and technological progress. *Renewable and Sustainable Energy Reviews*, *71*(December 2016), 475–501. https://doi.org/10.1016/j.rser.2016.12.076

Zhang, M., Hong, W., Xie, F., Su, Y., Han, L., & Wu, B. (2017). Influence of diluents on combustion and emission characteristics of a GDI engine. *Applied Thermal Engineering*, *124*, 746–755. https://doi.org/10.1016/j.applthermaleng.2017.06.043

Zhao, H., Stone, R., & Zhou, L. (2010). Analysis of the particulate emissions and combustion performance of a direct injection spark ignition engine using hydrogen and gasoline mixtures. *International Journal of Hydrogen Energy*, *35*(10), 4676–4686. https://doi.org/10.1016/j.ijhydene.2010.02.087

Zhao, L., Wang, X., Wang, D., & Su, X. (2020). Investigation of the effects of lean mixtures on combustion and particulate emissions in a DISI engine fueled with bioethanol-gasoline blends. *Fuel*, *260*(March 2019), 116096. https://doi.org/10.1016/j.fuel.2019.116096

Zhu, G., Liu, J., Fu, J., Xu, Z., Guo, Q., & Zhao, H. (2018). Experimental study on combustion and emission characteristics of turbocharged gasoline direct injection (GDI) engine under cold start new European driving cycle (NEDC). *Fuel*, *215*(September 2017), 272–284. https://doi.org/10.1016/j.fuel.2017.10.048

Zhuang, Y., & Hong, G. (2013). Primary investigation to leveraging effect of using ethanol fuel on reducing gasoline fuel consumption. *Fuel*, *105*, 425–431. https://doi.org/10.1016/j.fuel.2012.09.013

Zhuang, Y., Qian, Y., & Hong, G. (2017). The effect of ethanol direct injection on knock mitigation in a gasoline port injection engine. *Fuel*, *210*(August), 187–197. https://doi.org/10.1016/j.fuel.2017.08.060

Zou, P., Liu, J., Zhou, X., Chen, Z., Luo, B., Shen, D., Duan, X., & Fu, J. (2020). Effect of a novel mechanical CVVL system on economic performance of a turbocharged spark-ignition engine fuelled with gasoline and ethanol blend. *Fuel*, *263*(October 2019), 116697. https://doi.org/10.1016/j.fuel.2019.116697